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Investigation of influence of parameters of the digital telecommunication system on its efficiency

***Abstract**. The influence of parameters of the digital telecommunication system or telecommunication network on their technical efficiency is investigated. For example, the technical efficiency of a telecommunication network based on WiMAX technology IEEE 802.16e is investigated.*

Streszczenie:** W artykule analizowano wpływ parametrów cyfrowego systemu telekomunikacyjnego efektywność. Analizę przeprowadzono na przykładzie sieci WIFIMAX IEEE 802.16e. **Analiza wpływy parametrów cyfrowej sieci telekomunikacyjnej na jej skuteczność

Keywords: data rate, throughput, telecommunication system, telecommunication network.
Słowa kluczowe: szybkość transmisji danych, przepustowość, system telekomunikacyjny, sieć telekomunikacyjna.

Introduction

The necessity of increasing the efficiency of digital telecommunication systems or networks is due to the continuous increase of data volumes transmitted by such systems or networks. This task can be solved by optimizing a number of system or network parameters based on the adoption of certain compromises. To make the right decision, we need to know the impact of each parameter of telecommunication system or network on their efficiency. Recently, a lot of attention is focused on this issue [1-6]. However, the development of complex indicators to detect the influence of the parameters of a digital telecommunication system or network on their efficiency remains an actual task.

The purpose of this work is to study the influence of parameters of digital telecommunication system or network on their technical efficiency through the use of a complex indicator.

Basic parameters of the digital telecommunication system, which influence on its efficiency

Let's consider the basic parameters of the digital telecommunication system, which influence on its efficiency. Among them, the most important are the data rate, the ratio of the energy of one data bit to the power spectral density of the white noise and the system throughput.

The data rate V_b (bps) is:

(1) $$V_b = 1/T_b,$$

where T_b is the transmission time of one data bit, s.

The signal power P_s (W) in the digital telecommunication system is:

(2) $$P_s = E_b V_b,$$

where E_b is the energy of one data bit, W·s/bit.

The noise power P_n (W) in such a system is:

(3) $$P_n = N_0 \Delta F_{sys},$$

where N_0 is the power spectral density of the white noise, W/Hz; ΔF_{sys} is bandwidth of telecommunication system, Hz.

Taking into account (1) and (2) the energy of one data bit is:

(4) $$E_b = P_s T_b.$$

In this case we can write:

(5) $$\frac{E_b}{N_0} = \frac{P_s T_b}{P_n / \Delta F_{sys}} = \frac{P_s}{P_n}\left(\frac{\Delta F_{sys}}{V_b}\right).$$

Thus, the parameter E_b / N_0 is directly proportional to the ratio of the signal power to the noise power P_s / P_n, and the proportionality factor is the ratio of the bandwidth ΔF_{sys} of the telecommunication system to the data rate V_b in such a system. From equation (5) it can be seen that the parameter E_b / N_0 has a dimension of 1/bit.

An important parameter of the digital telecommunication system is throughput C_{sys} (bps), which is the maximum possible data rate obtained by variation of all possible data sources at the system input:

(6) $$C_{sys} = max(V_b).$$

The throughput C_{sys} of the digital telecommunication system does not exceed the throughput C_{ch} of the analog communication channel, which is its part and is described by the well-known Shannon's equation [7], if the additive white noise with the Gaussian distribution of amplitudes operated in this channel:

(7) $$C_{ch} = \Delta F_{ch}\, log_2\left(1 + \frac{P_s}{P_n}\right),$$

where ΔF_{ch} is the bandwidth of the analog channel, Hz.

$\Delta F_{sys} = \Delta F_{ch}$ and $C_{sys} = C_{ch}$ for the single-channel telecommunication system. The throughput of a multichannel system is equal to the sum of throughput of individual channels that are part of it. Theoretically, using complex methods for forming and processing of signals, data can be transmitted through the system (channel) at arbitrary bit rate V ($V_b \le C_{sys}$) with arbitrarily small bit error rate. If $V_b \le C_{sys}$, then there is no method for forming and processing of signals, on the basis of which it is possible to achieve an arbitrarily small bit error rate.

