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SYMMETRICAL ITERATIVE ALGORITHM FOR CANCELLING INTER-CHANNEL INTERFERENCE OF SEFDM SIGNALS

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Abstract. This article deals with spectrally efficient frequency-division multiplexing signals (SEFDM). Authors considered symmetrical and asymmetrical iterative algorithms to prevent BER performance degradation. These algorithms reduce inter-channel interference (ICI) between the subcarriers, which leads to better value of BER performance. The authors analyzed complexity and results of the algorithms, and determined the best conditions for a symmetrical algorithm with different number of subcarriers and different frequency multiplexing coefficient.

Keywords: SEFDM, demodulation, algorithm, BER performance, feedback on decision

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СИММЕТРИЧНЫЙ ИТЕРАЦИОННЫЙ АЛГОРИТМ КОМПЕНСАЦИИ МЕЖКАНАЛЬНЫХ ПОМЕХ SEFDM-СИГНАЛОВ

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Аннотация. Рассмотрены спектрально-эффективные сигналы с частотным мультиплексированием (SEFDM-сигналы). Представлен анализ симметричных и асимметричных итерационных алгоритмов для улучшения помехоустойчивости приёма. Предложенный подход к построению алгоритмов позволяет уменьшать межканальные помехи (ICI) между сигналами на поднесущих частотах, что приводит к улучшению помехоустойчивости приёма. Выполнен анализ сложности алгоритмов и определены наилучшие условия для применения симметричного алгоритма при разном количестве поднесущих и разном коэффициенте частотного мультиплексирования.

Ключевые слова: SEFDM, демодуляция, алгоритм, помехоустойчивость, обратная связь

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Introduction

Ideas of spectrally efficient frequency-division multiplexing (SEFDM) is used in Beyond 5G [1, 2] systems and as the foundation for 6G technology standard [3, 4]. SEFDM can provide many times more data than 5G [1]. The other way of using SEFDM is optical channels [5]. Based on Orthogonal frequency-division multiplexing (OFDM) we can achieve higher spectral efficiency by reducing separation between subcarriers frequencies [6]. Spectral efficiency can be expressed as $R/\Delta F$, where R – symbol rate and ΔF – occupied frequency bandwidth [7]. Unfortunately, SEFDM has a big disadvantage of inter-channel interference (ICI) between signals on subcarriers that leads to incorrect demodulation and bit error rate (BER) performance degradation [8]. It is shown that energy losses for SEFDM compared to OFDM at BER = 10^{-3} can achieve 5–15 dB depending on scenarios [9]. There are different demodulation algorithms solving this problem: algorithm with feedback on decision [7, 10], Viterbi algorithm [11], maximum likelihood sequence estimations (MLSE) algorithm [7, 12]. MLSE algorithm is rarely used in real communication systems due to excessive complexity of implementation. Viterbi algorithm is simpler than MLSE but Viterbi algorithm still requires top hardware platforms. So algorithms with cancelling inter-channel interference can provide low energy losses and low requirements for hardware. Usually algorithms with cancelling inter-channel interference are considered with interference of one signal on nearby frequency subcarrier. This article deals with development algorithms through considering more interference signals on different frequencies with estimation of operation complexity.

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The structure of transmitter and receiver of SEFDM signal

The transmitted discrete SEFDM signals can be expressed by the following expression [13]:

$$s_n = \sum_{k=-N/2}^{N/2-1} C_k e^{2j\alpha\pi\frac{kn}{N}}, \quad n = 0, 1, ..., L-1. \tag{1}$$

In this equation N is a number of subcarriers, $\{C_k\}_{k=1}^{N}$ is vector of modulated symbols, where k is a current number of subcarrier, $\alpha = \Delta fT$ is a factor of compressed bandwidth, Δf is the frequency distance between signals on subcarriers, T is transfer time of one OFDM symbol, $n = 0, 1, ..., L - 1$, L is the number of time samples in one SEFDM symbol [13–15].

