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Performance Analysis of the FBMC Modulation Format in Optical Fiber and Wireless Communications

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Abstract— **The FBMC is among the currently most researched techniques for signal processing and is explored here for passive optical access networks. This paper presents a performance analysis of the FBMC modulation format for applying in optical fiber and wireless communications. For analyzing, we realized simulation models that are based on well-known characteristics of the optical transmission medium and the free space environment that can describe mutual relations between optical signals and environmental influences. The FBMC model can be consequently applied for a purpose of advanced simulations performed in the complete optical transmission path. The results suggest that the FBMC format can be utilized for reliable optical fiber and wireless communication systems.**

Keywords— FBMC modulation format, FSO environment, optical fiber and wireless transmission path, numerical simulations

I. Introduction

Ever-increasing end-user requirements for higher capacity, lower cost and lower energy consumption lead to increased demands for the data transmission speed and thus to the need to develop novel approaches and technologies used in optical communication networks. Another of the key requirements for the next generation communication system is an effective integration with new generation optical, wireless and optical wireless networks. With the fiber reaching user premises, telecom operators require an unconstrained upgrade path and set the next generation passive optical networks (NG-PON) supporting optical 5G mobile fronthaul [1]. Moreover, a support of extremely high data rates per user requires completely new approaches for design of modulation formats with simple generation and detection as well as excellent spectral efficiency, sensitivity and chromatic dispersion tolerance.

The filter bank multicarrier (FBMC) technology, originally proposed in [2], has been recently subject to intensive research interest in the optical wireless communication (OWC) area. After being applied in 5G networks, it has been recently applied or proposed to optical mobile communication [3] and visible light communication [4]. The FBMC technology can solve problems due to overlap between subcarriers restricted to the adjacent channels. In comparison, there is a significant overlap among many subcarriers in the orthogonal frequency division multiplexing (OFDM) technology [5]-[7]. Utilization of the FBMC technology is being explored in a wide spectrum of possibilities for reaching even higher spectral efficiency. The FBMC technology seems to be suitable for NG-PON networks. In a developing process, it is very important to avoid expensive practical testing and demonstrations. Therefore, it is necessary to perform experimental efforts in an appropriate simulation platform for both optical transmission systems - the optical fiber and wireless communication - that can accurately describe a behavior of optical components at the signal transmission under varying working conditions. The FBMC modulation has been well studied for classical radiofrequency-based wireless communications as a potential substitute of the OFDM modulation for the 5G new radio. Ways to estimate the channel response and adapt the modulation to its variations are presented in [8], [9].

For the optical fiber communication channel, we created complex enhanced simulation tools for analyzing advanced signal processing techniques in the optical transmission path [10]-[12]. For optical wireless communication channels, there exist many network topologies that can be utilized in the outdoor environment. Configurations of equipment can be classified according to the directionality level of transmitters and receivers and according to the existence of a direct visibility between transmitters and receivers. An intensity modulation combined with direct detection is a primary method for implementation in optical wireless systems due to reduced costs and complexity. In the free space optical (FSO) environment, the atmospheric channel is very complex and dynamic environment influencing features of propagating optical beams that leads to optical losses, decreasing power level and fluctuating phase due to turbulences [13]. In principle, characteristics of the atmospheric channel are stochastic, therefore their influence can be characterized by statistical means - meteorological parameters, visibility, atmospheric attenuation, diffusion.

In this contribution, we focus on the FBMC modulation format promising some advantages - using the OQAM modulation, utilizing of filters for shaping of impulses, a high efficiency of the bandwidth and a suitability for environments with high mobility. As the first step for its practical utilization, we present a performance analysis of the FBMC modulation in optical fiber and wireless communications in the current state. Subsequently, acquired results will be used at development of adequate multicarrier and internal modulation formats and related signal processing techniques for suitable and possible deployment in NG-PON networks.

This contribution is organized as follows. In Section II, a modelling of the FSO environment is shortly described. In Section III, basic principles for the FBMC modulation format are characterized. In Section IV, the FBMC model incorporated into the optical fiber and wireless transmission path is described in detail. In Section V, results and evaluation of numerical simulations are presented and a performance of signal transmissions utilizing the FBMC modulation format in optical fiber and wireless communications is analyzed. Finally, a conclusion of our work is included.

