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RESEARCH ARTICLE

Method for limiting the peak factor using an additional compensation signal in a system with orthogonal frequency division multiplexing for a Gaussian channel

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Abstract
Objectives. Orthogonal frequency division multiplexing (OFDM) has become the standard for various high-speed wireless communication systems due to its several advantages, one of which is the efficient use of bandwidth. The main disadvantage of OFDM is the high peak-power-to-average-power ratio (PAPR), which is indicated by an increase in the bit error rate due to the nonlinearity of the power amplifier. The paper sets out to evaluate the possibility of reducing the PAPR value using a limitation method developed by the authors involving an additional compensation signal in a channel with white Gaussian noise, as well as to analyze its main parameters.
Methods. Statistical radio engineering and computer modeling methods are used according to optimal signal reception theory.
Results. The effect of the OFDM signal limitation level and the number of additional signals when using the limitation method with an additional compensation signal on the quality (reduction of transmission losses) of the OFDM signal is analyzed. The results show a decrease in the OFDM signal PAPR value, along with the dependencies of the bit error rate on the signal-to-noise ratio at fixed limitation values and a determined number of additional signals in the channel with white Gaussian noise.
Conclusions. The proposed limitation method with an additional signal when transmitting an OFDM signal in a channel with white Gaussian noise provides compensation for information losses due to signal level limitations in the transmission channel. Increasing the limitation level is shown to increase the PAPR value, while varying the number of additional signals changes PAPR insignificantly. In order to ensure the effective implementation of the limitation method with an additional compensation signal, the parameters of the threshold limitation level and number of additional signals should be selected depending on the predicted signal-to-noise ratio in the system.

Keywords: limitation method with additional signal, peak power to average power ratio, bit error rate, orthogonal frequency division multiplexing, white Gaussian noise

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НАУЧНАЯ СТАТЬЯ

Метод ограничения пик-фактора с дополнительным сигналом компенсации в системе с ортогональным частотным разделением каналов для гауссовского канала

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Резюме
Цели. Мультиплексирование с ортогональным частотным разделением каналов (orthogonal frequency division multiplexing, OFDM) стало стандартом для различных систем беспроводной связи с высокой скоростью передачи данных благодаря нескольким преимуществам, одним из которых является эффективное использование полосы частот. Главным недостатком OFDM является высокое значение отношения пиковой мощности к средней мощности – пик-фактору, на что указывает повышение частоты битовых ошибок из-за нелинейности усилителя мощности. Цель статьи – оценка возможности снижения значения пик-фактора с помощью разработанного авторами метода ограничения с дополнительным сигналом компенсации в канале с белым гауссовским шумом и анализ его основных параметров.
Методы. Использованы методы статистической радиотехники, теории оптимального приема сигналов и компьютерного моделирования.
Результаты. Проведен анализ влияния уровня ограничения сигнала OFDM и числа дополнительных сигналов при использовании метода ограничения с дополнительным сигналом компенсации на качество (уменьшение потерь при передаче) сигнала OFDM. Получены результаты, показывающие снижение величины пик-фактора OFDM-сигнала, и зависимости вероятности битовой ошибки от отношения сигнал/шум при фиксированных значениях ограничения и числа дополнительных сигналов в канале с белым гауссовским шумом.
Выводы. Предложен метод ограничения с дополнительным сигналом при передаче OFDM-сигнала в канале с белым гауссовским шумом, обеспечивающий компенсацию потерь информации, обусловленных ограничениями уровня сигнала в канале передачи. Установлено, что увеличение уровня ограничения увеличивает величину пик-фактора, а при изменении числа дополнительных сигналов пик-фактор изменяется незначительно. Для эффективной реализации метода ограничения с дополнительным сигналом компенсации необходимо выбирать параметры уровня ограничения порогового значения и число дополнительных сигналов в зависимости от прогнозируемого отношения сигнал/шум в системе.

Ключевые слова: метод ограничения с дополнительным сигналом, пик-фактор, вероятность битовой ошибки, ортогональное частотное разделение каналов, белый гауссовский шум

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INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is currently applied to various high-speed digital information transmission systems [1–4], including high-speed mobile communications, wireless local networks, video broadcasting, and high-speed cellular data transmission. For the wider application of OFDM systems, one of the problems requiring a solution is how to reduce high peak-to-average power ratios (PAPR) that increase the bit error rate (BER) of the system.

