Evaluation of the Multi-Carrier UFMC Modulation Candidate for Optical Wireless Communications

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***Abstract*—In present days, multi-carrier modulations are at the center of interest to many researchers to meet data and bandwidth requirements of fifth-generation fixed networks. This contribution is devoted to an evaluation of the universal filtered multi-carrier (UFMC) modulation format for examining optical wireless communications (OWC). The aim is to search for the most effective modulation scheme for advanced potential applications offered in the near future. For analysis, we realized a single-beam optical UFMC model in the OWC simulation platform where various comparisons with other multi-carrier modulation formats were executed. Simulation results demonstrate that the single-beam optical UFMC format has better performance for low-state internal modulation and is more reliable and effective for optical wireless communication systems.**

Keywords—optical wireless communications, simulation platform, single-beam multi-carrier modulations, coherent detection, free space optics, outdoor environment, turbulences, indoor environment, numerical evaluations

I. Introduction

Support of extremely high speed and capacity, high coverage, high responsivity, and high density for the fifth-generation fixed network (F5G) networks requires an investigation and development of multi-carrier modulation formats for supporting higher spectral utilization and efficiency [1]. The potential applications of the optical wireless communications (OWC) technology within the dynamic landscape of smart cities are diverse for contemporary urban and industrial scenarios and exemplify the adaptability to meet specific communication needs [2], [3], [4]. Many researchers are focusing on multi-carrier modulations as a major research problem for the next-generation communication networks to meet these key communication requirements. One critical parameter in the physical layer is selecting a suitable multi-carrier waveform with effective generation and detection [5]. Various multi-carrier modulations have been well-studied for radiofrequency-based wireless communications as potential substitutes for the orthogonal frequency division multiplexing (OFDM) modulation for the 5G new radio. Utilization of perspective modulations for OWC systems is under intensive research interest. To overcome the stated problem, various alternatives of waveforms are proposed, and different candidates of modulation schemes are considered in the development phase.

Our first examined attempt is with the non-orthogonal filter bank multi-carrier (FBMC) technique in contrast with the OFDM principle. It involves large changes in the filtering process of particular subcarriers. Each subcarrier is filtered individually, and, in this way, higher spectral efficiency compared to the OFDM modulation is acquired. For maximum exploitability, the offset QAM (OQAM) scheme must be used for separating real and imaginary parts of a given complex data symbol and for transmitting them separately. The FBMC format uses the inverse fast Fourier transformation (IFFT) with filters applying the overlaying factor for defining a fixed number of symbols in a given subcarrier path [6], [7], [8]. According to [9], the single-beam optical FBMC waveform can be considered for incorporation into OWC systems to achieve more effective utilization of the bandwidth. Subsequently, we introduced the multi-beam version of the optical FBMC waveform with applied data separations [10]. As a result, better efficiency of the coherent detection needed for multi-carrier modulation techniques is confirmed and its implementation in OWC systems operating in severe atmospheric conditions is possible.

Our second attention is focused on the universal filtered multi-carrier (UFMC) technology. UFMC can be considered for air interfaces for compromising complexity and out-of-band emission reduction due to its robustness against inter-carrier interference (ICI), low latency scenario, and less sensitivity to estimation error of frequency and time shifts [11], [12], [13]. For better results, a change in the filtering of subcarrier signals can be theoretically considered, concretely the allocation of subcarrier signals into subcarrier groups. This process can be provided by the UFMC modulation technique that can modify values of the transmitted IFFT symbols at need and set various bandwidths.

In the UFMC waveform, a bank of filters is used to process the signals on each subcarrier and a set of filters can be designed to have arbitrary frequency responses at sub-band levels. The choice of the block of subcarriers provides a flexibility in terms of spectrum usage in conjunction with support of flexible subcarrier spacing [14], [15], [16], [17].