Structure scheme of SEFDM transmitter is presented on Fig. 1*a* [13]. The first step to generate signal is creating modulation symbols from input bits using modulation with Mapper block. For our study, we chose quadrature phase-shift keying (QPSK). Therefore, this type of modulation transmits 2 bits per subcarrier. Next, the generation requires to put a vector of symbols in serial/parallel block and add $(N_{FFT} - N)$ zeros, where N_{FFT} is a number of samples in fast Fourier transform and N is the number of subcarriers to see the out-of-band emission on the spectrum. The result enters the inverse fast Fourier transform (IFFT) block with N_{FFT} size, where symbols become time samples. The next part is ignoring $(1 - \alpha)N_{FFT}$ samples to reduce duration of signal and then serial/parallel block.

Output signal from previous block has to be transformed with digit-to-analog converter, filters and power amplifiers. The last part of transmitting scheme is antenna.

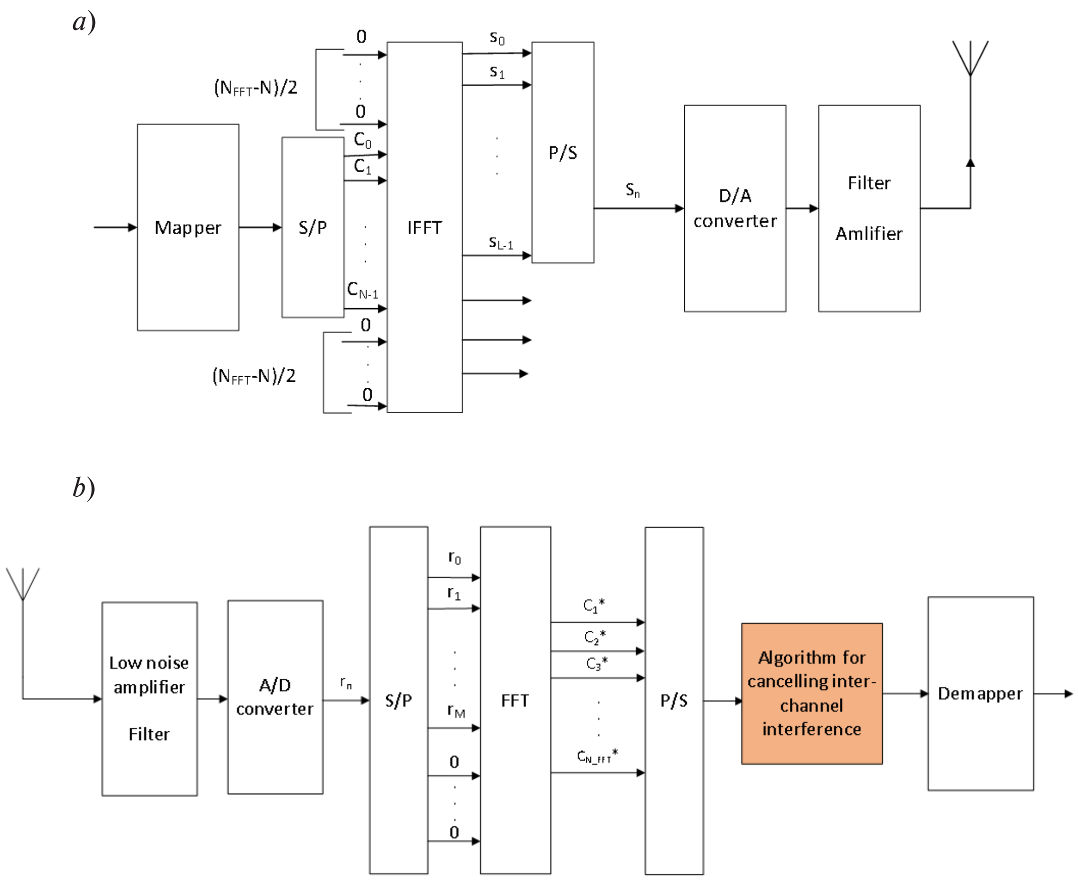

Fig. 1. Structure scheme of transmitter and receiver

Structure scheme of SEFDM signals receiver is presented in Fig. 1*b*. The mixture of SEFDM signal and AWGN is received by antenna with low noise amplifier, filters and analog-to-digit converter. Result samples of signal enter the S/P block with adding zeros afterwards to decompress spectrum from $\Delta F_{\text{SEFDM}} = \alpha \Delta F_{\text{OFDM}}$ to ΔF_{OFDM} and follow to FFT block. Following data come in the "Algorithm for cancelling inter-channel interference" block to improve BER performance. Fixed evaluations of symbols transform into bits in Demapper.

