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RESEARCH OF THE PERFORMANCE OF CASCADE-CODE CONSTRUCTIONS WITH IMPROVED PROPERTIES

ДОСЛІДЖЕННЯ РОБОТИ КАСКАДНО-КОДОВИХ КОНСТРУКЦІЙ З ПОКРАЩЕНИМИ ВЛАСТИВОСТЯМИ

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Abstract. The conducted studies have shown that cascade code constructions are a promising direction for the development of the theory of noise-resistant coding, and the improvement of methods and algorithms for ensuring the required noise resistance of discrete message transmission.
The *purpose* of the research is to increase the noise-immunity of transmission of discrete messages based on the use of cascade code structures with improved properties in information systems and special purpose networks, including control and communication systems.
This goal was achieved by applying the expediment of code algebra, Galois field theory and number theory to develop and study cascade code constructions with enhanced properties; expediments of statistical communication theory, probability theory and mathematical statistics to study the interference resistance of discrete message transmission using cascade code constructions; expediments of automata theory and complexity theory to develop proposals for implementing cascade codes with improved properties and to estimate the complexity of algorithms
The solution of this goal is realized through the solution of partial tasks, namely: the development of a simulation model of a discrete message transmission channel; the study of an improved method for constructing cascade code structures with improved properties, the procedure for their synthesis and software implementation; the studying an improved decoding expedient based on a computational algorithm for decoding cascade code constructions with an iterative exchange of soft solutions with software implementation; and analyzing the interference resistance of discrete message transmission using cascade code constructions and substantiating practical recommendations for their implementation.
The developed simulation model of the transmission channel of discrete messages made it possible to carry out an iterative procedure of statistical testing of the received code sequence for an empirical assessment of the probability of an error per bit at the output of the decoder at a given limit of the confidence interval.
Scientific novelty. An enhanced procedure for estimating the probability of false reception of message symbols at a fixed signal-to-noise ratio.
Practical significance. Experimental studies of the effectiveness of cascade code constructions carried out using the developed simulation model have shown that the practical application of the developed decoding method with iterative exchange of soft solutions allows to provide high noise immunity for the transmission of discrete messages.The empirical dependencies obtained as a result of modeling converge with the known results of solving similar problems and allow us to formulate recommendations for their use in cascade code constructions.
Key words: transmission channel; noise immunity code; turbo code; soft coding; cascade code construction.

Анотація. Проведені дослідження показали, що каскадні кодові конструкції є перспективним напрямом розвитку теорії завадостійкого кодування, та удосконалення методів та алгоритмів забезпечення необхідної завадостійкості передачі дискретних повідомлень.

Метою досліджень є підвищення завадостійкості передачі дискретних повідомлень на основі використання каскадних кодових конструкцій з покращеними властивостями в інформаційних системах та мережах спеціального призначення, у т.ч. у системах управління та зв'язку.
Досягнення цієї мети було реалізовано застосовуючи *методи* алгебри кодів, теорії полів Галуа і теорії чисел для розробки і дослідження каскадних кодових конструкцій з покращеними властивостями; методи статистичної теорії зв'язку, теорії ймовірності і математичної статистики для дослідження завадостійкості передачі дискретних повідомлень з використанням каскадних кодових конструкцій; методи теорії автоматів і теорії складності для розробки пропозицій по реалізації каскадних кодів з покращеними властивостями і оцінки складності алгоритмів.
Вирішення поставленої мети реалізовано через розв'язання часткових задач, а саме: розробки імітаційної моделі каналу передачі дискретних повідомлень; дослідження удосконаленого методу побудови каскадних кодових конструкцій з покращеними властивостями, процедури їх синтезу і програмної реалізації; дослідження покращеного методу декодування, створеного на основі обчислювального алгоритму декодування каскадних кодових конструкцій з ітеративним обміном м'якими рішеннями з програмною реалізацією; та здійснення аналізу завадостійкості передачі дискретних повідомлень з використанням каскадних кодових конструкцій і обґрунтування практичних рекомендацій по їх впровадженню.
Розроблена імітаційна модель каналу передачі дискретних повідомлень дозволила здійснити ітеративну процедуру статистичного тестування кодової послідовності, що приймається, для емпіричної оцінки ймовірності помилки на біт на виході декодера при заданій межі довірчого інтервалу.
Наукова новизна. Вдосконалена процедура оцінювання ймовірності помилкового прийому символів повідомлення при фіксованому співвідношенні «сигнал/шум».
Практична значимість. Проведені з використанням розробленої імітаційної моделі експериментальні дослідження ефективності каскадних кодових конструкцій показали, що практичне застосування розробленого методу декодування з ітеративним обміном м'якими рішеннями дозволяє забезпечити високі показники завадостійкості передачі дискретних повідомлень. А отримані в результаті моделювання емпіричні залежності, сходяться з відомими результатами вирішення аналогічних завдань і дозволяють формулювати рекомендації щодо використання їх у каскадних кодових конструкціях.
Ключові слова: канал передачі; завадостійкий код; турбокод; м'яке кодування; каскадно-кодова конструкція.