The main advantage of the UFMC modulation is better spectral efficiency than the OFDM modulation [18]. Thanks to the QAM utilization, the UFMC technique can be exploited in the MIMO system. However, the UFMC process is complicated due to the computing intensity for each subcarrier group at the transmitter side and for double IFFT transformation at the receiver side [19]. In the UFMC modulation, a very high combination of transmitted bits for particular subcarrier groups can be utilized, from 4-QAM up to 1024-QAM. A higher number of transmitted bits brings a better possibility for receiving a superior single without losses, however, the intensity of the IFFT computing process will be directly proportional to higher [20]. The UFMC waveform has been proven to be the most promising choice

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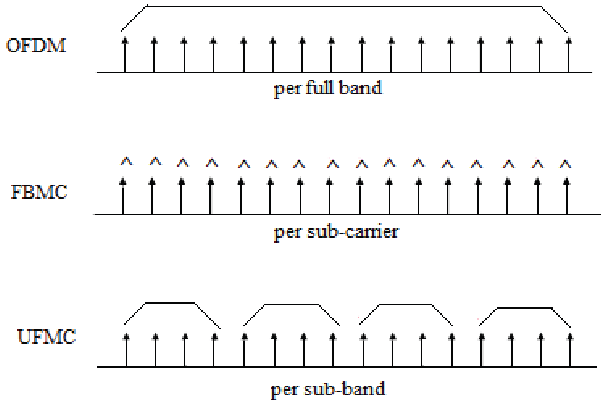

Fig. 1. Filtering methods applied in OFDM, FBMC and UFMC modulations

for short-burst communications and under very tight response time requirements, for example machine-to machine or vehicle-to-vehicle practical applicability [21], [22].

In this contribution, a focus is oriented on the multi-carrier UFMC modulation as the candidate for optical wireless communications. For analyzing advanced optical signal processing techniques, we realized the single-beam UFMC model and its incorporation into the OWC simulation platform [9], [10], [23], [24], [25], [26].

This paper consists of the following parts. In Section II, the basics of the optical UFMC modulation format are introduced. The OWC simulation platform with the optical single-beam UFMC signal transmission is described in detail in Section III. In Section IV, evaluations of optical UFMC and FBMC modulation techniques are characterized, and perspectives of the optical multi-carrier UFMC modulation candidate are analyzed for use in free space optics and visible light communications. Finally, a conclusion is included.

II. BASICS FOR OPTICAL UFMC MODULATION FORMAT

The UFMC modulation uses a filtering method where particular subcarriers are divided into groups of subcarriers (Fig. 1). Using the group filtering, the available spectrum can be theoretically more effectively utilized if unnecessary signal parts are filled in zeros and processing time is spared in turn. Subcarrier groups keep the orthogonality and, in this way, eliminate the intersymbol interference (ISI). Thanks to this orthogonality, the M-state QAM modulation that allows higher spectral efficiency within the same bandwidths can be utilized. Its disadvantage is higher M-QAM noise sensitivity and a requirement of linearity [27].

On the transmitter side (Fig. 2a), a specific number of particular filtered subcarrier signals is assigned to each subcarrier group. For each subcarrier group, the N-point IFFT transformation is calculated provides fast processing and minimum resource loading. Subsequent IFFF calculation values of each subcarrier group must be filtered by using the

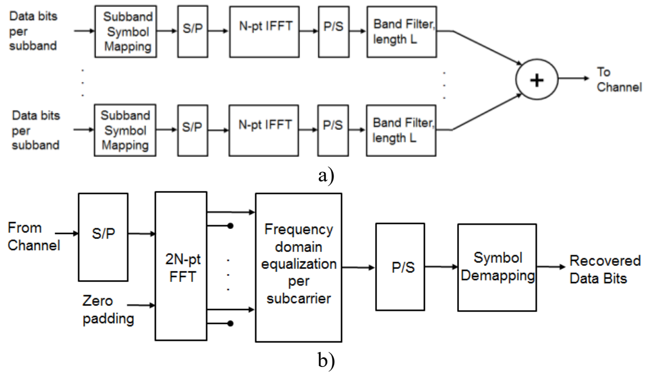

Fig. 2. Block schemes of a) the UFMC transmitter and b) the UFMC receiver

given filter length [18], [28], [29]. The resulting output signal y can be indicated as

$$y \ = H.Q^{-1}.y_i \tag{1}$$

where H is the Toeplitz matrix with $(N+L-1)$xN size, Q^{-1} presents the inverse Fourier matrix, N is a number of subcarrier groups, L je the filter length and y_i is the output on each subband/subcarrier.

On the receiver side (Fig. 2b), the $2N$ inverse Fourier transform is realized that converts the frequency band into the time range. To protect against the ISI influence, zeros are added in a case that subcarrier groups are not utilized.

