Method of High-Noise-Resistant Qudrature-Pulse Phase Modulation

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Abstract. The paper refers to the method of quadrature intra-pulse phase modulation (QIPPM). This method focuses on solving the relevant problem of improving the noise resistance of message transmission over communication channels with variable parameters. The problem is resolved by intra-pulse phase manipulation of signal quadratures by mutually orthogonal binary sequences of the Walsh function type. The advantage of the QIPPM modem over other modems is shown, and recommendations for its practical use in communication channels with pseudo-random tuning of operating frequency are given.

I. Introduction
The most common modulation methods for transmitting discrete messages are amplitude modulation (AM), frequency modulation (FM), and differential phase-shift keying (DPSK). AM finds application in variable parameter channels with absolute bi-pulse signals (ABPS) [1, 2]. FM signal modems are easy to implement and have a high noise immunity when transmitting messages over channels with rapidly changing parameters. FM signals with a large deviation, which are actually two frequency-diverse AM signals, have specially high noise resistance in this type of communication channels, for example, in short-wave ones [3].

DPSK modems have the highest noise resistance in the presence of additive noise in the communication channel [4]. However, in channels with rapidly changing parameters, DPSK signals lose their advantage over FM signals that provide the highest noise resistance [5].
Mainly FM modems are used for transmission of discrete messages with frequency-hopping spread spectrum (FHSS) over shortwave (SW) communication channels.

The results of the noise resistance are compared for a QIPPM modem [6] with an FM modem and quadrature amplitude modulation (QAM) modem [7] that is similar to the QIPPM modem and allows single pulse transmission of a large quantity of information bits. Comparison of modems is made provided messages of the same volume are transmitted over the same period.

The QIPPM modem shows the highest noise resistance among all examined modems.

2. Problem statement

The purpose of the study is to find the most noise resistant method for transmitting discrete messages over a SW communication channel, which is usually a channel with rapidly changing parameters. This property of the SW communication channel is particularly strong when transmitting discrete messages in the FHSS mode.

The noise resistance of three types of modems is compared: a QAM modem, an FM modem, and a newly developed QIPPM modem, provided one byte of information is transmitted over the same time interval.

3. Theory

When using QIPPM on the transmitting side of a radio line, radio pulse quadrature forms.

\[ u_c(t) = A \cos(2\pi ft + \varphi_0), \]

and

\[ u_s(t) = A \sin(2\pi ft + \varphi_0). \]

A pair of mutually orthogonal binary sequences (MOBS), for example, a pair of Walsh functions \( W_i(t) \) and \( W_j(t) \) is defined according to the message fragment being transmitted, which is a binary sequence containing \( k \) elements. The generation of Walsh functions can be performed as suggested in [8]. One radio pulse quadrature is manipulated intra-pulsely along the phase of one MOBS (similar to that in radar [9]), and the second radio pulse quadrature is manipulated intra-pulsely along the phase of the other MOBS:

\[ u_{cm}(t) = W_i(t) A \cos(2\pi ft + \varphi_0); \]

\[ u_{sm}(t) = W_j(t) A \sin(2\pi ft + \varphi_0). \]

The resulting quadratures are summed and transmitted over the communication channel.

On the receiving side, the signal is de-manipulated in phase in parallel with all MOBS used in the communication system (in this case with Walsh functions \( W_r(t) \)), which are synchronized in time with the manipulating ones in phase of MOBS received signal:

\[ u_{dm}(t) = W_r(t) A \cos(2\pi f(t-\varphi_0)); \]

\[ u_{dm}(t) = W_j(t) A \sin(2\pi f(t-\varphi_0)). \]

The multiplication of two Walsh functions results is known to be a new Walsh function [10]. Moreover, if Walsh functions of the same order are multiplied, the result of the multiplication is the
zero order Walsh function. Therefore, in the case when \( r = i \), at the output of the demanipulator there will be a signal:

\[
u_{dm} = K \left[ \cos(2\pi f(t-dt)+\phi_0) + W_i(t-dt)W_j(t-dt)\sin(2\pi f(t-dt)+\phi_0) \right],
\]

and in case when \( r = j \), there will be a signal at the output of the demanipulator:

\[
u_{dm} = K \left[ W_j(t-dt)W_i(t-dt)\cos(2\pi f(t-dt)+\phi_0) + \sin(2\pi f(t-dt)+\phi_0) \right].
\]

Only harmonic oscillations can reach the output of a narrow-band filter. Therefore, the oscillation occurs at the output of a narrow-band filter which corresponds to the Walsh function \( W_i(t) \):

\[
u_{dm} = KA\cos(2\pi f(t-dt)+\phi_0),
\]

and the oscillation appears at the output of a narrow-band filter which corresponds to the Walsh function \( W_j(t) \):

\[
u_{dm} = KA\sin(2\pi f(t-dt)+\phi_0).
\]

Taking into account specific pairs of filters with harmonic oscillations at their outputs, a decision is taken on a specific binary sequence corresponding to the transmitted message. The possible number of such filter pairs \( N \) is equal to the number of combinations of 2 out of the total number \( M \) of the used MOBS:

\[
N = \binom{M}{2} = \frac{M!}{(M-2)! \cdot 2}
\]

The result of identifying filters with harmonic signals at their outputs by comparing the signal levels at these outputs may be erroneous if the signal-to-noise ratio is not large enough. The probability of error in the simultaneous identification of two specific filters with the highest signal levels out of the total number of \( M \) is determined by the formula:

\[
P_{err} = 1 - \left( 1 - \frac{1}{2} e^{-\frac{h^2}{4}} \right)^{(2M-3)}. \tag{1}
\]

Here:
- \( h^2 \) is the ratio of the signal energy per bit of a message fragment transmitted by a single radio pulse to the noise power spectral density at the demodulator input;
- \( k \) is the number of message bits transmitted by a single radio pulse;
- \( M \) is the number of the MOBS used.