II. Modelling of the FSO environment

For the optical wireless transmission, meteorological conditions have a marked influence. For adjustment of the FSO channel, various statistical meteorological models can be applicable. A main parameter - the visibility V - is utilizable for forecast of atmospheric fluctuations caused by meteorological phenomenon, presents a maximum distance where it is possible to clearly see and is affected by three factors - a level of the source coherence, a distance of connection and a detector localization. Depending on the visibility, an effectiveness of the FSO system is determined [14], [15]. Thanks to the visibility, we can differ meteorological conditions presented in [13], [16]-[18].

The atmospheric attenuation coefficient α_{atm} is given according to the Kruse model by the equation:

$$\alpha_{atm} = \frac{13}{V} \cdot (\frac{\lambda}{550})^{-q} \quad [dB/km] \tag{1}$$

where V is the visibility [km] and λ is the wavelength [nm]. The q coefficient is depending on the size distribution of scattering particles and it is determined from experimental measurements [16]. Based on empirical evidence, Kim [17] amended the Kruse model for lower visibilities, proposing the following values for the q coefficient:

$$q = \begin{cases} 1{,}6 & V < 50\ km \\ 1{,}3 & 6\ km < V < 50\ km \\ 0{,}16. V + 0{,}34 & 1\ km < V < 6\ km \\ V - 0{,}5 & 0{,}5\ km < V < 1\ km \\ 0 & V < 0{,}5\ km \end{cases} \tag{2}$$

The total scattering (specific atmospheric attenuation) coefficient α_{scat} is given by the equation:

$$\alpha_{scat} = \left(\frac{3{,}91}{V}\right) . \left(\frac{550\ nm}{\lambda}\right)^{q} \quad [dB/km] \tag{3}$$

Ijaz [18] presented indoor-outdoor atmospheric models with controlled chambers and measurements.

At a practical position of FSO transceivers with the beam divergence θ angle in the L distance, geometrical losses can be mathematically expressed using:

$$P_R = P_T \cdot \frac{d_R^2}{(d_T + \theta . L)^2} \tag{4}$$

where P_R is the received signal power [mW], P_T is the transmitted signal power [mW], d_T is the transmitter diameter and d_R is the receiver diameter [13].

III. Principles for the FBMC modulation format

The FBMC transmitter converts a binary data stream into symbols using the OQAM (Offset Quadrature Amplitude Modulation) modulation, therefore complex symbols come through the OQAM block. The FBMC end-to-end modulation process has four phases [6], [7]:

- Pre-processing OQAM - it has two parts. The first one is a complex-to-real conversion where real and imaginary parts of complex symbols are separated and two new symbols are formed. The second one is the multiplication by sequence. Input signals entering to the IFFT block are purely real or imaginary.
- Synthesis Filter Bank - it consists of M up samplers and M synthesis filters. Input signals are first up sampled by a factor of M/2 and then filtered with synthesis filters.
- Analysis Filter Bank - it is constructed by M analysis filters and M down samplers. Input signals are first filtered with analysis filters and then down sampled by a factor of M/2.
- Post-processing OQAM - it has two parts. The first one is the multiplication by sequence. The second one is a real-to-complex conversion where two real-valued symbols form one complex symbol.

On the transmitter side, a binary data stream for each subcarrier is demultiplexed into multiple tributaries. Based on these individual branches, IQ stream generators create multilevel I and Q data points that subsequently enter pulse shaping filters with the g(t) impulse response. The continuous-time SMT (Staggered Multi Tone) signal generated at the output of the transmitter signal can be expressed using the equation

$$s(t) = \sum_{n=1}^{Ns} \sum_{m=0}^{N-1} a_{m,n} . g(t - n\tau_0) . e^{j2\pi m v_0 t} . e^{j\frac{\pi}{2}(m+n)} \tag{5}$$

where *Ns* presents the number of transmitted SMT blocks, *N* presents the total number of active subcarriers in the system and $a_{m,n}$ denotes the real-valued transmitted symbol of the subcarrier *m* at time index *n*. Due to the OQAM property here, two consecutive elements of $a_{m,n}$ at subcarrier *m* represent a QAM symbol, and the values for each of these two entities can be obtained by taking the real or imaginary parts of the complex QAM symbol that is required for transmission within one SMT symbol. The symbols for $a_{m,n}$ are generated by the output of the IQ stream generator. τ_0 and ν_0 represent the SMT block duration and the subcarrier frequency spacing respectively [5].