At the UFMC transmitting output, the interference between neighboring subcarrier groups and band groups comes into existence, and the orthogonality between subcarrier groups are not possible to keep by filtering. Therefore, the filter length plays an important role in the UFMC transmitter delivery and determines the size of the maximum subcarrier group band (*subbandSize*). The symbol interference between subcarrier groups is caused by the parameter of the side-lobe attenuation that is inversely proportional to the filter length [30].

III. THE OWC SIMULATION PLATFORM WITH THE OPTICAL SINGLE-BEAM UFMC SIGNAL TRANSMISSION

The OWC simulation platform (Fig. 3) is realized in the Matlab R2021A Simulink software program and is based on the FSO environment model presented in [9]. For analyzing and evaluating, we realized the functional optical single-beam UFMC model that was subsequently incorporated into the OWC simulation platform:

For comparison of optical UFMC and FBMC models, the same FSO channel is used for outdoor conditions without turbulences, outdoor conditions with turbulences, and indoor conditions. The simulation parameters - the path length, the visibility and the wavelength - were identical. Moreover, following FBMC parameters are used - 1024 IFFT points, 4 overlapping symbols, 212 guard bands, a selection of internal multi-state QAM determines bits per subcarrier.

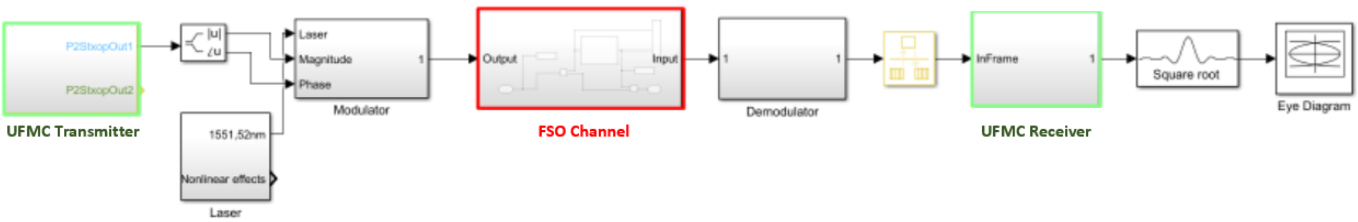

Fig. 3. The OWC simulation platform with the single-beam optical UFMC model

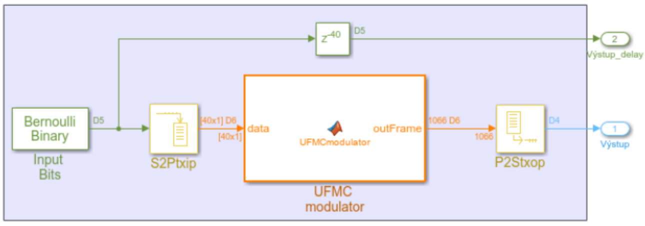

Fig. 4. The UFMC Transmitter in the Matlab interconnections

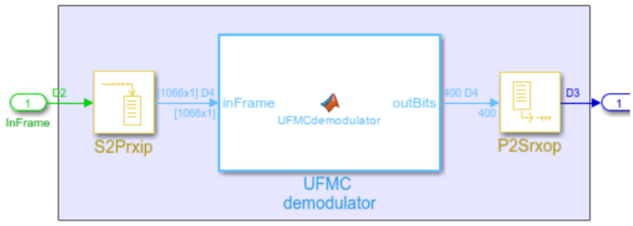

Fig. 5. The UFMC Receiver in the Matlab interconnections

The FSO Channel block is involving the outdoor environmental negative effects related to atmospheric attenuation, turbulences, and geometrical losses [10], [24], [25], [26]. The complete list of parameters used for the real FSO environment simulation is presented in Table I.

In the UFMC Transmitter block (Fig. 4), the input buffer value depends on a number of bits in the QAM modulation (*bitspersubcarrier*) and its multiple (*subbandSize*). In this block, the maximum field size txSig that is filled in zeros is calculated based on input parameters - several points (*numIFFT*) and the filter length (*filterLen*). The txSig field size enters the buffer and the FSO channel. A number of subcarrier groups (*numsubbands*) and a band size (*subbandsize*) is selected according focus and need, their multiplication can't overcome the values of determined points (*numIFFT*). Important is to set equalizing on the band center in the variable (*subbandOffset*). Also, values of the filter length (*filterLen*) can be changed. In our analysis, we use the same values for each filtered subcarrier.

