Performance Analysis of Concatenated Coding for OFDM Under Selective Fading Conditions

Bohdan Zhurakovskiy [1], Juliy Boiko [2], Volodymir Druzhynin [1] and Ilya Pyatin [3]

[1] *National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», 37, Beresteysky Aven., Kyiv, 03056, Ukraine*
[2] *Khmelnytskyi National University, 11, Instytuts'ka str., Khmelnytskyi, 29016, Ukraine*
[3] *Khmelnytskyi Polytechnic Professional College by Lviv Polytechnic National University, 10, Zarichanska str., Khmelnytskyi, 29019, Ukraine*

Abstract

This article is devoted to the study of a method for choosing the shape of orthogonal frequency division multiplexing signals in selective fading conditions. The result obtained is achieved by applying the concatenated coding method. The adequacy of the obtained results was verified by mathematical modeling of the orthogonal frequency division multiplexing channel with the proposed signals based on the components of the turbo codes. As a result of the study, it was found that the performance of the concatenated coding scheme in the orthogonal frequency division multiplexing channel depends on the number of decoding iterations, as well as the signal structure. The obtained results will be useful in choosing the coding method for orthogonal frequency division multiplexing communication channels.

Keywords [1]

OFDM, coding, SNR, synchronization, turbo codes, fading

1. Introduction

At the current stage of the introduction of modern infocommunication technologies, the use of channel coding (CC) plays a key role in improving the performance of channels in which Orthogonal Frequency Division Multiplexing (OFDM) is used [1, 2]. Since OFDM technology is the base for the deployment of 4G and 5G networks [3, 4, 5], the concept of organizing systems based on it creates the prerequisites for increasing the efficiency of CC, namely, increasing the resistance to fading in information transmission channels. In this regard, it is necessary to emphasize the important role of coding in the implementation of OFDM [6], based on the use of coded systems – COFDM [7, 8]. The main contribution of CC in combination with time and frequency interleaving is to create bit-to-bit communication in the data stream transmitted on individual carriers in the spectrum of the OFDM signal so that the transmitted information data in the fading channel can be updated in the receiving equipment.

A review of relevant literature sources allows you to find out the following. OFDM modulation method, the use of which allows you to effectively counteract the effects of interference and noise on the quality of information transmission [9]. In this case, the presence of frequency selectivity creates a certain advantage through frequency diversity [10]. Thus, the availability of information about the state of the channel in the case of CC creates the prerequisites for obtaining a certain gain [11].

An important task of effective implementation of OFDM is to determine the change in the probability of occurrence of bit errors in such systems due to distortions associated with the impact on maintaining the orthogonality of individual subcarriers [12]. The main factors of such distortions can be considered as fast fading effects, jitter, frequency offsets, non-linear distortions, etc. The main action

---

Information Technology and Implementation (IT&I-2023), November 20-21, 2023, Kyiv, Ukraine

EMAIL: zhurakovskiy@tk.kpi.ua (B. Zhurakovskiy); boiko_julius@ukr.net (J. Boiko); v_druzhinin@ukr.net (V. Druzhynin); ilkhmel@ukr.net (I. Pyatin)
ORCID: 0000-0003-3990-5205 (B. Zhurakovskiy); 0000-0003-0603-7827 (J. Boiko); 0000-0002-5340-6237 (V. Druzhynin); 0000-0003-1898-6755 (I. Pyatin)

of all these factors is directed ultimately to the occurrence of crosstalk between subcarriers of OFDM signals. The consequence of the formation of interference in the package OFDM - subcarriers is the impossibility of ensuring optimal signal reception due to the departure from the conditions of subcarrier orthogonality [13]. When the described phenomena occur, the issue of reliable data identification, channel estimation, and the issue of synchronization [14] come to the fore.

The above studies of well-known researchers are supplemented in the presented work. The specificity of the presented studies is based on the fact that, despite the significant advantages of the OFDM concept, a case is possible when deep fading accompanying the transmission of such signals has a selective effect on some subcarriers by suppressing them, and on others, on the contrary, amplifying them. This pattern ultimately leads to an increase in the average signal-to-noise ratio (SNR). Selective fading effects occur in the OFDM channel. The article presents mechanisms to counteract such effects in OFDM channels, which are based on the use of coding methods [15, 16] with forward error correction (FEC). Thus, the novelty of the study is focused on finding conditions for improving the noise immunity of signal reception in an OFDM channel under conditions of selective fading and multipath propagation by applying error-correcting coding (ECC) methods.

2. Generating channel coding component schemes

This section provides a description of the coding scheme. The features of the circuit implementation of encoders and decoders are given. Specific aspects when designing a decoder circuit are considered.

2.1. Description of the coding scheme

In accordance with the formulated task, we analyzed systems with OFDM in order to evaluate CC and improve the noise immunity of systems with digital modulation. In parallel, the work compares the efficiency of signal-code construction (SCC) based on turbo codes (TC) as part of a concatenated coding (CnC) in the context of their application in OFDM. Separately, the efficiency of an OFDM system in the case of a multipath channel with fading was studied. The studies were carried out in channels using digital phase shift keying (PSK) of various orders.

We carry out the description, in Fig. 1 shows a block diagram of a turbo encoder (TE) containing two convolutional recursive encoders (CRE) of length l=5 implemented on feedback shift registers. This design has a feature compared to the classical one for convolutional codes (CoC) [15, 17, 18]: each code block of the TC is triggered additionally for (l – 1) bits at the end of the frame of the information sequence. After encoding the last bit in the frame, the leftmost adder in each component encoder takes two copies of the same feedback bit and sets their outputs to zero. After the (l – 1) th bit, four memory cells are filled with zeros, but at other times the encoder continues to output non-zero encoded symbols. In this encoder design, the encoding rates were 1/3, 1/4 and 1/6 without the puncturing procedure.

