On features of implementation of SEFDM-transmitter with optimal shape of envelope

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Abstract. This article describes joint use of two improving spectral efficiency algorithms for multi-frequency signals: SEFDM (Spectrally Efficient Frequency Division Multiplexing) technology and smoothed envelopes. SEFDM-signals are generated with IFFT algorithm. Transmitter with different envelope shapes is realized on SDR-platform HackRF One. Waveforms, spectra and PAPR (peak-to-average power ratio) of SEFDM-signals were obtained from simulation, vector signal generator and SDR-platform.

1. Introduction

Data transmission systems of existing and next generations of communication are aimed at increasing the amount of transmitted information [1-4]. In other words, there is a tendency to try to increase the spectral efficiency $R/\Delta F$, where $R$ is the transmission rate, $\Delta F$ is the frequency band. There are several options for improving spectral efficiency. If we consider the multi-frequency signals, there is tendency to use SEFDM signals [5-12]. SEFDM signals are different from “classic” OFDM signals by a reduced value of the frequency spacing between subcarriers $\Delta f=\alpha/T<1/T$, where $T$ is the transmission time of one OFDM symbol. Due to the reduced value $\Delta f$, the value $\Delta F$ decreases, which leads to an increase in spectral efficiency. However, the signals transmitted at each subcarrier frequency become non-orthogonal, therefore BER performance degradation caused by increased interference of signals in the frequency domain takes place. In each case, it is necessary to make a trade-off between the reduction of $\Delta F$ and the degradation of BER performance.

Another option to increase spectral efficiency is to use smoothed envelopes [13-17]. The shape of such signals can be obtained as a solution to the optimization problem in the presence of a number of constraints on the characteristics of the signals in time and frequency. Unlike signals with a rectangular envelope, such optimal signals have an adjustable reduction rate of out-of-band emissions (OOBE), which is important for construction of infocommunication systems [18]. That is, it is possible to decrease the $\Delta F$. It must be taken into account that the more the reduction rate of OOBE, the wider the main spectrum lobe. On the other hand, in the case of multi-frequency signals, the use of a smoothed envelope leads to additional inter-channel interference. For this reason, the BER performance degrades.

However, the combined use of the technology of SEFDM signals and the smoothed envelope potentially allows to achieve a positive effect on the increase in spectral efficiency, which cannot be achieved for these technologies separately. The purpose of this work is to analyze the features of the
implementation of the SEFDM transmitter with a smoothed envelope obtained in the presence of constraints on the reduction rate of OOBE and peak-to-average power ratio (PAPR). The results of the simulation and testing using the vector signal generator and prototyping based on the SDR platform HackRF One will be presented.

2. Optimal signals
Smoothed envelope shapes include raised-cosine (RC) envelopes, root-raised cosine (RRC) envelopes and optimal envelopes obtained as a result of solving optimization problem with some constraints [13, 16-17]. Optimization functional \( J \) which has to be minimized looks as follows:

\[
\arg \min_{a(t)} J = \int_{-\infty}^{\infty} g(f) \left[ \int_{-\infty}^{\infty} a(t) \exp(-j2\pi ft) dt \right]^2 df ,
\]

where \( a(t) \) is required envelope shape, \( g(f) \) is weighing function which determines harmfulness of out-of-band emissions. Choosing \( g(f) = f^{2n} \) \((n=1, 2, \ldots)\) provides tending of energy spectrum to “ideal” rectangular shape when parameter \( n \) increases significantly.

In this work the constraint on PAPR is also added. To solve the optimization problem numerically it is convenient to use the expansion of the envelope into limited Fourier series. Then the problem of minimizing the optimization functional reduces to the search for \( m \) expansion coefficients \( \{a_k\}_{k=0}^{n-1} \) which minimize function of many variables:

\[
\min_{\{a_k\}_{k=0}^{n-1}} J \left( \{a_k\}_{k=0}^{n-1} \right), J \left( \{a_k\}_{k=0}^{n-1} \right) = \frac{T_s}{2} \sum_{k=0}^{n-1} \left( \frac{2\pi k}{T_s} \right)^{2n} a_k^2 .
\]

Results of solving the optimization problem are given (PAPR for OFRM signals less than 9.5 dB) are presented in table 1.

| \( a_0 \) | \( a_1 \) | \( a_2 \) | \( a_3 \) | \( a_4 \) | \( a_5 \) | \( a_6 \) | \( a_7 \) | \( a_8 \) | \( a_9 \) | \( a_{10} \) |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1.936   | 0.184  | -0.169 | 0.151  | -0.129 | 0.107  | -0.085 | 0.063  | -0.043 | 0.026  | -0.012 |

3. SEFDM-transmitter description
The generation of the SEFDM-signal for transmission is carried out in a “soft” modem at first (figure 1). Initially, data is sent to the BPSK modulator. Then scrambling and adding pilot subcarriers are performed. At the next stage, the data stream from the serial is converted into parallel, the guard intervals in frequency domain are added. Next, there is an IFFT (inverse fast Fourier transform), truncation of a part of the samples at the output of the IFFT block and resampling [19].