In the UFMC Receiver block (Fig. 5), the correct value of the buffer delay must be set. This value corresponds to the transmitted txSig field size. Also, other parameters must be adjusted to the parameters of the UFMC Transmitter. Because filtering of partial band prolongs the time window at receiving, the Fourier transform must be double realized coming out of the inFrame input parameter. The receiver must apply two points to realize a fast Fourier transform on the data from the channel when zero padding is used between consecutive IFFT symbols as a guard interval [11]. For this parameter, data values are taken off for each particular subcarrier and the frequency symbol pre-equalization /equalization (*EqualizedRxSymbols*) is executed for these values. Symbol values influenced by the FSO environment factors are coming to the output and the result signal is graphically displayed in the Eye Diagram block. From this eye diagram, the Q factor is determined and the BER value is calculated.

TABLE I
FREE SPACE OPTIC ENVIRONMENT IN SIMULATION PARAMETERS

Path length L [km]	1 and 10 / 2.5
Visibility V [km]	0.5 and 50
Wavelength λ [nm]	1551
Transmitter diameter d_T [m]	0.08
Receiver diameter d_R [m]	0.10
Beam divergence θ [mrad]	2.5

IV. EVALUATIONS OF THE OPTICAL UFMC AND FBMC MODULATION TECHNIQUES

The evaluation of considered modulation techniques is realized based on published numerical simulations with pre-determined parameters [9]. For both modulations, the time value for the Q factor reading is fixed to $T = 3.10^{-12}$ [s], where a transmitted signal appears to be stable and the Q factor value is unchanging. Thus, the BER values areare also steady running.

A. The coherent detection in the outdoor environment without turbulences

Simulations for various outdoor environments without turbulences were realized for distances ($L = 1/10$ [km]) and visibility parameters ($V = 0.5/50$ [km]). In Fig. 6, an evaluation of optical UFMC and FBMC modulations with the internal 4-QAM technique is displayed. It can be confirmed that the UFMC format has better BER values than the FBMC one for the low-state (4-QAM) internal modulation. For given conditions and input parameters of the UFMC modulator, higher-state internal modulations are inadaptable.

B. The coherent detection in the outdoor environment with turbulences

Simulations for various turbulence intensities ($C_n^2 = 10^{-16}/10^{-15}/10^{-14}$ [m$^{-2/3}$]) [10] were realized for distances ($L = 1/10$ [km]) and visibility parameters ($V = 0.5/50$ [km]). For some combinations due to increased turbulence intensities and their strong impact on the maximum possible transmission, transmitted optical signals can't be evaluated. In Fig. 7, an evaluation of optical UFMC and FBMC modulations with the internal 4-QAM technique is displayed for the shortened 2,5 km path length. For given conditions and input parameters, only the FBMC modulator can successfully adapt higher-state internal modulations.

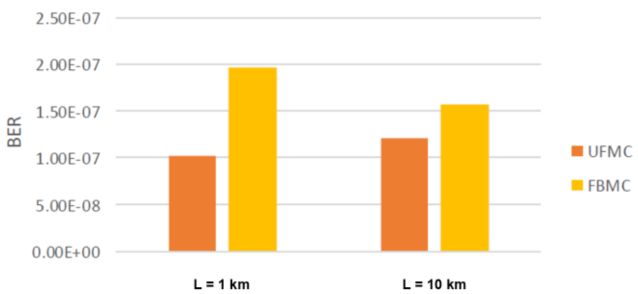

Fig. 6. The UFMC and FBMC modulation evaluation with the 4-QAM; $L = 1/10$ km; $V = 50$ km in the outdoor environment without turbulences.

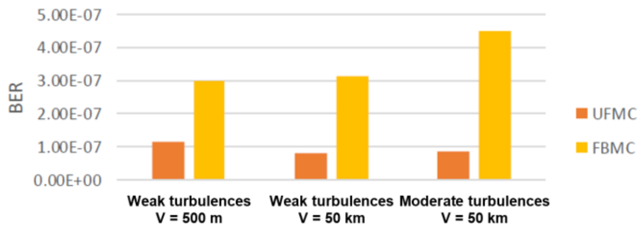

Fig. 7. The UFMC and FBMC modulation evaluation with the 4-QAM; $L = 2.5$ km; $V = 500$ m/50 km in the outdoor environment with various turbulence intensities.