IV. THE FBMC MODEL IN THE OPTICAL FIBER AND WIRELESS TRANSMISSION PATH

The presented FBMC model is implemented in the Matlab Simulink program environment because of its simplicity and functionalities. The FBMC model implements the FBMC modulation format as described in Section III. This FBMC model can be incorporated into a simulation platform for the optical fiber communication (OFC) created in the Matlab Simulink. The OFC simulation platform consists of the following functional blocks representing distinguished optical components:

- FBMC Transmitter (green)
- DFB Laser (turquoise)
- Internal Modulator and Demodulator (orange)
- Single mode optical fiber (red)
- FBMC Receiver (dark blue)
- Measurement units - constellation and eye diagrams (white)

The simulation platform is performed in the Matlab R2021A Simulink software based on previous works [19]-[21]. In Fig. 1, it is presented a complete block scheme for the optical fiber transmission path including main optical components. The FBMC Transmitter block presents initial two phases of the FBMC modulation process. The DFB Laser block represents the continuous-wave light stream produced by a distributed feedback laser on that is modulated information data stream using the Internal Modulator block. The FBMC is a multicarrier technique which data symbols can be transmitted simultaneously over multiple frequency subcarriers. It means that original data streams at lower data rates can be modulated separately in this system. By default, the OQAM modulation is used. The SMF block represents the transmission medium of the single-mode optical fiber including relevant environmental negative effects [22], [23]. Simulation parameters (according to the ITU-T G.652.D) for the single-mode fiber transmission channel are presented in Table I. Bear in mind that some parameters can vary depending on various wavelengths of optical signals. In the Internal Demodulator block, a demodulation process for a selected internal modulation is utilized. The FBMC Receiver block is executing final two phases of the FBMC modulation process. Measurement units present Constellation Diagram and Eye Diagram blocks used for evaluating transmitted optical signals and for estimating BER values, respectively.

TABLE I
SIMULATION PARAMETERS FOR THE OPTICAL SINGLE-MODE FIBER CHANNEL

Fiber length L [km]	10
Wavelength λ [nm]	1551
Attenuation coefficient α [dB/km]	0,21
CD [ps/km]	10
PMD [ps/(nm.√km)]	10
Brillouin gain g_B [-]	4.10^{-11}
Raman gain g_R [-]	7.10^{-14}
Kerr effect $\gamma.L_{eff}$ [-]	$2,23427.10^{-11}$
Four Wave Mixing [-]	$1,1695.10^{-8}$

The FBMC Transmitter block (Fig. 2) consists of the Bernoulli Generator block that generates bit sequences moving into a buffer and the FBMC Modulator block that executes procedures for pre-processing OQAM and synthesis filter bank presented in Section III. Important parts are Count Up and FrameNo blocks serving for bit encapsulation and frame forming. Buffer parameters used for this FBMC Transmitter block are 4096 rows and 1 column. However, these parameters can differ according to applied FBMC modulation variations, respectively to a number of overlapping symbols.

