Development of Aeronautical Communication System for Air Traffic Control Using OFDM and Computer Algebra Systems

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Abstract: The future aeronautical communication system will have to provide more communications capacity and increased capabilities than the existing one. These systems should be able to provide the performance required in the long term. The improvements are necessary to be able to cope with the expected air traffic growth in future. In this paper we deal with the development of new algorithms for the new generation of communication systems based on digital signal processing. The main idea is to automate the design procedure starting from the block diagram of the system and carrying out the implementation code on the target hardware. The role and importance of symbolic computation in communication systems is exemplified on OFDM (Orthogonal Frequency Division Multiplexing). An original approach to algorithm development is illustrated using computer algebra system. The development tools are Mathematica, and application software SchematicSolver.

Keywords: Air Traffic, Computer Tools, Symbolic Processing, OFDM.

1. Introduction

Two aeronautical communication systems, ATM (Air Traffic Management) and ATC (Air Traffic Control), were based mainly on analogue communication systems. They are using two types of modulations in the VHF range (Very High Frequency), AM (Amplitude Modulation) and DSBAM (Double Side-Band Amplitude Modulation). Due to the good propagation properties in the VHF band, new communications systems have to operate in the same frequency band. For new aeronautical communication systems, the B-VHF (Broadband VHF) system is planned. The B-VHF system is designed as an overlapping system based on OFDM (Orthogonal Frequency Division Multiplexing). This system can be implemented within the existing VHF system, but the interference between channels should be minimized as much as possible.

The simplified concept of the B-VHF overlapping system is shown in Figure 1 (a modified version of the figure from [1]). It can be seen that each

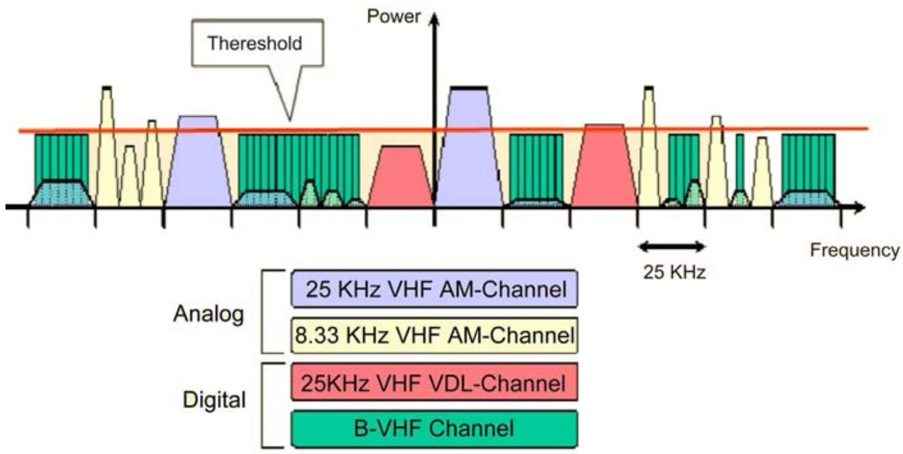

Figure 1. Overlapping concept of the VHF and B-VHF system

channel in the VHF band covers exactly the current time and frequency position. The frequency transitions of the B-VHF system are met using OFDM-based modulation techniques because captured channels are excluded from the OFDM transmission.

The system can be flexibly adapted to the changes of the allocated spectrum simple using the OFDM subcarrier of B-VHF system [1-5].

The spectra of the individual subcarriers overlap and the information can be completely recovered without any interference from other subcarriers. From a mathematical point of view, this is a consequence of the orthogonality of the base functions of the Fourier series. This technique is very popular for many applications in wireless communication systems [6].

In order to prove some properties or to gain better insight into analysed phenomena, such as those produced by OFDM technique, the numeric simulation can be engaged as the most common in practice [7-8]. The drawback of the numeric-based tools is that they usually generate a tremendous amount of numeric data, and the user might easily lose insight into the phenomenon being investigated. Even more, some authors have noticed that simulation and the real-time measured results were similar but not identical for the same input data [7]. In the case of OFDM, authors [7] only guess that different results are observed because they have used different FFT–IFFT blocks.

Usually, in many scientific papers typesetting errors in formulas exist, and intermediate results cannot be obtained, although the final result is correct [9]. The numeric-based tools cannot be of larger help, except to provide very speed calculation.

