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RESEARCH ARTICLE

Method of peak factor reduction with compensation signal in OFDM system using regression for parameter selection

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Abstract
Objectives. The article aims to investigate the authors' developed peak-to-average power ratio (PAPR) reduction method using an additional compensation signal in orthogonal frequency-division multiplexing (OFDM) systems, employing polynomial regression for method parameter selection.
Methods. The study utilizes statistical radio technique methods and mathematical modeling to approximate the relationship between bit error rate (BER) versus clipping threshold level and number of additional signals using polynomial regression analysis.
Results. We developed an algorithm for parameter selection in the PAPR reduction method with an additional compensation signal for OFDM systems using polynomial regression. This approach enables rapid system performance evaluation without additional computational overhead for mathematical modeling. The method significantly simplifies the optimization of clipping threshold and number of additional signals, eliminating the need for complete simulation cycles for each configuration. Both simulation and analytical calculations confirm that increasing the clipping threshold reduces BER, while increasing the number of additional signals improves clipping accuracy at the cost of higher computational complexity. Optimal parameter selection achieves a compromise between PAPR reduction and signal quality preservation. Furthermore, we established that for a fixed clipping threshold, there exists an optimal number of additional signals providing the best trade-off between error probability and peak value reduction.
Conclusions. An algorithm for selecting the parameters of the clipping method with an additional compensation signal based on polynomial regression has been developed. This algorithm enables real-time evaluation of system characteristics without additional computational costs associated with repeated mathematical modeling. The proposed approach reduces calculation time by more than a factor of five, offering flexibility and adaptability in the design of OFDM systems with PAPR reduction.

Keywords: method of peak factor reduction with compensation additional signal, OFDM signal, peak-to-average power ratio, PAPR reduction method, polynomial regression

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НАУЧНАЯ СТАТЬЯ

Метод ограничения пик-фактора с дополнительным сигналом компенсации в системе с ортогональным частотным разделением каналов при применении регрессии для выбора параметров

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Резюме
Цели. Целью статьи является исследование разработанного авторами метода ограничения пик-фактора с дополнительным сигналом в системе связи с мультиплексированием с ортогональным частотным разделением каналов (orthogonal frequency division multiplexing, OFDM) при использовании полиномиальной регрессии для выбора параметров метода.
Методы. В работе использованы методы статистической радиотехники, математического моделирования для аппроксимации зависимости вероятности битовой ошибки от величины уровня ограничения и числа дополнительных сигналов при использовании полиномиальной регрессии.
Результаты. Разработан алгоритм выбора параметров метода ограничения пик-фактора с дополнительным сигналом в системе связи с мультиплексированием с ортогональным частотным разделением каналов на основе полиномиальной регрессии, позволяющий оперативно оценивать характеристики системы без дополнительных затрат времени на математическое моделирование. Это значительно упрощает выбор оптимального уровня ограничения и числа дополнительных сигналов без выполнения полного цикла моделирования для каждой конфигурации. Моделирование и аналитические расчеты подтвердили, что увеличение уровня ограничения способствует снижению вероятности битовой ошибки, а увеличение числа дополнительных сигналов улучшает точность ограничения, однако вызывает рост вычислительных затрат. Оптимальный выбор параметров позволяет достичь компромисса между снижением пик-фактора и сохранением качества сигнала. Также установлено, что при фиксированном уровне ограничения существует оптимальное значение числа дополнительных сигналов, обеспечивающее наилучшее соотношение между вероятностью ошибки и снижением пиковых значений.
Выводы. Предложенный подход позволяет сократить время расчетов более чем в 5 раз, обеспечивая гибкость и адаптивность при проектировании OFDM-систем с ограничением пиковых значений.

