COMPARATIVE ANALYSIS OF THE EFFECTIVENESS OF DIGITAL MODULATION TYPES

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ABSTRACT

This article examines the effectiveness of digital modulation types. The issues of spectral and energy efficiency of various modulated signals used in the digital communication systems are highlighted. Comparatively compares the energy efficiency of various signals with the digital modulation. In the course of the analysis, conclusions are drawn about which type of modulation is the most effective in which cases and types of modulation are preferable.

Keywords: digital modulation, energy, spectrum, spectral efficiency, bandwidth, energy efficiency, bit error probability

1. INTRODUCTION

The main criteria for the effectiveness of various types of modulation are the criteria for spectral and energy efficiency. Energy efficiency characterizes the energy that must be expended to transmit information with a given reliability (error probability). Spectral efficiency characterizes the bandwidth required to transmit information at a specific rate. In addition to these criteria, the types of modulation are compared in terms of resistance to various types of interference and distortion, and the complexity of the hardware implementation. There are also specific criteria that are essential for individual communication systems, reflecting the characteristics of the communication channel.

Almost all communication systems use filters that limit the signal spectrum. For amplitude, phase and amplitude-phase types of modulation, a filter with a raised cosine characteristic is most often used, for frequency - a Gaussian filter. Thus, the spectral efficiency for amplitude, phase and amplitude- phase modes of modulation is the same and is determined by the filter bandwidth. It is shown that an increase in the positions (levels) of modulation (modulation M-ASK, M-PSK and MQAM) increases the spectral efficiency by a factor of $k = \log_2 M$ [1].

It was also noted that the MSK modulation possesses are the highest spectral efficiency among the frequency types of modulation. Comparison of MSK with Gaussian filtering (GMSK modulation) and relative bandwidth $BT_b = 0.3$ and QPSK modulation with a raised cosine filter with a roll-off factor α = 0,35 (optimal for many communication systems) reveals that 99% of the power contained in the relative bandwidth 1 for QPSK and 2,6 for GMSK. Thus, MSK is spectrally 2,6 times less efficient than QPSK and 1,3 times less efficient than BPSK. [2].

2. METHODOLOGY

Let's compare the types of modulation according to the criterion of energy efficiency. For this, we estimate for each type of modulation the energy required to transmit information with the same error probability per bit. In [3], [4], relations are defined that relate the probability of a bit error to the value of E_b/N_0 for various types of modulation:

$$BER = f\left(\frac{E_b}{N_0}\right), \quad (1)$$

where BER – is the error probability, E_b – is the energy required to transmit one bit of information, N_0 – power spectral density of the white noise in the channel. If the transmitter power is P, then the amount of energy per bit of information is $E_b = PT_b$, where T_b is the bit duration. Table 1 shows the dependences of the bit error probability on the ratio E_b/N_0 for various types of modulation.

Table 1.

Probability of error per bit for different types of modulation

Modulation type	**Bit Error Rate (BER)**
OOK	$F\left(\sqrt{E_b/N_0}\right)$
M-ASK Gray code	$\frac{2(M-1)}{M\log_2 M} F\left(\sqrt{\frac{\log_2 M}{(M-1)^2}\frac{E_b}{N_0}}\right)$
BPSK	$F\left(\sqrt{2E_b/N_0}\right)$
Incoherent DBPSK	$\frac{1}{2}\exp(-E_b/N_0)$
Coherent DBPSK	$2F\left(\sqrt{\frac{2E_b}{N_0}}\right)\left(1-F\left(\sqrt{\frac{2E_b}{N_0}}\right)\right)$
QPSK Gray code	$F\left(\sqrt{2E_b/N_0}\right)$
Coherent DQPSK at $E_b/N_0 \gg 1$	$2F\left(\sqrt{2E_b/N_0}\right)$
M-PSK Gray code	$\frac{2}{\log_2 M} F\left(\sqrt{\frac{2E_b \log_2 M}{N_0}}\sin^2\left(\frac{\pi}{M}\right)\right)$
FSK	$F\left(\sqrt{\left[1-\frac{\sin(2\pi\cdot m)}{2\pi\cdot m}\right]\frac{E_b}{N_0}}\right)$
MSK	$F\left(\sqrt{2E_b/N_0}\right)$
M-MSK	$\frac{2(M-1)}{M\log_2 M} F\left(\sqrt{\log_2 M\frac{E_b}{N_0}}\right)$
QAM Gray Code	for $k = \log_2 M$, k – even $BER = \frac{2P_0 - P_0^2}{\log_2 M}$, where $P_0 = \frac{2(\sqrt{M}-1)}{\sqrt{M}} F\left(\sqrt{\frac{3\log_2 M}{M-1}\frac{E_b}{N_0}}\right)$ for odd k: $BER \le \frac{1}{\log_2 M}\left[1-\left(1-2F\left(\sqrt{\frac{3\log_2 M}{M-1}\frac{E_b}{N_0}}\right)\right)^2\right]$

In Table 1, $F(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$ –error integral, M – number of positions for multi-position modulation types, m – is the modulation index for frequency modulation, BER – bit error probability.