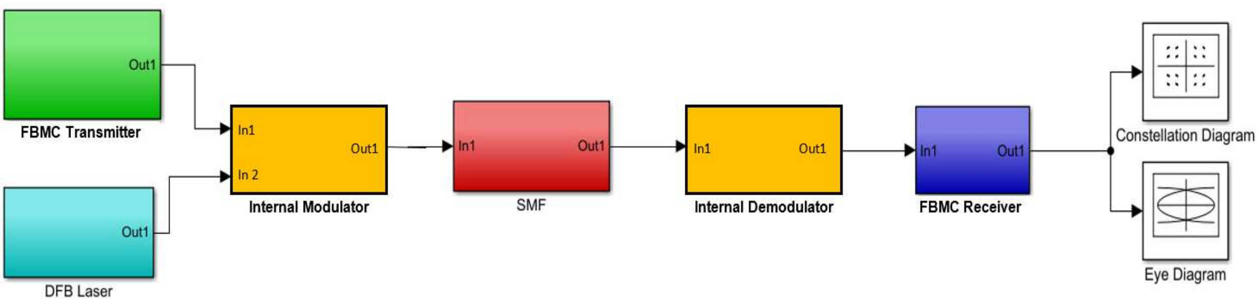


Fig. 1. The FBMC model in the optical fiber transmission path

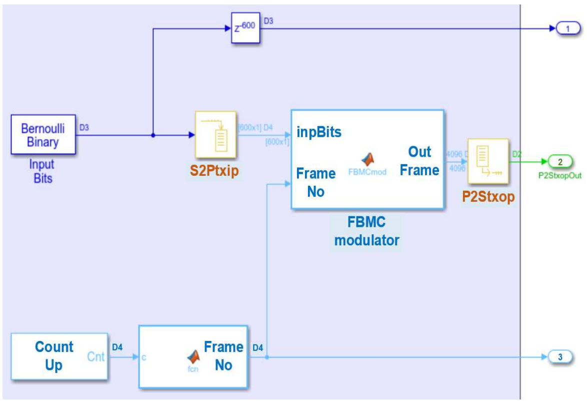


Fig. 2. The detailed scheme with internal connections of the FBMC Transmitter block

After transiting through the Internal Demodulator block, a signal is entering into the FBMC Receiver block (Fig. 3) where data from a buffer are shifted into the FBMC Demodulator block that executes procedures for analysis filter bank and post-processing OQAM presented in Section III. Optical signals outgoing this block are evaluated using the Constellation Diagram block and BER values are estimated using the Eye Diagram block.

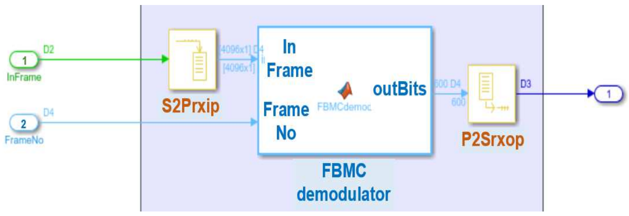


Fig. 3. The detailed scheme with internal connections of the FBMC Receiver block

The presented FBMC model can be also incorporated into a simulation platform for the optical wireless communication (OWC) created in the Matlab Simulink. The OWC simulation platform consists of following functional blocks representing distinguished optical components:

- FBMC Transmitter (green)
- DFB Laser (turquoise)
- Internal Modulator and Demodulator (orange)
- FSO Channel (purple)
- FBMC Receiver (dark blue)
- Measurement units - constellation and eye diagrams (white)

The simulation platform is performed in the Matlab R2021A Simulink software based on equations presented in Section II. In Fig. 4, it is presented a complete block scheme for the optical wireless transmission path including main optical components.

The FSO Channel block represents the outdoor wireless transmission environment including relevant environmental negative effects [13] and is consisting of three computational parts:

- First, the atmospheric attenuation is calculated based on the equation (1), when a condition according to the equation (2) corresponding to the Kim model must be satisfied. The V parameter value representing the visibility must be inserted and subsequently the q parameter is determined for the atmospheric attenuation's computation.
- Second, geometric losses can be calculated based on the equation (4), where transmitter and receiver parameters from real FSO system are necessary. Our FSO system is represented by SONAbeam® 10G-E+ equipment [24]. Requested parameters are the transmitter diameter d_T, the receiver diameter d_R and the beam divergence θ. Simulation parameters of the real FSO system are presented in Table II.
- Finally, the total attenuation of the FSO system is calculated using previous computations based on the following equation

$$P_R = P_T.\frac{d_R^2}{(d_T+\theta.L)^2}.e^{-(\alpha_{scat}.L)} \quad (6)$$

where P_R is the received signal power, P_T is the transmitted signal power, L is the path length and α_{scat} is the scattering coefficient.

