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TRANSMISSION OF CONTROL INFORMATION IN 5G BROADBAND TELECOMMUNICATION SYSTEMS

Abstract: This article discusses the polar code is applied to the transmission of control information in broadband telecommunications systems. Channel coding contains a set of procedures for error detection, error correction, rate matching, bit interleaving and mapping of information to physical control channels or transport layer. The article explores a downlink model with polar coding and multi-position digital phase modulation. This model presents the results of Bit Error Rate (BER) for coding scheme with different code rates. The structural scheme of the decision model on the modulation mode of the digital communication system is analysed in the paper. Dependencies of BER on the effective rate of the polar code with different types of modulation are explored. The modulation mode selection adaptive algorithm for code rate R=0.5 is developed on the basis of the obtained dependencies. The use of signal-code construction based on the polar code can increase the efficiency of the communication system.

Keywords: digital communication, polar code, modulation, adaptive mode, signal to noise ratio

Formulation of the problem

The transport network in cellular communication includes the area of the network between the operator's backbone network and the base station. 5th Generation wireless systems (5G) can use a set of available frequency bands. Frequencies in the range of 694-790 MHz will be used outside large cities due to the large coverage area. Frequencies in the range from 1 GHz to 6 GHz, in particular 4.4-3.8 GHz, 4.4-4.99 GHz and 5.9 GHz, will cover large cities. Frequencies in the millimetre range (above 24 GHz) - 24-29.5 GHz, 30-55 GHz, 66-75 GHz, 81-86 GHz will be suitable for spot coverage in places of the largest concentration of subscribers: airports, railway stations, stadiums, etc [1-3].

A characteristic feature of the 5th Generation standards is the concept, which is based on the implementation of two channel-coding scenarios. The first scenario is based on the implementation of channel coding based on polar codes, and the second based on codes with low-density parity checks (LDPC). Such signal-code constructions (SCC) are offered for replacement of systems of convolutional coding and turbo codes, which are widespread in the 4G standard. There are three main use cases for 5G that broadly embody the concepts of mobile broadband, machine-type communications, and reliable, low-latency communications. The main requirement for such a concept is to provide increased throughput and noise immunity in comparison with the standard 4G. In this case, the proposed SCC should adaptively rebuild the rate and code length depending on the level of interference and user requirements.

Most of the available literature does not take into account the capabilities of specific codes developed for 5G [4-7]. It is necessary to control the features of the process of their application in a complex interfering environment. In this case, the encoding and decoding may be accompanied by a significant loss of performance and speed [8-10].

The papers [1, 2] describe general approaches to the polar code encoding process that is used in 5G technology. Proposals for improving the reliability of polar coding are described.

In work [3-5], possible scenarios for the implementation of algorithms for adaptive signal processing for communication channels with error-correcting coding are considered. The results of an experimental study of adaptive decoding methods are presented.

Articles [6-10] identify the main scenarios for the application of polar codes for mobile broadband. The solutions to the problem of latency when applying the decoding algorithm of the successive cancellation type have been added. Recommendations are given on the structure and shape of the SCC based on polar codes for future telecommunications.

Articles [11-19] describe methods of algorithmic solutions for constructing error-correcting codes, methods for decoding them, principles of synchronization, and the like. A comparative analysis of the decoding algorithms for error-correcting codes is carried out. Thus, the proposed technology for processing polar codes consists in converting a continuous communication channel into a system of vector channels with cross-links. In this case, a complete exclusion from the analysis of the received sequence of those channels in which the transmission of bits turns out to be unreliable is carried out [11-13]. Data recovery is carried out at the expense of information obtained from reliable channels based on adaptive determination of the signal-to-noise ratio (SNR) [14-17]. It should be emphasized that when decoding polar codes, the result of each decoding step depends entirely on the reliability of the estimates of the information bits of the previous steps.

A description of the practical aspects of constructing polar codes is concentrated in the sources [20-26]. Here the features of the interleaving process in the synthesis of polar codes are considered, recommendations on the interleaving structure are given depending on the complexity of the code.

Possible directions of formation of signals with polar coding are proposed in articles [26-34]. Forms of combining polar codes with certain types of modulation for information transmission have been determined.

The proposed work complements those described in the references study. Proposals are given for the construction of an algorithm for adaptive selection of the type of multi-position baseband signal for broadband telecommunications. The results of experimental studies of the selection of the code rate for a specific SCC with a polar code are presented. The energy gain from modifying the SCC shape with a polar code and a specific code rate is determined.

Research Method

In this section, it is explained the results of research and at the same time is given the comprehensive discussion of the proposed Simulink model of the communication channel with polar codes. The features of recursive coding of polar codes are presented.

A Simulink-model of the communication channel with polar codes

We will develop and describe the structural diagram of a telecommunications system with polar coding for 5G [18-20]. We use polar coding in order to increase the throughput of the telecommunication channel. The proposed scheme should become an alternative to the channel with LDPC and turbo codes [11, 21, 22]. Consider the components that allow you to simulate a telecommunication channel with polar coding and using various types of modulation over the AWGN channel [23, 24]. The proposed Simulink-model of a signal processing system for a telecommunication channel with the corresponding block designation is shown in Fig. 1.