In order to improve the usage of computer tools, a knowledge based approach can be introduced [10] that is based on computer algebra systems.

Post processing using the computer algebra systems successfully overcomes some problems encountered in the traditional numeric-only approach. We present an original step-by-step procedure for simulations of OFDM transmitter using computer algebra systems and symbolic signal processing (*Mathematica* and *SchematicSolver*) [11-12] in Broadband VHF range. The knowledge embedded in the symbolic object was used to simulate an example OFDM system and to generate the implementation code of some critical parts of the system.

The paper is organized as follows. Section 2 describes the OFDM principles applied in the B-VHF system and overlapping concept. Section 3 describes the general concept of symbolic processing and computer algebra system, as well as usage of *Mathematica* as a development environment. Section 4 illustrates an implementation and simulation model of OFDM transmitter using computer algebra system. Section 5 illustrates the concept of post-processing.

2. The OFDM Principles Applied in the B-VHF System and Overlapping Concept

The basic principle of OFDM systems with multiple carrier distribution is a serial data stream in a large number of smaller parallel data streams, which can be transmitted simultaneously in the sub-channels. Each of the signals in sub-channel is modulated with the respective subcarrier. B-VHF system is used in parallel with other systems in the VHF band. Both, operational and development concept allow the system to be developed and used in the VHF range, as well as in other spectral bands provided for needs of communication in air traffic. It is expected that the B-VHF system can provide enough space for users for the projecting of the future of air traffic density and the exchange of communication requests. On the other hand, providing more channels and services should provide better performance in regard to the VHF systems that are in use.

Figure 2 shows an example of the B-VHF system [1].

Figure 3 gives the basic scheme OFDM systems [13]. The B-VHF integrated system designed to provide simultaneous support for almost all known classes of a safety-related communication services including ATM and data link communications. The B-VHF is a full-duplex system based on temporal distribution channels TDD (TDD - Time-Division Duplexing). The main advantage of the B-VHF system is that it does not use the neighboring group of the subcarriers. For this reason the known neighboring narrowband channels do not have to be used, so, it is possible to manage the VHF range, and thus

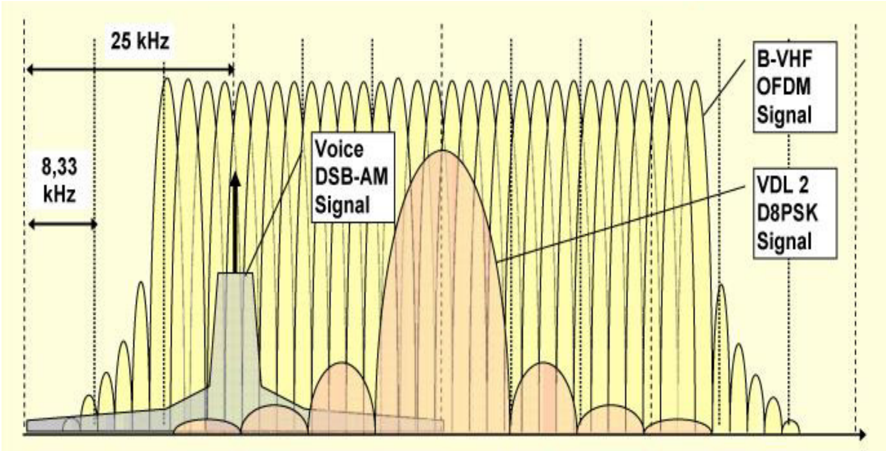

Figure 2. The B-VHF bands with various modulations

opens the way to the B-VHF implemented a new development concept. The concept of overlapping allows that only part of narrowband VHF channels be received as real interference depending on the current position of the B-VHF receiver, while others will arrive from remote sources and will be below the lower threshold of the received noise.