3. SIMULATION RESULTS AND EVALUATIONS

Table 1 shows that with an increase in the positionality of the modulation, the probability of a bit error increases (for example, the formulas M-ASK and M-PSK, $F(x)$ is a decreasing function of the argument). Thus, as a rule, with an increase in the spectral efficiency, the energy efficiency decreases.

However, BER for BPSK and QPSK are described by the same formulas (Table 1), while QPSK is 2 times more spectrally efficient than BPSK. Therefore, QPSK is always significantly more efficient than BPSK, and it usually makes sense to use QPSK rather than BPSK. Physically, this is because in the case of QPSK, an additional degree of freedom is added: the quadrature component $Q(t)$. In the case of BPSK, only the common-mode component $I(t)$ is used. The quadrature form of the coherent phase demodulator results in two detector channels providing independent reception of two binary phase modulated signals.

A similar phenomenon occurs when comparing DBPSK and DQPSK (with relative coding) modulations. Although expressions for BER slightly differ, they coincide with a high degree of approximation (Fig. 1). Relatively coded modulations have a small energy loss compared to conventional BPSK and QPSK (0.3–0.9 dB) [5]. DBPSK with incoherent detection also has a small loss compared to DBPSK with coherent detection (about 0.5 dB), (Fig. 1.) Energy gain is understood as the difference in the value of E_b/N_0 with the same value of the error probability per bit.

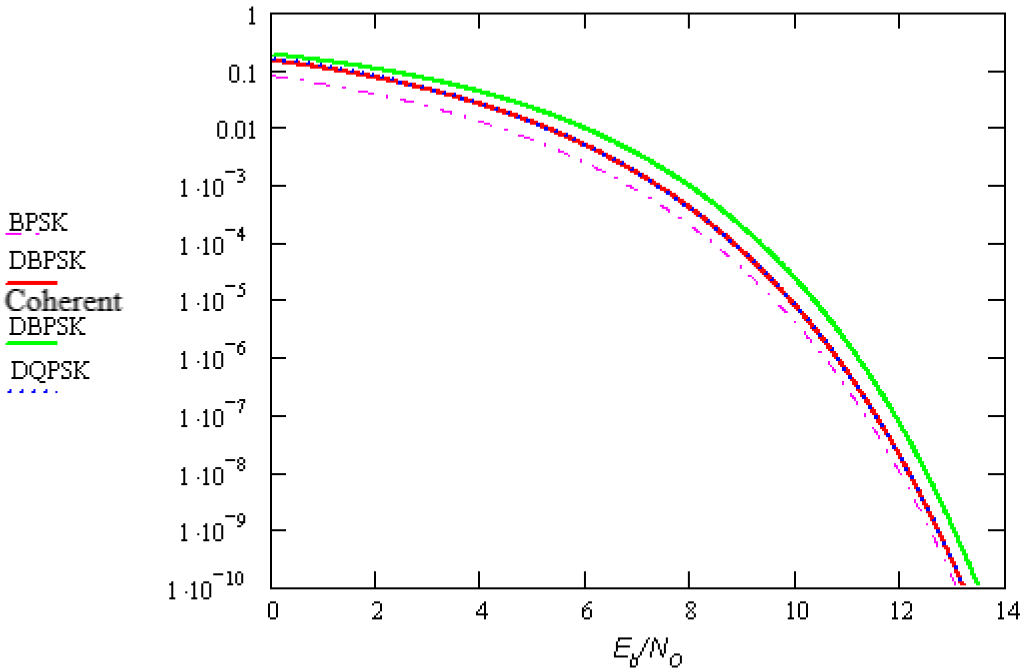


Figure 1. Comparison of energy efficiency of modulations with relative coding: DBPSK, DQPSK and incoherent DBPSK

Thus, it makes sense to compare modulation types with the same number of positions. Let's compare two-tier OOK, BPSK and MSK. As can be seen from Table 1, OOK and MSK have the same efficiency and are inferior to BPSK (and, accordingly, QPSK) in terms of energy efficiency by about 3 dB (Fig. 2) [5].