The formation of the polar code was carried out by calculating the reliability of each subchannel in the adaptive mode. The final result of the formed ordered code sequence is stored for the maximum code length [25-28]. This sequence is computed for given rate-matched output length E, and information length K [27-29]. For the code rate $R = 0.5$, the adaptive modulation mode [28-30] selection algorithm is presented in Fig. 2. By reducing the code rate by 10 times, the SNR for the application of each type of modulation can be reduced by 7dB.

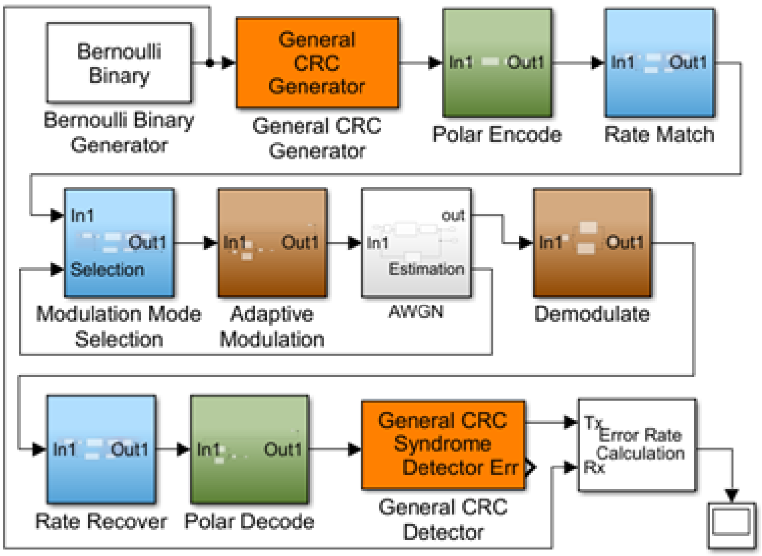

Figure 1. Is a Simulink-model of a signal processing system for a telecommunication channel with polar codes: (General CRC Generator) is cyclic redundancy check; (PE) is the polar encoder; (RM) is rate match; (M) is the modulation mode selection; Adaptive Modulation is the adaptive modulation mode selection; (AWGN Channel); (D) is the demodulator; (RR) is rate recover; (PD) is the polar decoder; (GCRC) is general of cyclic redundancy check detector

The algorithm of the Adaptive Modulation unit Simulink-model (Fig. 2) consists of mapping calculating in accordance with the determined SNR value. The mapping takes binary values of 0 or 1 as input data and creates complex modulation symbols at the output [31].

When using $\pi/2-$ BPSK modulation for the SCC form to display the constellation diagram $r(j)$ of the modulation symbol, we obtain the expression:

$$r(j)_{BPSK}=e^{j\frac{\pi}{2}(imod2)}/\sqrt{2}[(1-2l(j))+i(1-2l(j))] \tag{1}$$

The transition to quadrature modulation requires taking into account a larger number of components. For example, to modulate 64QAM to obtain the final expression, you need to consider the following set of bits: $l(6j)$, $l(6j+1)$, $l(6j+2)$, $l(6j+3)$, $l(6j+4)$, $l(6j+5)$. Then for to display the diagram of the constellation $r(j)$ of the modulation symbol, we obtain the expression:

$$r(j)_{QAM}=1/\sqrt{42}\left\{\left(1-2l(6j)\right)\left[4-\left(1-2l(6j+2)\right)\left[2-\left(1-2l(6j+4)\right)\right]\right]\right\}+$$
$$+i\left(1-2l(6j+1)\right)\left[4-\left(1-2l(6j+3)\right)\left[2-\left(1-2l(6j+5)\right)\right]\right] \tag{2}$$

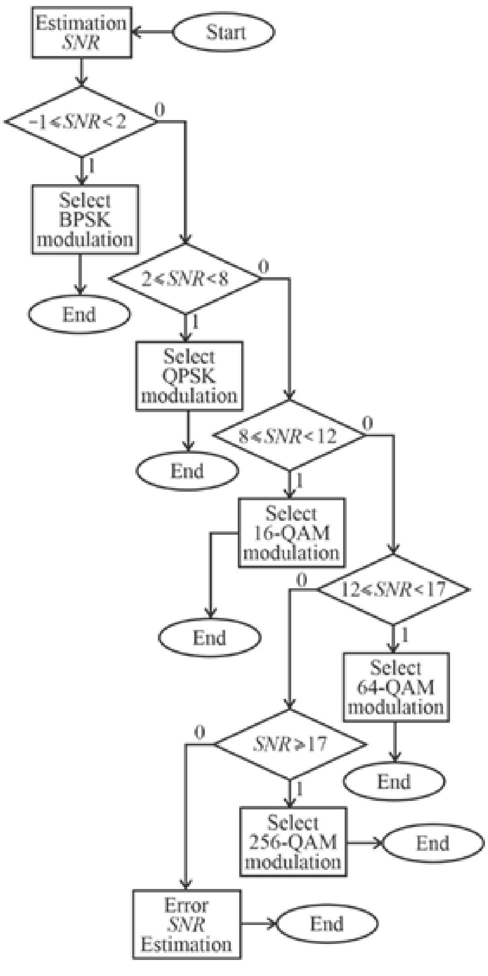

Figure 2. Adaptive modulation mode selection algorithm of telecommunication with polar coding

Features of coding of polar codes

A promising method for increasing the noise immunity and efficiency of information transmission in modern telecommunications is noise-immune coding. Polar codes are capable of achieving the bandwidth of a memoryless binary symmetric channel. Such codes are characterized by simplicity of construction, encoding and decoding [15, 16].