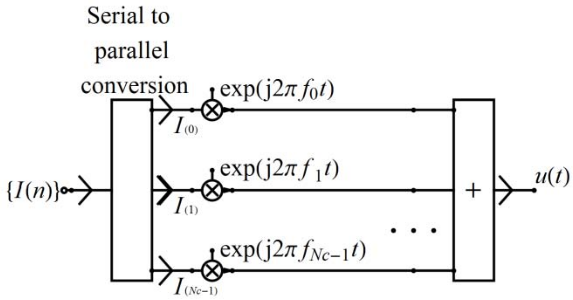

Figure 3. The OFDM transmitter

The array of complex values of symbol is leaded to the input of the modulator after serial to parallel conversion, where each symbol has a duration of T_S . Those symbols are used for modulation with corresponding carrier in every branch with frequency of $f_n, n = 0,..., N_c - 1$, where N_c is number of subcarriers. The carrier frequency can be calculated using by expression:

$$f_n = \frac{n}{T_0}, n = 0,..., N_c - 1 \quad (1)$$

where T_0 is the duration of OFDM symbols. Modulated signals are added and so the OFDM signal is generated, which can be represented by the expression:

$$u(t) = \frac{1}{N_c} \sum_{n=0}^{N_c - 1} I(n) \cdot e^{j2\pi f_n t}, 0 \le t < T \quad (2)$$

The benefit of this system lies in the fact that in the present environment with fading channel, caused by different delays, each subcarrier can be analyzed separately and can be easily done equalization delay using adaptive systems. The OFDM allows to almost completely avoiding inter-symbol interference introduction of protection interval (Guard) at the beginning of each OFDM symbol. This protection interval containing cyclic prefix CP (Cyclic Prefix) OFDM symbols that can be used for equalization, which is more efficient than using the impulse response of the channel. The CP provides to reduce the influence of intersymbol interference by maintaining orthogonality between the subcarrier by its shape. Every solution has good features as well as shortcomings, so, the use of CP has drawbacks: (1) the total duration of symbols can be longer than the maximum delay which is limited by the data stream in each of the subcarrier including CP; (2) the energy, required for the transmission, increases with the length of CP leading to a reduction of the signal/noise ratio. Influence of guard interval duration to inter-channel interference in DVB-T2 signals based on OFDM was analyzed in [14].

While in each OFDM symbol transmission transmit individual subcarrier, the symbol data is distributed in data stream through several subcarriers. Since a symbol of data is transmitted with more than one subcarrier, data stream decreases through the link. Data symbols are transmitted over the same group of the subcarrier. Figure 4 shows a block diagram of OFDM transmitter and receiver.

3. Symbolic Processing and Computer Algebra System

Modern research in the field of engineering science usually starts with theoretical analysis. Symbolic processing works with symbols. Any symbol can be replaced by a number when symbolic expressions become impractical, for example, for plotting a response to a specific excitation. Therefore, writing programs using symbolic processing can be seen as a set of instructions that manipulate the symbols and can be used to perform a much wider range of activities [12]. Term "computer algebra system" (CAS) represents computations using the arithmetic from particular algebraic constructions. The values used are elements of mathematically defined sets, such as algebraic extensions, quotients and so on. The elements might be represented in any one of a number of ways. The use of CAS and symbolic processing can help to gain insight into how a complex system works, which is preferred to experimenting with numeric simulations. The concept of symbolic processing is as follows. Each variable is denoted in the same manner when used in an analytical expression. Complete description of the analytical expressions is done in the notebook.

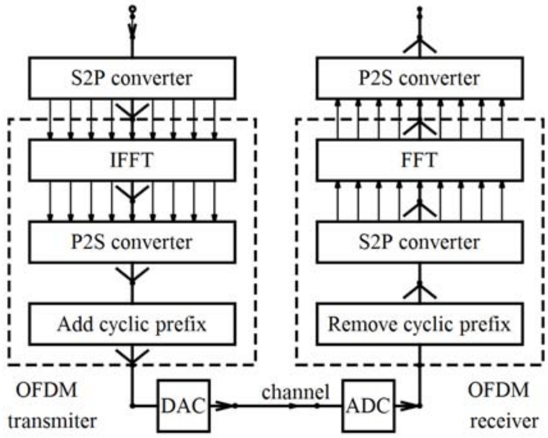

Figure 4. Block schema of implemented OFDM system: transceiver, channel, and receiver.