In the present work, the possibility of reducing the PAPR value using a limitation method with an additional signal for an OFDM system in a channel with white Gaussian noise is evaluated along with the main method parameters.

OFDM SIGNAL

A discrete-time OFDM signal can be mathematically represented as a set of time samples of a signal following the inverse discrete Fourier transform:

$$S_{\text{OFDM}}(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k)\mathrm{e}^{\frac{j2\pi kn}{N}}, \quad n = \overline{0, N-1}, \tag{1}$$

where N is the number of subcarriers, $X(k)$ is the transmitted information on the kth subcarrier, n is the OFDM signal sample number, and j is an imaginary unit.

For a discrete-time OFDM signal $S_{\text{OFDM}}(n)$, the value of the peak-to-average power ratio (PAPR) is defined as the ratio of the signal maximum power to its average power [5, 6], which can be represented in the following form:

$$\text{PAPR}(S_{\text{OFDM}}(n)) = \frac{\max_n \left|S^2_{\text{OFDM}}(n)\right|}{P_{\text{avg}}\left\{\left|S^2_{\text{OFDM}}(n)\right|\right\}}, \tag{2}$$

where $\max_n \left|S^2_{\text{OFDM}}(n)\right|$ is the OFDM signal maximum power, $P_{\text{avg}}\left\{\left|S^2_{\text{OFDM}}(n)\right|\right\}$ is the OFDM signal average power, and $\left|S_{\text{OFDM}}(n)\right|$ is the nth sample amplitude of the OFDM signal.

The PAPR parameter represents the value of the peak-to-average power ratio, i.e., its higher value; thus, a high PAPR means higher maximum power.

LIMITATION METHOD WITH ADDITIONAL SIGNAL

One of the methods for reducing PAPR is the limitation method with additional signal for OFDM signal [7, 8]. According to this method, the amplitudes of OFDM signal samples are limited when a certain threshold value is exceeded while preserving the original phase of the nth sample. This can be represented in the following form:

$$S_{\text{lim}}(n) = \begin{cases} S_{\text{init}}(n) \text{ at } \left|S_{\text{init}}(n)\right| \le C, \\ C\mathrm{e}^{j\phi_n} \text{ at } \left|S_{\text{init}}(n)\right| > C, \end{cases} \tag{3}$$

where S_{lim} is the signal following OFDM signal limitation, C is the threshold value or signal limitation level, $\left|S_{\text{init}}(n)\right|$ is the amplitude of the initial nth signal sample, and ϕ_n is the phase angle of the nth signal sample.

According to the limitation method with an additional signal for signal $S_{\text{OFDM}}(n)$, a search is carried out for the positions (position numbers are denoted by p) where the signal amplitude is greater than the threshold value C. In this case, the positions are limited in accordance with expression (3). When transmitting a signal limited in this way, a loss of information may occur in some positions. In order to compensate for these losses, the transmitted signal S_{lim} is augmented with samples containing information about position numbers p and additional data $S_{\text{add}}(p)$ as the difference between the initial and limited samples, which can be described by the following expression:

$$S_{\text{add}}(p) = S_{\text{init}}(p) - S_{\text{lim}}(p). \tag{4}$$

Thus, the transmitted signal S_{lim} does not contain samples whose amplitude exceeds the threshold value C; however, no loss of information occurs since it is possible to restore the original samples using their numbers p and additional data $S_{\text{add}}(p)$. The number of additional samples reserved for transmitting position numbers p and values of $S_{add}(p)$ is denoted as the number of additional signals m.

In order to achieve the optimal system performance, it is necessary to select the level of limitation C and the number of additional signals m. When the level of signal limitation C is significant (a large number of signals are subjected to transformation (3)) while keeping the possible number of additional signals m low, full compensation cannot be achieved resulting in a high number of bit errors occurring in the system. A high value of m results in an increased length of the transmitted information and consequent loss of energy and power. At an insignificant level of limitation C and high value of m, many additional signals do not carry any information since the number of signal samples S_{init} exceeding the limitation is insignificant.