Puncturing was used at a coding rate of 1/2 (1/3). For frame lengths of 1632 to 16384 bits, different interleaver were taken, including pseudo-random and regular, operating according to the permutation rule with records of results in a look-up table. The diagram is shown in Fig. 1, synchronization elements are provided. In particular, the synchronization marker serves to control the state of the input buffer (control of the contents of the buffer); with respect to the original buffer (multiplexer), it fixes the frame synchronization pointer; in component encoders, fixes the moment of expiration of the code block. It should be noted that the encoding process is necessarily accompanied by signal time delays (timings) [15], and the entire information block of l-bits must be read before the next block is submitted for encoding.

Next, a construction of a CC based on the component TC and the Reed-Solomon (RS) code is proposed. Therefore, when synthesizing the structure of the TC encoder, we will place the following accents. The implementation of the TE has its own peculiarities. In particular, the information block must be buffered and read in a certain order during the encoding process. Such buffering is absent in the CoC, and the buffer size is comparable to the interleaver size for the RS code. Thus, the TE generally replaces the concatenated design based on the CoC and the RS code, and is not an alternative to the convolutional encoder (CoE) in the above concatenated design. However, a combination of such codes will be proposed to improve the efficiency of concatenated structures.

The design of the decoder is formed by two decoders (DC), organized according to the principle of "Soft in - Soft out" (SISO), one for each stream formed by a single CRE block.

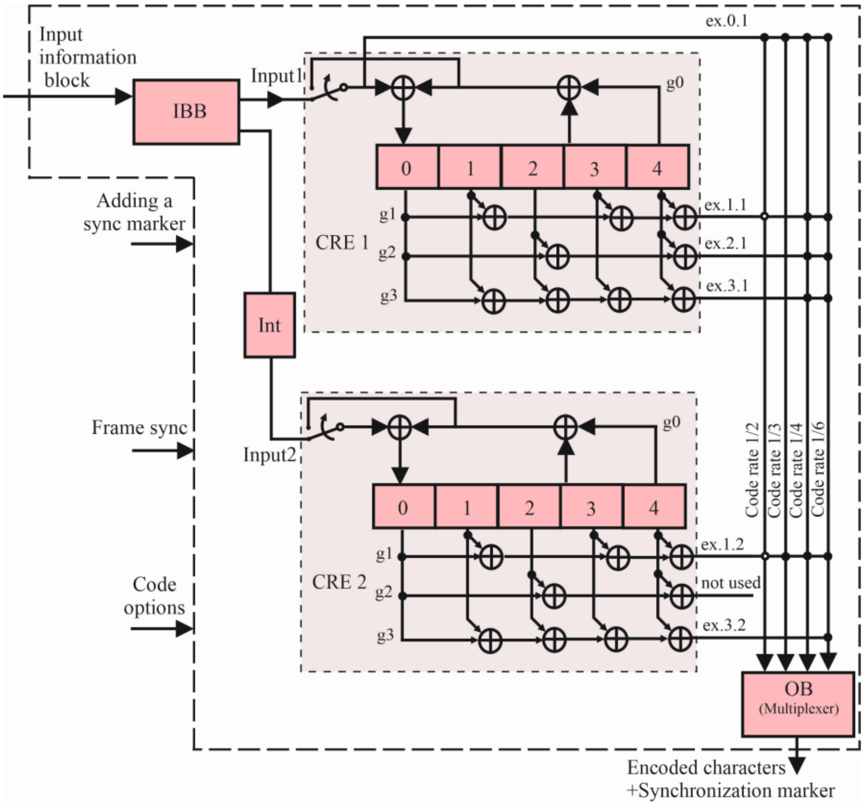


Figure 1: TC encoder block diagram: Int is the interleaver; IBB is the information block input buffer; OB is the output buffer

2.2. The nuances of the decoder circuit

They process the systematic part of the code (denoted as X_k in Fig. 2) and the redundancy bits associated with the Y_{k1} (and/or Y_{k2}) streams and external information coming from another encoder. The implementation of the decoder determines the process of its functioning, which can be parallel or sequential, but the recursiveness is preserved.

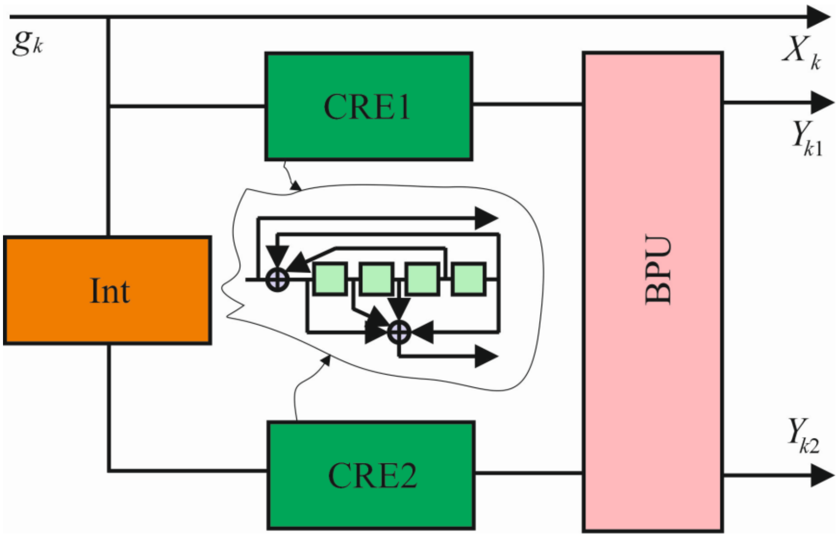


Figure 2: TE design for analytical description (coding rate 1/3): BPU is the bit puncturing unit

On Fig. 3 practical scheme of the TC decoder (TD). There are a number of algorithms for the functioning of TC decoders. Minimum decoder scheme error probability (SISO) provides a maximum a posteriori (MAP) decoding algorithm [15].