OBJECTIVE

At the present stage, an important condition for the development of the information community in Ukraine is the continuous improvement of the national telecommunications infrastructure. This requires the use of modern telecommunication technologies. One of the ways to ensure a given reliability of information transmission is the use of noise immunity code structures in the technical implementation of telecommunication systems and networks.

This is especially true nowadays, when Ukraine is under the influence of the aggressor on its territory, and the efficiency of many systems depends on the timeliness and security of discrete messages transmitted. Therefore, there is a need to create communication systems that, on the one hand, would reduce the transmitter power, save frequency bandwidth, increase communication range, and the ability to operate at low signal-to-noise ratios, and, on the other hand, would increase the reliability of information transmission.

The analysis of the operation of information systems and communication networks in relation to the effectiveness of existing expedients of noise-immunity coding has shown that the greatest energy gain from coding during information transmission is obtained by using convolutional codes and parallel cascade code structures based on them (turbo codes) [4, 5, 6]. At the same time, the existing methods and algorithms for fast decoding are not optimal in terms of minimizing the probability of error, and the scheme with hard decisions does not allow achieving high noise immunity for the transmission of discrete messages.

Thus, research aimed at creating and studying new methods for constructing and decoding cascade code structures with improved properties is an urgent complex scientific and technical task that will increase the noise immunity of discrete message transmission.

One of the ways to study the operation of an information system, using improved methods of constructing and decoding cascade code structures with improved properties, and obtaining recommendations for their implementation is simulation modelling [2]. The main advantages of using simulation modeling in the study and optimization of complex information systems include:

– the speed of obtaining the necessary information;

– the ability to determine the efficiency of the system with sufficient accuracy and avoid unnecessary material costs;

– the ability to study the peculiarities of the system functioning and vary the system parameters within any wide limits, reproducing arbitrary, both real and hypothetical, situations;

– the ability to predict the behavior of the system and evaluate the effectiveness of its functioning.

ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

Analysis and comparative studies of known expedients of noise-immunity coding have shown that there is a scientific and technical contradiction between the current state of the scientific and methodological apparatus of the theory of noise-immunity coding, the capabilities of the applied error-correcting code systems, the existing methods and algorithms of noise-immunity coding (decoding) and the necessary to practically ensure the specified level of noise resistance of transmissions of discrete messages in telecommunication systems and special-purpose networks, including transport. As shown by the results of studies [3, 4, 5], the elimination of this contradiction can be carried out on the basis of the development of promising cascade code constructions with improved properties.

In accordance with the general tendency in the development of the theory of noise-immunity coding, methods for forming cascade code constructions have also developed in two main directions.

Based on the further development of the first direction, which operates with tree-like codes with probabilistic procedures for synthesizing and decoding codes, works [2, 3] investigated cascade code structures on convolutional codes in various embodiments with different construction features.

In research [4, 5], cascade schemes of continuous and block codes are proposed, which are widely used in modern mobile communication systems, data transmission protocols of telecommunication systems and networks for various purposes [6, 7].

Later, on the basis of cascade code constructions with convolutional codes and soft decoding procedures, a new direction in the theory of noise-immunity coding emerged – turbo codes (parallel cascade code constructions on recursive systematic convolutional codes) [8, 9, 10].

In the development of the second direction of the theory of error-controlled codes, which operates mainly with algebraic procedures for synthesizing and decoding codes, ewxperdients and algorithms for cascading block codes, including iterated codes and codes with error localization, are proposed in [3, 4].