All further analytical manipulation, transformation, and mathematical analysis are left to the computer algebra system capabilities to do so, and it is called a symbolic processing. The efficiency of symbolic processing becomes more important if systems and signals are more complex. Even then, the final result can be expressed in a form of special function that can be computed for known numerical values of system parameters. Symbolic processing can help to error-free derive simulation code, and to find typewriting errors if they exist calculating by hand. Next, symbolic processing can be used for finding the processing errors as the closed-form expression for computing the number of required iteration steps; or the error function due to finite word-length [10], [15]. Therefore, symbolic processing can help gain insight into how a system works, which is preferred to experimenting with numeric simulations. Symbolic processing repairs certain disagreement between theoretical performance and numerical simulations.

3.1 *Mathematica* as a development environment

The software package *Mathematica* [16] can be used as a development environment for designing, implementing and testing algorithms necessary for the implementation of telecommunications equipment. Detailed descriptions of the capabilities of the software *Mathematica* as an algebraic computer system are given in [16-19]. Some of important features are the ability to generate dynamic object so that it is possible to see graphics that change their shape in real time to changing system parameters. With significantly improved numerical properties, primarily in the speed, and the use of color to highlight the variables and functions, and with a rich graphical user interface development environment provides a high level of comfort and ease of visualization algorithms.

4. The Simulation Model of OFDM Transmitter

The simulation model based on the OFDM signals is described in detail in [18-19].

4.1 OFDM symbol generation

The first step is to load the package *SchematicSolver* in CAS *Mathematica* with the command `Needs` in the working notebook.

The next step is to draw a block diagram of the OFDM symbol generation using point-and-click interface for drawing systems. A simplified model is shown in Figure 5.

The carrier frequency is close to 90 MHz. The appropriate simulation period T is defined as the elementary period for a baseband signal, and it relates to a time-period, $1/R_S$.

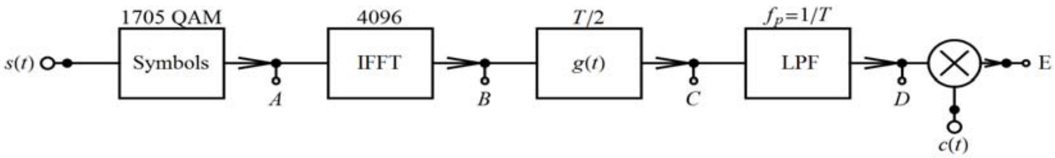

Figure 5. Block diagram of OFDM symbol generation.

For simplicity, we use $R_S = 40/T$.

Numerical values for the OFDM parameters for the 2k mode are specified on the same way described like in *Mathematica* as follow:

```
Tu=224*10^-6;
(*Tu is useful OFDM symbol
period*)
T=Tu/2048;
(*T is baseband elementary
period*)
G=0;
(*G is 1/4,1/8,1/16,or 1/32 *)
delta=G*Tu; (*guard band
duration*)
Ts=delta+Tu;
(*Ts is total OFDM symbol period*)
Kmax=1705;
(*Kmax is number of subcarriers*)
Kmin=0;
FS=4096; (*IFFT/FFT length*)
q=10; (*carrier period to
elementary period ratio*)
fc=q*1/T; (*carrier frequency*)
Rs=4*fc; (*simulation period*)
M=Kmax+1;
```

Notice that all variables are integers, and thus computer algebra system operates as with as symbols, that as with exact numbers.

The OFDM spectrum is centered on carrier frequency. One simple way to achieve the centering is to use a 2N-IFFT and T/2 as the elementary period (N=2048). FFT is Fast Fourier Transform and IFFT is inverse FFT. Therefore, 4096-IFFT was used in [7].

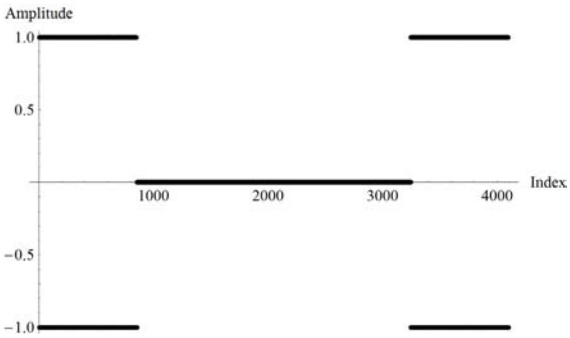

Figure 6. Information signal at A.