Iterative algorithm for cancelling inter-channel interference

After the FFT block, interference samples of each subcarrier iteratively can be saved in Block storage as k_{ij}, where i^{th} subcarrier affects j^{th} subcarrier. k_{ij} can be called coefficients of mutual interference from different subcarriers (Fig. 2).

For example, normalized value of interference for signals at current subcarrier and at neighboring $i = \pm 1$ subcarrier is equal to 0.64 with $\alpha = 0.5$, if $\alpha = 0.1$ interference value increases to 0.98.

The idea of the algorithm is iterative subtraction from considered subcarrier of every interference sample of any other subcarrier. This way, the expression for received samples can be written as Eq. (2). For the convenience we reassigned received modulated symbols as $\left\{C_k^*\right\}_{k=1}^{N}$, symbols after the first iteration of algorithm – C_i'.

$$C_i^* - \sum_{j=1}^{i-1} k_{ij} C_j^* = C_i'. \tag{2}$$

The idea of this algorithm is similar with algorithm for one-frequency Faster-than-Nyquist signals, proposed in [16]. Note, that this algorithm is not similar with algorithms based on feedback on decision and has some common solutions with error-correcting coding.

Eq. (2) is supposed to subtract ICI only from one of the sides, the left one. This type of feedback on decision algorithm can be called asymmetrical. By analogy, algorithms with feedback on decision with subtraction from both sides can be called symmetrical. For Eq. (2) we can express structure scheme of the first iteration of our algorithm (Fig. 3). Note, that symbols C_i' can be transmitted to demapper to form output bits or to the second iteration of algorithm.

First received sample from IFFT block C_1^* goes through without any changes and improving. Second received sample C_2^* gets subtracted with product of k_{12} and C_1^*. That leads to removal ICI from the first subcarrier. These two operations can be united in "Block 1.2". Here and further delay line for pro-