Resampling is carried out to make the number of samples in the SEFDM-signal to become equal to the number of samples in the OFDM-signal. After that, the data from the parallel stream is converted to serial and the cyclic prefix is added. The next step is the generation of the envelope. Moreover, the envelope is added to the SEFDM symbol with a cyclic prefix. At the final stage, packets are formed, and preamble is added to them. An OFDM symbol is used as the preamble.
Figure 1. Soft modem.

An implemented transmitter has these parameters:
- Number of subcarriers: 256.
- Number of used subcarriers: 192.
- IFFT/FFT size: 256.
- Cycle prefix length: 64.
- \( \alpha \) values: 0.5…1.
- Carrier frequency: 600 MHz.
- Sampling frequency: 10 MHz.
- Frequency spacing between subcarriers: \( \alpha \cdot 39.1 \text{ kHz} \).
- Modulation: BPSK.
- 48 information symbols per package.

The preamble is generated by the pseudo-random sequence, every second subcarrier is modulated. These features of preamble generation allow to realize clock synchronization based on two algorithms of preamble detection, such as detection by repetitive parts and by the cyclic prefix. After packages generation data is sent to SDR-platform, which structure scheme is presented in figure 2. Digital-to-analog conversion, filtration, amplification and emitting are automatically realized in the HackRF One platform.

Figure 2. SDR platform HackRF One structure scheme.

SEFDM-signals waveforms and spectrums were obtained (figure 3), PAPR values were estimated during research. Signal was emitted from platform HackRF One and from vector signal generator Agilent Technologies E8267D, which were connected first to the oscilloscope Agilent Technologies DSO9104A and then to the spectrum analyzer Agilent Technologies N9342C. The oscilloscope recorded the signal, which was then loaded into Matlab to estimate the PAPR value.
4. Results

SEFDM-symbol waveforms with different envelope shapes are presented in figure 4: (a) rectangular envelope shape, (b) smoothed envelope shape (cos), (c) smoothed envelope shape (optimal). Value of \( \alpha \) is equal to 0.8. As we can see, the shape of the SEFDM-signal follows the shape of the envelope. Moreover, the shape of the signal with the optimal envelope integrated the positive properties of both the rectangular shape of envelope and the envelope of the cosine shape. At the same time, the value of the PAPR of the signal with the optimal envelope decreases and approaches the value of the PAPR of the signal with a rectangular shape of envelope. As it is known, the reduction of the PAPR leads to an increase in the efficiency of the power amplifiers and the transmitter as a whole.

Consider the spectral properties of SEFDM signals with different shapes of envelope in more detail. Figure 5 shows the energy spectrum obtained as a result of simulation. The combined use of the smoothed shape of the envelope and the SEFDM technology makes it possible to reduce frequency bandwidth and increase the reduction rate of OOBES, which is important for the design of telecommunication networks.

![SEFDM-transmitter scheme](image)

**Figure 3.** SEFDM-transmitter scheme.

![SEFDM-symbol waveforms](image)

**Figure 4.** SEFDM-symbol waveforms: (a) rectangular form of envelope, (b) smoothed form of envelope (cos), (c) smoothed form of envelope (optimal).
The frequency bandwidths are presented in Table 2. It can be seen that the bandwidths decrease in proportion to the value of $\alpha$. For comparison, experimental spectrums were obtained (Figure 6). The character of the spectrums and the dependence of frequency bandwidth coincide with the simulation results.

Table 2. Frequency bandwidth values for different spectrum levels.

| Spectrum level, dB | $\Delta F$, MHz |
|-------------------|-----------------|
|                   | OFDM            | SEFDM, $\alpha = 0.8$, rectangular | SEFDM, $\alpha = 0.8$, cos | SEFDM, $\alpha = 0.8$, optimal |
| $-3$               | 7.5             | 5.9                         | 5.9                          | 5.9                          |
| $-20$              | 7.7             | 6.4                         | 6.1                          | 6.2                          |

Figure 6. Experimental energy spectrum: (a) OFDM, (b) SEFDM with rectangular form of envelope, (c) SEFDM with optimal form of envelope.

Move on to the consideration of the value of PAPR. A feature of the implementation of the SEFDM signal generation is the truncation of part of the samples and resampling to the original number of samples. The PAPR dependence of $\alpha$ value is shown in Figure 7. This dependency is obtained through simulation.
Figure 7. PAPR dependence of the $\alpha$ value (simulation).

To check the value of PAPR, both the vector generator and the HackRF One SDR platform (table 3) were used. The experimental results differ from the simulation results. On average, the PAPR value when using a vector generator exceeds the simulation result by 1 dB for an arbitrary envelope shape. In the case of using the SDR platform HackRF One, the excess is already 3-3.5 dB. This difference is explained by the presence of filters and amplifiers at the output of the transmission path. All elements of this type lead to appearance of transition processes and parasitic amplitude modulation, which increase the value of the PAPR. Moreover, the difference with the simulation results is greater for the case of using the HackRF One SDR platform. This is due to the fact that the vector generator has a higher quality element base. The difference in the PAPR value between the case of using a vector generator and simulation is about 1 dB, and for envelopes of various shapes.

5. Conclusion
This article shows the features of the implementation of the SEFDM-transmitter with applying the optimal envelope shape. The possibility of choosing an envelope with a given reduction rate of the level of out-of-band emissions with an insignificant increase in the PAPR level is shown. Such signals will be widely used in broadband access networks 5-6 G.

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