Usually, a random generator is used for simulating information signal. In this paper we are using the same information signal generated in [7] using MATLAB code, in order to compare signals obtained by MATLAB and *Mathematica*, as two sequences **`an1`** and **`an2`**. Alternatively, we can use the command **`Random`** to generate information signal in *Mathematica*. The input signal *a* consists of 1705 symbols (+1 or -1) and it is shown in Figure 6. The 2391 zeros are added to the information signal at (A) to achieve over-sampling. Signal at B is computed using IFFT. *SchematicSolver* provide appropriate commands, so the code is very simple.

The signal **`carriers`** use T/2 as its time period, as it is shown in Figure 7 for carriers inphase at B.

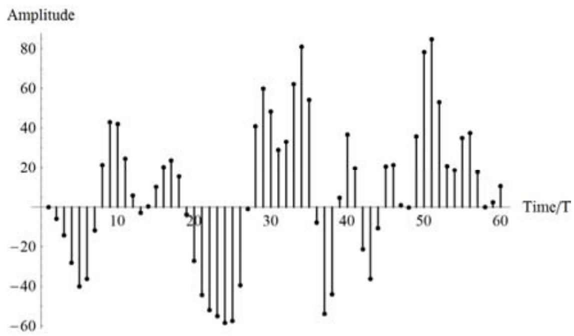

Figure 7. Carriers inphase at B.

The 4096-FFT of the signal at B is shown in Figure 8. As it can be expected, it is similar to the magnitude of information signal.

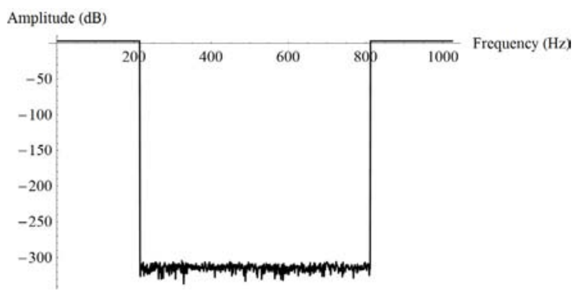

Figure 8. Carriers 4096-FFT at B.

The information signal is the discrete-time signal and the carriers at B should be also the discrete-time signal. In order to simulate continuous-time signal, a pulse shape $g(t)$ signal is generated transforming list of values to a sequence.

4.2 Generation of continuous signal

The signal $u(t)$ at the output of pulse shaping block, at C, is up-sampled signal by a factor of 20, and filtered using finite impulse-response filter (FIR), as shown in Figure 9 for the real part of the signal.

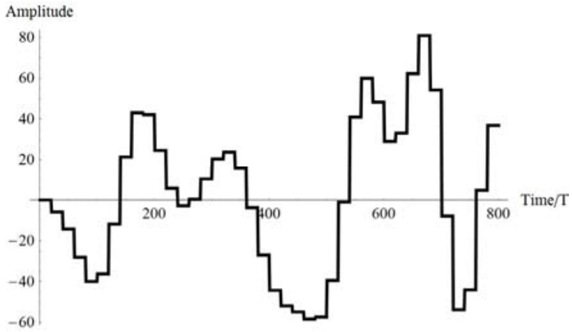

Figure 9. Inphase part of the signal u at C.

The next step is to reject images using a lowpass filter. The proposed reconstruction or "D/A filter" response is the 13th-order Butterworth filter with the cut-off frequency of approximately 1/T. Butterworth filters are characterized by a magnitude response that is maximally flat in the passband and monotonic overall. So, we can draw the filter using application package *SchematicSolver*, construct the digital filter and perform filtering. The filtered signals are shown in Figure 10.

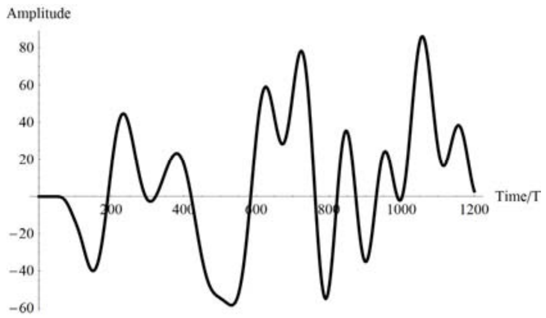

Figure 10. Inphase filtered signal at D.

The spectrum of the filtered signal shows that all spectral images are eliminated, as it is shown in Figure 11.