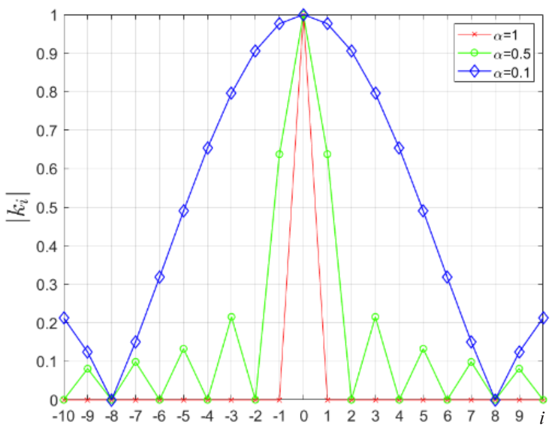

Fig. 2. Inter-channel interference on nearby subcarriers

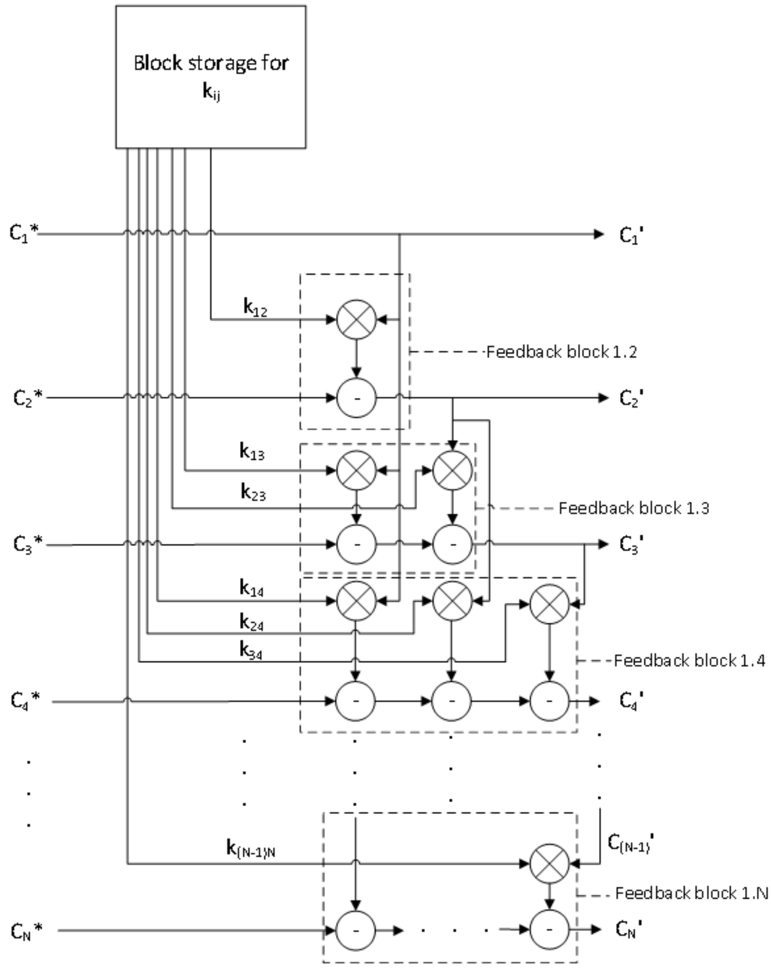

Fig. 3. Structure scheme of algorithm (first iteration)

cessing time is injected in block of subtraction. For C_3^* process repeats but amount of operations doubles. In this way we continue till the C_N^* sample.

We can use the second iteration of the algorithm for better results as shown in Fig. 4. Second iteration is the reverse version of the first. C'_N goes through without any changes. C'_{N-1} gets subtracted with $k_{N(N-1)}$ and C'_N. Step by step, ICI is reduced in every symbol. In addition, we can write off the equation for every symbol:

$$C'_i - \sum_{j=i+1}^{N} k_{ij} C'_j = C''_i. \tag{3}$$

This way, if we use only the first iteration (Fig. 5), then we use asymmetrical algorithm with N_{FB_left} subcarriers, $N_{FB\_right} = 0$. If we use the first and the second iteration, then we use symmetrical algorithm with $N_{FB} = N_{FB\_left} + N_{FB\_right}$. Fig. 5 serves for better understanding of N_{FB} positions and the structure of interference.

Modeling and results

Modeling was made in programming and numeric computing platform MATLAB.

After Demapper, we can calculate BER and find out how reduction of frequency space between subcarriers influences BER. For the BER performance, we need to use E_b/N_0 parameter, where E_b is