Shannon's work shows that the parameters P_s, P_n and ΔF_{ch} limits the data rate of transmission, and not the bit error rate. Using equation (7), we obtain equation (8) for a one-channel system that displays the dependence of the system's normalized throughput $C_{sys} / \Delta F_{sys}$ (bps/Hz) on the ratio of signal power to noise power P_s / P_n in the system:

(8) $$\frac{C_{sys}}{\Delta F_{sys}} = log_2\left(1 + \frac{P_s}{P_n}\right).$$

This dependence is shown in Fig. 1. The curve described in (8) limits the area of the possible realization of the telecommunication system.

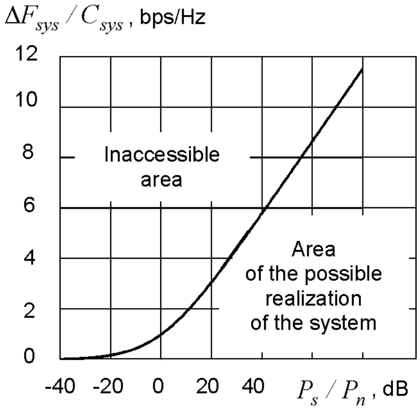

Fig. 1. The dependence of the system's normalized throughput $C_{sys} / \Delta F_{sys}$ on the ratio P_s / P_n

We can see from Fig. 1 that there is no lower limit of the ratio of signal power to noise power P_s / P_n during the data transmission, so the transmission can be carried out at signal power that is less than noise power, in case of decreasing of this ratio P_s / P_n is compensated by an increase of bandwidth ΔF_{sys} of the telecommunication system.

To obtain the dependence of the system's normalized throughput on the ratio E_b / N_0, we make substitution of equation (3) in equation (8) and obtain the following:

$$\frac{C_{sys}}{\Delta F_{sys}} = log_2\left(1 + \frac{P_s}{N_0 \Delta F_{sys}}\right). \tag{9}$$

If the data rate is equal to the system's throughput ($V_b = C_{sys}$), then we can write the following using equation (5):

$$\frac{P_s}{N_0 C_{sys}} = \frac{E_b}{N_0}. \tag{10}$$

We multiply the left and right sides of equation (10) by $C_{sys} / \Delta F_{sys}$, and then we use the result for the following transformations of equation (9):

$$\frac{C_{sys}}{\Delta F_{sys}} = log_2\left(1 + \frac{E_b}{N_0}\left(\frac{C_{sys}}{\Delta F_{sys}}\right)\right), \tag{11}$$

$$2^{C_{sys} / \Delta F_{sys}} = 1 + \frac{E_b}{N_0}\left(\frac{C_{sys}}{\Delta F_{sys}}\right) \tag{12}$$

and we obtain the following equation

$$\frac{E_b}{N_0} = \frac{\Delta F_{sys}}{C_{sys}}\left(2^{C_{sys} / \Delta F_{sys}} - 1\right). \tag{13}$$

The diagram of dependence of the system's normalized throughput $C_{sys} / \Delta F_{sys}$ on the ratio E_b / N_0 described by equation (13) is shown in Fig. 2.

In Fig. 2 we can see that there is a lower limit of the ratio of the energy of one data bit to the power spectral density of the white noise E_b / N_0, below which the data transmission neither can be carried out without bit error at any data rate (below which a throughput of the telecommunication system $C_{sys} \to 0$ bps).

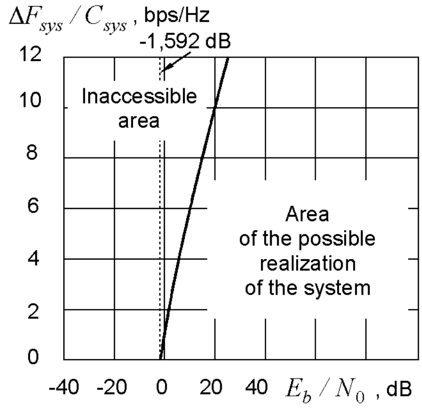

Fig. 2. The dependence of the system's normalized throughput $C_{sys} / \Delta F_{sys}$ on the ratio E_b / N_0

