A STUDY OF NOISE IMMUNITY OF MULTICHANNEL RADIO CIRCUIT WITH A BAND-SAVING MODULATION METHOD UNDER THE INFLUENCE OF NOISE FROM NEIGHBOURING CHANNEL

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Abstract

In this paper, we present the results of investigation of influence of interchannel interference (ICI) on the merit of the reception of different coherent multichannel digital radio systems, used band-saving modulation methods. We show that the estimation of merit of the reception depends on power of ICI, as well as it depends on timing shifts and phase shifts of ICI relative to useful signal. In addition, in general, that's true to take into account as the influence of near-by ICI channels, as the influence of distant ICI channels. In paper we present the results of comparisons of the merit of reception in the presence of influence of ICI and Gaussian noise for band-saving modulation methods and systems.

1. Introduction

Quadrate phase shift keying (QPSK)\(^{(1)}\), minimum shift keying (MSK)\(^{(2)}\), tamed frequency modulation (TFM)\(^{(3)}\) are the band-saving modulation methods. These methods are efficient for application in multichannel coherent satellite data transmission (DT) radio systems\(^{(4)}\); QPSK signal has been examined for application in multichannel coherent digital television (TV) radio systems\(^{(5)}\).

Symbol error probability is the performance of efficiency for digital DT systems. For TV systems merit of received images is determined with help of vision evaluation in multichannel digital radio systems, in general, adjacent channel signal is different from useful signal by amplitude (U), carrier frequency shift (df), informative symbols sequence, symbol timing shift (db) and carrier phase shift (df). For useful signal the adjacent channel signal is ICI. We can assume that symbol's duration of ICI is a little relative to duration of communication time interval, and in addition, U and df are fixed. These is the case of non fading reception in practice.

Then, if ICI from everybody interfering channels and white Gaussian noise act, symbol error probability (P) is evaluated as the average over all random sequences of interference symbols. However, P depends on dt and df, i.e. \( P = P(dt, df) \) (lengths of \( dt, df \) vectors are determined by the number acting interfering channels). The actual questions appear:

A. What does P depend on shifts influence?

B. What cases and systems do we must consider the shifts influence in?

C. What cases do we can take the average over \( (dt, df) \) in?

There are several papers \( (1),(6)-(8) \) which are regarded the problem of P evaluating in the presence of the influence of ICI and Gaussian noise.

For example, in \( (6) \) there were deriving expressions for worst case of carrier phase shift in MSK systems, but influence of random ICI symbols and influence of symbol timing shifts were not taken into account.

In other analysis \( (7) \) there were represented average estimations over all shifts in MSK systems. An equivalent white Gaussian noise model for ICI is used in \( (1) \) for to estimate performance degradation because of ICI influence in binary phase shift keying (BPSK), QPSK systems.

An analogous model of ICI is employed in order to investigate MSK, TFM systems in \( (6) \).

In these and others published researches there were not found the answers on asked questions above. In addition, all published results taken into account the influence of only near-by interference channels (two channels influence). The problem of image merit estimation in the presence of the influence of ICI and the question of band-saving MSK, TFM methods application in TV systems are little studied today too.

In our investigation, we create theoretical techniques and sufficiently convenience design means of simulating in order to estimate ICI influence on reception merit in multichannel coherent digital DT and TV systems of different modulation methods, even if synchronization errors and intersymbol interference (ISI) are present.

In this paper, we present as the timing shifts \( (dt) \) and phase shifts \( (df) \) influences results on P, as interfering acting channels number influence results on P for coherent multichannel digital DT and TV systems with BPSK, QPSK, MSK, TFM modulation methods application. Channel optimization techniques and result are shown too in paper. We publish the results of ICI and Gaussian noise influence comparison in different systems for several type cases.

2. The choice of criterion

In concrete communication interval, the P depends on stability of channel symbol and carrier frequency oscillators, as well as the P depends on communication interval duration (CID)\(^{(10)}\).

In the case of high stability of oscillators and little CID, we can consider that dt and df are fixed. Then P depends on random fixed shifts. Since, in independent channels the values of shifts are not known, that’s true to estimate P for most dangerous shifts. Then the best modulation method (B) is determined (on j=1..I multitude of all modulation methods) by MINIMAX criterion as

\[
B = \min_{j=1}^{I} \max \left( P(\Delta t_j, \Delta f_j) \right) \tag{1}
\]

In the case of low stability of oscillators and large CID, the communication merit is estimated by average P. Then the best modulation method is determined by AVERAGE criterion as

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3. The descriptions of investigated signals and systems

We examine QPSK, MSK, TFM band-saving modulation methods in this work, and BPSK (1) traditional modulation method is included for comparison.