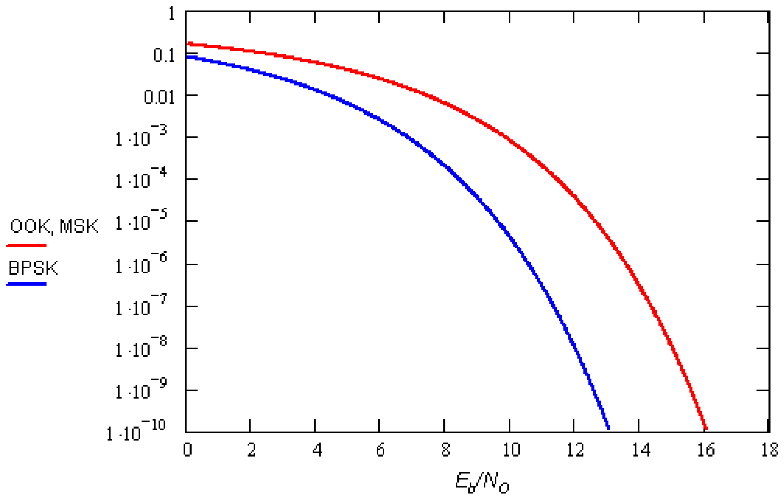


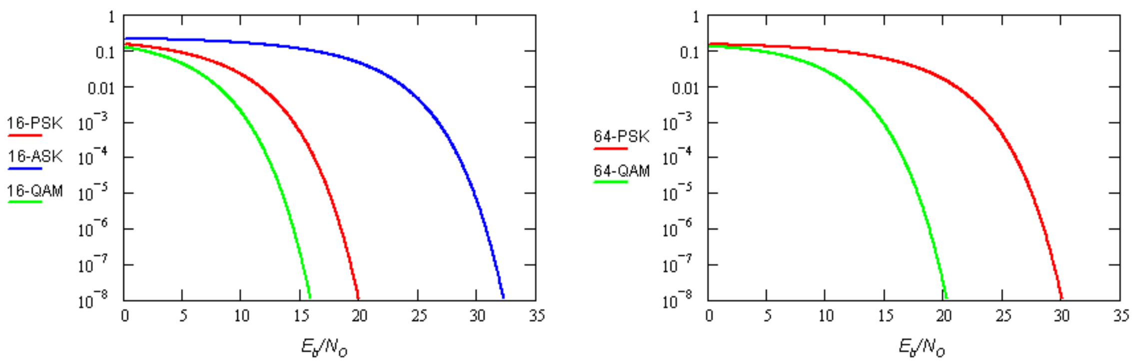
Figure 2. Comparison of energy efficiency of OOK, MSK and BPSK modulations

Based on the results of this comparison, it can be concluded that with the number of levels up to 4, inclusive, QPSK is the spectrally and energetically most efficient type of modulation. However, one important note should be made here regarding GMSK modulation. Its spectral efficiency is lower than QPSK in linear amplification systems. GMSK, as a form of frequency modulation, allows the use of highly efficient non-linear amplifiers and limiters, which gives an energy gain.

When QPSK passes through such devices, its spectrum expands (some sidelobe recovery occurs). Therefore, in some cases, GMSK can be more efficient than QPSK. In particular, in the GSM standard, the choice was made in favor of GMSK, and in CDMA - OQPSK. However, advanced QPSK modulations (e.g. FQPSK) are superior to GMSK anyway [6].

Let us now compare modulations with the number of levels M> 4. In fig. 3 shows a comparison of the energy efficiency for amplitude, phase and amplitude-phase keying at M = 16 and M = 64.

As can be seen from Fig. 3, amplitude modulation is significantly (more than 10 dB at *M*=16) inferior to phase and amplitude-phase, therefore, at *M*=64, no comparison with it is made. When comparing M-PSK with M-QAM, it can be seen that M-QAM is superior in efficiency to M-PSK, and the energy gain of M-QAM increases with increasing M. For example, for *M*=16, the gain is about 4 dB, and for *M*=64 about 10 dB. Physically, this is due to the fact that the distance between adjacent points in the M-PSK constellation is less than that of M-QAM.



a) b)

Figure 3. Comparison of the energy efficiency of M-ASK, M-PSK and M-QAM modulations: a – *M*=16, б – *M*=64

The M-PSK signal constellation is a circle with points evenly distributed on it, and the M-QAM– constellation is a square with points evenly distributed over its area. The greater the distance between points in the constellation, the less likely an error in detecting a neighboring symbol. Multi-position frequency modulation is used much less often, since with an increase in the number of levels and maintaining the modulation index, its spectrum does not narrow, but expands, due to the fact that new frequencies are introduced and the spectrum width grows according to the law $\frac{M}{\log_2 M}$.

As can be seen from Table 1, however, with an increase in the number of M-MSK levels, in contrast to all other types of modulation, the probability of a bit error decreases. We get energy efficiency gains by reducing spectral efficiency.

Thus, with a limited bandwidth, with $M \leq 4$, QPSK modulation is most effective, and with $M > 4$ – QAM. QPSK is a special case of QAM when M=4. QAM can be considered the most efficient type of modulation at any number of levels. Even greater gains compared to conventional QPSK and QAM are provided by their advanced modifications, such as Fever modifications (FQPSK, FQAM), trellis-coded modulation (TCM), constellation optimization and the use of multidimensional constellations.

CONCLUSIONS

Based on the results of the analysis, the following conclusions were made:

1. with increasing positionality of modulation, the probability of a bit error increases; when the spectral efficiency increases, the energy efficiency decreases;

2. with the number of levels up to 4 inclusive, QPSK is the spectrally and energetically most efficient type of modulation;

3. M-QAM outperforms M-PSK, and the power gain of M-QAM increases with increasing M;

4. with an increase in the number of M-MSK levels, in contrast to all other types of modulation, the probability of a bit error decreases, we get a gain in energy efficiency due to a decrease in spectral efficiency;

5. with limited bandwidth, with M≤4, the most effective modulation is QPSK, and with M> 4 - QAM.

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