C. *The signal transmission in the indoor environment*

In the indoor environment that is reserved for visible light communications, no computing of turbulences, Kim model and geometrical losses is necessary, only the room size and the device distribution are considered. The working wavelength in this environment is changed to 880 nm because of labor safety and eye protection. The apartment size is 4 m x 4 m, the hall size is 20 m x 20 m. There are three positions of the transmitter: in the room center, between the room center and the wall, and in the close near the wall. For this environment, the time value for Q factor reading is fixed to $T = 4.10^{-12}$ [s]. In Fig. 8, an evaluation of optical UFMC and FBMC modulations with the internal the 4-QAM modulation technique is displayed for various rooms and positions of the transmitter. For given conditions and input parameters, BER values of the UFMC signal are changing only slightly.

For presented comparison of optical modulation techniques, the UFMC modulator is not able to adapt to higher-state internal modulations. The reason is that parameters of the transmitted signals are optimized for the FBMC modulation with 1024 IFFT points. Utilizing the 2N-point FFT transformation, higher-state internal modulations are unavailable for this number of points. So, the number of FFT points must be optimized together with subcarrier bands. Using different FFT-sizes can improve the UFMC performance in parallel processing environments [22].

V. Conclusion

In this contribution, the evaluation of the multi-carrier UFMC modulation candidate for its possible implementation in OWC systems is presented. The actual optical single-beam UFMC model is incorporated into the OWC simulation platform. In the enhanced model, optical multi-beam radiation can be successfully realized by means of multichannel modeling including on different wavelength channels.

Results of our evaluations confirm premise that the single-beam optical UFMC signal transmission with the 4-QAM internal modulation is more reliable than the appropriate FBMC modulation. For higher-state internal modulations when bits per subcarrier are greater than 6, the UFMC modulator doesn't outperform the FBMC under given conditions optimized for the FBMC waveform. So, appropriate input parameters must be optimized before the UFMC testing and examination [12], [15].

Ultimately, the OWC simulation platform can be used for different multi-carrier modulation candidates with specific parameters. After this manner, the fast and inexpensive analysis of multiple candidate waveforms can be executed and effective optical wireless communications can be achieved.

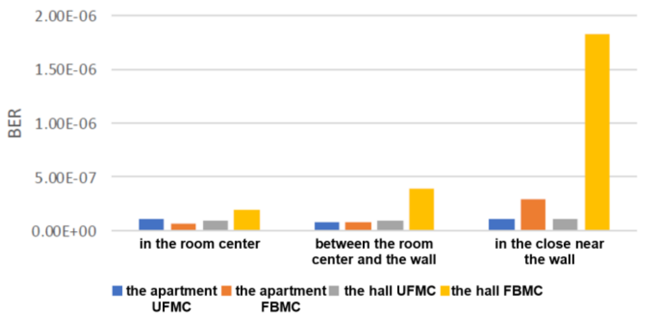

Fig. 8. The UFMC and FBMC modulation evaluation in the indoor environment.

Because the UFMC is reaching a lower peak-to-average power ratio compared to another multi-carrier formats [16], various research directions can be tried to improve the UFMC system performance and eliminate the spectral inefficiency of the UFMC waveform [21]. For high-level internal QAM modulation in UFMC systems, different windowing techniques can be used for out-of-band emission reduction [11]. To better overall UFMC performance, large FFT and M-QAM values in parallel processing environments can be considered where added computational complexity is suppressed from multiprocessing techniques [22]. Moreover, effective and efficient channel estimation techniques can be analyzed for ensuring quality signal reception and to improve the system throughput [31].

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Rastislav Róka has implemented the conceptualization, the methodology, the resources, the writing – original draft preparation, the visualization, the supervision, the project administration and the funding acquisition.

Nikolas Merva carried out the software, the validation, the formal analysis, the investigation and the data curation.

Lucia Hudcová has implemented the resources, the writing – review and editing and the project administration.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.