This area has been most developed with the advent of algebraic methods for constructing and decoding linear block codes [4, 5, 7], computationally efficient software and hardware implementation procedures. Subsequently, the well-studied cascade block codes, iterated codes, and error localization codes were generalized into a new large class of generalized cascade block codes, the algebraic theory of construction and decoding of which is most fully described in the following research [3, 4].

At present, a new direction has emerged on the basis of turbo coding expedients and cascade block codes – turbo-productive codes, which combines both high noise-immunity provided by soft iterative decoding procedures and low computational complexity of implementation peculiar to algebraic block coding methods [5, 6].

These features and advantages of turbo-productive codes encourage further development of this area in the theory of noise-immunity coding, improvement of expedients and algorithms for constructing and decoding promising cascade coded structures with improved properties for increasing noise immunity and transmitting discrete messages.

This area has been most developed with the advent of algebraic methods for constructing and decoding linear block codes [8, 9], computationally efficient software and hardware implementation procedures. Subsequently, the well-studied cascade block codes, iterated codes, and error localization codes were generalized into a new large class of generalized cascade block codes, the algebraic theory of construction and decoding of which is most fully described in [2, 3].

The aim of the study is to increase the noise immunity of discrete message transmission through the use of cascade code constructions with improved properties in information systems and special-purpose networks, including control and communication systems.

To achieve this goal, we used:

– the expedients of code algebra, Galois field theory and number theory for the development and research of cascade code structures with improved properties.

– the expedients of statistical communication theory, probability theory and mathematical statistics to study the noise immunity of discrete message transmission using cascade code constructions.

– the expedients of automata theory and complexity theory to develop proposals for the implementation of cascade codes with improved properties and to assess the complexity of algorithms.

The research object is the process of increasing the noise-immunity of discrete message transmission using cascaded code structures with improved properties.

The research subject is a model of construction and decoding of cascade code structures with improved properties.

BASIC MATERIAL

As a result of the analysis of the existing expedients of building and decoding cascade code structures, the following were proposed:

1. Algebraic procedures for the synthesis of developed cascade code structures, using non-binary block codes (RS codes and algebra-geometric codes). The developed algebraic procedures made it possible to practically realize the synthesis of the proposed cascade code constructions with improved properties.

2. An improved expedient of soft decoding of cascade code structures with iterative exchange of soft solutions,

which differs from known expedients by an accelerated procedure for selecting test equations with the most reliable symbols, which allows decoding of code words according to the criterion of minimizing false reception of symbols and speeding up the turbo process – decoding of cascade codes.

In order to check the performance and evaluate the effectiveness of the developed expedients, a simulation model of the discrete message transmission channel was developed based on cascade code structures and decoding methods with iterative exchange of soft solutions: (Fig. 1).

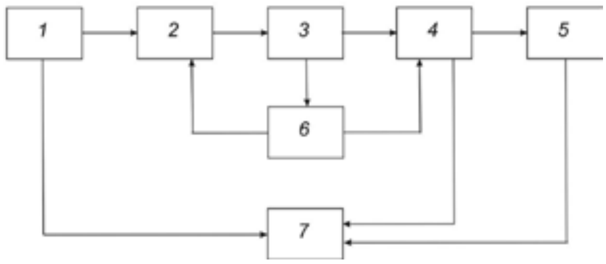

Fig. 1. Schematic of the model of a discrete message transmission channel based on cascade code constructions and decoding methods with iterative exchange of soft solutions: 1 – message source simulation unit, 2 – coding unit, 3 – data transmission channel simulation unit, 4 – decoding unit, 5 – discrete message recipient simulation unit, 6 – matching unit, 7 – statistical processing unit for experimental results

The proposed simulation model structurally consists of a discrete message source simulation unit 1, a linear cascade block code coding unit 2, a data transmission channel simulation unit (AdditivewhiteGaussiannoise, AWGN) 3, decoding unit with iterative exchange of soft solutions design 4, simulation unit of the receiver of discrete messages 5, matching unit 6 and statistical processing unit of experimental results 7.

Simulation's block of the source of discrete messages 1 simulates the performance of the source of information (that is, the source of discrete messages) in the form of probabilistic procedures for the formation of information symbols.

Encoding block 2 with a linear cascade block code, simulates the operation of an noise-immunity encoding device [2] and implements algorithms for converting information sequences into blocks of code symbols (code words).

The AWGN 3 data channel, or rather its simulation block, distorts the code symbols in the channel.

