Properties of chosen OFDM-generated radar waveforms

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ABSTRACT

Within research presented in this article, several radar waveforms were designed. Waveforms based on common simple and complex radiolocational signals were combined using OFDM (Orthogonal Frequency Division Multiplexing). Combined with the ever-increasing technological possibilities, OFDM can be a valuable tool to overcome the challenges of modern radiolocation, such as limited spectrum resources and the improvement of electronic intelligence (ELINT) and electronic warfare (EW) methods. Despite it has become quite common in today's radiolocation, OFDM still appears to be an innovative solution with high development potential and a lot of still unused possibilities. Due to above, an attempt was made to explore the properties of waveforms significantly differing from typical telecommunications modulations. Designed signals were subjected to the analysis of properties in the time and frequency domains using cross-sections of the ambiguity function. The results were compared with the properties of classic radar signals in a given frequency band. The goal of the simulations was to illustrate the potential benefits and losses in the time-frequency waveforms of the synthesized signal compared to classic solutions. Potential degradation of signal parameters is a particularly important issue for combined radar-communication systems. The proprietary element of the study is the synthesis and analysis of signals containing different types of modulation on individual sub-bands simultaneously. The collected results will be used for further research on the methods of synthesis and processing of radiolocation signals using OFDM technology.

Keywords: DSP, OFDM, radar waveform, ambiguity function, signal synthesis

1. INTRODUCTION

OFDM modulation technique is used in telecommunication area for nearly sixty years[1]. One of the first commonly known implementations of OFDM was ADSL (Asymmetric Digital Subscriber Line). Nowadays, OFDM acronym is most commonly associated with popular state-of-the-art technologies like DVB-T (Digital Video Broadcasting – Terrestrial)[2] or LTE (Long-Term Evolution)[3]. Basic idea of OFDM operation in communication is to dismantle one, high speed data stream to numerous parallel streams of significantly less data transmission speed. Thanks to multiplication of data streams, overall system throughput is preserved, whereas thanks to lower transmission speed in particular channels, transmission is more tolerant about unfavorable propagation conditions. During an over fifty-years period of OFDM usage in the communications, a number of constructs and enhancements have been developed - naming pilot signals, guard interval or cyclic prefix as examples - to address problems such as transmitter-receiver synchronization, Doppler-connected distortions or multipath propagation issues.

Interesting in multi-carrier techniques for radar applications has appeared relatively late comparing to telecommunications, at the beginning of XXI century[4]. Since then, although, intensive development of this area can be observed. OFDM-generated waveforms are commonly used for multistatic radars, due to feasibility of modulation with mutually orthogonal complementary sequences[5]. Research on novel methods in such sequences finding can be observed[6], to extend the usage of multistate modulation capabilities of OFDM. Important part of radar OFDM research is concerned on waveform designing and optimization methods. A number of approaches has been developed with various issues addressed. Undertaken trials has exploited various features of the signal, system or processing methods. Exemplary solutions can be pointed as: chirp optimisation[7], adaptive waveforms for cognitive radar with target and clutter estimation[8], code matrix design and correlation optimization based on sparse delay-Doppler space matrix[9], sidelobe suppression for spatially generated OFDM signal of MIMO radar[10] or analytical determination of IQ imbalance-robust waveform[11].

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Radioelectronic Systems Conference 2019, edited by Piotr Kaniewski, Jan Matuszewski, Proc. of SPIE
Vol. 11442, 114420B · © 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2565235

However an idea of data transmission via OFDM radar is present on the field since a decade[5], it can be observed that it became one of the most popular scientific issues of the field recently. An embedded communication in radars, which allows for resource sharing between sensing and communication tasks. In such area, an important task is to investigate an influence of data transmission on typical radar capabilities of the system, alongside with proposals of improvement methods[12]. Data transmission ability looks to be specifically useful in SAR (Synthetic Aperture Radar) systems[13]. OFDM technique can be used in multistatic systems, with passive location, with alternative (to matched filter) methods of processing[14]. Radar signals generated in OFDM technique still are subject of time-frequency features analysis[15]. OFDM implementations in radar will probably keep growing in popularity, being driven by increases: of hardware capabilities on the one hand and of RF spectrum traffic on the other.