In formula (1), the quadratures of the radio pulse are taken into account at the output of the filters, and the power of each quadrature is 2 times less than the power of this radio pulse.

The table 1 below shows the number \( M \) of MOBS that is required for QIPPM to transmit the corresponding number of \( K \) bits of information by a single radio pulse.
Table 1. Dependence of the quantity M of mutually orthogonal binary sequences on the number k of message bits transmitted by a single radio pulse

| Number k of bits transmitted by a single radio pulse | 2   | 4   | 5   | 6   | 8   |
|-----------------------------------------------------|-----|-----|-----|-----|-----|
| The number M of MOBS                                | 4   | 7   | 9   | 12  | 24  |
| Number N of vertices in the signal constellation    | 4+2 | 16+5| 32+4| 64+2| 256+20 |

Figure 1 shows the noise immunity curves for different values of the QIPPM signal constellation: (4+2), (16+5), (64+2) and (256+20), recalculated for the equivalent error probability of message elements by the formula

\[ P_{\text{er BIT(QIPPM)}} = \left( 1 - \frac{k}{4} P_{\text{er N}} \right). \]

Figure 1. Dependence of the equivalent probability of symbol error on the signal-to-noise ratio in the QIPPM modem

The graphs in Fig.1 show that, in contrast to QAM, with an increase in the value of the signal constellation in QIPPM, there is no energy expenditure to maintain noise resistance at a certain level, but on the contrary, there is a certain energy gain. However, in this case the spectra of the QIPPM high-speed modem signals occupy a larger bandwidth on the air compared to the spectra of the QAM modem signals, which occupy the same bandwidth being independent on message transmission speed increase when the value of the signal constellation increases.

Thus, in contrast to QAM in QIPPM modems, increasing the message transmission rate by increasing the number of vertices in the signal constellation does not require any increase in the transmitter capacity.

In order to compare the noise resistance of FM and QIPPM modems the curves of error probability dependences for both message elements and code combinations representing message bytes were calculated as shown in Figure 2.
The error probability of message elements for the FM modem is calculated by the formula [4]:

\[ P_{\text{erBIT(FM)}} = \frac{1}{2} e^{-\frac{h^2}{2}}. \]

The probability of byte errors transmitted using the FM modem is calculated by the formula:

\[ P_{\text{erBYTE(FM)}} = 1 - \left( 1 - \frac{1}{2} e^{-\frac{h^2}{2}} \right)^8. \]

The probability of byte errors transmitted using the FM modem is calculated by the formula:

\[ P_{\text{erBYTE(QIPPM)}} = 1 - \left( 1 - \frac{1}{2} e^{-2h^2} \right)^{45}. \]

The equivalent error probability of message elements for the QIPPM modem is calculated by the formula:

\[ P_{\text{erBIT(QIPPM)}} = 1 - \sqrt[8]{1 - P_{\text{erBYTE(QIPPM)}}}. \]

The noise-resistant curves for QAM-256 are obtained by extrapolating the bitwise error probability dependencies for QAM-16, QAM-32, and QAM-64 taken from [7].
4. Computer simulation results

Figure 2 shows the results of simulation modeling to determine the estimates of the QIPPM modem byte error probability in the form of the rings. The number of errors in simulation modeling for all values of byte errors probabilities is equal to 20, and that corresponds to the condition of sample sufficiency, providing relatively high accuracy of estimation of byte errors probability [11].

5. Results discussion

Comparison of simulation results and calculation results shows a good match. Graphs in Fig. 2 reveal that energy gain of the QIPPM modem compared to the FM modem is 4.8 dB, and for the QAM modem, it is more than 20 dB.

6. Conclusion

When using QIPPM, each individual radio pulse contains information that is stored in specific forms of mutually orthogonal binary sequences that manipulate the initial phases of the transmitted radio pulse quadrature.

Under the QIPPM, in contrast to QAM, a single radio pulse (with intra-pulse phase manipulation) can transmit a large number of bits. For example, a single pulse can transmit 8 bits, i.e. one byte of information. In this case, since each pulse is transmitted with the same maximum possible amplitude, and the main selectivity filter is designed for the duration of the radio pulse itself, the maximum possible noise immunity of its reception is provided. In case of additive Gaussian noise energy gain of the QIPPM modem relative to the FM modem is 4.8 dB, and relative to the QAM modem it exceeds 20 dB.

QIPPM radio pulses can transmit discrete messages in the FHSS mode with a reliability higher than that of all other known modulation methods.

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