Polar code C is specified by a set of parameters (n, k, a_c), where n is the length of the code word; k is the size of the information part of the code word; a_c a set of symbols used as check symbols and $|a_c| = n - k, a_c \in \{0, \dots, n-1\}$.

The denumerable set a_c can be obtained using channel polarization. The channel polarization is described by a linear transformation, which is set by the matrix $G^{\otimes q}$, where G is the polarization core; $G = \begin{vmatrix} 1 & 0 \\ 1 & 1 \end{vmatrix}$; $\otimes\, q$ is the n-multiple products of Kronecker matrices; $q = \log_2 n$, n is the length of the code word [11].

The encoding procedure is represented by the following expression $x_1^n = u_1^n F_n$, where x_1^n is a codeword; u_1^n is a vector including information symbols ($u_i \notin a_c$, $1 \le i \le n$) and relocated bits ($u_i \in a_c$, $1 \le i \le n$), F_n is a generating matrix which we represent by the expression $F_n = B_n G^{\oplus q}$, where B_n is a permutation matrix.

To carry out the polarization operation, it is necessary to transform the scalar channel into a vector channel. Let us describe such a channel using the conditional probability density function of the output symbol [32-34]. We will carry out such a description by creating copies of a discrete symmetric channel in a recursive way, as shown in Fig. 3. Recursion starts at level 0 ($q = 0$) by applying only one instance of P. After that, P is assigned to $P = P_0$. At the first level of recursion, the diagram combines two independent copies of P_0. Thus, we get the P_1 channel with the transition probability $P_1(y_0|y_1|u_0, u_1) = P_1(y_0 \mid u_0 \otimes u_1) \cdot P(y_1 \mid u_1)$. The diagram for building such a system is a multiple of step 2 if you start from scratch. Figure 3 shows the permutation matrix B_n. The permutation matrix has inputs which we denote as $(j_0, j_1, j_2, \dots, j_{n-1})$.

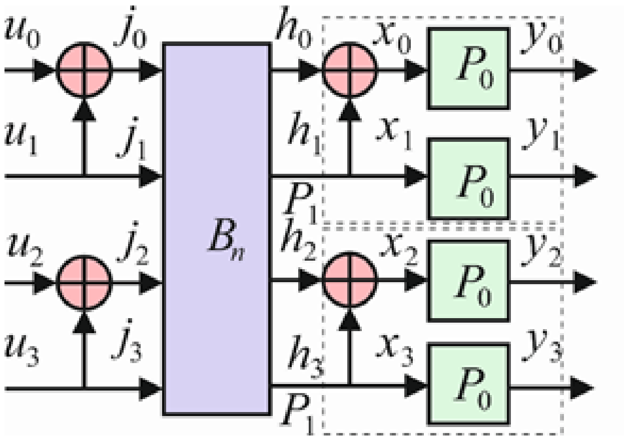

Figure 3. Is a block diagram of code vector formation by recursive method

The general form of recursive dependence is equal to $P_n(y_0^{n-1}|u_0^{n-1}) = P^n(y_0^{n-1}|u_0^{n-1} \cdot F_n)$. The process of forming the matrix B_n satisfies the following relationship for the case when m=2: $j_0 \to h_0$, $j_1 \to h_1$, $j_2 \to h_2$, $j_3 \to h_3$. Thus, the inputs are ranked by even and odd numbers. Outputs are assigned to this design, which are numbered strictly in order from the zero point. The specified method consists in the formation $P_n(y_0^{n-1}|u_0^{n-1})$ and $P' = \left\{P_n^{(i)}(y_0^{n-1}, u_0^{n-1}|u_i), 0 \le i \le n\right\}$ of binary channels which can be represented in Fig. 4.

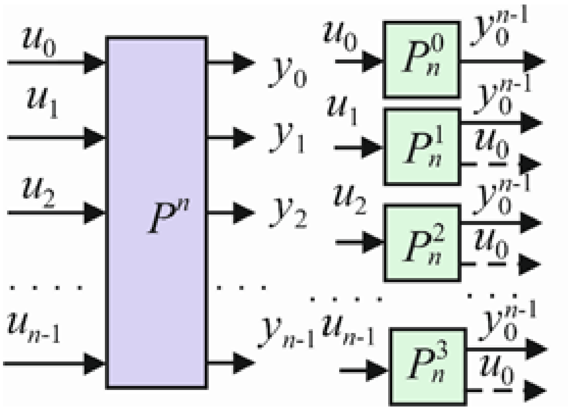

Figure 4. Is a block diagram of formation binary channels

To decode polar codes, we use an adaptive modification of the sequential elimination algorithm [6]. The algorithm is based on calculating the likelihood coefficient for each symbol at each channel polarization level and calculating the constellation diagram of digital modulation in accordance with a certain level of SNR. The number of nodes is defined as $n(\log_2 n + 1)$. Note that the proposed decoding algorithm is a soft decision algorithm. The use of soft methods for processing the obtained data allows you to achieve additional energy gain when using polar codes.

Results and Analysis

The defining requirement for the use of polar coded SCC in telecommunications is to ensure high data transfer rates. Therefore, the search for a signal conditioning system that meets the requirements of 5G, and especially in the gigabit range, is a very urgent task [6].