Shannon's limit

Let's define the lower limit value of ratio E_b / N_0 below which the throughput of the telecommunication system is $C_{sys} \to 0$ bps. To calculate this value let's assume that

$$x = \frac{E_b}{N_0}\left(\frac{C_{sys}}{\Delta F_{sys}}\right).$$

After transformation we will get

$$1 = \frac{E_b}{N_0} log_2 (1 + x)^{1/x}. \tag{14}$$

Let's define the value of ratio E_b / N_0 below which the data transmission through the telecommunication system will cease, that is, the ratio of the throughput of the telecommunication system to its bandwidth goes to zero $C_{cys} / \Delta F_{sys} \to 0$ (similarly $x \to 0$). After using the known equation

$$\lim_{x \to 0} (1 + x)^{1/x} = e$$

we obtain from equation (14) at $C_{cys} / \Delta F_{sys} \to 0$

$$\left.\frac{E_b}{N_0}\right|_{C_{sys} / \Delta F_{sys} \to 0} = \frac{1}{log_2 e} = 0{,}693 \tag{15}$$

whether, in decibels

$$\left.\frac{E_b}{N_0}\right|_{C_{sys} / \Delta F_{sys} \to 0} = -1{,}592 \text{ dB}. \tag{16}$$

This value E_b / N_0 is called the Shannon's limit.

If we make the corresponding transformations (10) taking into account (15), then we can get

$$\left.\frac{C_{sys}}{\Delta F_{sys}}\right|_{P_s / P_n \to 0} = \frac{P_s}{P_n} \cdot log_2 e = \frac{P_s}{P_n} \cdot 1{,}443. \tag{17}$$

This equation allows us to calculate the throughput of the telecommunication system at ratio $P_s / P_n \to 0$, that is, it is suitable for use at ratio $C_{sys} / \Delta F_{sys} \to 0$. The relative error during definition the value of ratio $C_{sys} / \Delta F_{sys}$ when using the equation (17) compared to the value obtained using the equation (8) at other values of ratio $P_s / P_n \le 0{,}1$ does not exceed 5% according to the authors' research. So, equation (17) makes it possible to calculate approximately the value of ratio $C_{sys} / \Delta F_{sys}$ at small values of ratio P_s / P_n.

For large values of ratio P_s / P_n, equation (8) is simplified as follows:

(18) $$\frac{C_{sys}}{\Delta F_{sys}}\Big|_{P_s / P_n \to \infty} = log_2\left(\frac{P_s}{P_n}\right).$$

It can be seen that the relative error during definition the value of ratio $C_{sys} / \Delta F_{sys}$ when using the equation (18) compared to the value obtained using the equation (8) at ratio $P_s / P_n \geq 10$ does not exceed 4% according to the authors' research.

It was established on the basis of the analysis of equation (18) that to n times increase of ratio $C_{sys} / \Delta F_{sys}$ at high values of ratio P_s / P_n it is necessary 2^n times increase of ratio P_s / P_n.

The bandwidth increase is more efficient to increase the throughput of the telecommunication system, since changing bandwidth directly affects the change in throughput. However, throughput of the telecommunication system becomes a nonlinear function of bandwidth with an increase in the bandwidth to infinity. Let's show this by converting equation (9) with taking into account the properties of the logarithms:

$$C_{sys} = \Delta F_{sys}\, log_2\left(1 + \frac{P_s}{N_0 \Delta F_{sys}}\right) =$$
$$= \Delta F_{sys}\, log_2 e \cdot ln\left(1 + \frac{P_s}{N_0 \Delta F_{sys}}\right).$$

Throughput C_{sys} limit at bandwidth $\Delta F_{sys} \to \infty$ is equal

$$C_{sys}\Big|_{\Delta F_{sys} \to \infty} = \lim_{\Delta F_{sys} \to \infty} C_{sys} =$$
$$= log_2 e \cdot \lim_{\Delta F_{sys} \to \infty} \Delta F_{sys}\, ln\left(1 + \frac{P_s}{N_0 \Delta F_{sys}}\right).$$

Since $ln(1+\varepsilon) \approx \varepsilon$ at $\varepsilon \to 0$, then

(19) $$C_{sys}\Big|_{\Delta F_{sys} \to \infty} = \Delta F_{sys} \frac{P_s}{N_0 \Delta F_{sys}} log_2 e = \frac{P_s}{N_0} log_2 e.$$

Consequently, throughput of the telecommunication system at the bandwidth $\Delta F_{sys} \to \infty$ depends only on the ratio of the signal power P_s to the power spectral density N_0 of the white noise.