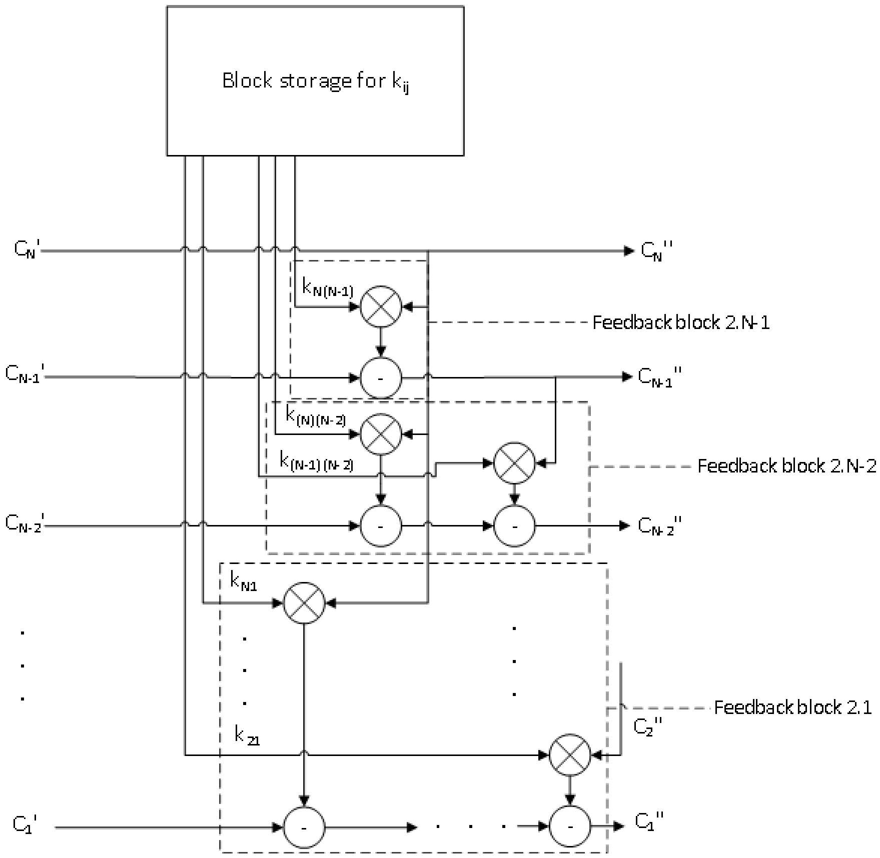

Fig. 4. Structure scheme of algorithm (2nd iteration)

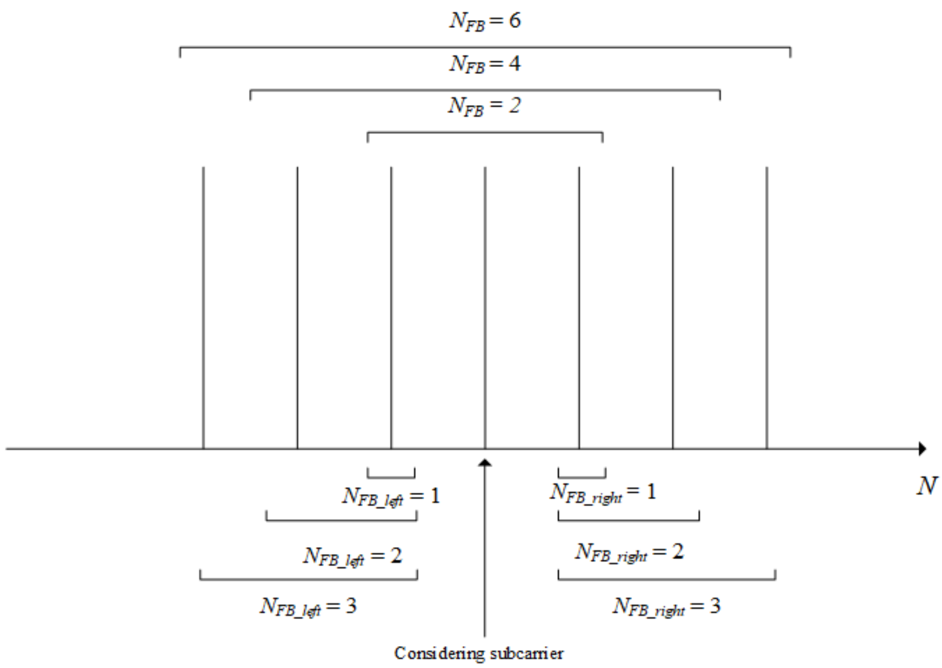

Fig. 5. Simplified scheme of N_{FB} positions

the energy bit and N_0 is spectral density of average power of noise [7]. At least 10^6 information bits are transmitted to calculate each value of BER.

Fig. 6*a* demonstrates this situation for various α, $N = 256$. At this graph we can see different curves matching different α. "Theory, QPSK (α = 1)" is the theoretical BER performance of OFDM signals (α = 1) with QPSK modulation of signals on each subcarriers. As we can see, modulation of case α = 1 perfectly matches with "Theory, QPSK (α = 1)".

Let us compare BER performance of standard demodulation and demodulation with asymmetrical algorithm on one subcarrier ($N_{FB\_left} = 1$) (Fig. 6*b*). Both of them transmit 64 bits with $N = 32$. As we can see, the asymmetrical algorithm gives us small coding gain at these values of E_b/N_0.