The impact of limiting the level of C parameters and number of additional signals m on the OFDM signal compensation efficiency was studied using mathematical modeling based on the above formulas. The block diagram of the algorithm using *MATLAB*[1] mathematical package is shown in Fig. 1. Following modification using the limitation method with an additional signal at given values of C and m, OFDM signals are transmitted through a channel with white Gaussian noise. On the receiving side, the received data array is compared with the original array following the OFDM signal recovery process (demodulation with allowance for additional compensating information) to obtain the BER value.

[1] https://www.mathworks.com/products/matlab.html. Accessed March 29, 2024.

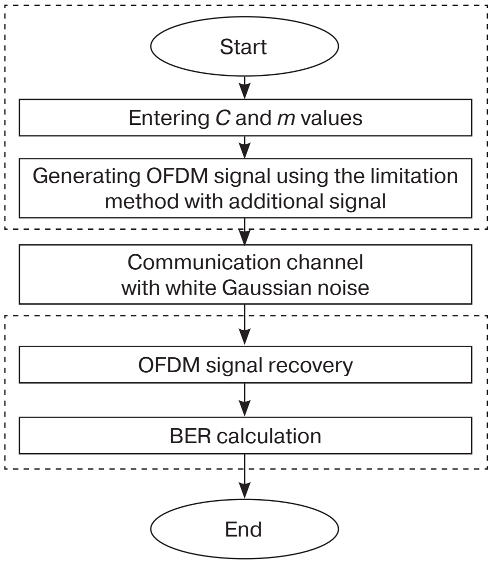

Fig. 1. Block diagram of the algorithm for modeling the impact of parameters C and m on the quality of OFDM signal compensation

The block diagram of the algorithm for calculating PAPR is presented in Fig. 2. The results are obtained for two cases. In the first case, when $m = 16$ for each value of C is fixed, OFDM signals are limited according to (3); here, the PAPR value after limiting the OFDM signal is calculated using formula (2). In the second case, similar calculations are performed at the fixed value $C = 0.18$ for each value of m. The resulting PAPR dependencies are shown in Figs. 3a and 3b.