Decoding block 4 implements procedures for soft turbo decoding of the code cascade word. The performance of the decoding unit 4 is based on an improved algorithm, an improved expedient of soft decoding, which allows you to obtain an estimate of the soft output of the decoder, the resulting estimate and the symbol *c(j)* after performing a given number of iterations of turbo-decoding of a cascade code structure containing m complex codes.

Block of simulation of the receiver of discrete messages 5, simulates the operation of the receiver of information.

The AWGN 3 data channel, or rather its imitation unit, distorts the code symbols in the channel.

To verify and analyze the proposed coding and decoding algorithms, the model includes a statistical processing unit for the results 7. This unit analyzes the coded and decoded words and, according to the proposed methodology [2], calculates the probability of erroneous reception of the coded symbol and the accuracy of the corresponding estimate.

The model works as follows.The functioning of the simulation model begins with the procedure for initializing the parameters of the cascade code structure (number of cascades and parameters of the component codes), the parameters of the decoder with iterative exchange of soft solutions (number of iterations and features of the formation of the solving function) and statistical parameters for processing experimental results (setting the confidence interval or), confidential probability, the range of signal-to-noise ratios in which experimental studies will be conducted).

Next, the message source 1 generates an information sequence that is sent to the coding unit 2 by a linear cascade block code. The generated codewords are sent to the transmission channel simulation unit 3. Due to the interference that exists in any transmission channel, a distorted codeword is obtained from it, because the unit simulates the distortion of the code signal. This word is sent to the decoding unit 4 with an iterative exchange of soft decisions between the component decoders of the cascade code construction.The decoded codeword is sent to the unit for simulating the recipient of discrete messages 5 and the unit for statistical processing of experimental results 7.

The block of statistical signal processing 7 calculates the estimate of the probability of false reception of a code symbol and the accuracy of the corresponding estimate. If the value of the accuracy of the estimate corresponds to the given (at a fixed (specified) confidence probability for the given "signal/noise" ratio), the operation of the simulation model is stopped, the obtained estimate of the probability of false reception of the code symbol symbol is taken as a probability. Otherwise, the simulation continues until the occurrence of an event, when the obtained accuracy of the estimate will meet the target.

To test the work of the developed simulation model of the discrete message transmission channel, a program was created in the high-level Delphi language that implements algebraic coding procedures and the soft decoding method with iterative decision exchange, as well as statistical processing of experimental results.

In Fig. 2 it is shownthe main input-output form of the software implementation of the developed simulation model of the discrete message transmission channel.

At the top of the form is the main field for directly displaying the process of forming information sequences and the corresponding code words of the iterative code.

In the middle part of the input-output form there are two service fields designed to display the estimation results: in the left field – the logarithm of the likelihood ratio as a result of channel measurements by the receiver; in the right field – the logarithm of the a priori probability ratio equal to the value of the logarithm of the ratio of the likelihood functions of the binary code symbols C_1 and C_2, as a result of decoding at the previous iteration of the turbo decoder. At the first iteration of turbo decoding, the data are considered to be equally likely, which gives an initial a priori value of zero.

In the lower part of the input-output form there are two fields designed to display the results of evaluating hard decision symbols: in the left part, binary data is displayed as a result of evaluating the received signals with a hard decision (before decoding); in the right part, binary data are displayed as a result of evaluating the code symbols with a hard decision (after decoding).

At the bottom of the input-output form are the keys for controlling the modeling process. The “m1” and “m2” fields are used to set the parameters of the code structure (see the example at the end of Chapter 3). The Data Zero button is used to zero the information sequence and the corresponding codeword.

The “Data randomly” key is intended for pseudo-random generation of the information sequence by the built-in random number generation procedure.

The “Encode” key is used to generate the code word of the iterative code corresponding to the entered information sequence. The “E/N, dB” field is used to enter the ratio of the binary signal energy to the noise power spectral density at which the AWGN channel will be modeled.

The “Accept” button is used to simulate the AWGN data transmission channel by generating a random variable and artificially distorting the useful signal. To do this, the noise variance in the AWGN channel is calculated: where is the relative redundant code rate, which is calculated using the previously entered values “m1” and “m2”. A random variable with a normal distribution is generated by the built-in “RandG” procedure.

The “Load” key is used to generate a mixture of useful signal and noise, as well as to set the initial states of the turbo decoder.