It also follows from equation (19) that the ratio $E_b / N_0 = P_s T / N_0$ (T - time of data transmission, s) must exceed a certain threshold for the transmission of information through the telecommunication system with noises. So, the amount of data that can be transmitted through the telecommunication system with throughput C_{sys} over time T can not exceed the value

$$I = C_{sys} T \leq \frac{P_s T}{N_0} log_2 e = \frac{E_b}{N_0\, ln 2}.$$

Therefore, to transmit $I = 1$ bit of data it is necessary to have the signal energy

(20) $$E_b = P_s T \geq N_0\, ln 2 = 0{,}693 N_0.$$

Thus, Shannon's limit indicates that it is necessary that the value of ratio E_b / N_0 be at least equal to $ln 2$ for the ability to transmit a binary data. It is seen from equation (20) that achieving such a ratio E_b / N_0 is possible at arbitrarily small signal power (even with $P_s << P_n$), provided that the time of transmission of one data bit is sufficiently large.

Indicators of technical efficiency of systems and networks for data transmission, which are constructed using a variety of methods for forming and processing of signals

Let's consider one of the most important local indicators of efficiency – technical efficiency. To evaluate the technical efficiency of a digital telecommunication system or network, the concept of frequency efficiency γ (bit), energy efficiency β (bit) and information efficiency η (dimensionless value) are traditionally used [8]:

(21) $$\gamma = v_b / \Delta F_s,$$

where ΔF_s is the width of the signal spectrum (assuming it is equal to the bandwidth ΔF_{sys} of the telecommunication system or network), Hz;

(22) $$\beta = v_b / \rho_0 = N_0 / E_b,$$

where ρ_0 is the ratio of the signal power P_s to the power spectral density N_0 of white noise in the telecommunication system or network, Hz;

(23) $$\eta = v_b / C_{sys}.$$

Taking into account (5) and (23), we can write that

(24) $$\frac{E_b}{N_0} = \frac{\Delta F_{sys}}{v_b}\frac{P_s}{P_n} = \frac{1}{\gamma}\frac{P_s}{P_n}.$$

The equation (24) establishes the relationship between the ratio of the energy of one data bit to the power spectral density of the white noise E_b / N_0 and the ratio of the signal power to the noise power P_s / P_n. We see that the coefficient of proportionality between these relations is frequency efficiency γ.

Given (5) we received

(25) $$\gamma = \rho\beta,$$

where $\rho = P_s / P_n$ is the ratio of the signal power to the noise power in the bandwidth $\Delta F_{sys} = \Delta F_s$.

From the equation (23) using (22), (25) and the Shannon's equation for throughput (7) at $\Delta F_{sys} = \Delta F_s = \Delta F_{ch}$, we obtain an equation for the calculation of information efficiency, which is related to two other indicators so [8]:

(26) $$\eta = \frac{\gamma}{log_2\left(\frac{\gamma}{\beta} + 1\right)}.$$

Consequently, the technical efficiency of a telecommunication system or network depends on its parameters: the data rate, bandwidth, the energy of one data bit, the power spectral density of the white noise, throughput. These parameters depend on the methods for forming and processing of signals used in designing of such a system or network. Methods for forming and processing of signals include signal modulation methods, correcting coding methods, channel compression / division methods, data transmission methods with managing feedback. Let's consider their influence on the indicators of technical efficiency of the telecommunication system or network.

Traditionally, energy efficiency β, frequency efficiency γ and information efficiency η are used to evaluate the efficiency of telecommunication system or network when applying a particular chosen signal modulation method. If the signal modulation is used together with the signal coding (i.e., the signal-code construction is used), it is expedient to use the concepts of energy efficiency of modulation β_{mod} (bit), energy efficiency of coding β_{cod} (dimensionless value), frequency efficiency of modulation γ_{mod} (bit) and frequency efficiency of coding γ_{cod} (dimensionless value).

The energy efficiency of the coding method β_{cod} determines the increase of the energy efficiency of the system when it is applied. The frequency efficiency of the coding method is calculated as follows:

(27) $$\gamma_{cod} = k_{cod} /(k_{cod} + r_{cod}),$$

where k_{cod} is the number of information bits in the code word; r_{cod} is the number of check bits in the code word.