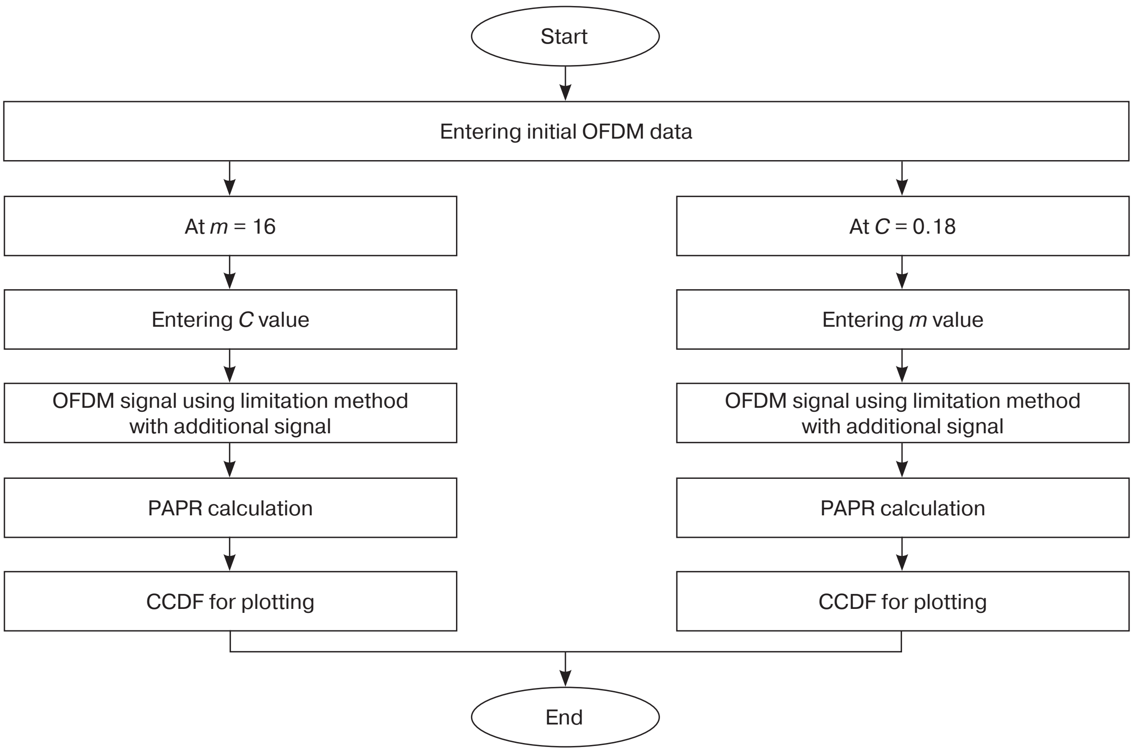

Fig. 2. Block diagram of the algorithm for calculating PAPR

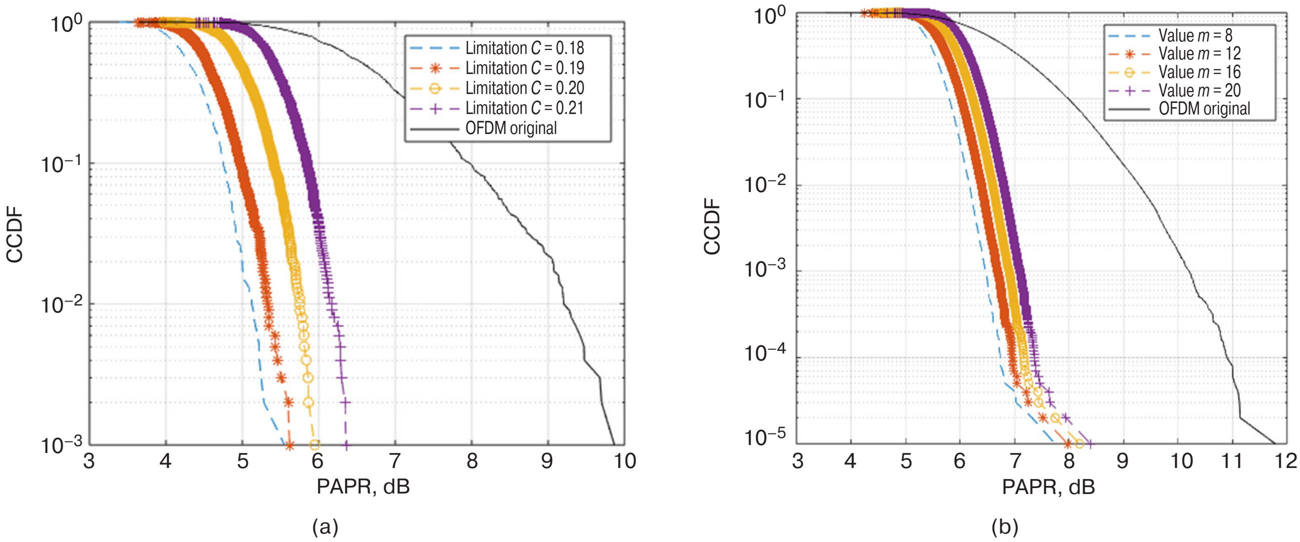

Fig. 3. Results of the OFDM signal PAPR reduction using the limitation method with an additional signal: (a) at $m = 16$, (b) at $C = 0.18$. CCDF is the complementary cumulative distribution function

As a result of modeling, the change in the BER value when changing the limitation level C and fixed m is estimated. BER dependencies are similarly obtained when changing the value of m at a fixed level of C. Since the maximum amplitude of OFDM signal amounts to 0.4229 (dimensionless value normalized to 1 V) in the model with $N = 64$ subcarriers, values of C are chosen less than this value.

The reduction of the OFDM signal peak power when limited with an additional signal at different values of parameters C and m is estimated using the PAPR parameter from relation (2). In order to estimate the PAPR reduction efficiency, the complementary cumulative distribution function (CCDF) is used to indicate the probability of the OFDM signal PAPR exceeding the specified threshold level PAPR0.

The results of reducing PAPR with the number of additional signals $m = 16$ at different values of C are shown in Fig. 3a; the results of PAPR reduction at threshold value $C = 0.18$ when varying m are shown in Fig. 3b.