Ключевые слова: метод ограничения с дополнительным сигналом, OFDM-сигнал, пик-фактор, метод снижения пик-фактора, полиномиальная регрессия

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INTRODUCTION

In wireless communication systems, modulation is an essential component for efficient information transmission and reduced interference effects. The orthogonal frequency division multiplexing (OFDM) is a modern and widely used modulation method that solves key problems in this area [1–5]. It provides high data transfer rates, reduces the bit error rate (BER) [6, 7], and utilizes bandwidth efficiently. However, one of the main challenges of OFDM is its high peak-to-average power ratio (PAPR), which can lead to performance issues. The development of methods to reduce PAPR is crucial for improving system performance and usability. In order to address this problem, the present authors have developed a method called MODS (modulation of the peak factor with additional signals). The effectiveness of this method, which involves limiting the peak factor of an additional signal, depends on two main parameters: the set clipping threshold C and the number of additional signals m. Since these parameters affect the ability of the method to reduce PAPR, their study and evaluation are essential for the successful application of MODS in specific situations.

The paper considers the selection of MODS parameters when using polynomial regression.

OFDM SIGNAL

A discrete OFDM signal can be mathematically expressed in the following way:

$$L_{\mathrm{OFDM}}(v) = \frac{1}{H}\sum_{g=0}^{H-1} K(g)\mathrm{e}^{\frac{j2\pi g v}{H}},\ v = \overline{0, H-1}, \quad (1)$$

where H is the total number of subcarriers; $K(g)$ represents the information transmitted on the gth subcarrier; v is the OFDM sample number; j stands for the imaginary unit.

For a discrete-time OFDM signal, the peak factor is defined as the ratio of the maximum signal power to the average power [8–12]. This can be expressed as follows:

$$\mathrm{PAPR}(L_{\mathrm{OFDM}}(v)) = \frac{P_{\max}\left\{\left|L^2_{\mathrm{OFDM}}(v)\right|\right\}}{P_{\mathrm{avg}}\left\{\left|L^2_{\mathrm{OFDM}}(v)\right|\right\}}, \quad (2)$$

where $P_{\max}\left\{\left|L^2_{\mathrm{OFDM}}(v)\right|\right\}$ is the maximum power of the OFDM signal, $P_{\mathrm{avg}}\left\{\left|L^2_{\mathrm{OFDM}}(v)\right|\right\}$ is the average power of the OFDM signal, and $\left|L_{\mathrm{OFDM}}(v)\right|$ represents the amplitude of the vth sample of the OFDM signal.

When using this method, the amplitude of the OFDM signal is limited to a certain threshold value while maintaining the initial phase of each sample, which can be expressed as follows:

$$L_{\mathrm{ltd}}(v) = \begin{cases} L_{\mathrm{int}}(v) \text{ at } \left|L_{\mathrm{int}}(v)\right| \le C, \\ C\mathrm{e}^{j\phi_n} \text{ at } \left|L_{\mathrm{int}}(v)\right| > C, \end{cases} \quad (3)$$

where C is the clipping threshold; $\left|L_{\mathrm{int}}(v)\right|$ is the amplitude of the initial signal; ϕ_n is the phase angle of the initial sample.

For the $L_{\mathrm{OFDM}}(v)$ signal, we search for those positions (position numbers are denoted by q) where the signal amplitude is greater than the clipping threshold C. When transmitting data with signal clipping, information is lost at some of these positions. To compensate for this loss, the transmitted L_{ltd} signal is supplemented with samples containing information about position q and the $L_{\mathrm{add}}(q)$ signals are added, which is the difference between the initial and clipped signals [13–15]:

$$L_{\mathrm{add}}(q) = L_{\mathrm{int}}(q) - L_{\mathrm{ltd}}(q). \quad (4)$$

Thus, there are no samples in the transmitted signal L_{ltd} whose amplitude exceeds the threshold value C. However, there is no information loss, as it is possible to reconstruct the original samples using their numbers q and additional data $L_{\mathrm{add}}(q)$. The number of extra samples reserved for transmitting the position numbers q and values of $L_{\mathrm{add}}(q)$ is denoted by m.