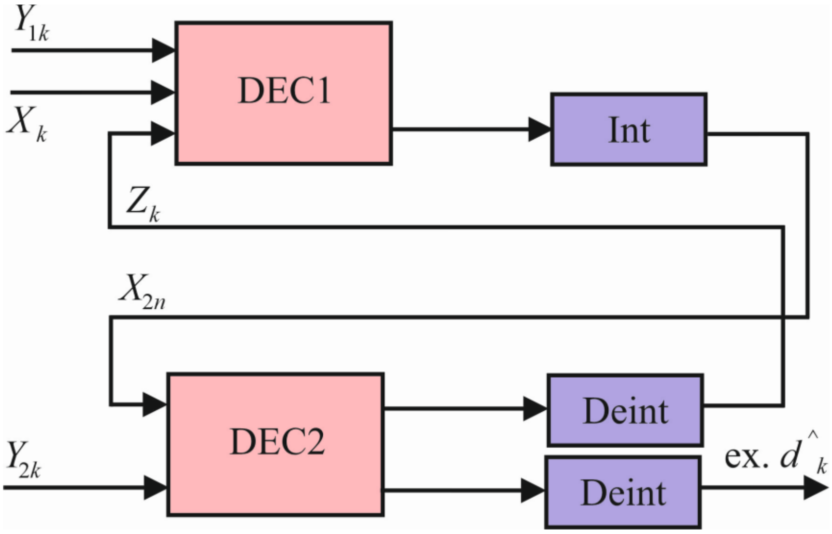


Figure 3: Practical block diagram of a TD: DEC is the decoder SISO: Deint is the deinterleaver

TE uses an iterative decoding algorithm. Each component decoder provides a likelihood estimate, with the received uncoded information symbols available to both decoders to perform these estimates. Each decoder sends its likelihood estimates to the other decoder and uses the corresponding estimates from the other decoder to determine new likelihood estimates by extracting redundant information contained in the other decoder's estimates based on parity symbols only available to it. In general, the following decoding algorithms can be used in TE: MAP, logarithmic MAP (max-log-MAP, APP), Soft Viterbi (SOVA) decoding algorithm [17].

Mathematically, for a systematic code, the soft decoding process $\Lambda(\hat{g}_k)$ can be represented as follows:

$$\Lambda(\hat{g}_k) = \Lambda_c(X_k) + \Lambda(g_k) + \Lambda_e(\hat{g}_k) \tag{1}$$

where $\Lambda(g_k)$ is the a priori logarithmic ratio of the likelihood function (LLF); $\Lambda_c(X_k)$ is the metric obtained during channel estimation; $\Lambda_e(\hat{g}_k)$ is the metric is obtained on the basis of external information from the decoding process and is generally independent of the decoder input X_k.

Thus, the metrics $\Lambda_c(X_k)$, $\Lambda_e(\hat{g}_k)$, and $\Lambda(\hat{g}_k)$ are used by the second decoder as an observation of g_k in order to organize the iterative process.

On Fig. 4 shows a scheme for investigating a transmission system with OFDM and TC-based channel coding.

As follows from the diagram, the input frames of the TC are grouped, each block of packets forms an OFDM frame, which begins with a synchronization symbol, followed by a reference symbol [1, 2, 8]. The first symbol will be used to determine the frame start time and estimate the frequency offset, and the second will be used to estimate the frequency response of the channel. That is, the issue of ensuring synchronization conditions is very important. Let's touch it in detail.

Synchronization of TC blocks is achieved through the use of a synchronization marker (Fig. 5). In this case, the length of the TC block and the synchronization marker is inversely proportional to the nominal coding rate R.

Therefore, the synchronization efficiency depends on the encoding rate. On the receiving side of the telecommunication channel, the synchronization marker is identified by the features of its structure. It should be noted that each of the decoders of the composite decoder (see Fig. 3) cannot always correctly identify the effective size of the synchronization marker, which is very important. Indeed, when decoding a long TC, the decoders of the constituent decoder must clearly identify the boundaries of the code block, including taking into account the delimited and deinterleaved data in the decoder structure.

Therefore, the synchronization marker usually includes a channel symbol (domain) that defines the framing method.

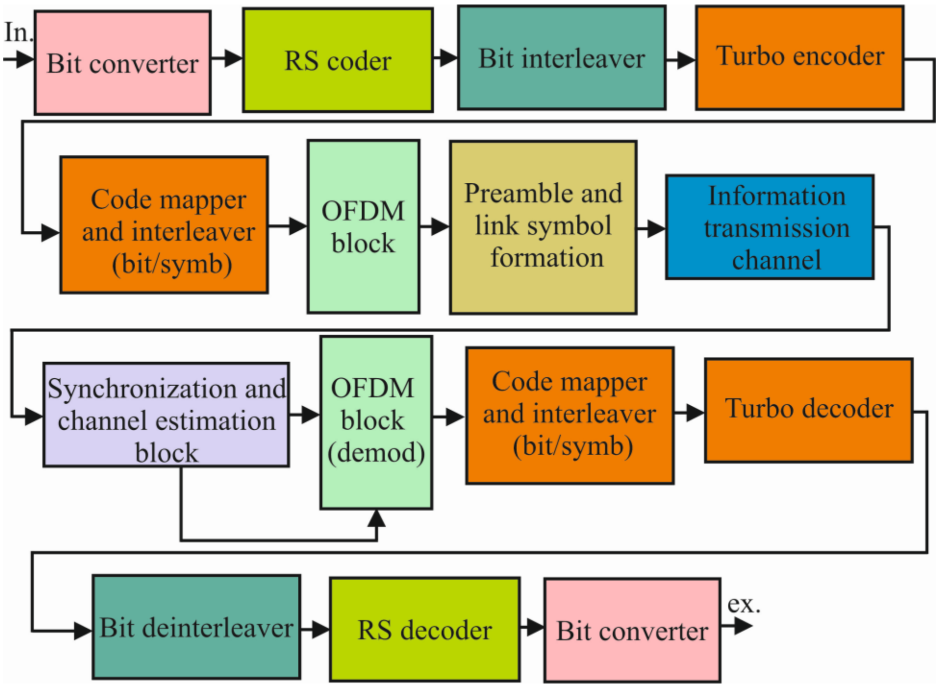


Figure 4: Block diagram of signal generation and processing in an OFDM system with a concatenated coding procedure