It is evident from Fig. 3 that the stronger the limitation (low value of C), the smaller the PAPR value when preserving the number of additional signals m. When maintaining the threshold value and changing the number of additional signals, the PAPR value changes insignificantly.

The main parameter determining the quality of a digital communication system is BER during signal recovery. For evaluating the OFDM system performance, the BER value should be estimated depending on three main parameters: the limitation value C, the number of additional signals m, and the signal-to-noise ratio (SNR) representing the ratio of signal power to noise power in the bandwidth in the presence of white Gaussian noise in the channel [9–11].

The BER calculation results determined when modulating 16-QAM OFDM signal in a Gaussian channel when fixing threshold value $C = 0.18$ with different values of m depending on the noise level are shown in Fig. 4. For comparison, BER for the standard OFDM limitation method is evaluated [12–18].

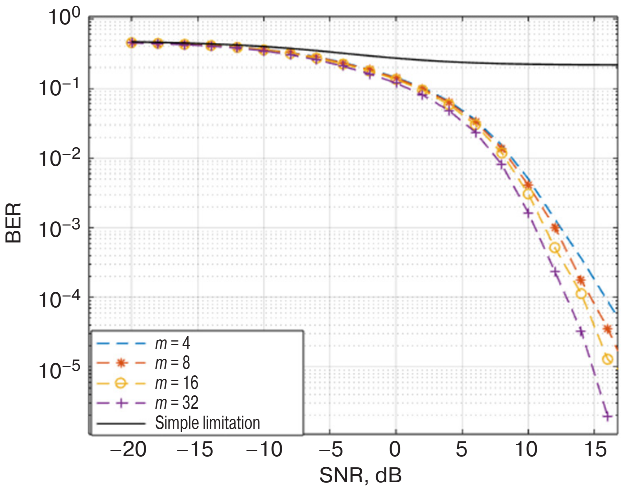

Fig. 4. BER dependence on SNR at fixed value of $C = 0.18$

The advantage of the limitation method with additional signal (at limitation level $C = 0.18$ when the maximum amplitude of the unlimited signal amounts to 0.4229) over the conventional PAPR limitation method is evident from Fig. 4. When the value of m increases, BER decreases.

The BER calculation results at a fixed number of additional signals $m = 16$ with different values of limitation threshold C depending on the noise level is shown in Fig. 5.

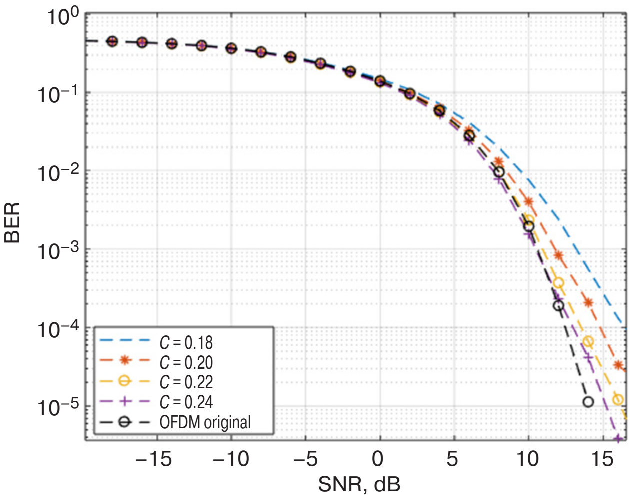

Fig. 5. Dependence of BER on SNR at fixed value of $m = 16$

It can be seen from Fig. 5 that BER decreases with the increased limitation level of C. For comparison, the results for the OFDM signal without limitations (original OFDM) are given. Although these are obviously better, their hardware implementation is physically impossible.

The BER dependencies on the threshold value in the Gaussian channel at SNR = 10 dB and SNR = 15 dB are shown in Fig. 6.

According to the analysis of the results, BER decreases with increased limitation level C and number of additional signals m.

CONCLUSIONS

From the study of the limitation method with additional compensation signal for an OFDM signal in the channel with white Gaussian noise and analysis of its main parameters, the following conclusions can be drawn:

1. At a higher limitation level C, the signal PAPR decreases, whereas it changes insignificantly when the number of additional signals m is changed.
2. In the channel with white Gaussian noise, the effective implementation of the limitation method with an additional compensation signal requires selection of the limitation level C and the number of additional signals m depending on the predicted SNR in the system.