PARAMETER SELECTION FOR POLYNOMIAL REGRESSION

In the MODS method, BER is influenced not only by the signal-to-noise ratio (SNR) but also by specific method parameters, such as the clipping threshold C and the number of reserved additional samples m [16]. To streamline the optimization of these parameters through mathematical modeling, the process can be simplified by approximating simulation results using polynomial curves derived from the previously obtained data.

The nth-degree polynomial regression is expressed through the following equation [17]:

$$z = b_0 + b_1 x + b_2 x^2 + \ldots + b_n x^n, \tag{5}$$

where $b_0, b_1, b_2, \ldots b_n$ are the regression coefficients that need to be determined.

The process for finding these coefficients involves several key steps:

Step 1. Generate the initial dataset by forming pairs of points $(x_1, z_1), (x_2, z_2), \ldots, (x_k, z_k)$ derived from the graph created through mathematical modeling.

Step 2. Identify the degree of the polynomial n in accordance with equation (5).

Step 3. Develop a system of equations.

The system of linear equations is created based on the initial data to find the coefficients. Each data point generates an equation in the following form:

$$\begin{cases} b_0 + b_1 x_1 + b_2 x_1^2 + \ldots + b_n x_1^n = z_1, \\ b_0 + b_1 x_2 + b_2 x_2^2 + \ldots + b_n x_2^n = z_2, \\ \ldots \\ b_0 + b_1 x_k + b_2 x_k^2 + \ldots + b_n x_k^n = z_k. \end{cases} \tag{6}$$

In matrix form, the system of equations can be written as follows:

$$\begin{pmatrix} 1 & \ldots & x_1^n \\ 1 & \ldots & x_2^n \\ \vdots & \vdots & \vdots \\ 1 & \ldots & x_k^n \end{pmatrix} \begin{pmatrix} b_0 \\ b_1 \\ \vdots \\ b_n \end{pmatrix} = \begin{pmatrix} z_1 \\ z_2 \\ \vdots \\ z_k \end{pmatrix}, \tag{7}$$

or $\mathbf{G} \cdot \mathbf{b} = \mathbf{z}$.

Step 4. Solve the system of equations to determine the coefficients $b_0, b_1, b_2, \ldots b_n$.

The solution can be found using the least squares method:

$$\mathbf{b} = (\mathbf{G}^{\mathrm{T}}\mathbf{G})^{-1}\mathbf{G}^{\mathrm{T}}\mathbf{z}. \tag{8}$$

The BER dependence on the clipping threshold C for SNR = 10 dB and m = 16 is shown in Fig. 1, based on simulation results.

The graph analysis shows a decrease in the BER value with an increase in the clipping threshold C.

The BER curve and the data obtained using the polynomial regression method are shown in Fig. 2:

$$p(C) = 0.5609 - 0.0287 \cdot C + 6.1966 \cdot 10^{-4} \cdot C^2 - \\ - 6.0957.10^{-6} \cdot C^3 + 2.2886 \cdot 10^{-8} \cdot C^4.$$

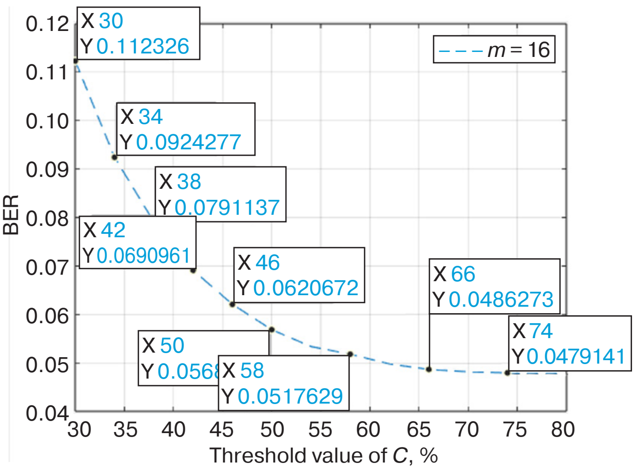

Fig. 1. Numerical values for the BER dependence on the clipping threshold C for SNR = 10 dB and m = 16 (simulation)