For better values of BER performance, we can increase amount of N_{FB} step by step on every side and watch dependence of energy losses of our algorithm in comparison with the theory (Fig. 7) (value of BER is constant and equals 10^{-2}). An analysis confirms the idea presented above about ICI tending to zero with N_i tending to infinity. As we can see in Fig. 7, energy loss tends to limit with increasing N_{FB} because furthest subcarriers have lower values of coefficients of mutual interference than nearby subcarriers. That is the reason why the idea of using $N_{FB} = N$ is very resource-intensive and moreover meaningless.

This way we can find the limit for N_{FB} for every N, when BER performance doesn't change anymore. For example, we can consider a situation when signal is transmitted with $N = 128$ subcarriers (Fig. 7*a*), E_b/N_0 is constant and equal to 10 dB. From this plot we can understand that for α = 0.7 the limit that can be taken is $N_{FB} = 4$, for α = 0.75 – 6, for α = 0.8 – 8, for α = 0.85 – 11, for α = 0.9 – 14. Furthermore, we will see that the limit for N_{FB} almost does not change with increasing N.

Conclusion

The article presents the idea of a symmetrical iterative algorithm for cancelling inter-channel interference of SEFDM signals from both sides of considered subcarrier by iterative analysis of every received subcarrier and interference of each of the neighboring ones. This work demonstrated existence of a limit for the number of subcarriers used for feedback when energy loss cannot be reduced any more, which can be used for optimizing settings and saving computing resources. As for numerical results (Fig. 8), the developed algorithm with found limit N_{FB} in comparison with algorithm on one subcarrier gives

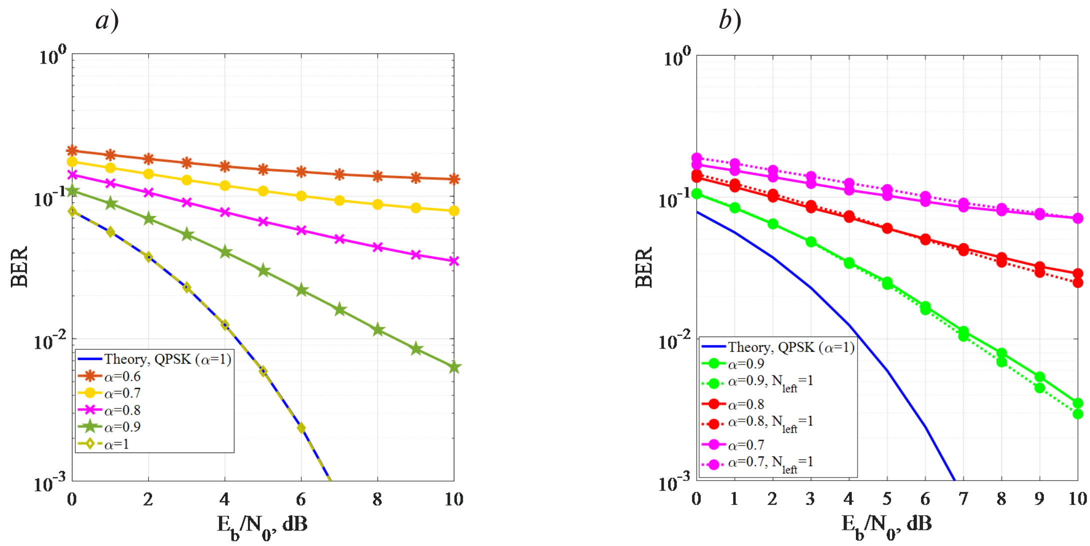

Fig. 6. BER performance: *a* – SEFDM signal with various α ($N = 256$); *b* – comparison of standard demodulation algorithm and asymmetrical FB demodulation algorithm ($N = 32$, $N_{FB\_left} = 1$)