Proposed paper presents chosen features of some waveforms generated with the OFDM technique. Method of synthesis was heuristic, which can be considered as a short in sophistication, comparing to presented state of the art [7-11], but firstly, such approach is also used in the research of the field[16], and secondly papers presented above barely show final modulating data streams explicitly, underlining rather theoretical origin than implementational aspects of presented solutions. Within the scope of presented research, simulation waveform generator was designed, alongside with tools to control digital data payload applied on subcarriers in OFDM. Besides of explicit digital I, Q data streams presented next to resulted correlation, results of non-standard and mixed modulation patterns, e.g. crossed pair of chirps or chirp plus BPSK, were obtained.

2. METHODS

Goal of the tests performed within the scope of presented research was to preliminarily explore possibilities of OFDM-based waveform synthesis. Using this multicarrier technique allows for arbitral definition of an in-phase and quadrature components of the waveform's spectrum. Due to that, a number of approaches can be implemented and tested. Those tests can be assigned to novel waveform designing trials area of radar OFDM studies mentioned above. What is more, an influence of communication data presence on the waveform's detection capabilities can be evaluated. Finally, analysis results presented in this paper pose a starting point for development of novel methods of processing, which would be alternative or supplementary to the classical compression filter.

Implemented simulations are based on quite widely understood, implementation-oriented, OFDM signal definition. An OFDM signal is thereby understood as a signal generated by IFFT (Inverse Fast Fourier Transform) performed on arbitrary given I and Q waveform's spectral components:

$$s_m(n) = \text{IFFT}[S_{m,I}(k) + jS_{m,Q}(k)] \tag{1}$$

$$s(o) = s_1(n)^\frown s_2(n)^\frown \ldots s_M(n) \tag{2}$$

where:
m = 1, 2, ... M, n = 1, 2, ... N, k = 1, 2, ... K, o = 1, 2, …, M x N,
M – signal segments number,
N – time segments length,
K – IFFT points,
s(o) – overall synthesized signal in discrete time domain,
$s_m(n)$ – m-th segment samples,
$S_{m,I}(k)$, $S_{m,Q}(k)$ – real and imaginary components of m-th segment spectrum,
$^\frown$ – concatenation operator.

Overall signal spectrum is given as a M x N table, where each m-th row contains complex samples of N-point segment spectrum, so the input modulation table can be considered as a spectrogram with discrete time resolution N. Another remark is that spectrum and segment lengths are equal, N = K, which guarantees proper segment length to intercarrier distance, thus preserves orthogonality.

During the tests, independent modulations of each carrier were examined alongside with sub-bands aggregated variants. But even if overall modulation shape spanned over multiple carriers, each of them was driven separately with proper I,Q pair. Beside OFDM, a linear frequency modulation (LFM) signal with was generated, with time length and bandwidth equal to the OFDM signal.

Due to matched filter processing, signal autocorrelation function (ACF) main lobe width and sidelobes magnitude can be considered as fundamental radar waveform features. According to that, OFDM signal generated as above, was subjected to ACF calculation for features extraction. LFM signal autocorrelation results provided benchmark values for comparison.

To perform the tests, simulation of processing system was implemented in the Matlab software. Following assumptions and parameters of system have been set:

- sampling frequency F_s = 250 MHz,
- IFFT transform points K = 256,
- signal carrier frequency f_c = 62,5 MHz,
- signal bandwidth B = 12,7 MHz,
- signal duration time T_{pulse} = 13,3 µs.

Those values result in 13 signal segments and 13 sub-carriers of spectrum used. Depending on modulation variant, those sub-carriers were used independently or aggregate in one or some channels.

3. RESULTS

Results are presented in form of multiple figures for each modulation. Presented sets consist of 4 figures which present consecutively:

a) real part of modulation payload spectrogram,
b) ACF of signal under analysis, with the LFM ACF in a background,
c) ACF of signal under analysis, with the LFM ACF in a background – zoomed on the peak,
d) two-dimensional ambiguity function.