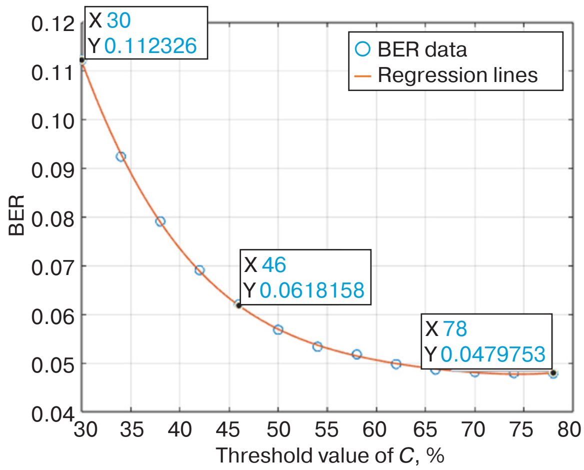

Fig. 2. Numerical values for the BER dependence on the clipping threshold C (regression)

The analysis of Figs. 1 and 2 confirms the close agreement between the simulation and approximation results. The use of pre-computed coefficients for polynomial regression significantly reduces the number of computations required for analyzing MODS parameters.

CALCULATION RESULTS

A. SNR is 5 dB

The BER dependence on the clipping threshold C at SNR = 5 dB for various m values obtained through simulation is shown in Fig. 3.

The corresponding dependencies calculated using the regression method are shown in Fig. 4.

The regression line equations for m = 4, 8, and 16 are the following:

$$p_1(C) = 0.4517 - 0.018 \cdot C + 4.2528 \cdot 10^{-4} \cdot C^2 - \\ - 4.5383 \cdot 10^{-6} \cdot C^3 + 1.8219 \cdot 10^{-8} \cdot C^4,$$

$$p_2(C) = 0.3818 - 0.0121 \cdot C + 2.543 \cdot 10^{-4} \cdot C^2 - 2.4828 \cdot 10^{-6} \cdot C^3 + 9.3811 \cdot 10^{-9} \cdot C^4,$$

$$p_3(C) = 0.4517 - 0.018 \cdot C + 4.2528 \cdot 10^{-4} \cdot C^2 - 4.5383 \cdot 10^{-6} \cdot C^3 + 1.8219 \cdot 10^{-8} \cdot C^4.$$

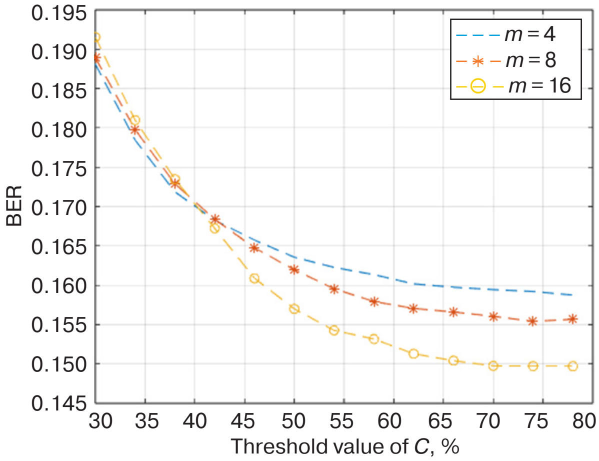

Fig. 3. BER dependence on the clipping threshold *C* (simulation)