The next step is to perform the quadrature multiplex double-side band amplitude modulation of filtered signal. In this modulation, the inphase signal and the quadrature signal are modulated using the code in *Mathematica*.

Time response of signal $s(t)$ at E is shown in Figure 12, while the frequency response is shown in Figure 13.

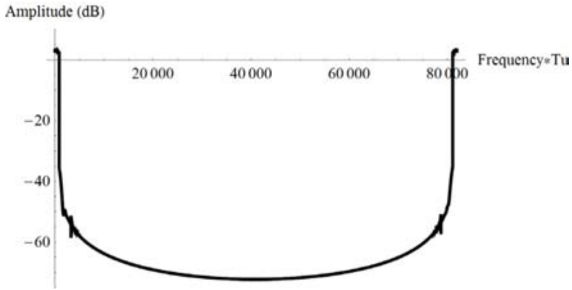

Figure 11. Frequency response of the filtered signal at D.

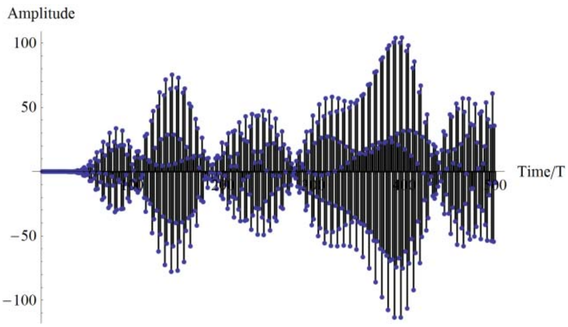

Figure 12. Transmitted signal at E.

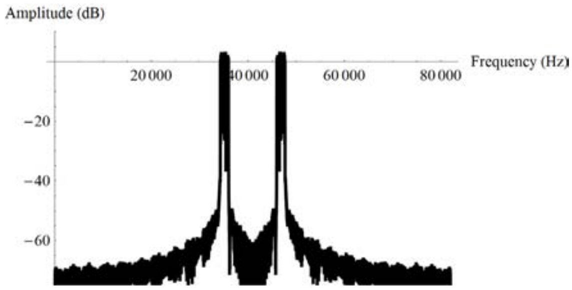

Figure 13. Frequency response of the transmitted signal at E.

5. Post-processing

The *SchematicSolver* describes a system as a symbolic object in the form of a list of elements. Two different representations exist: (1) the graphical representation of the block-diagram and (2) the textual description of the block-diagram. Symbolic processing can be carried out as follows: (1) automatically generate a code that implements the system, (2) compute the input sequence whose elements can be symbols or numbers, and (3) process the input sequence with the code that is the same for simulation and implementation. A variable precision can be used for computing the frequency response or filtering the signal. A direct form implementation of the filter has the same frequency response as in [7] for double precision. The frequency response of the filter designed using CAS has no pass-band variations as in [7]. Therefore, a cascade connection of second-order sections is more appropriate for implementation than the direct form.

For testing purposes, this system can be further used in conjunction with systems for testing and verification, so that the whole system can be simulated and evaluated in more complex environment. For example, the system for motion testing and verification of devices for pilot training and flight simulation can be connected with analyzed communication system and the testing of motion of those devices can be performed. The knowledge from each device can be incorporate in the control system and all functions can be tested on targeted platform. Several examples of knowledge embedded systems are already presented for simple problems [10, 12]. The computer algebra system can be used for developing new algorithms and proving the accuracy as closed-form solution (as presented in [9]) instead of exhaustive numeric simulations.

6. Conclusion

In this paper, the problems that are expected in the development of communication systems for air traffic management and control are analyzed using computer algebra system in a knowledge-based approach. It is presented the procedure for proving existing solutions and for developing of new algorithms. The presented approach provides possibility for testing and verification of complex systems without the usage of all parts of systems. The knowledge of each part of the whole system can be embedded in simplified testing environment. In this way, communication system and control system can be analyzed separately.

Specifically, in this paper we have presented how to develop software testing of communication in broadband VHF range operation using computer algebra systems. Complete analyze is done using advanced digital signal processing techniques, especially systems with multiple frequency selection in order to implement efficient and reliable signal processing algorithms. Post processing with the computer algebra systems was used for simulation of OFDM transmitter, and similar solution is developed for receiver. It is proved that the unexpected frequency response reported in some previously published papers is due to numeric errors of the direct form filter implementation, and that cascaded biquads are more appropriate for implementation.