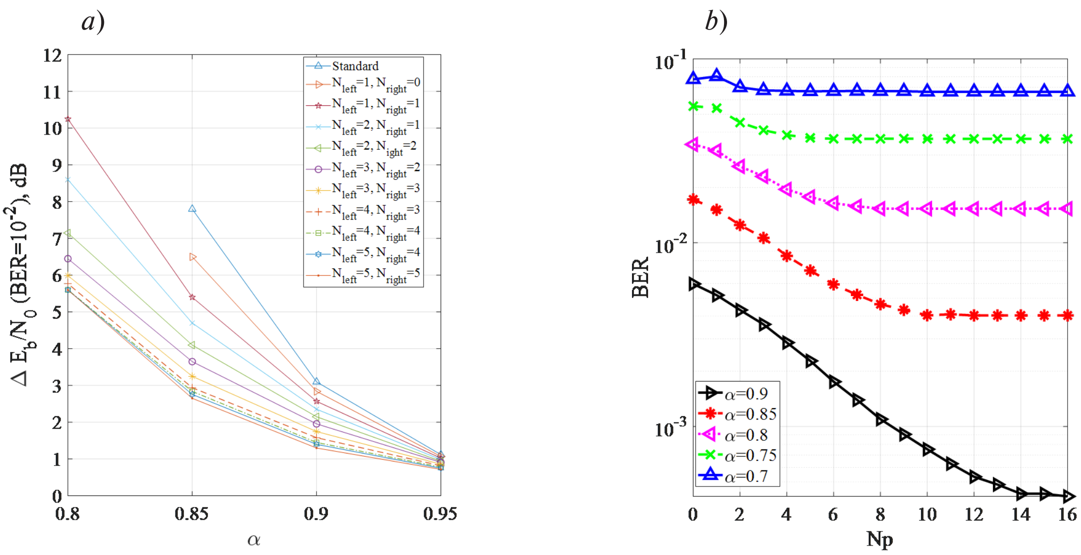

Fig. 7. *a* – Dependence of energy loss versus α at various N_{FB} (BER = 10^{-2});
b – dependence of BER performance versus $N_{FB} = N_{FB\_left} + N_{FB\_right}$ (E_b/N_0 = 10 dB)

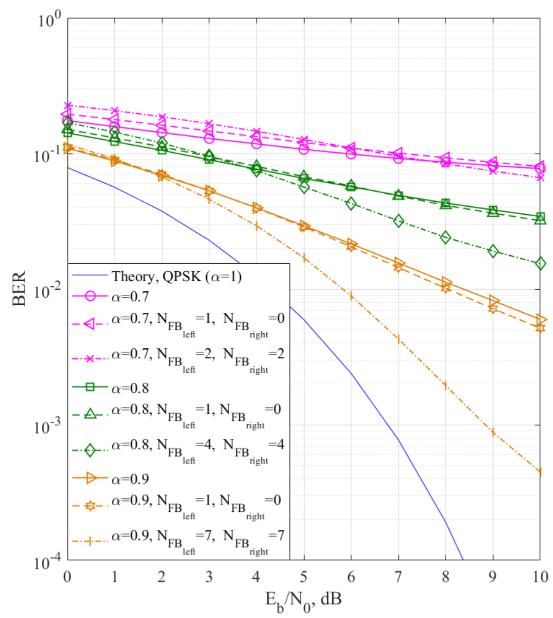

Fig. 8. Comparison of standard demodulation algorithm, asymmetrical feedback algorithm on one subcarrier (N_{FB_left} = 1) and symmetrical feedback algorithm

coding gain in value of 2 dB in case of α = 0.9, N = 128 and BER = 10^{-2}. For case the case of α = 0.8, coding gain is about 15 dB. For α = 0.7, energy coding cannot be detected as the algorithm BER curve is too high on one subcarrier that does not exceed the value of BER = 10^{-2}. For the lowest α, the coding gain will be increasing even further.