So, the criterion for using the signal conditioning system should be determined by the distance between the base station and the user. This situation is due to high SNR values. In the case of close placement, as studies have shown, it is advisable to use QAM modulation. For remote subscribers, it is advisable to use QPSK since the SNR value is rather low. In this case, it is easier to ensure the speeds specified in the 5G standard [1]. Thus, the studies presented below should form recommendations for choosing the correct signal-code structure and the form of the polar code in order to increase the data transfer rate by reducing the probability of bit error.

Modern telecommunication systems often require knowledge of the SNR in the receiver. For example, SNR estimates are commonly used in mobile power management, maintenance, and adaptive modulation schemes, as well as soft decoding procedures [31-33].

Dependencies of BER on the bit energy ratio to the power-to-noise spectral density (E_b/N_0) for 16-QAM, 64-QAM and 256-QAM modulation at an effective code rate R=0.5 are shown in Fig. 5.

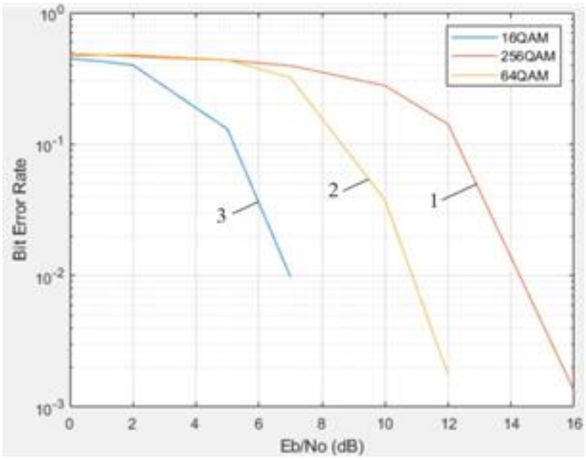

Figure 5. Dependence of the probability of error per bit (BER) on the SNR (E_b/N_0) for the communication system with the polar code of the effective rate $= 0.5$ and modulation (1 is the 256-QAM; 2 is the 64-QAM; 3 is the 16-QAM)

Dependencies of BER on the bit energy ratio to the power-to-noise spectral density E_b/N_0 for BPSK and QPSK modulation at an effective code rate $R = 0.5$ are shown in Fig. 6.

For an effective polar code rate of $R = 0.5$, a maximum bit rate of 8 bits per symbol with an error of BER=10E-3 can be achieved by using 256-QAM modulation at a SNR more than 17dB. 64-QAM modulation reduces the rate transmission by 3/4 times, and reduces the SNR requirements by 3.5 dB with an error of BER=10E-3. 16-QAM modulation reduces the rate transmission by 2 times (compared to 256-QAM modulation), but reduces the SNR ratio requirements by 7 dB with an error of BER=10E-3.

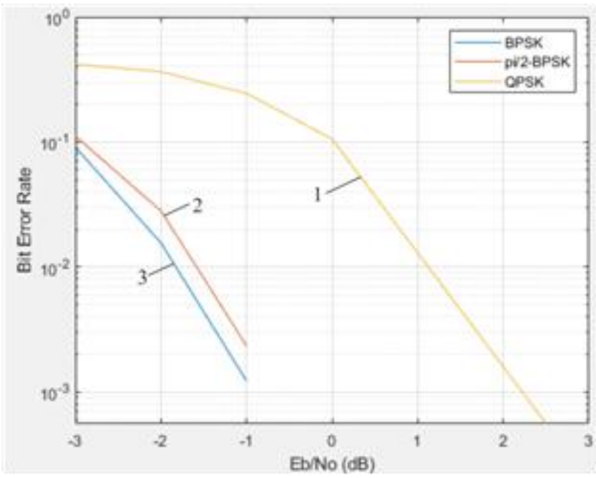

Figure 6. Dependence of the probability of error per bit (BER) on the SNR (E_b/N_0) for the communication system with the polar code effective rate code $R = 0.5$ and modulation (1 is the QPSK; 2 is the $\pi/2 -$ BPSK; 3 is the BPSK)

For the SNR (E_b/N_0) 2dB, QPSK modulation with a polar code is more efficient than BPSK, the error rate is reduced by 2.3 times. pi/2-BPSK modulation with a polar code is more efficient than BPSK, the frequency of errors is reduced by 1.1 times. QPSK modulation with a polar code rate of $R = 0.5$ is more effective than BPSK modulation by 3dB. For an effective polar code rate $R = 0.5$, BPSK modulation is more effective than QPSK modulation by 3dB, error BER=10E-3 is achieved at a lower SNR.

The dependence of BER on the bit energy ratio to the power-to-noise spectral density (E_b/N_0) for 16-QAM, 64-QAM and 256-QAM modulation at an effective code rate R=0.05 is shown in Fig. 7.