The “Decoder” key is used to start the turbo decoding process. One press of the button corresponds to one decoding iteration. At the end of each iteration, the fields on the right side in the middle and lower part of the input-output form are updated, that is the values of the logarithms of the a priori probability ratio are updated according to the value of the logarithm of the ratio of the likelihood functions of the binary code symbols as a result of

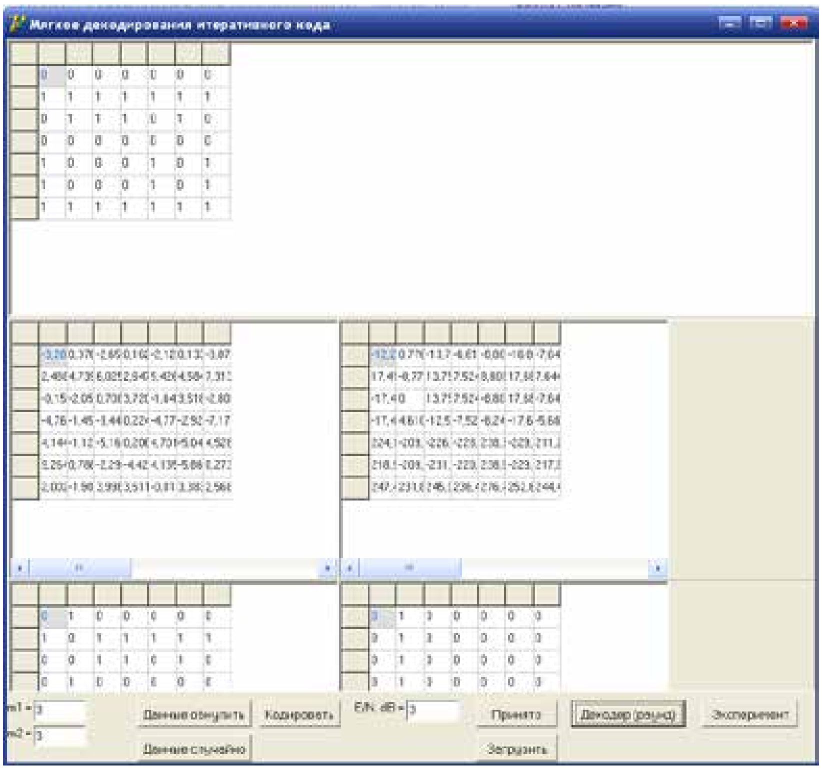

Fig. 2. The main form of input-output of the developed simulation model of the discrete message transmission channel

Table 1. Recommended parameters of turbo productive codes

The number and parameters of component codes		
(15,11,3)(15,11,3)		
(15,11,3)(31,26,3)	(31,26,3)(31,26,3)	
(15,11,3)(63,57,3)	(31,26,3)(63,57,3)	(63,57,3)(63,57,3)
(15,11,3)(15,11,3)(15,11,3)		
(15,11,3)(15,11,3)(31,26,3)	(15,11,3)(31,26,3)(31,26,3)	(31,26,3)(31,26,3)(31,26,3)
(15,11,3)(15,11,3)(63,57,3)	(15,11,3)(31,26,3)(63,57,3)	(31,26,3)(31,26,3)(63,57,3)
(15,11,3)(63,57,3)(63,57,3)	(31,26,3)(63,57,3)(63,57,3)	(63,57,3)(63,57,3)(63,57,3)

decoding and the corresponding binary data are updated as a result of the evaluation of the accepted code symbols with a hard decision after this decoding iteration.

Thus, the above mentioned controls and input-output fields allow you to explore the turbo decoding process in a step-by-step mode with an iterative exchange of soft solutions.

Simulation modeling of performance of the discrete message transmission channel using high-quality cascade code structures and pipe decoding with iterative exchange of soft solutions confirmed the correctness of the research results and the existence of a relationship between the probability of erroneous reception of symbols and the length of the cascade code structure, namely: in the channels transmission of data with a high probability of erroneous reception of phase-manipulated signals, it is necessary to use cascade code structures with short composite codes; when improving the quality of the data transmission channel, it is necessary to increase the length of the code to sharply reduce the probability of an error at the output of the decoder.

The developed simulation model makes it possible to study and analyze the behavior of the dependence of the error probability on the number of turbo decoder iterations, which allows us to draw adequate conclusions about the effectiveness of the proposed decoding method and justify recommendations for its practical use.