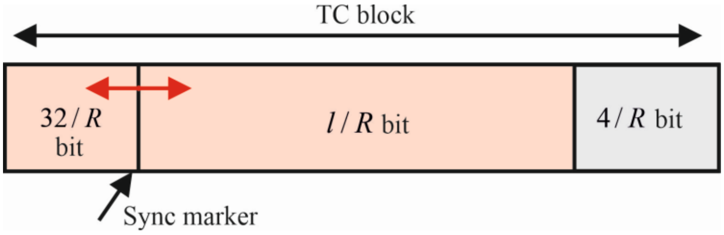


Figure 5: Schematic of the resulting turbo code block with the sync marker attached: *I* is the information data block length; *R* is the declarative encoding rate

The bit mapper block calculates the bit probability of the received character v_k using the formula:

$$\Lambda(v_{k,i}) = \frac{|H(i)|^2}{4}\left[\min_{\gamma J \in X_{J_k}^0}(y(i)-\gamma Y)^2 - \min_{\gamma J \in X_{J_k}^1}(y(i)-\gamma Y)^2\right] \equiv |H(i)|^2 B_{Y,k} \tag{2}$$

where $H(i)$ is the channel response; $X_{J_k}^0$ and $X_{J_k}^1$ subsets described on the Gray code mapping [8], and $B_{Y,1} = -|y_Y[i]|$ is the parameter for using QPSK; 16QAM (64QAM):

$$B_{Y,1} = \begin{cases} y_Y[i], & |y_Y[i]| < 2 \\ 2(y_Y[i]-1), & y_Y[i] > 2 \\ 2(y_Y[i]+1), & y_Y[i] < 2 \end{cases} \tag{3}$$

$$B_{Y,2} = -|y_Y[i]| + 2 \tag{4}$$

Let us consider the issue of choosing an interleaver in the channel turbo coding scheme, having analyzed the results shown in Fig. 6 dependencies of the initial positions (Output) of bits in the coded blocks on the input (Input) for different types of interleavers [19].

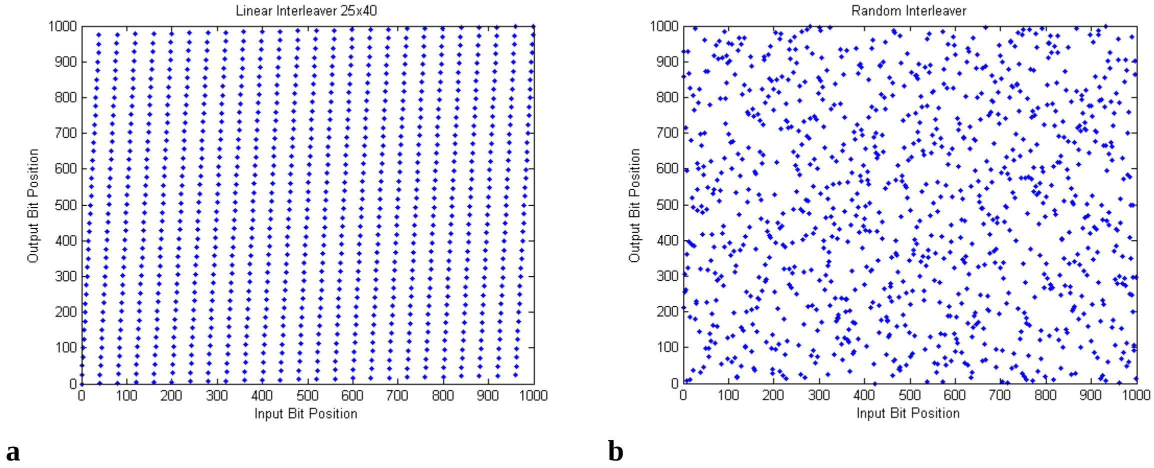


Figure 6: Dependence of the initial position of bits in the block on the input position for different types of interleavers: a is the periodic interleaver; b is the pseudo-random interleaver

In general, both periodic and pseudo-random data interleaving schemes can be implemented. Periodic interleavers are divided into block and convolutional interleavers. The advantage of convolutional interleavers is that the latency and storage capacity is half that of block interleavers. For TC, the choice of the interleaver is quite important, since its structure has a direct impact on the minimum distance and the number of low weights codewords, and these, in turn, according to formula (5), have a direct impact on the efficiency of the TC. In the case of a pseudo-random interleaver, the bits of the initial block in the interleaved block are located pseudo-randomly, and this ultimately has a rather positive effect on the overall efficiency of the TC.

Bit error probability for TC takes the form:

$$P_{prob} \leq \sum_{i=d}^{N} \frac{c_i}{l} p_i \tag{5}$$

where N is the length of the code block; l is the block size that can be interleaved; c_i is the total information weight of all code words of weight i; p_i is the probability of choosing an incorrect code word that differs from the correct one in i positions.

3. Investigation of noise immunity of OFDM systems with channel coding

On Fig. 7 shows a scheme for studying a transmission system with OFDM and channel coding based on a CnC (an external encoder based on a Reed-Solomon (RS) code, an internal encoder based on a TC) [15, 20]. Dependences of Bit Error Ratio (BER) on the corrective ability of RS codes make it possible to establish that the RS code has the best performance (255, 173) [21]. As follows from the diagram (Fig. 7), the input frames of the TC are grouped, each block of packets forms an OFDM frame, which, as described above in the article.

To implement OFDM in the scheme of Fig. 7, we have carried out the formation of subsystems of blocks of the OFDM modulator and demodulator. The blocks convert a sequence of complex symbols into a multicarrier complex envelope OFDM waveform (see Fig. 8). In the diagram in Fig. 8, the bit sequence enters the bit mapper (MAP) and then to the subcarrier signal generator (Subcarrier MAP) [22]. Next, OFDM signals are generated.