Basic modulation methods analytical expressions are represented as (1)-(3)

**BPSK:**
\[ U_s(t) = U_s I_s(t) \cos(2\pi f_s t + F_s) + \]  
\[ U_c(t) = U_c I_c(t) \sin(2\pi f_s t + \pi/2 + F_s) \]  
\[ J_s(t) = \frac{1}{\sqrt{2}} \sum_{m=-\infty}^{\infty} I_s(t) \delta(t - T_s m) \]  
\[ J_c(t) = \frac{1}{\sqrt{2}} \sum_{m=-\infty}^{\infty} I_c(t) \delta(t - T_c m) \]  
\[ TFM: U_s(t) = U_s I_s(t) \cos(2\pi f_s t + \pi/2) \sum_{m=-\infty}^{\infty} I_s(t) \delta(t - T_s m) \]  
\[ TFM: U_c(t) = U_c I_c(t) \sin(2\pi f_s t + \pi/2) \sum_{m=-\infty}^{\infty} I_c(t) \delta(t - T_c m) \]

Where: \( U_s, I_s, F_s \) denote, according to, the amplitude, carrier frequency, initial phase of signal; \( I_s(t) \) the informative symbols sequence of Ts duration; \( I_c(t) \) is the informative symbols sequence of ZT duration, accordingly to, for different quadrature channels; \( T_s, T_c \) is the time variable, and \( 0 < T_s, T_c < T_0 \) denotes TFM premadulation impulse response.

In our work, we use TFM premadulation filter response with 7-symbols length truncation (3).

Informative symbols are \( \pm 1 \) with 0.5 probability. The analytical expressions of ICI accord (3)-(6) expressions of signals, but all represented variables of according ICI have 'i' index instead signal 's' index. In different from BPSK, the QPSK, MSK, TFM methods are quadrature methods. Fig. 1 represents the coherent reception part scheme structure of one quadrature channel. This scheme consits of according optimum (in the presence of white Gaussian noise only) coherent demodulator, decision device (DD) and decoding relative device (differential decoder). We will call this reception structure as basic reception channel. In addition, when transmitter does not distort basic modulation method spectrum (there are not narrow-band filters in sending side), then we will call this channel as basic channel.

![Figure 1. Coherent reception structure of basic channel](image)

In this work, we examine as basic channels of different modulation methods, as basic channels with addition of different receiver's filters and transmitter's filters (rectangular filters, Nyquist filters etc).

4. Theoretical techniques of investigation

The theoretical investigation (6,10) is released in order to estimate \( P \) in influence of ICI and Gaussian noise in systems with absence of ISI. This systems are BPSK, QPSK, MSK basic channels.

Let in the input of basic reception channel there is the mixture of \( n \)-realization of useful signal \( U_{in}, I_{in}(t) \)-realization of ICI of every body acting channels \( U_{in}, I_{in}(t) \), white Gaussian noise \( N(t) \).

Then input voltage is represented as

\[ U_{in}(t) = U_{in}(t) + N(t) \]  
\[ \text{(7)} \]

Let we consider that optimum demodulator is linear and synchronization is ideal.

Then conditional error probability of useful k-symbol is estimated as (10)

\[ P_k = 1 - \Phi \left[ \frac{M_i n(t) + K_i l(t)}{\sqrt{2}} \right] \]  
\[ \text{(8)} \]

where: \( M_i n(t) \), \( l(t) \), \( I_i, I(t) \) denote, according to, voltage of \( n \)-realization of useful signal and voltage of l-realization of sum ICI of everybody acting channels in the input of DD at the t counter time moment; \( D \) is dispersion of Gaussian noise in DD input, \( \Phi \) denotes probability integral, \( \Phi = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-x^2/2} dx \).

If ICI is absence, then in basic channels\( M_i n(t) = M_0 \) for any n.

Then we can decompose the expression (8) in the line of Teller for \( M_0 \) point on \( \frac{K_0}{\sqrt{2}} \) degrees, and we can write (9,10)

\[ P_k = 1 - \Phi(\eta) + \sum_{c=2}^{\infty} \frac{K_c}{\lambda} \left[ M_c l(t) \right] \]  
\[ \text{(9)} \]

where \( \frac{K_c}{\lambda} \) is the average of the combination of ICI symbols at the demodulation's time interval, and after we take into account that odd degrees members of line equal zero, then we obtain the estimation

\[ \lambda = \sqrt{\frac{\sum_{c=2}^{\infty} \left[ M_c l(t) \right]^2}{M_0^2}} \]  
\[ \text{(10)} \]

Necessary number of members of line (10) is determined by required exactitude of \( P \) estimation, as well as by parameter

\[ \lambda \approx \sqrt{\frac{\sum_{c=2}^{\infty} \left[ M_c l(t) \right]^2}{M_0^2}} \]  
\[ \text{(11)} \]

For example, if required exactitude of \( P \) estimation is 30% and \( M_0 \), then \( \left[ M_0 l(t) \right] \) second moment of ICI is sufficient for estimation.