DISCUSSION OF THE RESULTS

The obtained research results should be used to increase the reliability of discrete message transmission in telecommunication systems and special-purpose networks, in particular in control and communication systems. The main difference between the organization of the transmission of discrete messages in such systems is a system of strict restrictions on the transmission time and the reliability of the transmitted data.

It should be noted that the information circulating through communication channels is transmitted either in short formalized messages or in data packets of small length (from several hundred to several thousand bits). In such conditions, it is most advisable to use turbo-performance codes with the number of component codes 2-3 and the length of each component code 24-26.

Table 1 shows the recommended parameters of iterative codes for their use in conjunction with the developed turbo decoding method.

The results of simulation modeling showed that the application of the developed algorithms for constructing cascade code structures with improved properties, the structural scheme of the noise-immunity coding device for data transmission over an AWGN channel allowed to reduce the probability of decoding error and obtain an energy gain of 4.5–5.5 dB.

CONCLUSIONS

Thus, an important scientific and technical task has been formulated and solved, which consists in developing expedients and algorithms for constructing cascade code structures with improved properties to increase the noise immunity of discrete message transmission.

The use of cascade codes with the recommended parameters when using the developed soft decoding method will increase the noise immunity of data transmission over channels with random errors and ensure the required reliability of information.

REFERENCES

[1] Bojko, Yu. M., Druzhinin V. A. & Tolyupa, S. V.(2018). *Teoretichni aspekti pidvishennya zavadostijkosti j efektivnosti obrobki signaliv v radiotehnichnih pristroyah ta zasobah telekomunikacijnih sistem za nayavnosti zavad* [*Theoretical aspects of improving the noise immunity and efficiency of signal processing in radio engineering devices and telecommunication systems in the presence of interference*] : Monografiya. Kiyiv: Logos[in Ukrainian].

[2] Bojko, Yu. M., & Pyatin, I.S. (2020). Modeli sistem zavadostijkogo koduvannya u telekomunikaciyah [Models of noise immunity coding systems in telecommunications]. *Visnyk Khmelnytskoho natsionalnoho universytetu*, no. 4, pp. 174-183. [in Ukrainian].

[3] Berkman, L., Turovsky, O., & Kyrpach, L., Varfolomeeva, O., Dmytrenko, V., Pokotylo, O. (2021). Analyzing the code structures of multidimensional signals for a continuous information transmission channel. *Eastern-European Journal of Enterprise Technologies*. (Vol. 5. no. 9.), pp. 70-81. Retrieved from https://doi.org/10.15587/1729-4061.2021.242357.

[4] Bereziuk, I. & Zubenko, V. (2021). Udoskonalennia metodu miakoho dekoduvannia z vykorystanniam uporiadkovanykh pidmnozhyn perevirochnykh rivnian liniinykh blokovykh kodiv [Improvement of the soft decoding expedient using ordered

subsets of verification equations of linear block codes]. Proceedings of the I International Scientific and Practical Conference: *Scientific practice: modern and classical research methods: Collection of scientific papers «LOGOS».* (Vol. 1, pp. 195-201). Boston-Vinnytsia: Primedia eLaunch & European Scientific Platform [in Ukrainian].

[5] Prykhodko, S.Y., Husev, S.A. & Zubenko V.A. (2011). Yssledovanye metodov postroenyia kaskadnykh kodovykh konstruktsyi dlia povyshenyia pomekhoustoichyvosty peredachy dyskretnykh soobshchenyi [Research of methods for constructing cascading code structures to improve the noise immunity of discrete message transmission]. *Systemy upravlinnia, navihatsii ta zviazku*, no. 17, pp. 219-224 [in Russian].

[6] Zubenko, V.O., Miroshnichenko, M.S. (2017). Pidvyshchennnia zavadostiikosti peredachi dyskretnykh povidomlen na osnovi vykorystannia kaskadno-kodovykh konstruktsii. [Increasing the noise immunity of discrete message transmission based on the use of cascade-code constructions]. Proceedings from all-Ukrainian scientific and practical internet conference: *Avtomatyka ta kompiuterno-intehrovani tekhnolohii u promyslovosti, telekomunikatsiiakh, enerhetytsi ta transporti.* (pp. 58-60). Kropyvnytskyi: CNTU [in Ukrainian].