On Fig. 9 we present part of the signal processing subsystem with OFDM. The scheme includes the SC DMAP block - a block that provides the allocation of data subcarriers from an OFDM symbol.

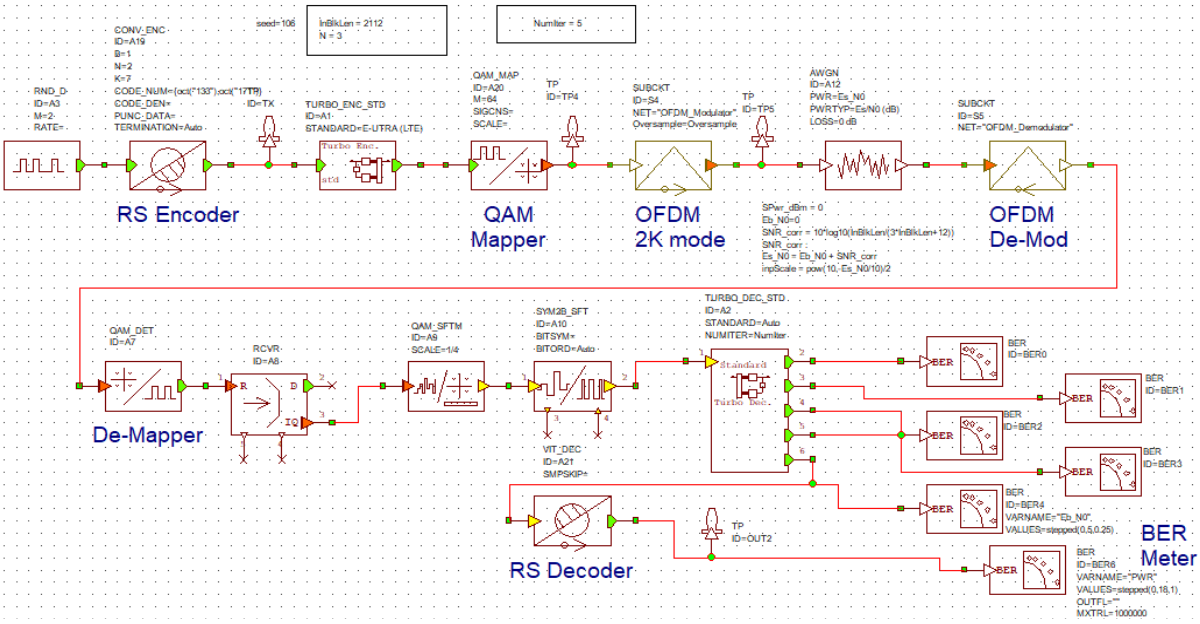


Figure 7: Simulink - a signal generation and processing model in an OFDM system with a concatenated coding procedure

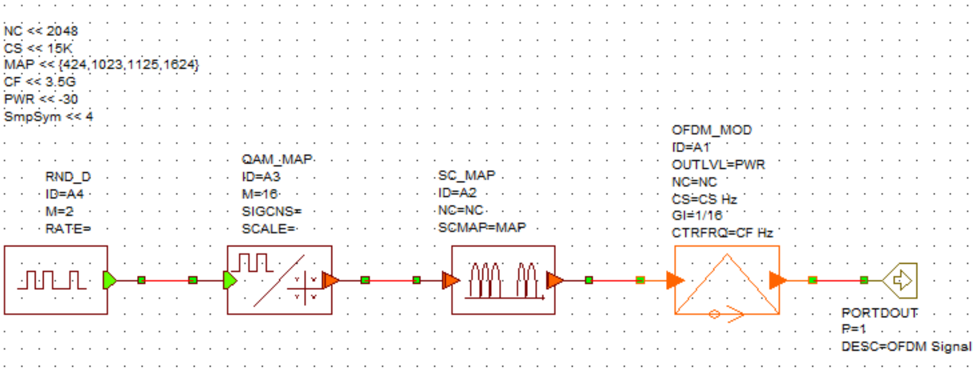


Figure 8: Signal generation subsystem with OFDM modulation

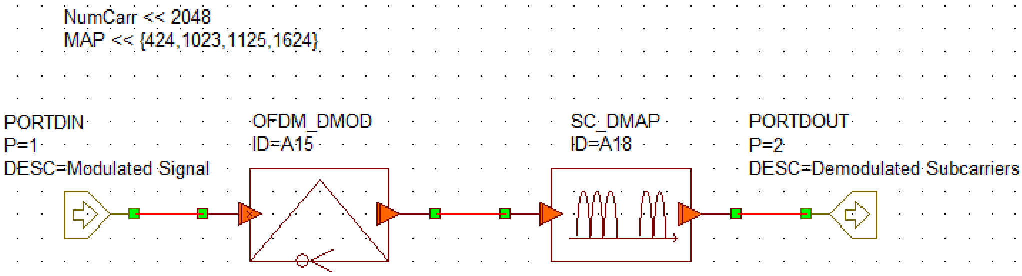


Figure 9: Signal processing subsystem with OFDM modulation

The performance of the system was evaluated by conducting a series of numerical simulation experiments in various configurations of coding/decoding schemes in the AWGN channel. For research, constructions of 100 frames in size were used, which contained 20 packets each. Programmatically, the model had settings according to the known structure of information transmitted in the channel, in addition, in the case of studying the effectiveness of coding, the synchronization mechanism was organized as ideal. The research process included steps to determine the impact of the TC structure on performance and evaluated the impact of the number of decoding iterations, encoding rate and SCC shape. In the experiment, the characteristics of the TC as a composite encoder in the OFDM channel were studied. The idea of using the concatenated design was to achieve the channel performance at the level of the bit error probability BER=10E-9. It was proved in [21] that such an approach will eliminate the saturation effect inherent in TC and thus improve the channel performance as a whole.

Thus, in the scheme, the internal decoder reduces the probability of obtaining a BER to the level of 10E-4÷10E-5 (Fig. 7), in order to obtain a concatenated code (RS +TC) of performance 10E-9 at the output. On Fig. 10 shows a typical distribution of errors at the output of the TC in terms of the probability of a bit error at the level of 10E-5, depending on the number of iteration cycles during decoding.