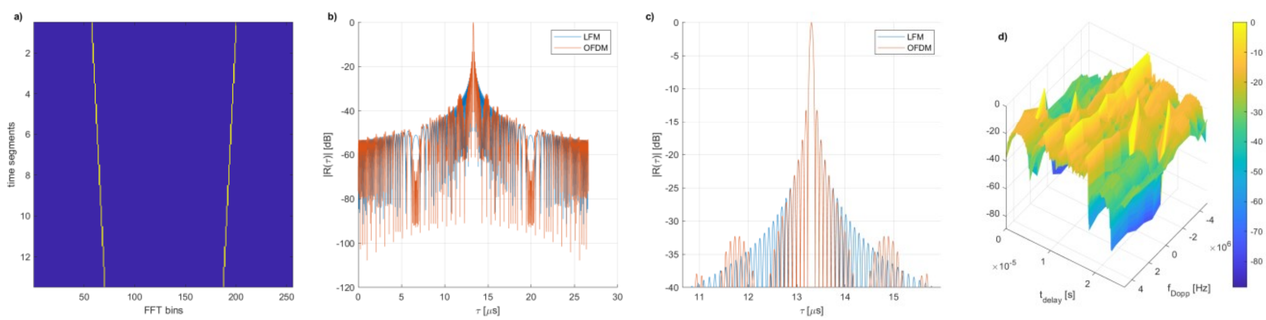

Figure 1. Modulation type: stepped-frequency modulation generated with OFDM method.

First trial was performed with quasi-LFM modulation, every consecutive payload frame subjected to IFFT consisted of non-zero weight for one physical frequency (pair of positive and negative frequency in terms of spectrum). Resultant signal was stepped-linear frequency modulated (SLFM). Comparing to LFM, ACF plot for mainlobe neighbourhood was almost identical, which should be expected.

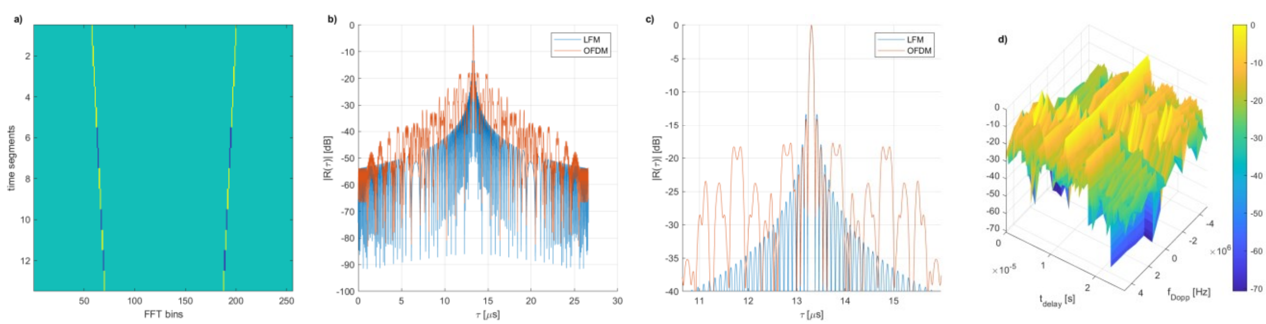

Figure 2. Stepped-frequency modulation with Barker-13 code binary phase shift keying (BPSK) modulation added.

Second waveform based on the previous, with phase modulation added. BPSK encoded Barker-13 code to the signal. Intention was to extract compressing features of both, SLFM and Barker-coded waveforms, known in the radar applications. Obtained sidelobes were reduced by less than 1 dB, which pose as almost neglectable improvement. Possible better results would be obtained by adding phase-continuity preserving mechanism between consecutive signal frames.

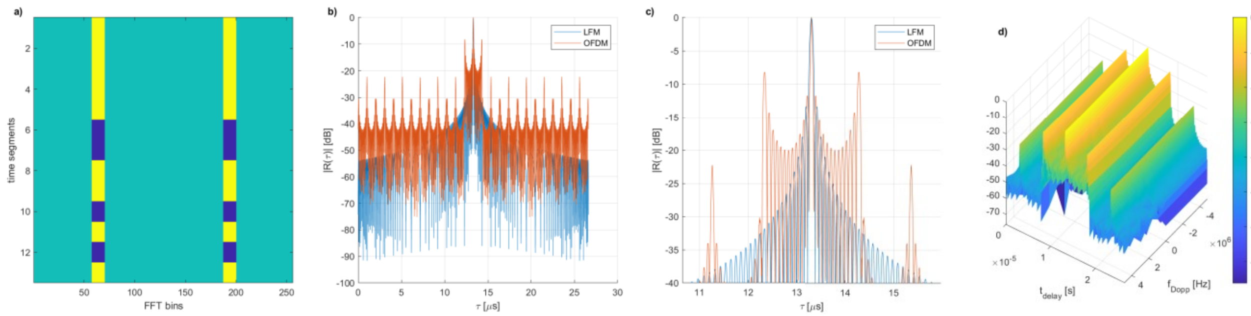

Figure 3. Barker-13 code on all sub-carriers parallelly.