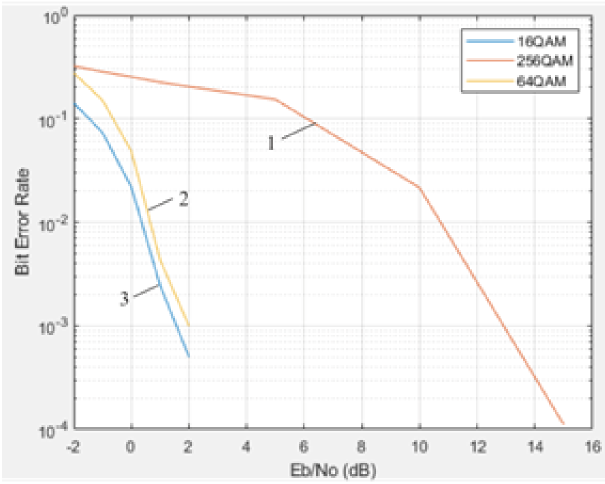

Figure 7. Dependence of the error probability per bit (BER) on the SNR (E_b/N_0) for the communication system with the polar code of the effective rate $= 0.05$ and modulation (1 is the 256-QAM; 2 is the 64-QAM; 3 is the 16-QAM)

The maximum rate transmission of 8 bits per symbol with an error of BER=10E-3, for an effective polar code rate of $R = 0.05$ can be achieved by using 256-QAM modulation at a SNR more than 13dB. The use of 64-QAM and 16-QAM modulation reduces the SNR requirements by 11 dB with an error of BER=10E-3.

The dependence of BER on the effective code rate for QPSK and BPSK modulation at the bit energy ratio to spectral power-noise density $E_b/N_0 = -8\text{dB}$, which corresponds to a SNR of 0.16 in absolute units is shown in Fig. 8.

The dependence of BER on the effective code rate for QPSK and 16-QAM modulation at the bit energy ratio to spectral power-noise density $E_b/N_0 = -5\text{dB}$, which corresponds to the SNR of 0.316 in absolute units is shown in Fig. 9.

The maximum rate transmission of 8 bits per symbol with an error of BER=10E-3, for an effective polar code rate of $R = 0.05$ can be achieved by using 256-QAM modulation at a SNR more than 13dB. The use of 64-QAM and 16-QAM modulation reduces the SNR requirements by 11 dB with an error of BER=10E-3. For SNR $= 1$dB, 16-QAM modulation with a polar code is more efficient than 64-QAM and 256-QAM, the error rate is reduced by almost two times, and for SNR $= 4$dB, the frequency of errors is reduced by twenty times.

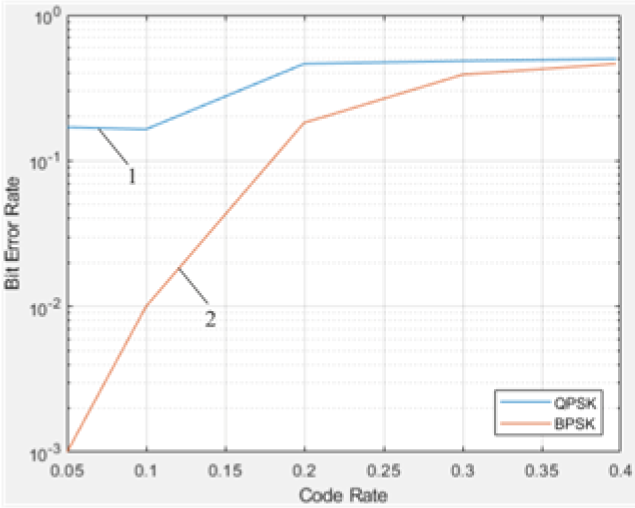

Figure 8. BER dependence on the effective code rate at the bit energy ratio to spectral power-noise density $E_b/N_0 = -8$dB for modulation: (1 is the QPSK; 2 is the BPSK)

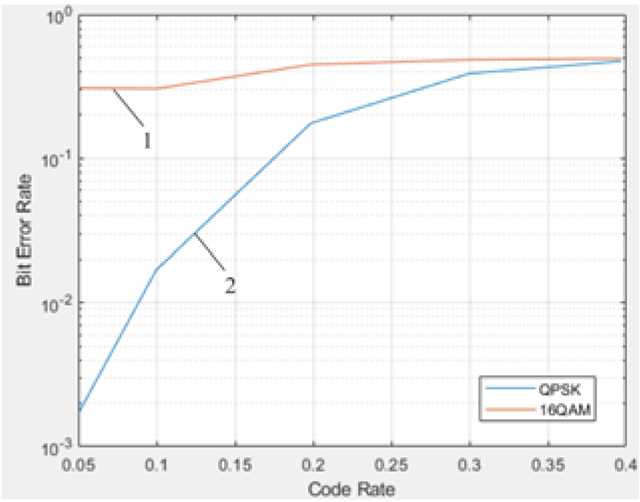

Figure 9. BER dependence on the effective code rate at the bit energy ratio to spectral power-noise density $E_b/N_0 = -5$dB for modulation: (1 is the 16-QAM; 2 is the QPSK)

The dependence of BER on the effective code rate for 16-QAM and 64-QAM modulation at the bit energy ratio to spectral power-noise density $E_b/N_0 = 1$dB, which corresponds to the SNR of 1.26 in absolute units is shown in Figure 10.

The dependence of BER on the effective code rate for 64-QAM and 256-QAM modulation at the bit energy ratio to the spectral power-noise density $E_b/N_0 = 5$dB, which corresponds to the SNR of 3.16 in absolute units is shown in Fig. 11.

At an effective code rate $R = 0.05$ and $E_b/N_0 = 5$dB ratio, 64-QAM modulation is 22dB more efficient than 256-QAM modulation.

The dependence of BER on the effective code rate for 64-QAM and 256-QAM modulation at the bit energy ratio to spectral power-noise density $E_b/N_0 = 12$dB, which corresponds to the SNR of 15.9 in absolute units is shown in Fig. 12.