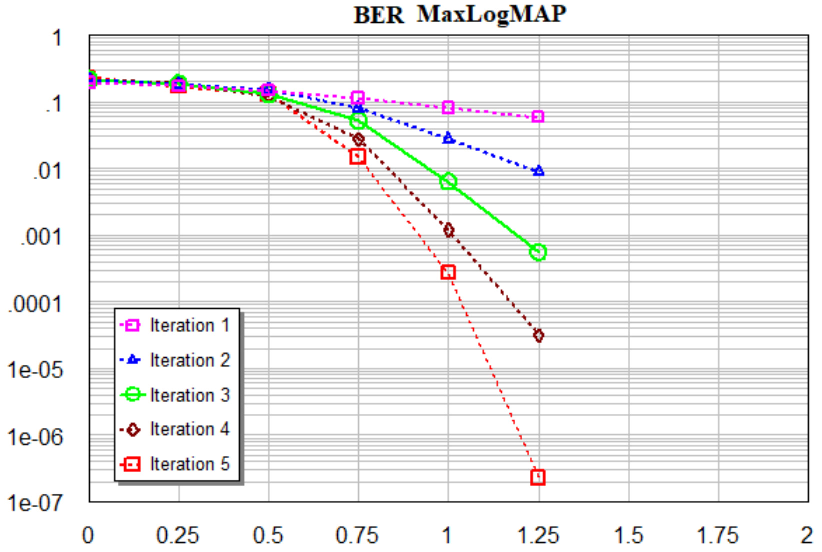


Figure 10: Channel noise immunity graphs with TC (logMAP decoding algorithm, *R*=1/3, block length - 2298 bits)

In the diagram in Fig. 4, it is proposed to use an outer interleaver in order to ensure the correct distribution of errors formed by the grouped areas of damaged data that can enter the channel from the TC constituent convolutional encoder (Fig. 2). The spectrum of the OFDM signal [23] on the transmitting (TX) and receiving side (RX) of the channel is shown in Fig. 11.

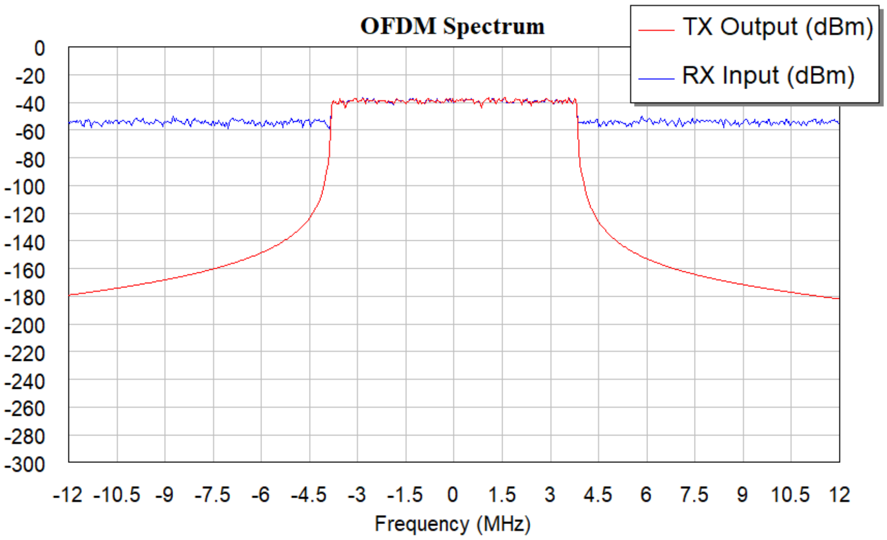
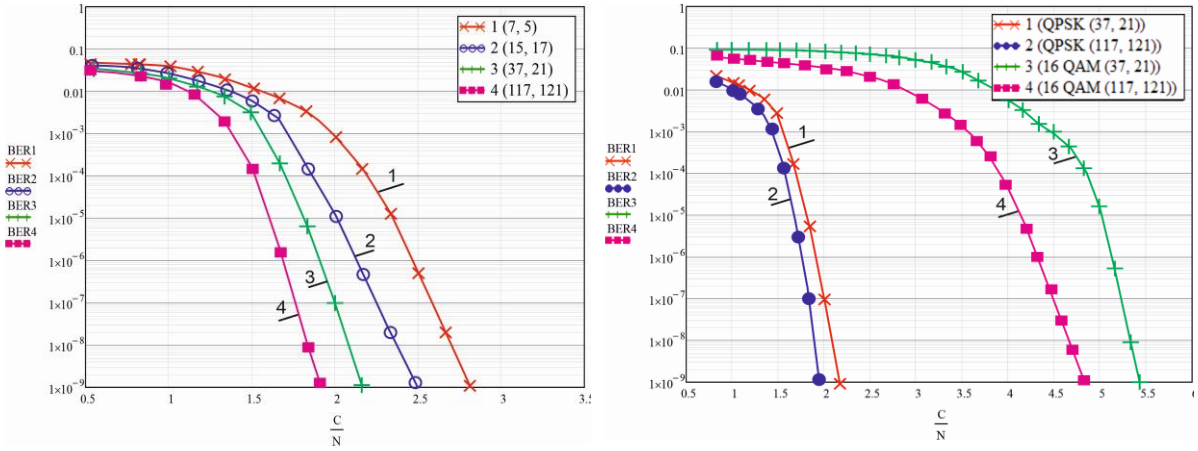


Figure 11: Spectrum of an OFDM signal on the transmitting (TX) and receiving side (RX) of the channel

Fig. 12 a shows graphs of noise immunity (versus carrier-to-noise ratio (C/N)) of a telecommunication channel with OFDM and CnC. During the experiment, 3 iterations, coding rate 1/3, codes (7, 5), (15, 17), (37, 21), (117, 121) and QAM modulation were used. The best indicators have a code like (117, 121), the energy gain of coding (EGC) was almost 2 dB.