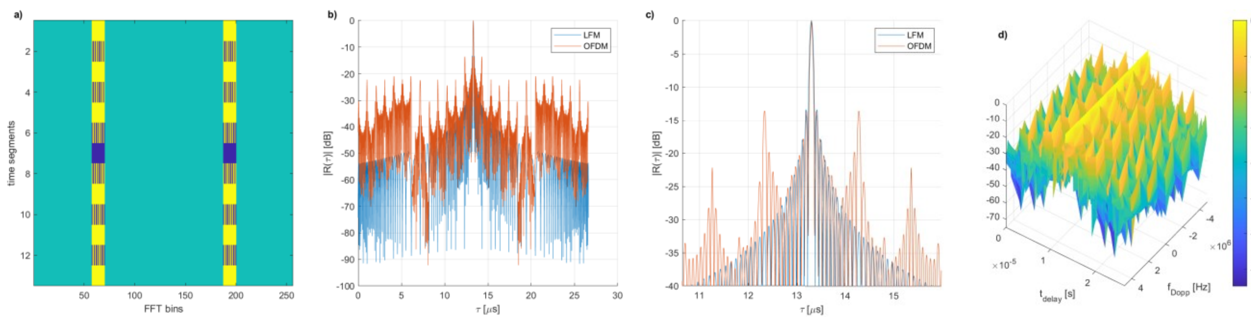

Figure 4. Barker-13 in straight and inverse order, alternately, on all sub-carriers.

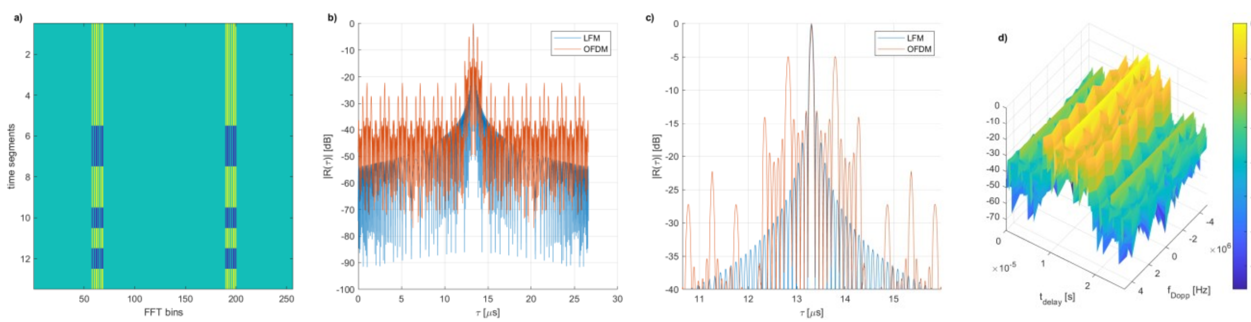

Figure 5. Barker-13 on an every-second sub-carrier.

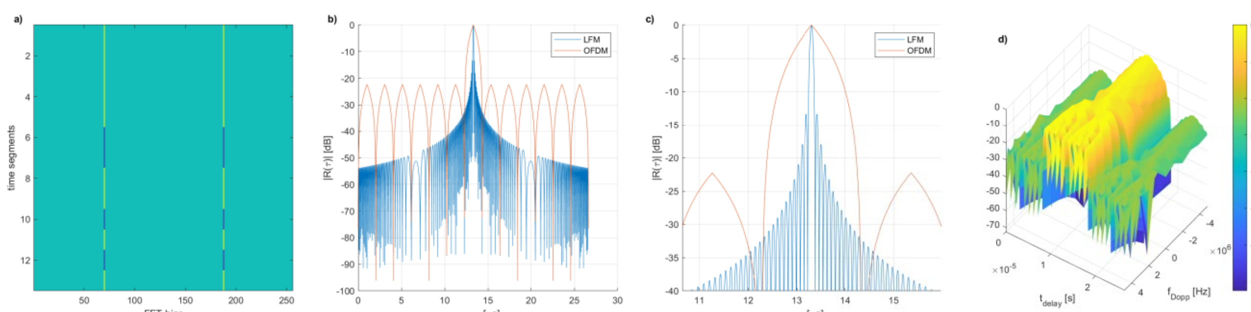

Figure 6. Barker-13 on a single sub-carrier.

