Improving the effectiveness of the multi-frequency signals application under conditions of amplitude limitation

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Abstract. In this paper, simulation modelling of information transmission using spectrally efficient multi-frequency (SEFDM) signals with an amplifier and a limiter on transmission has been held. SEFDM signals have a high peak-to-average power ratio (PAPR). Therefore, we need to limit the value of PAPR to increase the efficiency of the amplifier stages of transceiver devices. An effective value for PAPR limiting has been found. For signal-to-noise ratio 7 dB, level of bit error rate reaches minimum value when the PAPR limit value is within 4.5-5.5 dB. Besides that, a comparison of the effectiveness of detection algorithms with and without feedback has been made. The results showed that detection algorithm with feedback increases the effectiveness of the multi-frequency signals application under conditions of amplitude limitation.

1. Introduction

Effective use of limited frequency resource is an important problem in current research activities, especially for networks such as LTE, 5G [1-4]. One of the methods for spectrum saving is to use technology with orthogonal frequency division multiplexing (OFDM) in case of non-orthogonal frequency separation between subcarriers – spectrally efficient frequency division multiplexing (SEFDM). Because of the shorter bandwidth, SEFDM signals have a better spectral efficiency than OFDM signals. But SEFDM signals have a high peak-to-average power ratio (PAPR) [5-11]. This leads to the need to limit the value of PAPR to increase the efficiency of the amplifier stages of transceiver devices [12].

In paper [13] the possibility of increasing the average radiation power while limiting the PAPR is shown. The effective value of the PAPR restriction which ensures given level of bit error rate (BER) performance of reception is 4.5-5 dB for signal-to-noise ratio \(E_b/N_0=7\) dB (\(E_b\) is the signal energy per bit and \(N_0\) is spectral noise density).

However, in that paper the use of element-by-element signal detection algorithm can lead to inaccurate results. We can improve the results with minor additional computational costs with the help of the signal detection algorithm with using of the feedback.

The paper is organized as follows. In section 2 we will describe characteristics of SEFDM signals, simulation model with preamplifier and limiter on the transmission and feedback detection algorithm to study the effect of reducing the PAPR on the quality of information transmission. In section 3 we
will present the simulation results. Finally, conclusions about the effectiveness of this method and the necessary parameters will be drawn in section 4.

2. Simulation model

The simulation model includes an information source; a block of transmitter model with modulator of SEFDM signals, preamplifier, limiter and power amplifier; calculation blocks of spectral characteristics and PAPR; a block simulating a transmission channel with additive white Gaussian noise (AWGN) and a block of receiver model with feedback (FB) detection algorithm. This model was built in the Matlab system (figure 1).

**Figure 1. Structural diagram of the simulation model**

In the information source block, a pseudo-random sequence of zeros and ones of a given volume is formed depending on the number of used subcarriers and equiprobable symbols. At each point of PAPR limitation, at least $6 \times 10^5$ information bits were transmitted. SEFDM signals generation progress and PAPR limitation for SEFDM signals are applied as in the paper [13]. In this work, only modulation type of BPSK is performed. The amplified signal is transmitted to the calculation blocks of spectral characteristics and PAPR values. At the same time, the received SEFDM signal in the limiter is transmitted via the communication channel, where the AWGN is added, with $E_b/N_0$ ranging from 0 to 10 dB [14]. Moreover, the noise is added at the same level as the SEFDM signal without amplitude limitation. The receiver model performs the procedures for detecting and demodulating SEFDM signal received from the communication channel. A detection algorithm using feedback is applied for receiver.

Like in paper [15-17], baseband SEFDM-symbols with duration $T$ is considered to have the following formula:

$$s(t) = \sum_{k=1}^{N} C_k \cos(2\pi k \Delta f t), t \in [0; T].$$

(1)

where value of symbols $C_k = \pm 1$ for BPSK modulation [18]; $\Delta f$ is the interval between adjacent subcarriers. For SEFDM signals, $\Delta f = \alpha/T$, where $\alpha < 1$. For OFDM signals, $\alpha = 1$, therefore, $\Delta f_{\text{OFDM}} = 1/T$.

The form of the signal at the receiver’s input [16]:

$$x(t) = s(t) + n(t)$$

(2)

where $n(t)$ is noise in the communication channel.

Let us consider multistep modification of detection algorithm with feedback in receiver.

On the first step we determine the value of $C_1$ by finding $j$ satisfying the condition
\[ \min_{j=1,2} \int_{0}^{T} (S_{ij}(t) - x(t))^2 \, dt \]

where \( S_{ij}(t) = C_{ij} \cos(2\pi \Delta ft), t \in [0; T] \), \( C_{ij}=\pm 1, j=1,2 \).

On the \( i \)-th step, we consider

\[ S_{ij}(t) = \sum_{k=1}^{N} C_{ij} \cos(2\pi k \Delta ft), t \in [0; T] \], \( C_{ik}=\pm 1, j=1,2 \). \]

The value of \( C_i \) is determined by the values \( C_i, C_{i1}, \ldots, C_{i-1} \) received from the previous steps and satisfying the condition

\[ \min_{j=1,2} \int_{0}^{T} (S_{ij}(t) - x(t))^2 \, dt \]. \]

After the \( N \)-th step, the appropriate \( C_k (k=1,2,\ldots,N) \) set corresponding to the input realization of the process \( x(t) \) in (2) is found.

3. Results and discussions

Analysing the graphs in figure 2, we can see the dependency of BER performance of SEFDM signals on the PAPR limitation level for the cases of detection algorithm without and with feedback for signal-to-noise ratio \( E_b/N_0 = 7 \) dB and different values of \( \alpha \).

In both cases, it is easy to see that increasing spectral efficiency of SEFDM signals (i.e. decreasing \( \alpha \)) leads to a greater number of errors. Besides, with an increase in the \( \Delta PAPR \) limit value the BER value decreases and reaches minimum value when \( \Delta PAPR \) is within 4.5–5 dB. When \( \Delta PAPR > 5 \) dB, the BER performance of the reception starts to deteriorate. This means that the effective PAPR limit value is 4-5 dB. For example, it can be seen that when \( \alpha = 1 \), the received OFDM signal has the best BER performance, and for both detection algorithms the BER value is identical at all points of PAPR limitation. It decreases and reaches a minimum of \( 5\cdot10^{-7} \) at the 4.5 and 5.0 dB points.

![Figure 2. BER of received SEFDM signals depending on the \( \Delta PAPR \) limit](image)

We can also realize that, in the case of applying the detection algorithm with feedback, the BER performance is better than in the case of using the element-by-element detection algorithm. In the case of \( \alpha = 1 \), i.e. for OFDM signals this effect is not shown. But, when \( \alpha<1 \), i.e. for SEFDM signals the effect is very clear. For example, when \( \alpha = 0.8 \), the BER value reaches a minimum of \( 9\cdot10^{-3} \) for algorithm with feedback and \( 9\cdot10^{-2} \) for algorithm without feedback.
4. Conclusions
To conclude, the application of detection algorithms with feedback helps to improve the effectiveness of application of multi-frequency signals under conditions of amplitude limitation. For example, when alpha=0.9, the minimal value of error probability equal to $3\times10^{-4}$ is achieved for the value of PAPR limit 4.5 dB if element-by-element detection algorithm is used. On the other hand, for the case of feedback detection algorithm the PAPR limit of 7 dB can be reached to achieve the same value of error probability. This means, we can increase the efficiency of the amplifier stages of transceiver devices.

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