In this case, the energy efficiency β_{SCC} (bit), frequency efficiency γ_{SCC} (bit) and information efficiency η_{SCC} (dimensionless) of the signal-code construction are:

(28) $$\beta_{SCC} = \beta_{mod}\beta_{cod},$$

(29) $$\gamma_{SCC} = \gamma_{mod}\gamma_{cod},$$

(30) $$\eta_{SCC} = \gamma_{SCC} / log_2\left(\frac{\gamma_{SCC}}{\beta_{SCC}}+1\right).$$

In order to evaluate the efficiency of a system or network that uses the channel compression / division methods, the information efficiency of the channel compression / division method η_d (dimensionless value) is used:

(31) $$\eta_d = \frac{1}{C_{sys1}}\sum_{i=1}^{N_{ch}} Cch_i ,$$

where C_{sys1} is the total bandwidth of a single-channel telecommunication system with the same ratio of signal power to noise power and bandwidth, as in multichannel telecommunication system, bps; N_{ch} is number of channels in the multichannel telecommunication system; Cch_i throughput of i th channel, bps.

The data transmission methods with managing feedback are used in a number of telecommunication systems and networks to retransmit data that is corrupted in the communication channel, transmit certain service signals, etc. The efficiency of the data transmission method η_{TM} (dimensionless value) in a system or network is determined as follows:

(32) $$\eta_{TM} = T_d / T_{inf},$$

where T_d is the time of data transmission, s; T_{inf} is the total time of transmission of a certain amount of data, s.

The time of data transmission depends on the time of the signal propagation on the system or the network, and the total time of transmission of a certain amount of data depends on the method of transmission and takes into account the time of data transmission and service information.

It is proposed to use a complex indicator – signal efficiency η_s (dimensionless value) to take into account the influence of different methods for forming and processing of signals on the technical efficiency of telecommunication system or network. This indicator is calculated according to the following equation:

(33) $$\eta_s = \gamma_{SCC}\eta_{TM}\eta_d / log_2\left(\frac{\gamma_{SCC}}{\beta_{SCC}}+1\right).$$

An example of using of the proposed complex indicator for calculation the efficiency of a telecommunication network based on WiMAX technology is given below.

Research of indicators of technical efficiency of the fourth generation cellular networks

Let us explore the indicators of technical efficiency of the fourth generation cellular networks on an example of the WiMAX standard IEEE 802.16e. The telecommunication channels with different parameters are used in this standard (Table 1).

Table 1. Parameters of the telecommunication channel according to the standard 802.16e

Parameter	Value			
Bandwidth, MHz	1,25	5	10	20
Number of subcarriers	128	512	1024	2048
Ratio T_{CP} / T_a	1/32, 1/16, 1/8, 1/4			
Sampling rate	28/25			
Sampling frequency, MHz	1,4	5,6	11,2	22,4
Dissemination of subcarriers by frequency, kHz	10,94	10,94	10,94	10,94
Active symbol duration T_a, μs	91,4	91,4	91,4	91,4
Cyclic prefix T_{CP} at $T_{CP} / T_a = 1/8$, μs	11,4	11,4	11,4	11,4
The duration of the OFDM symbol $T_{sym} = T_a + T_{CP}$, μs	102,9	102,9	102,9	102,9

The main feature of the IEEE 802.16e standard is the allocation of channel resource in the frequency domain in the form of subchannels. The standard provides different options for channel resource allocation. PUSC (Partial Usage of Subcarriers) is used more often. This mode is required at the beginning of each subframe of downstream.

Protective intervals on both sides of the channel bandwidth and central subcarrier are not used for data transmittion. The subcarriers that use for data transmittion are divided into minimal channel units – clusters. Each cluster is a association of 14 subcarriers that are located near to each other. One cluster always consists of 2 consecutive OFDM symbols, that is, consists 28 subcarriers. Data is transmitted on 24 subcarriers, pilot signals are transmitted on 4 subcarriers. One subchannel is composed of two clusters. The numbering of physical clusters starts from the lower boundary of the bandwidth of the channel, the numbers are increased with increasing frequency. Distribution of subcarriers, the number of formed clusters and subchannels depending on the bandwidth of the channel in PUSC mode are shown in Table 2.