Modulation data for tests 3 to 6 was prepared to extract Barker-13 signal processing gain from a number of frequencies simultaneously. Obtained results show high interference of closely placed frequency channels in code domain, that is weak orthogonality of Barker-13 coded signals with similar frequencies, which results in very high level of sidelobes. To extract information from such prepared signal, method other than matched filtering should be used. First, signal frequencies should be unplotted via OFDM receiver, and after that, Barker-13 matched filtering should be performed on every single extracted frequency. Methods of processing are out of the scope of this paper, but above results show interesting direction of further studies.

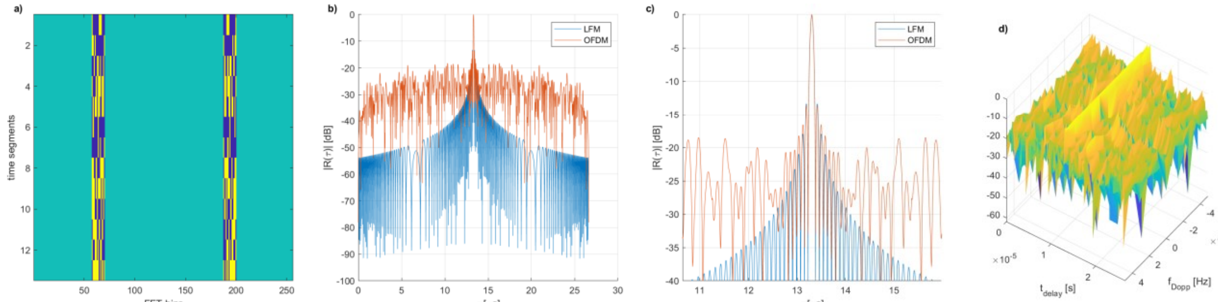

Figure 7. Random digital data coded onto sub-carriers with binary phase shift keying modulation.

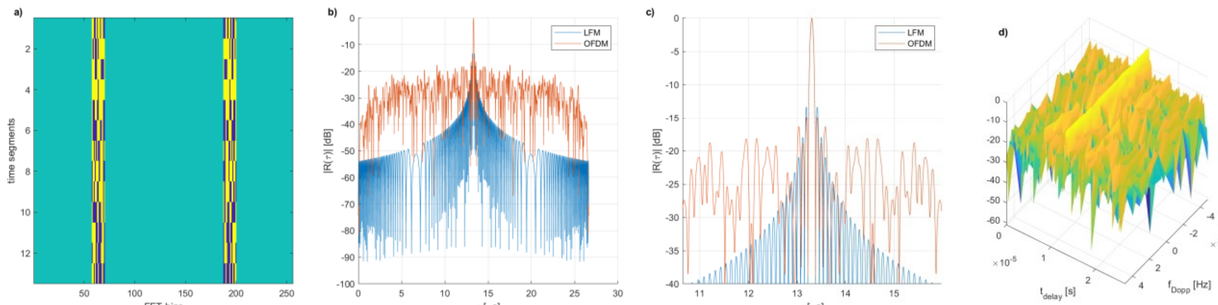

Figure 8. Random digital data coded onto sub-carriers with quaternary phase shift modulation.