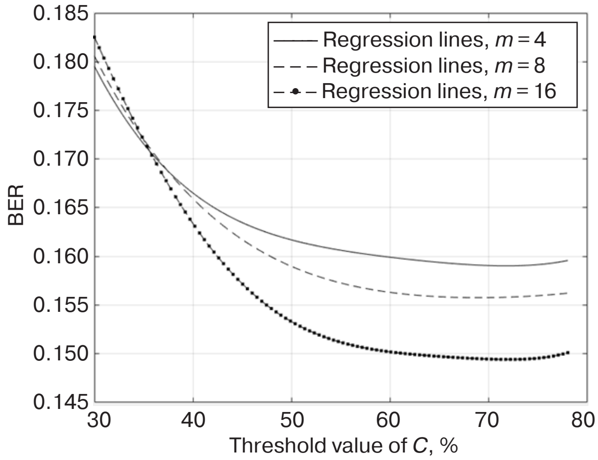

Fig. 4. BER dependence on the clipping threshold *C* (regression)

B. SNR is 10 dB

The BER dependence on the clipping threshold C at SNR = 10 dB for various m values obtained through simulation is shown in Fig. 5.

The corresponding regression lines are shown in Fig. 6.

The regression line equations for m = 4, 8, and 16 are the following:

$$p_1(C) = 0.741356 - 0.03974 \cdot C + 8.8787 \cdot 10^{-4} \cdot C^2 - 8.973 \cdot 10^{-6} \cdot C^3 + 3.355 \cdot 10^{-8} \cdot C^4,$$

$$p_2(C) = 0.67576 - 0.0348 \cdot C + 7.5598 \cdot 10^{-4} \cdot C^2 - 7.4855 \cdot 10^{-6} \cdot C^3 + 2.8257 \cdot 10^{-8} \cdot C^4,$$

$$p_3(C) = 0.61 - 0.0289 \cdot C + 5.701 \cdot 10^{-4} \cdot C^2 - 5.1075 \cdot 10^{-6} \cdot C^3 + 1.744 \cdot 10^{-8} \cdot C^4.$$

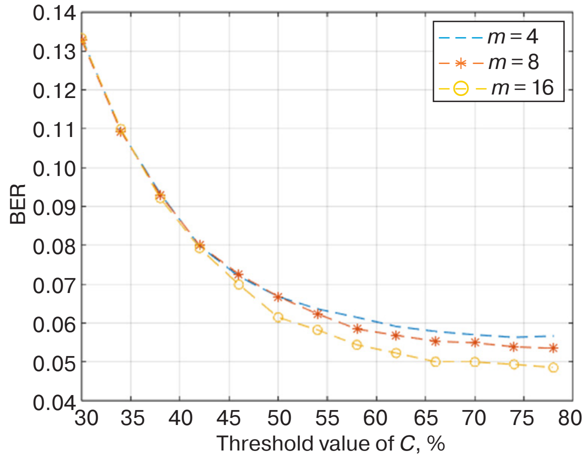

Fig. 5. BER dependence on the clipping threshold *C* (simulation)

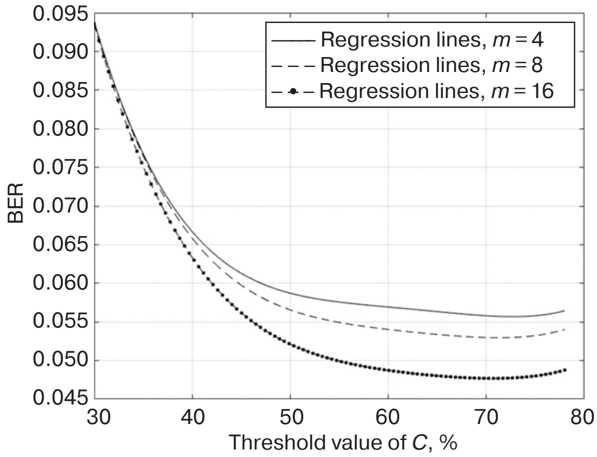

Fig. 6. BER dependence on the clipping threshold *C* (regression)

C. SNR is 15 dB

The BER dependencies for SNR = 15 dB obtained by simulation and regression are shown in Figs. 7 and 8, respectively.