[7] Khmelnytskyi, Yu. V., Kablukov, O. A. (2019). Metody ta zasoby zabezpechennia zavadostiikoi peredachi informatsii v telekomunikatsiinykh merezhakh [Methods and means of providing noise-immunity information transmission in telecommunication networks]. *Zbirnyk naukovykh prats Viiskovoho instytutu Kyivskoho natsionalnoho universytetu imeni Tarasa Shevchenka*, no. 64, pp. 133-143. [in Ukrainian].

[8] Prokys Dzh. (2000). *Tsyfrovaia sviaz [Digital communication]*. Moscow: Radyo y sviaz [in Russian].

[9] Skliar Bernard. (2004). *Tsyfrovaia sviaz. Teoretycheskye osnovi y praktycheskoe prymenenye [Digital communication. Theoretical foundations and practical applications].* Moscow: Yzdatelskyi dom «Vyliams» [in Russian].

[10] Kushnir, M., Semenko, A., Kosovan, G., Bokla, N., & Shestopal, Y. (2019). Increasing the Cryptosecurity of Telecommunication Systems with Spread Spectrum by Using Pseudorandom Sequences Based on Two Ergodic Chaotic Signals. Proceedings from: *3rd International Conference on Advanced Information and Communications Technologies, AICT 2019.* (pp. 455–458). Lviv: Institute of Electrical and Electronics Engineers Inc.

BIBLIOGRAPHY

[1] Бойко Ю. М., Дружинін В. А., Толюпа С. В. (2018). Теоретичні аспекти підвищення завадостійкості й ефективності обробки сигналів в радіотехнічних пристроях та засобах телекомунікаційних систем за наявності завад : монографія. Київ: Логос. 227с.

[2] Бойко Ю. М., Пятін І. С., Заєць А. В. (2020). Моделі систем завадостійкого кодування у телекомунікаціях. *Вісник Хмельницького національного університету. Технічні науки*. № 4, т. 1. С. 174-183.

[3] Berkman L., Turovsky O., Kyrpach L., Varfolomeeva O., Dmytrenko V., Pokotylo O. (2021). Analyzing the code structures of multidimensional signals for a continuous information transmission channel. *Eastern-European Journal of Enterprise Technologies*. Vol. 5, № 9. P. 70–81.

[4] Березюк І. А., Зубенко В. О. (2021). Удосконалення методу м'якого декодування з використанням упорядкованих підмножин перевірочних рівнянь лінійних блокових кодів. *Scientific practice: modern and classical research methods: Collection of scientific papers «ΛΌΓΟΣ» with Proceedings of the I International Scientific and Practical Conference* – Boston-Vinnytsia: Primedia eLaunch & European Scientific Platform. P. 195-201.

[5] Гусев С.А., Гусев С.А., Зубенко В.А. (2011). Исследование методов построения каскадных кодовых конструкций для повышения помехоустойчивости передачи дискретных сообщений. *Системи управління, навігації та зв'язку*. Випуск 1 (17). С. 219-224.

[6] Зубенко В.О., Мірошніченко М.С. (2017). Підвищенння завадостійкості передачі дискретних повідомлень на основі використання каскадно-кодових конструкцій. *Матеріали всеукраїнської науково-практичної інтернет-конференції «Автоматика та комп'ютерно-інтегровані технології у промисловості, телекомунікаціях, енергетиці та транспорті» (16-17 листопада 2017 року)*. Кропивницький. С. 58-60.

[7] Хмельницький Ю.В, Каблуков О.А., Ряба Л.О., Солодєєва Л.В., Ткач А.О. (2019). Методи та засоби забезпечення завадостійкої передачі інформації в телекомунікаційних мережах. *Збірник наукових праць Військового інституту Київського нац. університету імені Тараса Шевченка*. № 64. С. 133-144.

[8] Прокис Джон. (2000). Цифровая связь /пер. с англ. под ред. Д.Д. Кловского. Москва: Радио и связь. 800 с.

[9] Скляр Б. (2003). Цифровая связь: Теоретические основы и практическое применение. Москва: Издат. дом «Вильямс». 1104 с.

[10] M. Kushnir, A. Semenko, G. Kosovan, N. (2019). Bokla Increasing the Cryptosecurity of Telecommunication Systems With Spread Spectrum by Using Pseudorandom Sequences Based on Two Ergodic Chaotic Signals. *3rd International Conference on Advanced Information and Communications Technologies (AICT)*. Lviv: Institute of Electrical and Electronics Engineers Inc, P. 455-458.

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