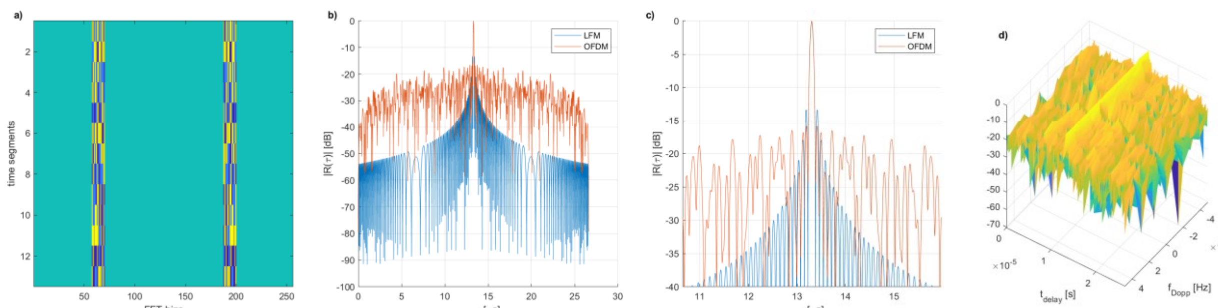

Figure 9. Random digital data coded onto sub-carriers with 16-state phase-amplitude modulation (QAM-16).

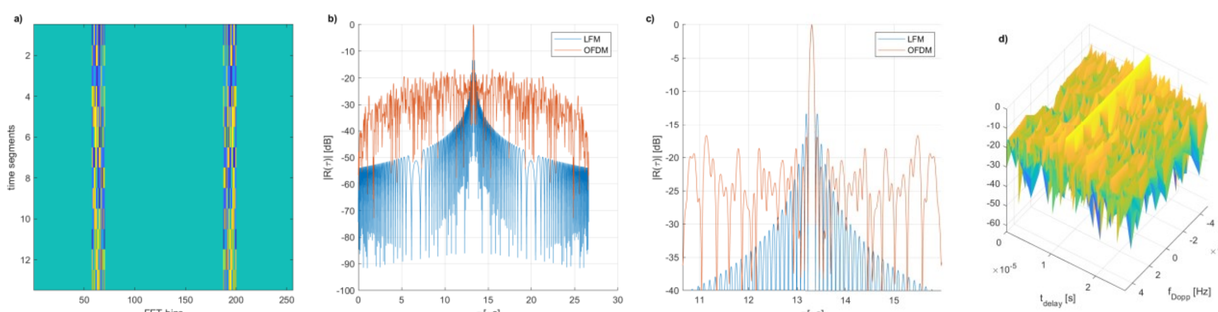

Figure 10. Random digital data coded onto sub-carriers with 64-state phase-amplitude modulation (QAM-64).

Tests 7-10 were performed with typical OFDM modulated signal carrying digital data. Data payload was generated randomly. Even with that, sidelobes reduction is noticeable (up to 4 dB) and linearly dependent on modulation states quantity. Result is expected, as such signal has spectral and statistical properties similar to noise. Making use of digital data for processing gain increase poses a very promising direction of further research on processing methods.

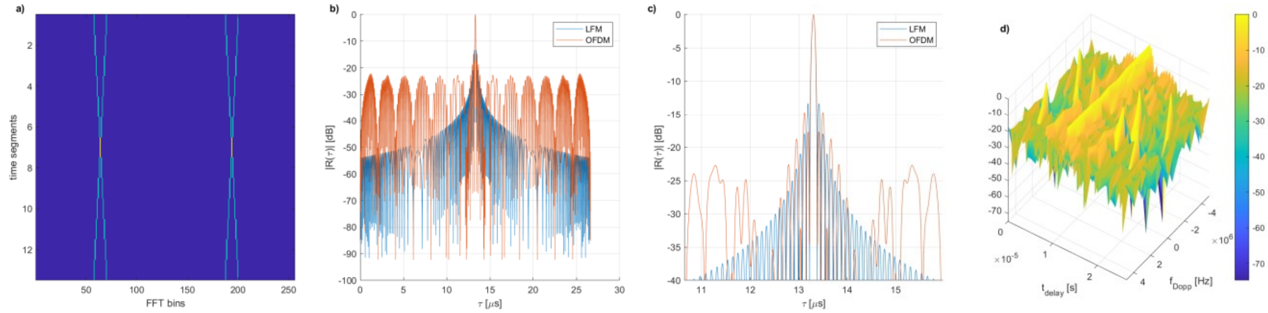

Figure 11. Composition of rising and falling frequency stepped-frequency modulation.