Taking into account the data of the Table 1, the efficiency of the data transmission method for the network of the WiMAX standard IEEE 802.16e using equation (32) is calculated using such equation:

$$\eta_{TM} = T_a / T_{sym} .$$

Taking into account the data of the Table 2, the information efficiency of the channel compression / division method for the network based on the WiMAX standard IEEE 802.16e using equation (31) is calculated using such equation:

(34) $$\eta_d = N_{DT} / N_{ALL} .$$

Table 2. Distribution of subcarriers in the telecommunication channel in PUSC mode

Parameter	Value			
Bandwidth, MHz	1,25	5	10	20
Number of subcarriers N_{ALL}	128	512	1024	2048
The number of subcarriers in the cluster	14	14	14	14
Number of clusters	6	30	60	120
Number of subchannels	3	15	30	60
Subcarriers used for data transmission N_{DT}	72	360	720	1440
Pilot subcarriers	12	60	120	240
Protective subcarriers (left / right)	22/21	46/45	92/91	184/183

The energy efficiency β_{SCC}, frequency efficiency γ_{SCC} and information efficiency η_{SCC} of signal-code constructions used in the subcarriers of WiMAX network based on IEEE 802.16e standard during the forming of OFDM symbols, as well as the signal efficiency η_s of the WiMAX network using the above-mentioned equations are investigated.

Table 3. Efficiency of the WiMAX network based on IEEE 802.16e standard when using different signal-code constructions

SCC: modulation, correcting coding	β_{mod}, дБ	γ_{mod}, дБ	β_{cod}, дБ	γ_{cod}, дБ	β_{SCC}, дБ	γ_{SCC}, дБ	η_{SCC}	η_s
QPSK, 1/2	-9,9	3,0	4,6	-3,0	-5,3	0	0,469	0,235
QPSK, 3/4	-9,9	3,0	3,6	-1,2	-6,3	1,8	0,520	0,26
16-QAM, 1/2	-14,0	6,0	4,6	-3,0	-9,4	3,0	0,474	0,237
16-QAM, 3/4	-14,0	6,0	3,6	-1,2	-10,4	4,8	0,589	0,294
64-QAM, 1/2	-18,6	7,8	4,6	-3,0	-14,0	4,8	0,48	0,24
64-QAM, 2/3	-18,6	7,8	4,2	-1,8	-14,4	6,0	0,589	0,295
64-QAM, 3/4	-18,6	7,8	3,6	-1,2	-15,0	6,6	0,629	0,315
64-QAM, 5/6	-18,6	7,8	3,2	-0,8	-15,4	7,0	0,672	0,336

As can be seen from the results of the research, it is necessary to use signal-code constructions with lower information efficiency at reducing the ratio of signal power to noise power in a WiMAX network radio channel for data transmission, which reduces the signal efficiency of the network in general.

Conclusions

As a result of the carried out research, the following conclusions can be drawn:

– there is no lower limit of the ratio of signal power to noise power P_s / P_n in the telecommunication system or network during the data transmission, so the transmission can be carried out at signal power that is less than noise power, in the event that a decrease of this ratio P_s / P_n is compensated by an increase of bandwidth ΔF_{sys} of the telecommunication system;

– there is a lower limit of the ratio of the energy of one data bit to the power spectral density of the white noise E_b / N_0 in the telecommunication system or network during the data transmission, below which the data transmission neither can be carried out without bit error at any data rate (below which a throughput of the telecommunication system $C_{sys} \to 0$ bps).

– it is necessary that the value of ratio E_b / N_0 be at least equal to $ln 2$ for the ability to transmit a binary data; achieving such a ratio E_b / N_0 is possible at arbitrarily small signal power (even with $P_s << P_n$), provided that the time of transmission of one data bit is sufficiently large;

– It is proposed to use a complex indicator – signal efficiency η_s to take into account the influence of different methods for forming and processing of signals on the technical efficiency of telecommunication system or network;

– the example of research of technical efficiency of a telecommunication network based on technology WiMAX IEEE 802.16e with the use of the proposed complex indicator (signal efficiency η_s) is given.

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