Regression line equations are the following:

$$p_1(C) = 0.8899 - 0.0584 \cdot C + 0.0014 \cdot C^2 - 1.5618 \cdot 10^{-5} \cdot C^3 + 6.3155 \cdot 10^{-8} \cdot C^4,$$

$$p_2(C) = 0.859 - 0.0567 \cdot C + 0.0014 \cdot C^2 - 1.5295 \cdot 10^{-5} \cdot C^3 + 6.2075 \cdot 10^{-8} \cdot C^4,$$

$$p_3(C) = 0.8003 - 0.0533 \cdot C + 0.0013 \cdot C^2 - \\ - 1.4625 \cdot 10^{-5} \cdot C^3 + 5.9732 \cdot 10^{-8} \cdot C^4.$$

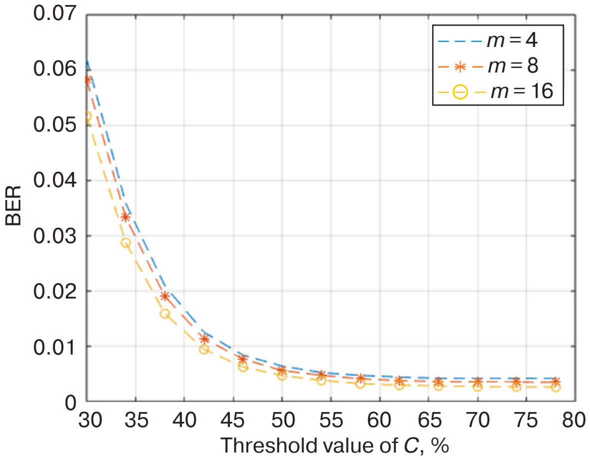

Fig. 7. BER dependence on the clipping threshold C (simulation)

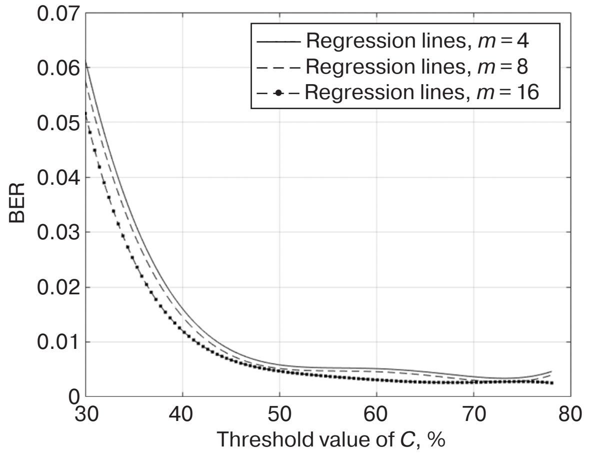

Fig. 8. BER dependence on the clipping threshold C (regression)

A comparative analysis of Figs. 3–8 confirms the identity of the results obtained by modeling and polynomial regression methods for different SNR values.

CONCLUSIONS

The study of the parameters for reducing the peak-to-average power ratio with an additional compensation signal in OFDM systems reveals that the effectiveness of this technique significantly depends on the optimal selection of the clipping threshold C and the number of additional signals m. These two parameters are closely interrelated.

Given a specific SNR, polynomial regression can be used to estimate and optimize the C and m parameters, allowing for the approximation of curves without the need for full-scale simulations. This method significantly reduces the time required for design and increases the flexibility of system configuration. Optimizing the C and m parameters effectively reduces the peak factor of the system.

Promising directions for future research include the development of adaptive algorithms for selecting parameters based on channel characteristics and transmission quality requirements, as well as a comparative analysis of these methods with current optimization techniques.

Authors' contributions

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

A.I. Starikovskiy—processing the results.

Pham Thanh Tuan—conducting computer calculations.

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