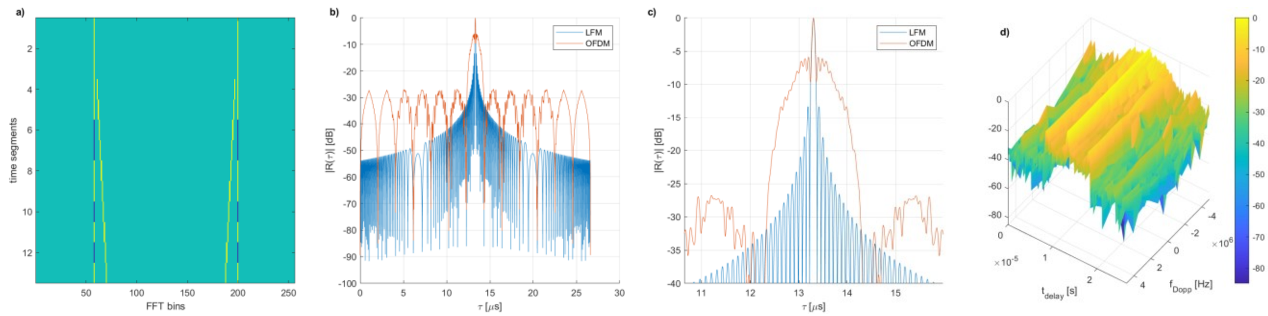

Figure 12. Composition of stepped-frequency modulation and Barker-13 code BPSK modulation.

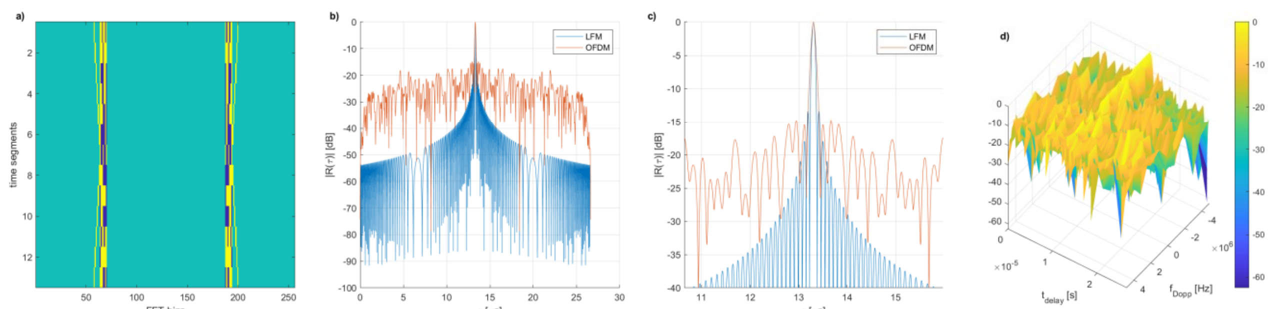

Figure 13. Composition of signals: rising-falling LFM in one channel and random digital data coded with BPSK in another.

Last group of tests, numbered 11 to 12, has been designed by binding different kinds of modulation into one waveform. With crossed SLFMs, almost 2 dB of sidelobes suppression was obtained, what is more, such crossings could be use for messages encoding. None gain was noted in the test no. 12. Results of the last test are interesting, as by the cost of slight mainlobe widening, a possibility of digital "footprint" can be used, as a counter-countermeasure feature.

4. CONCLUSIONS

Based on performed tests, further develop is planned toward stepped-frequency and typical data communication modulations direction. Contrary to expectations, various implementations with Barker's code hasn't yielded any gains. Possible improvements in such approach should include alternative methods of processing, as classical matched filtration results of raw signals degrades due to weak orthogonality of Barker-13 coded signals of adjacent frequencies in code domain, despite orthogonality in frequency domain is preserved. Interesting results of QAM modulations pose an issue to investigate about relations between digital payload (quasi-) randomness and radar features quality of given waveform.

What is more, as those communication-capable signals has shown neglectable negative impact on matched filtering results, further studies for digital payload exploitation of such signals appears to be well-reasoned.

Implemented simulation of signal generation and processing system allowed for preliminary verification of number of OFDM modulation variants. Heuristic method was used, what can be legitimized as a coarse direction finder for further research. Promising results for data-capable signals encourage to develop research on digital-data based detection methods, supporting classical approach of matched filtering.

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