Authors' contributions

Th.T. Pham—making calculations, processing the results.

O.V. Tikhonova—the research idea, consultations on the issues of conducting all stages of the study.

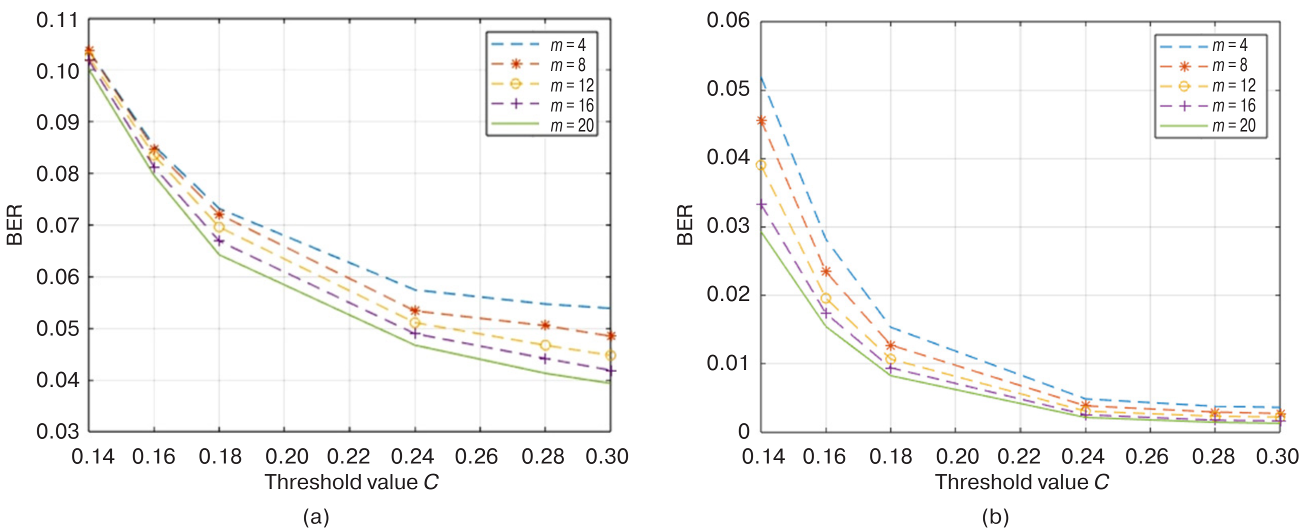

Fig. 6. BER dependence on the limitation level C: (a) SNR = 10 dB, (b) SNR = 15 dB