In described systems, we find the estimations of \( \left[ M_0 l(t) \right] \) as \( \text{Min}(M_0 l(t), \delta t/4) \) \( F \) is some function \( G \), that allows to obtain as minimax criterion estimations of \( P \), as average criterion estimations of \( P \) for different modulation methods.

In addition, by means of these theoretical techniques we investigate the influence of number of taken into account acting ICI channels on estimation of \( P \) for different modulation methods.
5. The results of theoretical investigation

Table 1 represents the results of theoretical investigation for next conditions: symbol energy ratio Eb/N0=10 db (Eb is the energy per bit, N0 is white Gaussian noise spectral density), frequency shift between channels relative to symbol frequency (1/T0) df=1.6, input interference to signal ratio (U/IUs)=0 db, and informative rates of everybody channels are equal. Next conclusions follow from obtained results. P is increased because of ICI influence. Value of P depends on power of ICI, as well as it depends on timing shifts and phase shifts of ICI relative to useful signal. Therefore, that's true to consider the P estimation by average criterion (average P) and by minimax criterion (worst case).

<table>
<thead>
<tr>
<th>Modulation method</th>
<th>Number of accounted channels of ICI</th>
<th>Criterion</th>
<th>Average</th>
<th>MINIMAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFSK</td>
<td>6</td>
<td>8.6·10⁻⁴</td>
<td>5.0·10⁻³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.0·10⁻⁴</td>
<td>5.0·10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>QPSK</td>
<td>6</td>
<td>3.0·10⁻⁴</td>
<td>7.0·10⁻⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.6·10⁻⁴</td>
<td>3.4·10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>MSK</td>
<td>6</td>
<td>1.0·10⁻⁵</td>
<td>1.5·10⁻⁵</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.8·10⁻⁵</td>
<td>1.1·10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>TFM</td>
<td>6</td>
<td>1.0·10⁻⁴</td>
<td>1.0·10⁻⁴</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.0·10⁻⁴</td>
<td>1.0·10⁻⁴</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Estimations of symbol error probability (P) in the case of Eb/N0=10 db, df=1.6, (U/IUs)=0 db.

In general, P depends on influence of near-by channels (on frequency), as well as it depends on influence of distant channels. Moreover, if influence of distant channels is not taken into account in P estimation, then it can lead to significant errors in P estimation in some cases (see Table 1).

The number of channels of ICI taken into account in P estimation depends on filtering properties of receiver, as well as it depends on modulation method.

For example, in basic channels of BFSK, QPSK modulation methods, it is required to take into account in P estimation the influence of not less than 6 channels of ICI. In MSK, TFM systems influence of shifts and number of ICI channels on P is significant smaller.

From the released investigation it follows, that in general, the information about energy spectrum of ICI is not sufficient in order to estimate P. It is significant to take into account as power of ICI, as timing structure and statistical properties of ICI. Only in the case of: large noise (Eb/N0≥10db, df=1.6, (U/IUs)=0 db), P estimation obtained with help of energy spectrum is true by average criterion exceptionally.

In addition, by means of theoretical methods with help of obtained moments of ICI, the coefficient of excess of DD input mixture of ICI and Gaussian noise was investigated. In result, conclusion was released that's true by means of Gaussian noise model (1.8) to take into account the influence of distant channels of ICI (for example, beginning with 7 channel in BFSK, QPSK systems), since in this case the DD input mixture (for distant ICI channels) is practically Gaussian. However, in general, with considering of influence of near-by ICI channels, the DD input mixture is not Gaussian. Consequently, the influence of near-by channels of ICI is not true to take into account by means of Gaussian noise model, and it is required to determine this influence according to expression (3).

6. The account-and-simulation model

Described above theoretical methods are sufficient in order to investigate simple systems, such as basic channels. However, the investigation of more complex systems with addition of different filters is difficult or it requires the significant admissions.

So, the account-and-simulation model (ASM) was created in (12). The ASM is based on the combination of statistical experiment and account. Advantage of this ASM is high time action. In the result of original method of determination of P, the time interval of statistical experiment is decreased more than in 10 time relative to usual simulation model on P<10⁻⁴.

The ASM, at not long time interval, for high immunity systems, in presence of the influence of ICI and Gaussian noise, allows to investigate different modulation methods and channel structures, to create the optimization of parameters of channel structures, to estimate the influence of synchronization errors on reception merit. In ASM the acting ICI channels are simulated with took into account of timing shifts and phase shifts relative to useful signal, that allows to obtain the minimax criterion and average criterion estimations.