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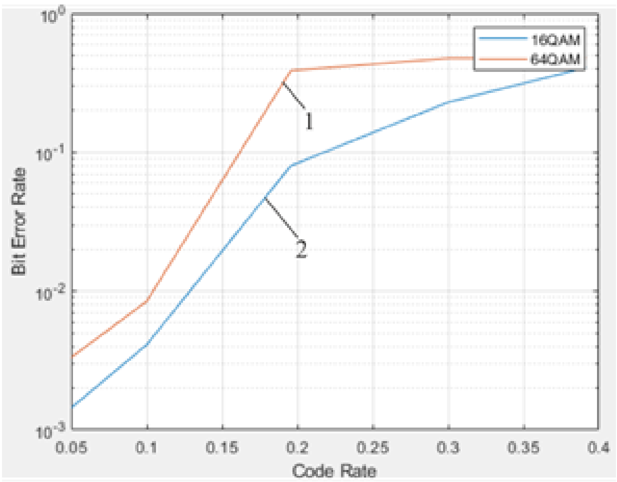

Figure 10. BER dependence on the effective code rate at the bit energy ratio to spectral power-noise density $E_b/N_0 = 5$dB for modulation: (1 is the 16-QAM; 2 is the 64-QAM)

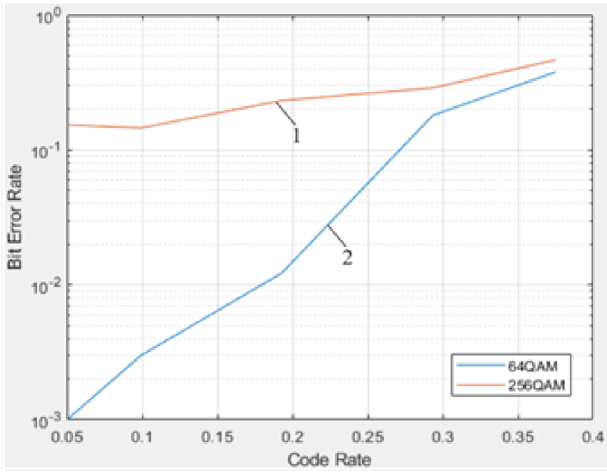

Figure 11. BER dependence on the effective code rate at the bit energy ratio to spectral power-noise density $E_b/N_0 = 5$dB for modulation: (1 is the 256-QAM; 2 is the 64-QAM)

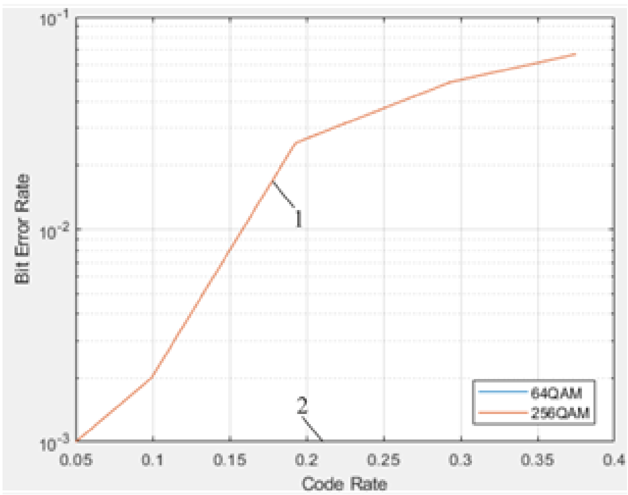

Figure 12. Dependence of BER on the effective code rate at the bit energy ratio to spectral power-noise density $E_b/N_0 = 12$dB for modulation: (1 is the 256-QAM; 2 is the 64-QAM)

To discuss the research done. The results of experimental studies allow us to establish that high modulation orders for SCCs with polar codes and a high information transfer rate are characteristic of an ideal channel. The transition to low-efficiency modulation mode is typical for low SNRs.

Note that SNR control allows you to set an upper bound on the bandwidth (or data rate) in telecommunications. Therefore, estimating SNR in telecommunications is a must. The investigated SNR estimate allows its level switching, channel power control and provides the necessary information about the channel quality. Improving the performance of the signal conditioning system is realized through the adaptive modulation mode [35].

Conclusions

A study of communication system with polar coding and adding a cyclic redundancy check, specified in 3GPP for the Downlink control information (DCI), Uplink control information (UCI) of new radio channel and broadcast channel (BCH) is investigated in the paper. It shows the use of components at all stages of processing (encoding, rate matching, rate recovering and decoding) and uses them with different types of modulation for transmission over AWGN channel [29, 36].

For an effective polar code rate $R = 0.5$ max rate transmission of 8 bits per symbol with error BER=10E-3 can be achieved using 256-QAM modulation under the SNR more than 17dB.

16-QAM modulation reduces rate transmission by 2 times (compared with 256-QAM modulation), but reduces the SNR requirements of 7 dB at the error BER=10E-3.

For an effective polar code rate $R = 0.05$ maximum rate transmission of 8 bits per symbol with error BER=10E-3 can be achieved using 256-QAM modulation under the SNR more 13dB. 64-QAM and 16-QAM modulation reduces the SNR requirements of 11 dB in case of error BER=10E-3. Decreasing the effective rate of the polar code, reduced requirements the SNR limit (E_b/N_0) for a given digital modulation.

REFERENCES

1. Bioglio V., Condo C., Land I. Design of Polar Codes in 5G New Radio / V. Bioglio, C. Condo, I. Land // IEEE Communications Surveys & Tutorials. - 2020. - pp.1.