On Fig. 12 b shows the resulting graphs of the noise immunity of a telecommunication channel with OFDM signals and CnC (RS + TC) for the configuration of codes (37, 21) and (117, 121) 5 iterations and a coding rate of 1/3 for various modulation schemes. We used multiposition signals QPSK and 16QAM.

The simulation result indicates performance losses in the case of increasing modulation levels, and for the case of the same code structure (37, 21) when using QPSK and 16QAM, the performance drop was about 3.9 dB, while the transition to the code structure (117, 121) for a similar type of signals resulted in a loss of performance of 3.1 dB.



a **b**

Figure 12: Graphs of noise immunity of OFDM signals with CnC (RS+TC): 1 is the (7, 5), 2 is the (15, 17), 3 is the (37, 21); 4 is the (117,121); QPSK - a and b is the graphs of noise immunity of OFDM signals with CnC (RS+TC): 1 is the QPSK (37, 21); 2 is the QPSK (117, 121); 3 is the 16QAM (37, 21); 4 is the 16QAM (117, 127)

On Fig. 13 shows the results of studying the performance of a channel with OFDM signals in the case of a change in the number of iterations when decoding an external TC decoder.

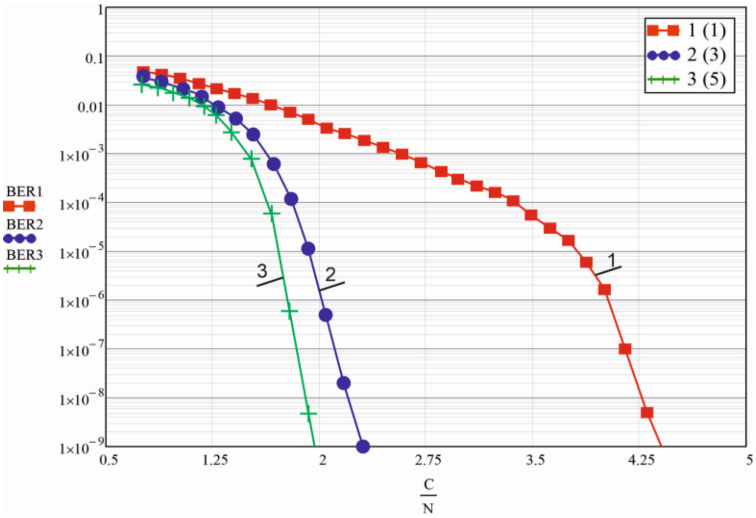


Figure 13: Graphs of noise immunity of OFDM signals with CnC (RS+TC (37, 25)): 1 is the 1st iteration; 2 is the 3rd iterations; 3 is the 5 iterations

During the study, the number of iterations was changed from 1 to 5 (coding rate 1/3). As a result of the study, EGC was set when the number of iterations changed. So, in the case of an increase in the number of iterations from 1 to 3, the channel performance increased by 2 dB, and an increase in the number of iterations to 5 led to an increase in performance by 0.25 dB.

The results of the study (Fig. 13) suggest that the performance of the CnC scheme for an OFDM channel depends on the number of decoding iterations, as well as the SCC structure. Increasing the length of the code sequence improves the performance of the circuit, but has a direct impact on the complexity of decoding. Increasing the number of iterations increases the decoding performance, but affects the speed and, accordingly, the computational complexity of decoding. However, optimal in terms of speed and computational complexity, the selection of a circuit and a TC decoding algorithm makes it possible to find a compromise on the design of concatenated circuits in OFDM channels and ultimately obtain a satisfactory performance gain.

4. Conclusion

A technique for improving the noise immunity of OFDM systems with efficient coding is described. Recommendations on the use of FEC coding methods are given. The scientific problem of increasing the noise immunity of signal reception in an OFDM channel under conditions of selective fading and multipath propagation is solved by applying ECC methods. A coding scheme with FEC in an OFDM channel based on CnC SCC is proposed.

Based on the results of the study, it was determined that with an increase in the length of the code sequence and the number of decoding iterations, the productivity of the proposed SCC increases to almost 2 dB. However, performance decreases by 3.9 dB when changing the waveform and moving to higher order modulation in SCC. When deploying networks based on OFDM, it is necessary to optimize the selection of SCCs in terms of coding rate and computational complexity, which will ultimately make it possible to find a compromise in performance indicators.

Future research will focus on the design of SCC for OFDM based on the use of polar codes and LDPC codes and their implementation through Field Programmable Gate Array (FPGA) for 5G (6G) information systems.

5. References

[1] J. Boiko, I. Pyatin and O. Eromenko, Signal Processing in the Synchronization System of Communication Channel with OFDM, in: Proceedings of the 2022 IEEE 4th International Conference on Advanced Trends in Information Theory, ATIT, IEEE Press, Kyiv, Ukraine, 2022, pp. 14-18, doi:10.1109/ATIT58178.2022.10024232.

[2] Ö. Özdil and C. Toker. "Rate maximizing OFDM parameter optimization on HF channels." Physical Communication 45 (2021): 101280. doi:10.1016/j.phycom.2021.101280.

[3] A. Makarenko, N. H. Qasim, O. Turovsky, N. Rudenko, K. Polonskyi and O. Govorun. "Reducing the impact of interchannel interference on the efficiency of signal transmission in telecommunication systems of data transmission based on the OFDM signal." Eastern-European Journal of Enterprise Technologies 1.9 (2023): 82–93. doi:10.15587/1729-4061.2023.274501.

[4] K.-y. Lee and J.-S. Jang, Novel method for synthesis of synchronization signal abstraction for 5G RF repeater, in: Proceedings of the 2022 IEEE 16th International Conference on Application of Information and Communication Technologies, AICT, IEEE Press, Washington DC, DC, USA, 2022, pp. 1-4, doi:10.1109/AICT55583.2022.10013649.