We created the investigations (12) of verification of adequacy and statistical reliability of ASM results. In order to verify the adequacy of ASM, the ASM results were compared with theoretical reliable results, obtained with absence of significant admissions in used theoretical method. In addition, we compared the ASM results with analogous results of usual simulation model on P<10⁻⁴.

In order to verify the statistical reliability of ASM results, we obtained the line of quantities of selected P and we examined the statistical distribution of this line. The results of examination follow to consider that mean-square error of obtained ASM estimations not exceeds the 30% from P for taken selection of statistical experiment. In the result of described investigations we created the conclusion that ASM is adequacy and ASM results are statistical reliable.

By means of ASM we investigated BFSK, QPSK, MSK, TFM modulation methods and systems (12). Investigated coherent channel structure of these systems consists of the according basic channel (fig. 1) or basic channel with addition different receiver's filters and transmitter's filters. For example, one of the class of the investigated channels, is class of channels with rectangular receiver's filter with bandwidth taken as optimum bandwidth by criterion of minimum of P. The optimum bandwidth was found by means of approached theoretical methods and by means of ASM.
For high immunity systems worked in the conditions of little level of noise \( \text{E} (\text{b}/\text{n}) \times 10^6 \) db, the approach estimation (A) of optimum bandwidth of receiver's filter, for taken into account the influence from H acting ICI channels, is determined by numerical solving of equation (11)

\[
\sum_{i=1}^{H} \left[ G_s(A/2+2\pi f_i) + G_s(A/2-2\pi f_i) \right] = G_s(A/2) = 0
\]

where \( G_s(f) \) denotes the energy spectrum of received signal.

If the shape of frequency performance of transmitter's filter is \( W(t) \), and if the energy spectrum of according basic modulation method is \( S_b(t) \), then \( G_s(t) \) is determined as

\[
G_s(t) = W(t) \cdot S_b(t)
\]

In addition, by means of ASM we investigated the channels with Nyquist filters too.

7. The results of ASM investigations

In the results of ASM investigations (12), we obtained the dependency of energy loss (L) (relative to ideal BPSK basic channel in presence of Gaussian noise only) from \( \Delta f \) in case of conditions: \( P = 10^6 (U_i/U_s) = 0 \) db (see fig. 2) by minimax criterion, and \( P = 10^6 (U_i/U_s) = 20 \) db (see fig. 3) by average criterion.

In represented cases informative rates of channels are equal, and synchronization is ideal. Influence of synchronization errors is investigated separately. In the base of obtained results we came to following conclusion.

8. The results of Investigations of TV systems

With help of investigations of TV systems by means of created simulation TV model, we determined the ratio between the subjective (visonial) and objective (word error probability Pw) estimation of merit of image, that allows to use the results of above represented investigation of digital DD systems in order to estimate the influence of ICI and Gaussian noise on the merit of received images in coherent multichannel TV systems, but with account of this ratio. For example, in the result of the TV simulation we obtain that in the presence of influence of ICI and Gaussian noise the 'good' quality of vision image estimation of merit of received images accord the \( \text{Pw} \times 10^6 \) (in the case of basic fixed parameters of origin transmitter images). We obtain that the application of MSK, TPM band-saving modulation methods provides the best quality received images (relative to application of BPSK, QPSK modulation methods) in the case of large level of influence of ICI \((U_i/U_s) = 0 \) db and little level of noise \( \text{E} (\text{b}/\text{n}) \times 10^6 \) db.

In addition to written above, we want to say that our investigations in some other way \( \text{14} \) show that significant improvement of merit of received images is connected with took into account the properties and particulars of subjective visional system. In this system the intellectual sensory receiver of visional information is appeared. This way leads to creating the intellectual systems possessing the properties of artificial intellect. We were a success to create new original conception of building of intellectual receiver basing on the combination of the biological and informationally-technical principles. In result, we create the structure scheme of visional system allowing to improve the merit of received images by means of the following optimization of channel parameters \( \text{16} \).

9. Conclusion

The results of investigation show that the application of QPSK, MSK, TPM band-saving modulation methods in coherent.
Figure 4. Received images for basic channels for case of: $E_b/N_0=7.5$, $U_1/U_2=12$ dB, $d_f=3.0$.

Figure 5. Received images for basic channels for case of: $E_b/N_0=10$ dB, $U_1/U_2=15$ dB, $d_f=3.0$.

Figure 6. Received images for basic channels for case of: $E_b/N_0=10$ dB, $U_1/U_2=12$ dB, $d_f=1.0$.

Figure 7. Received images for basic channels for case of: $E_b/N_0=10$ dB, $U_1/U_2=6$ dB, $d_f=1.0$. 
multichannel digital DD and TV systems is more efficient than
the application of BPSK traditional modulation method,
especially in the case of large level of ICI (dI<10, O and (UI/Uo)>10
db) and little level of noise (E/N0>10 db).

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