REFERENCES

1. **Liu X., Xu T., Darwazeh I.** Coexistence of orthogonal and non-orthogonal multicarrier signals in beyond 5G scenarios. *2020 2nd 6G Wireless Summit* (*6G Summit*), 2020, Pp. 1–5. DOI: 10.1109/6GSummit49458.2020.9083780

2. **Ghannam H., Darwazeh I.** SEFDM: Spectral efficiency upper bound and interference distribution. *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing* (*CSNDSP*), 2018, Pp. 1–6. DOI: 10.1109/CSNDSP.2018.8471782

3. **Ziegler V. Yrjölä S.** How to make 6G a general purpose technology: Prerequisites and value creation paradigm shift. *2021 Joint European Conference on Networks and Communications & 6G Summit* (*EuCNC/6G Summit*), 2021, Pp. 586–591. DOI: 10.1109/EuCNC/6GSummit51104.2021.9482431

4. **Mahmood N.H., Alves H., López O.A., Shehab M., Osorio D.P.M., Latva-Aho M.** Six key features of machine type communication in 6G. *2020 2nd 6G Wireless Summit* (*6G Summit*), 2020, Pp. 1–5. DOI: 10.1109/6GSummit49458.2020.9083794

5. **Xu T., Xu T., Bayvel P., Darwazeh I.** Non-orthogonal signal transmission over nonlinear optical channels. *IEEE Photonics Journal*, 2019, Vol. 11, no. 3, Pp. 1–13, Art no. 7203313. DOI: 10.1109/JPHOT.2019.2904960

6. **Darwazeh I., Ghannam H., Xu T.** The first 15 years of SEFDM: A brief survey. *2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing* (*CSNDSP*), 2018, Pp. 1–7. DOI: 10.1109/CSNDSP.2018.8471886

7. **Zavjalov S.V., Volvenko S.V., Makarov S.B.** A method for increasing the spectral and energy efficiency SEFDM signals. *IEEE Communications Letters*, 2016, Vol. 20, no. 12, Pp. 2382–2385. DOI: 10.1109/LCOMM.2016.2607742

8. **Ahmed S.I.A.** Spectrally efficient FDM communication signals and transceivers: Design, mathematical modelling and system optimization, communications and information. Systems Research Group Department of Electronic and Electrical Engineering University College London, Oct. 2011. Available: *https://discovery.ucl.ac.uk/id/eprint/1335609* (Accessed: 05.04.2022).

9. **Makarov S.B., Zavjalov S.V., Nguyen D.C., Ovsyannikova A.S.** Coherent detection of non-orthogonal spectrally efficient multicarrier signals using a decision feedback algorithm. *Journal of the Russian Universities. Radioelectronics*, 2021, Vol. 24, no. 5, Pp. 22–35. DOI: 10.32603/1993-8985-2021-24-5-22-35

10. **Yu B., Zhang S., Dai X. Zhang H.** Iterative decoder for coded SEFDM systems. *2017 IEEE 17th International Conference on Communication Technology* (*ICCT*), 2017, Pp. 145–150. DOI: 10.1109/ICCT.2017.8359620

11. **Gelgor A., Gorlov A., Nguyen V.P.** Performance analysis of SEFDM with optimal subcarriers spectrum shapes. *2017 IEEE International Black Sea Conference on Communications and Networking* (*BlackSeaCom*), 2017, Pp. 1–5. DOI: 10.1109/BlackSeaCom.2017.8277680

12. **Makarov S.B., Tsikin I.A.** *Peredacha diskretnykh soobshcheniy po radiokanalam s ogranichennoy polosoy propuskaniya*. Moscow: Radio i Svyaz Publ., 1988. 304 p. (rus)

13. **Rashich A., Kislitsyn A, Fadeev D., Ngoc Nguyen T.** FFT-based trellis receiver for SEFDM signals. *2016 IEEE Global Communications Conference* (*GLOBECOM*), 2016, Pp. 1–6. DOI: 10.1109/GLOCOM.2016.7841841

14. **Gelgor A., Nguyen V.P.** Outperforming conventional OFDM and SEFDM signals by means of using optimal spectral pulses and the M-BCJR algorithm. *2019 26th International Conference on Telecommunications* (*ICT*), 2019, Pp. 130–134. DOI: 10.1109/ICT.2019.8798793

15. **Gelgor A., Gorlov A., Nguyen V.P.** The design and performance of SEFDM with the Sinc-to-RRC modification of subcarriers spectrums. *2016 International Conference on Advanced Technologies for Communications* (*ATC*), 2016, Pp. 65–69. DOI: 10.1109/ATC.2016.7764831

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