[5] J. Boiko, I. Pyatin and O. Eromenko, Analysis of Signal Synchronization Conditions in 5G Mobile Information Technologies, in: Proceedings of the 2022 IEEE 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering, TCSET, IEEE Press, Lviv-Slavske, Ukraine, 2022, pp. 01-06, doi:10.1109/TCSET55632.2022.9766899.

[6] G. Kongara, C. He, L. Yang and J. Armstrong. "A Comparison of CP-OFDM, PCC-OFDM and UFMC for 5G Uplink Communications," IEEE Access 7 (2018): 157574-157594. doi:10.1109/ACCESS.2019.2949792.

[7] M. W. Akhtar, M. Junaid, H. Ahmad, R. Iqbal and F. A. Siddiqui, A hybrid approach to develop a real time COFDM based data link using TI C64xx DSP and XC5VSX95T FPGA, in: Proceedings of the 2017 14th International Bhurban Conference on Applied Sciences and Technology,

IBCAST, IEEE Press, Islamabad, Pakistan, 2017, pp. 799-804. doi:10.1109/IBCAST.2017.7868147.

[8] I. Pyatin, J. Boiko, O. Eromenko and I. Parkhomey. "Implementation and analysis of 5G network identification operations at low signal-to-noise ratio." TELKOMNIKA (Telecommunication Computing Electronics and Control) 21.3 (2023): 496-505. doi:10.12928/telkomnika.v21i3.22893.

[9] D. Mattera and M. Tanda. "Windowed OFDM for small-cell 5G uplink." Physical Communication 39 (2020): 100993. doi:10.1016/j.phycom.2019.100993.

[10] A. Chakrapani. "On the Design Details of SS/PBCH, Signal Generation and PRACH in 5G-NR." IEEE Access 8 (2020): 136617-136637. doi:10.1109/ACCESS.2020.3010500.

[11] F. Sandoval, G. Poitau and F. Gagnon. "Optimizing Forward Error Correction Codes for COFDM With Reduced PAPR." IEEE Transactions on Communications 67.7 (2019): 4605-4619. doi:10.1109/TCOMM.2019.2910811.

[12] A. Suhartomo and V. Vincent, Comparison of BER Performance for M-ary QAM and PSK on DWT-based OFDM System with PTS Technique Through AWGN Channel, in: Proceedings of the 2020 IEEE Inter. Conf. on Sustainable Engineering and Creative Computing, ICSECC, IEEE Press, Indonesia, 2020, pp. 5-10, doi:10.1109/ICSECC51444.2020.9557556.

[13] P. Neshaastegaran and A. H. Banihashemi. "Log-Likelihood Ratio Calculation for Pilot Symbol Assisted Coded Modulation Schemes with Residual Phase Noise." IEEE Trans. on Communications 67. 5 (2019): 3782-3790. doi:10.1109/TCOMM.2019.2896190.

[14] S. N. Liyanage and S. A. Senanayake, Content Caching and Clock Synchronization Assisted Low-Latency Communication in 5G Networks, in: Proceedings of the 2020 5th Inter. Conf. on Innovative Technologies in Intelligent Systems and Industrial Applications, CITISIA, IEEE Press, Sydney, Australia, 2020, pp. 1-6, doi:10.1109/CITISIA50690.2020.9371822.

[15] J. Boiko, I. Pyatin, R. Chornyi and T. Davydova, Design and Performance Evaluation of Channel Coding Schemes for Information Technologies, in: Proceedings of the 2021 IEEE 3rd International Conference on Advanced Trends in Information Theory, ATIT, IEEE Press, Kyiv, Ukraine, 2021, pp. 195-200, doi:10.1109/ATIT54053.2021.9678589.

[16] J. Bae, A. Abotabl, H. Lin, K. Song and J. Lee. "An overview of channel coding for 5G NR cellular communications." APSIPA Transactions on Signal and Information Processing 8 (2019): E17. doi:10.1017/ATSIP.2019.10.

[17] D. Spasov, Decoding of LTE Turbo Codes Initialized with the Two Recursive Convolutional Codes, in: Proceedings of the 2020 43rd International Convention on Information, Communication and Electronic Technology, MIPRO, IEEE Press, Opatija, Croatia, 2020, pp. 393-396, doi:10.23919/MIPRO48935.2020.9245282.

[18] G. M. Kraidy. "On Progressive Edge-Growth Interleavers for Turbo Codes." IEEE Communications Letters 20.2 (2016): 200-203. doi:10.1109/LCOMM.2015.2504364.

[19] N. C. Shekhar, B. Amulya, G. Praveen and K. S. Reddy, Bit Error Rate Performance of Hybrid Interleaver in Turbo Codes, in: Proceedings of the 2021 IEEE Second International Conference on Electronics and Sustainable Communication Systems, ICESC, IEEE Press, Coimbatore, India, 2021, pp. 539-546, doi:10.1109/ICESC51422.2021.9532864.

[20] L. Trifina and D. Tarniceriu. "On the Equivalence of Cubic Permutation Polynomial and ARP Interleavers for Turbo Codes." IEEE Transactions on Communications 65.2 (2017): 473-485. doi:10.1109/TCOMM.2016.2628744.

[21] B. Zhurakovskyi, J. Boiko, V. Druzhynin, I. Zeniv and O. Eromenko. "Increasing the efficiency of information transmission in communication channels." Indonesian Journal of Electrical Engineering and Computer Science (IJEECS) 19.3 (2020): 1306-1315. doi:10.11591/ijeecs.v19.i3.pp1306-1315.

[22] E. Shafter, A. M. Hamed and R. K. Rao, PAPR and BER performance analysis of OFDM system with multi-h CPFSK mapper, in: Proceedings of the 2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering, CCECE, IEEE Press, Windsor, ON, Canada, 2017, pp. 1-4, doi:10.1109/CCECE.2017.7946743.

[23] J. Boiko and O. Eromenko. "Signal processing in telecommunications with forward correction of errors." Indonesian Journal of Electrical Engineering and Computer Science (IJEECS) 11.3 (2018): 868-877. doi:10.11591/ijeecs.v11.i3.pp868-877.