REFERENCES

1. Kovalev V.V., Seletskaya O.Yu., Pokamestov D.A. Formation and processing of OFDM signals. *Molodoi uchenyi = Young scientist*. 2016;14(118):151–154 (in Russ.). Available from URL: https://moluch.ru/archive/118/32800/
2. Galustov G.G., Meleshkin S.N. *Mul'tipleksirovanie s ortogonal'nym chastotnym razdeleniem signalov* (*Multiplexing with Orthogonal Frequency Division of Signals*): textbook. Taganrog: TTI SFU; 2012. 80 p. (in Russ.).
3. Van Nee R., Prasad R. *OFDM for Wireless Multimedia Communications*. Boston; London: Artech House; 2000. 260 p.
4. Wu Y., Zou W.Y. Orthogonal frequency division multiplexing: A multi-carrier modulation scheme. *IEEE Trans. Consumer Electronics*. 1995;41(3):392–399.
5. Luferchik P.V., Konev A.N., Bogatyrev E.V., Galeev R.G. Methods for improving the energy characteristics of OFDM modems in frequency selective fading communication channels. *Sibirskii aerokosmicheskii zhurnal = Siberian Aerospace Journal*. 2022;23(2):189–196 (in Russ.). https://doi.org/10.31772/2712-8970-2022-23-2-189-196
6. Hassan G.M., Mukred M., Gumaei A.H. Modified Method of PAPR Reduction using Clipping and Filtering for Image Transmission with OFDM. *Al-Mustansiriyah Journal of Science*. 2023;34(4):75–86. https://doi.org/10.23851/mjs.v34i4.1400
7. Pham Th.T., Tikhonova O.V. Limitation method with an additional signal to PAPR reduction in the system with orthogonal frequency division of channels. *Voprosy elektromekhaniki. Trudy VNIIEM = Electromechanical Matters. VNIIEM Studies.* 2023;193(2):34–38 (in Russ.).
8. Pham Th.T., Tikhonova O.V. Method for limiting the peak factor of an OFDM signal with an additional signal. In: *Actual Problems and Prospects for the Development of Radio Engineering and Infocommunication Systems Radioinfocom-2023: Collection of Scientific Articles of the 7th International Scientific and Practical Conference*. Moscow: RTU MIREA; 2023. P. 140–142 (in Russ.).
9. Sklar B. Tsifrovaya svyaz'. *Teoreticheskie osnovy i prakticheskoe primenenie* (*Digital Communication. Theoretical Foundations and Practical Application*): transl. from Engl. Moscow: Vil'yams; 2017. 1100 p. (in Russ.).
[Sklar B. *Digital Communication: Foundamentals and Applications*. Prentice-Hall PTR; 2001. 1079 p.]
10. Proakis J. *Tsifrovaya svyaz'* (*Digital Communication*): transl. from Engl. Moscow: Radio i svyaz'; 2000. 800 p. (in Russ.).
[Proakis J. *Digital Communications.* N.Y.: McGraw-Hill Publ.; 1995. 928 p.]
11. Bairwa M.K., Porwal M.K. BER Performance of OFDM System over AWGN channel with Different Modulation Schemes. *Int. J. Eng. Tech. Res.* (*IJETR*). 2014;2(8):117–119.
12. Shatrughna P.Y., Subhash C.B. PAPR Reduction using Clipping and Filtering Technique for Nonlinear Communication Systems. In: *International Conference on Computing, Communication and Automation*. IEEE; 2015. P. 1220–1225. https://doi.org/10.1109/CCAA.2015.7148590
13. Kannadhasan S., Karthikeyan G., Indumathi G. PAPR Reduction in OFDM Systems using Adaptive Active Constellation Extension Algorithm. *Int. J. Innov. Res. Computer and Commun. Eng*. (*IJIRCCE*). 2013;1(4):950–957.
14. Puksa A.O. Reduction of peak-factor of OFDM signal by methods based on signal limitation. *Mezhdunarodnyi nauchno-issledovatel'skii zhurnal = Int. Res. J.* 2017;12(66):124–127 (in Russ.). https://doi.org/10.23670/IRJ.2017.66.145
15. Wang L., Tellambura C. A simplified clipping and filtering technique for PAPR reduction in OFDM systems. *IEEE Signal Processing Letters*. 2005;12(6):453–456. https://doi.org/10.1109/LSP.2005.847886
16. Tellambura C., Jayalath A.D.S. PAR reduction of an OFDM signal using partial transmit sequences. In: *IEEE 54th Vehicular Technology Conference. NTC Fall 2001. Proceedings*. IEEE; 2001. P. 465–469. https://doi.org/10.1109/VTC.2001.956642
17. Kumar P., Ahuja A.K., Chakka R. BCH/hamming/cyclic coding techniques: comparison of PAPR-reduction performance in OFDM systems. In: *International Conference on Intelligent Computing and Applications*. Springer; 2018. P. 557–566. https://doi.org/10.1007/978-981-10-5520-1_50
18. Han S.H., Lee J.H. An overview of peak-to-average power ratio reduction techniques for multicarrier transmission. *IEEE Wireless Commun.* 2005;12(2):56–65. https://doi.org/10.1109/MWC.2005.1421929