2. Kaykac Egilmez Z. B., Xiang L., Maunder R. G., Hanzo L. The Development, Operation and Performance of the 5G Polar Codes / Z. B. Kaykac Egilmez, L. Xiang, R. G. Maunder, L. Hanzo // IEEE Communications Surveys & Tutorials. - 2020. - Vol. 22, No. 1. - pp. 96-122.

3. Boiko J., Pyatin I., Eromenko O., Stepanov M. Method of the adaptive decoding of self-orthogonal codes in telecommunication / J. Boiko, I. Pyatin, O. Eromenko, M. Stepanov // Indonesian Journal of Electrical Engineering and Computer Science. - 2020. - Vol. 19, No. 3. - pp. 1287-1296.

4. Hussain G. A., Audah L. UFMC system performance improvement using RS codes for 5G communication system / G. A. Hussain, L. Audah // Telkomnika (Telecommunication Computing Electronics and Control). - 2020. - Vol. 18, No. 4. - pp. 1843-1848.

5. Hreshee S. S. Automatic recognition of the digital modulation types using the artificial neural networks / S. S. Hreshee // International Journal of Electrical and Computer Engineering. - 2020. - Vol. 10, No. 6. - pp. 5871-5882.

6. Bae J., Abotabl A., Lin H., Song K., Lee J. An overview of channel coding for 5G NR cellular communications / J. Bae, A. Abotabl, H. Lin, K. Song, J. Lee // APSIPA Transactions on Signal and Information Processing. - 2019, No. 8. - E17.

7. Dhuheir M., Öztürk S. Polar Codes Analysis of 5G Systems / M. Dhuheir, S. Öztürk // Proceedings 2018 IEEE 6th International Conference on Control Engineering & Information Technology (CEIT). - (Istanbul, 25-27 Oct. 2018). – 2018. – P. 1-6.

8. İşcan O., Xu. W. Polar Codes with Integrated Probabilistic Shaping for 5G New Radio / O. İşcan, W. Xu. // Proceedings 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall) – (Chicago, 27-30 Aug. 2018). – 2018. - P. 1-5.

9. Sasoglu E. (2012) Polarization and Polar Codes. / E. Sasoglu // Polarization and Polar Codes. – 2012. – Vol.8, No. 4. – pp. 259-381.

10. Toghuj W. Modifying Hamming code and using the replication method to protect memory against triple soft errors / W. Toghuj // Telkomnika (Telecommunication Computing Electronics and Control). – 2020. - Vol. 18, No. 5. - pp. 2533-2542.

11. Fang Y., Bi G., Guan Y. L., Lau F. C. M. A Survey on Protograph LDPC Codes and Their Applications / Y. Fang, G. Bi, Y. L. Guan, F. C. M. Lau // IEEE Communications Surveys & Tutorials. – 2015. - Vol. 17, No. 4. - pp. 1989-2016.

12. Li J., Gao Z., Lv Y. Gaussian Approximation Optimized SC- Flip Decoding Algorithm of Polar Codes / J. Li, Z. Gao, Y. Lv // Proceedings 2020 IEEE 4th Information Technology, Networking, Electronic and Automation Control Conf. (ITNEC). – (Chongqing, 12-14 June 2020). – 2020. – P. 1124-1127.

13. Hanif M. A., Vafi S. An Efficient Serially Concatenated Polar Code with Unequal Error Protection Property / M. A. Hanif, S. Vafi // Proceeding 2019 IEEE 4th International Conf. on Computer and Communication Systems (ICCCS). – (Singapore, 23-25 Feb. 2019). – 2019. - P. 497-501.

14. Boiko Y. M., Boryachok R. O. Improving effectiveness for processing signals in data transmission channels with phase manipulation / Y. M. Boiko, R. O. Boryachok // Proceeding 2013 IEEE 23rd International Crimean Conference "Microwave & Telecommunication Technology". – (Sevastopol, 8-14 Sept. 2013). – 2013. - P. 262-263.

15. Cheng J., Li H., Ye,M., Wang L., Zhang C. (2019) Systematic Polar Codes Based on 3x3 Kernel Matrix / J. Cheng, H. Li, M.Ye, L. Wang, C. Zhang // Proceeding 2019 IEEE International Conf. on Communications, Information System and Computer Engineering (CISCE). – (Haikou, 5-7 July 2019). – 2019. - P. 77-79.

16. Hu M., Li J., Lv Y. (2017) A comparative study of polar code decoding algorithms / M. Hu, J. Li, Y Lv // Proceeding 2017 IEEE 3rd Information Technology and Mechatronics Engineering Conference (ITOEC). – (Chongqing, 3-5 Oct. 2017). – 2017. - P. 1221-1225.

17. Boiko J., Pyatin I., Eromenko O., Barabash O. Methodology for Assessing Synchronization Conditions in Telecommunication Devices / J. Boiko, I. Pyatin, O. Eromenko, O. Barabash // Advances in Science, Technology and Engineering Systems Journal. -2020. - Vol. 5, No. 2. - pp. 320-327.

18. Boiko J., Eromenko O. (2018) Signal Processing in Telecommunications with Forward Correction of Errors / J. Boiko, O. Eromenko // Indonesian Journal of Electrical Engineering and Computer Science. – 2018. - Vol. 11, No. 3. - pp. 868-877.

