Experimental research of receiver based on SEFDM-signals with optimal envelopes

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Abstract. This article describes a research of receiver which is part of SDR-modem based on SEFDM-signals (Spectrally Efficient Frequency Division Multiplexing) with optimal envelopes. Three envelope types and two values of frequency spacing between subcarriers in SEFDM-signals are implemented. Influence of combined use of methods of increasing spectral efficiency on BER performance is considered. Receive algorithm of SEFDM-signals is symbol-by-symbol coherent detection algorithm.

1. Introduction
The constant growth in the amount of transmitted information, the emergence of new electronic devices and the raise in their number, the need for a higher information rate increases the requirements for the next generation of communications. The development of communication technologies implies an increasing the spectral efficiency of existing modulation types.

On nowadays, OFDM-signals is widespread: LTE, WiFi, DVB-T2 and etc, use this technology. We can increase spectral efficiency of OFDM-signals by two ways: reduce frequency spacing value between subcarriers that allow to decrease frequency bandwidth and use optimal shapes of envelope, which have an adjustable reduction rate of out-of-band emissions and also allow to reduce different important signal characteristics like PAPR value.

The first method is called SEFDM-signals [1-4]. SEFDM-signals are generated from OFDM-signals by redaction frequency spacing between subcarriers $\Delta f<1/T$, where $T$ is the transmission time of one OFDM-symbol. Accordingly, frequency bandwidth of whole SEFDM-signal has dependency on value $\Delta f$ or normalized ratio $\alpha = \Delta f/\Delta f_{OFDM}$, where $\Delta f_{OFDM}$ is frequency spacing value between subcarriers for OFDM-signal. However, in the case of non-orthogonal subcarriers inter-carrier interference arises and leads to BER performance degradation.

The second method implies non-rectangle shapes of envelope. Optimal 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 [5, 6]. The application of optimal signals significantly reduces the level of out-of-band emissions consequently it allows adjacent channels of communication systems to be closer to each other with minimized inter-channel interference. On the other hand, BER performance degrades in the case of SEFDM-signals with optimal envelopes by reason of additional inter-carrier interference.

Thus, the influence of the described ways of increasing spectral efficiency on BER performance is investigated. Results of research are important for next generation communication systems design.
2. System description
Research of optimal signals are currently being conducted [7-11], but they are limited by single-frequency signals or simulation or processed not in real time or by wired data transmission. This article describes the research of the receiver as part of the transceiver based on SDR platform HackRF One and used optimal SEFDM-signals. Real-time modem uses wireless packet data transmission and can be deployed on any personal computer. The features of implementation SEFDM-transmitter with optimal shape of envelope were described by the author in [8]. The modem has the following characteristics in table 1.

Table 1. SDR-transceiver parameters.

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Modulation                       | BPSK                       |
| Number of subcarriers            | 256                        |
| Number of used subcarriers       | 192                        |
| Cycle prefix length              | 64                         |
| Envelope types                   | rectangle, cos, optimal    |
| Equalizer                        | linear                     |
| Carrier frequency                | 600 MHz                    |
| Sampling frequency               | 10 MHz                     |
| Frequency spacing between subcarriers | $\alpha \cdot 39.1$ kHz   |
| Frequency bandwidth on label -10 dB | $\alpha \cdot 7555$ kHz   |
| Rate                             | 7 Mbit/s                   |
| Polar coding                     | Rate = $\frac{1}{2}$       |

Receiver consist SDR-platform and soft modem (figure 1). Such operations of digital signal processing like signal transition to baseband, analog-to-digital conversion, filtration and decomposition to I/Q components are automatically realized on SDR platform. Further processes occur in soft modem: clock synchronization, multiple to envelope, cyclic prefix remove, FFT [9], channel estimation by pilot subcarriers, equalization, BPSK demodulation and bit error calculation.

Three shapes of envelope are researched in receiver: rectangle, cos, optimal. Optimal envelope is obtained as solving the optimization problem by PAPR of SEFDM signals less than 9.5 dB.

Bit error calculation is implemented in the receiver of SEFDM-transceiver. This made it possible to estimate the BER performance in the AWGN channel for different values of normalized ratio frequency spacing between subcarriers of spectral-efficient multi-frequency signals $\alpha$ with different types of envelopes using polar code.

![Figure 1](image_url)  
**Figure 1.** Receiver scheme

The choice of polar coding is due to its use in 5G technology. The length of the encoder input block is 512 bits and encoder output block - 1024 bits.
3. Experiment
It is not possible to estimate the signal-to-noise ratio in the real transmission channel of the described system, therefore to evaluate the BER performance of the optimal spectral-efficient multi-frequency signals the experiment was performed as follows (figure 2).

First, signal was recorded from the transmitter output and then several implementations of AWGN in MATLAB were added to the record. Further the noisy sequence of IQ-samples was loaded into the vector generator Agilent Technologies E8267D and emitted to the SDR platform, which worked in the receive mode and calculated the error probability. Receiver has symbol-by-symbol coherent detection algorithm of SEFDM-signals.

4. Results
The results of the experiment are shown in figure 3. The difference between the BER performance for rectangular envelope signals at $\alpha = 1$ and $\alpha = 0.8$ from the theoretical BER performance is due to the effect of the equalizer on the reception.
in our case, non-rectangular envelopes reduce the PAPR value, and the deterioration of the BER performance of such signals compared to signals with a rectangular envelope is compensation for gain in PAPR values. We can observe SEFDM-signals with a cosine type envelope have the worst BER performance. The optimal envelope combines the positive properties of both the rectangular envelope and the cosine envelope, therefore, the BER performance of the signals with the optimal envelope lies between them. As we see, signals with an optimal envelope have a smaller loss in BER performance than signals with an envelope of the cosine form.

As you can see polar coding has a large effect on the bit error. For signals with $\alpha = 1$ with polar coding the bit error is less than $10^{-3}$ in the case of a rectangular envelope with a signal-to-noise ratio greater or equal to 6 dB, in the case of optimal envelopes with a signal-to-noise ratio greater or equal to 7 dB.

In this research SEFDM-signals with optimal shape of envelope allow to increase spectral efficiency by 15% compare to rectangle shape of envelope with energy losses less than 0.5 dB. As we can see on BER performance, SEFDM-signals with optimal envelopes have energy losses compare to signals with rectangle envelope due to inter-carrier interference. Results of research show the need of using receive algorithm with compensation inter-carrier interference for optimal envelopes of SEFDM.

5. Conclusion

This article describes the experimental research of the receiver based on SEFDM-signals with applying the optimal envelope. Results of research shows possibility to increase spectral efficiency by 15% compare to rectangle shape of envelope with energy losses less than 0.5 dB. Such signals will be widely used in broadband access networks of next generation communication.

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