REFERENCES

1. B-VHF CONSORTIUM, **Broadband VHF Aeronautical Communications System Based on MC-CDMA**, www.b-vhf.org, (2002-2006).
2. SCHNELL, M., E. HAAS, C. RIHACEK, M. SAJATOVIC, **BVHF - An Overlay System Concept for Future ATC Communications in the VHF Band,** Proc. 23rd Digital Avionics Systems Conf. (DASC 2004), Salt Lake City, USA, October 2004.
3. GINESI, A., F. POTEVIN, **OFDM Digital Transmission Techniques for Broadband Satellites**, 24th AIAA International Communications Satellite Systems Conference (ICSSC, San Diego, California), June 2006, pp. 1-4.
4. CHEVILLAT, P, G. UNGER BOECK, **Optimum FIR Transmitter and Receiver Filters for Data Transmission over Band-limited Channels**, IEEE Transactions on Communications, vol. COM-20, No. 8, August 1982.
5. MOOSE, P., **A technique for orthogonal frequency division multiplexing frequency offset correction**, IEEE Transactions on Communications, vol. 42, No. 10, October 1994, pp. 2908-2914.
6. SCHULZE, H., C. LUDERS, **Theory and Applications of OFDM and CDMA - Wideband Wireless Communications,** West Sussex: John Wiley & Sons, 2005.
7. ACOSTA, G., **OFDM Simulation Using Matlab,** Smart Antenna Research Laboratory. Available: http://www.ece.gatech.edu/research/labs/sarl/ tutorials/OFDM/Tutorial_web.pdf 2001.
8. MATLAB, **MathWorks**, Inc., Natick, MA, 2005
9. MLADENOVIC, V., M. D. LUTOVAC, M. M. LUTOVAC, **Automated Proving Properties of Expectation-Maximization Algorithm using Symbolic Tools**,

TELFOR Journal, vol. 4, no. 1, 2012, pp. 54-59.

10. MILIĆ, D. L., D. M. LUTOVAC, D. J. ĆERTIĆ, **Design of First-order Differentiator utilizing FIR and IIR Sub-filters**, International Journal of Reasoning-based Intelligent Systems, Special Issue on Emerging Trends in Information and Communication Technologies vol. 4, no. 1, 2013.
11. LUTOVAC, M., D. TOŠIĆ, **SchematicSolver Version 2.2**, 2010. Available: books.google.com/books?id=9ue-uVG__JsC
12. LUTOVAC, M., D. TOŠIĆ, **Symbolic Analysis and Design of Control Systems using Mathematica,** International Journal of Control, Special Issue on Symbolic Computing in Control, vol. 79, no. 11, 2006, pp. 1368-1381.
13. NEE, R., R. PRASAD, **OFDM Wireless Multimedia Communications**. Norwood, MA: Artech House, 2000.
14. MISKOVIC B., M. D. LUTOVAC, **Influence of Guard Interval Duration to Interchannel Interference in DVB-T2 Signal**, Mediterranean Conference on Embedded Computing (MECO), 2012, pp. 220-223
15. LUTOVAC, M., J. ĆERTIĆ, L. MILIĆ, **Digital Filter Design Using Computer Algebra Systems**, Circuits Syst. Signal Process, Vol. 29, no. 1, 2010, pp. 51-64.
16. WOLFRAM, S., **The Mathematica Book**, Cambridge: Cambridge University Press, Wolfram Media, 2003.
17. TOŠIĆ, D., M. LUTOVAC, **Advances in Symbolic Simulation of Systems**, The IPSI BgD Transactions on Advanced Research, vol. 3, no. 1, Jan. 2007.
18. LUTOVAC, M., V. MLADENOVIC, **Development of Aeronautical Communication System using Computer Algebra Systems,** in Proc. XXV Symposium of a new technologies in post office and telecommunication traffic – PosTel-2007, Belgrade, December 2007.
19. MLADENOVIC, V., D. PORRAT, M. LUTOVAC, **Simulation of OFDM Transmitters and Post Processing with SchematicSolver and Mathematica as a Computer Algebra System**, 5th European Conference on Circuits and Systems for Communications (ECCSC-10), November 23–25, 2010, Belgrade, Serbia.