СПИСОК ЛИТЕРАТУРЫ

1. Ковалев В.В., Селецкая О.Ю., Покаместов Д.А. Формирование и обработка OFDM сигналов. *Молодой ученый*. 2016;14(118):151–154. URL: https://moluch.ru/archive/118/32800/
2. Галустов Г.Г., Мелешкин С.Н. *Мультиплексирование с ортогональным частотным разделением сигналов:* учебное пособие. Таганрог: Изд-во ТТИ ЮФУ; 2012. 80 с.
3. Van Nee R., Prasad R. *OFDM for Wireless Multimedia Communications*. Boston; London: Artech House; 2000. 260 p.
4. Wu Y., Zou W.Y. Orthogonal frequency division multiplexing: A multi-carrier modulation scheme. *IEEE Trans. Consumer Electronics*. 1995;41(3):392–399.
5. Луферчик П.В., Конев А.Н., Богатырев Е.В., Галеев Р.Г. Методы повышения энергетической эффективности OFDM модемов в каналах связи с частотно-селективными замираниями. *Сибирский аэрокосмический журнал*. 2022;23(2):189–196. https://doi.org/10.31772/2712-8970-2022-23-2-189-196
6. Hassan G.M., Mukred M., Gumaei A.H. Modified Method of PAPR Reduction using Clipping and Filtering for Image Transmission with OFDM. *Al-Mustansiriyah Journal of Science*. 2023;34(4):75–86. https://doi.org/10.23851/mjs.v34i4.1400

7. Фам Т.Т., Тихонова О.В. Метод ограничения с дополнительным сигналом для уменьшения значения пик-фактора в системе с ортогональным частотным разделением каналов. *Вопросы электромеханики. Труды ВНИИЭМ*. 2023;193(2):34–38.
8. Фам Т.Т., Тихонова О.В. Метод ограничения пик-фактора сигнала OFDM с дополнительным сигналом. В сб.: Актуальные проблемы и перспективы развития радиотехнических и инфокоммуникационных систем «*Радиоинфоком-2023*»: *Сборник научных статей VII Международной научно-практической конференции*. М.: РТУ МИРЭА; 2023. С. 140–142.
9. Скляр Б. *Цифровая связь. Теоретические основы и практическое применение*: пер. с англ. М.: Вильямс; 2017. 1104 с.
10. Прокис Дж. *Цифровая связь*: пер. с англ.; под ред. Д.Д. Кловского. М.: Радио и связь; 2000. 800 с.
11. Bairwa M.K., Porwal M.K. BER Performance of OFDM System over AWGN channel with Different Modulation Schemes. *Int. J. Eng. Tech. Res.* (*IJETR*). 2014;2(8):117–119.
12. Shatrughna P.Y., Subhash C.B. PAPR Reduction using Clipping and Filtering Technique for Nonlinear Communication Systems. In: *International Conference on Computing, Communication and Automation*. IEEE; 2015. P. 1220–1225. https://doi.org/10.1109/CCAA.2015.7148590
13. Kannadhasan S., Karthikeyan G., Indumathi G. PAPR Reduction in OFDM Systems using Adaptive Active Constellation Extension Algorithm. *Int. J. Innov. Res. Computer and Commun. Eng*. (*IJIRCCE*). 2013;1(4):950–957.
14. Пукса А.О. Уменьшение пик-фактора OFDM-сигнала с помощью методов, основанных на ограничении сигналов. *Международный научно-исследовательский журнал*. 2017;12(66):124–127. https://doi.org/10.23670/IRJ.2017.66.145
15. Wang L., Tellambura C. A simplified clipping and filtering technique for PAPR reduction in OFDM systems. *IEEE Signal Processing Letters*. 2005;12(6):453–456. https://doi.org/10.1109/LSP.2005.847886
16. Tellambura C., Jayalath A.D.S. PAR reduction of an OFDM signal using partial transmit sequences. In: *IEEE 54th Vehicular Technology Conference. NTC Fall 2001. Proceedings*. IEEE; 2001. P. 465–469. https://doi.org/10.1109/VTC.2001.956642
17. Kumar P., Ahuja A.K., Chakka R. BCH/hamming/cyclic coding techniques: comparison of PAPR-reduction performance in OFDM systems. In: *International Conference on Intelligent Computing and Applications*. Springer; 2018. P. 557–566. https://doi.org/10.1007/978-981-10-5520-1_50
18. Han S.H., Lee J.H. An overview of peak-to-average power ratio reduction techniques for multicarrier transmission. *IEEE Wireless Commun.* 2005;12(2):56–65. https://doi.org/10.1109/MWC.2005.1421929

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