19. Cyriac A., Narayanan G. Polar Code Encoder and Decoder Implementation / A. Cyriac, G. Narayanan // Proceeding 2018 IEEE 3rd International Conf. on Communication and Electronics Systems (ICCES). – (Coimbatore, 15-16 Oct. 2018). – 2018. - P. 294-302.

20. Luo F. Deep Learning Techniques for Decoding Polar Codes / F. Luo // Machine Learning for Future Wireless Communications. – 2020. – pp.287-301.

21. Chiu M. Interleaved Polar (I-Polar) Codes / M. Chiu // IEEE Transactions on Information Theory. – 2020. - Vol. 66, No. 4. - pp. 2430-2442.

22. Condo C., Bioglio V., Hafermann H., Land I. Practical Product Code Construction of Polar Codes / C. Condo, V. Bioglio, H. Hafermann, I. Land // IEEE Transactions on Signal Processing. – 2020. - Vol. 68. - pp. 2004-2014.

23. Chen P., Bai B., Ren Z., Wang J., Sun S. Hash-Polar Codes with Application to 5G / P. Chen, B. Bai, Z. Ren, J. Wang, S. Sun // IEEE Access. – 2019. - Vol. 7. - pp. 12441-12455.

24. Vangala H., Viterbo E., Hong Y. A comparative study of polar code constructions for the AWGN channel / H. Vangala, E. Viterbo, Y. Hong // arXiv preprint arXiv:1501.02473. – 2015. - pp. 1-9.

25. Mahdavifar H., El-Khamy M., Lee J., Kang I. Polar Coding for Bit-Interleaved Coded Modulation / H. Mahdavifar, M. El-Khamy, J. Lee, I. Kang // IEEE Transactions on Vehicular Technology. – 2016. - Vol. 65, No. 5. - pp. 3115-3127.

26. Zhurakovskyi B., Boiko J., Druzhynin V., Zeniv I., Eromenko O. Increasing the efficiency of information transmission in communication channels / B. Zhurakovskyi, J. Boiko, V. Druzhynin, I. Zeniv, O. Eromenko // Indonesian Journal of Electrical Engineering and Computer Science. – 2020. - Vol. 19, No. 3. - pp. 1306-1315.

27. Arikan E. Systematic Polar Coding / E. Arikan // IEEE Communications Letters. – 2011. - Vol. 15, No. 8. - pp. 860-862.

28. Chen P., Xu M., Bai B., Ma X. Design of polar coded 64-QAM / P. Chen, M. Xu, B. Bai, X. Ma // Proceeding 2016 IEEE 9th International Symposium on Turbo Codes and Iterative Information Processing (ISTC). – (Brest, 5-9 Sept. 2016). – 2016. - P. 251-255.

29. Wu X., Yuan J. Partially Information Coupled Bit-Interleaved Polar Coded Modulation for 16-QAM / X. Wu, J. Yuan // Proceeding 2019 IEEE Information Theory Workshop (ITW). – (Visby, 25-28 Aug. 2019). – 2019. - P. 1-5.

30. Boiko J. M., Pyatin I. S., Eromenko O. I., Parkhomey I. R. Investigation of signals distortion during interpolation in SDR transmitters with QPSK modulation / J. M. Boiko, I. S. Pyatin, O. I. Eromenko, I. R. Parkhomey // Adaptive systems of automatic control. – 2019. - No 1(34). - pp. 5-15.

31. Boiko J. Synthesis and analysis of information-control systems of synchronization of means of telecommunications / J. Boiko // Adaptive systems of automatic control. – 2017. - No 1(30). - pp. 8-28.

32. Jia X., Wang F., Sun Y., Zhang S. A Novel Modulation Scheme of Polar Codes / X. Jia, F. Wang, Y. Sun, S. Zhang // Proceeding 2018 IEEE 14th International Wireless Communications & Mobile Computing Conf. (IWCMC). – (Guangzhou, 10-13 Nov. 2017) – 2017. - P. 1385-1390.

33. Ciflikli C., Al-Obaidi W., Al-Obaidi M. The Performance of Convolutional Coding Based Cooperative Communication: Relay Position and Power Allocation Analysis / C. Ciflikli, W. Al-Obaidi, M. Al-Obaidi // International Journal of Computer Networks & Communications (IJCNC). – 2019. - Vol.11, No.3, pp. 51-66.

34. Parkhomey I., Boiko J., Tsopa N., Zeniv I., Eromenko O. Assessment of quality indicators of the automatic control system influence of accident interference / I. Parkhomey, J. Boiko, N. Tsopa, I. Zeniv, O. Eromenko // Telkomnika (Telecommunication Computing Electronics and Control). – 2020. - Vol. 18, No. 4. - pp. 2070-2079.

35. Modi B., Olabiyi O., Annamalai A. Joint-Design of Link-Adaptive Modulation and Coding with Adaptive ARQ for Cooperative Amplify and Forward Relaying System / B. Modi, O. Olabiyi, A. Annamalai // International Journal of Computer Networks & Communications (IJCNC). – 2016. - Vol.8, No.3. - pp. 195-212.

36. Boiko J. M., Druzhynin V. A., Toljupa S. V. Teoretychni aspekty pidvyshhennja zavadostijkosti j efektyvnosti obrobky syghnaliv v radiotekhnichnykh prystrojakh ta zasobakh telekomunikacijnykh system za najavnosti zavad / J. M. Boiko, V. A. Druzhynin, S. V. Toljupa. - Kyjiv : Loghos, 2018. – 227 s.