TABLE II
SIMULATION PARAMETERS OF THE REAL FSO SYSTEM

Path length L [km]	10
Wavelength λ [nm]	1551
Transmitter diameter d_T [m]	0,08
Receiver diameter d_R [m]	0,10
Beam divergence θ [mrad]	2,5

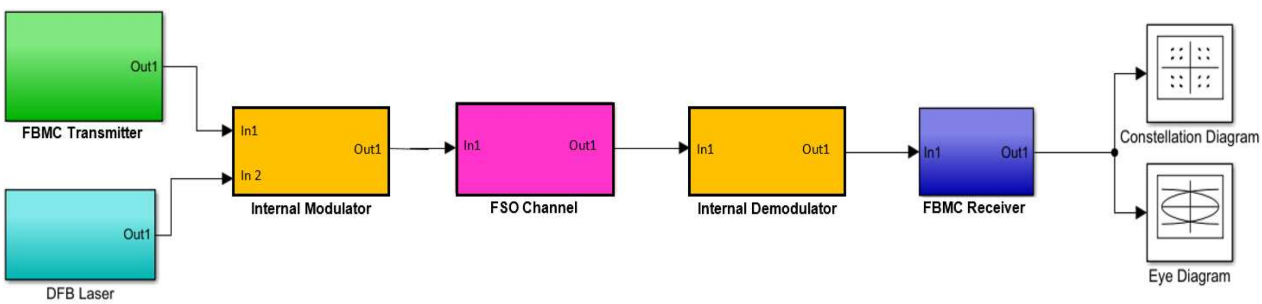
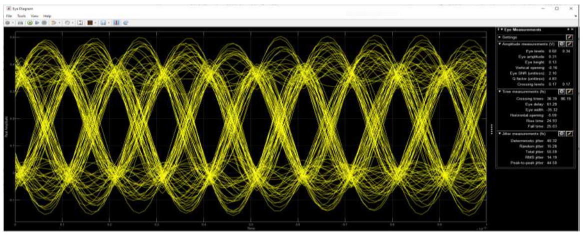


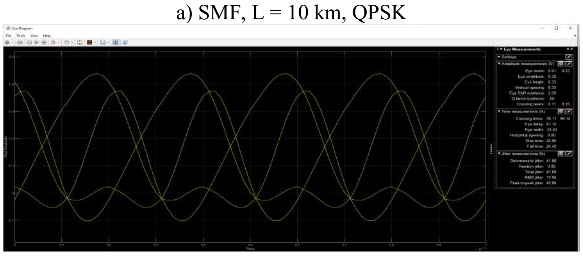
Fig. 4. The FBMC model in the optical wireless transmission path

V. RESULTS AND EVALUATION OF THE FBMC NUMERICAL SIMULATIONS

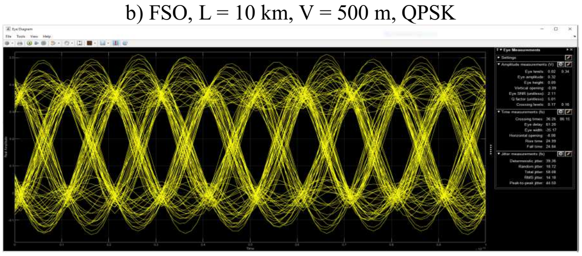
For better presenting simulation results, we introduce some concrete examples of eye diagrams related to transmitted QPSK optical signals using optical fiber and wireless transmission paths (Fig. 5). Requested BER values are calculated based on the *Q* factor with values estimated from these eye diagrams. Results acquired from realized numerical simulations of different internal modulations utilized in the FMBC model in optical fiber and wireless transmission paths are presented in Table III. For the FBMC modulation format, following parameters are used: a number of FFT points is 1024, a number of overlapping symbols is 4, a number of guard band on both sided is 212, a number of bits per subcarrier is dependent on selected internal modulations - QPSK, multi-level QAM.



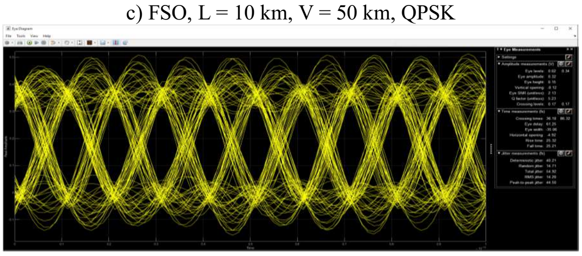
a) SMF, L = 10 km, QPSK



b) FSO, L = 10 km, V = 500 m, QPSK



c) FSO, L = 10 km, V = 50 km, QPSK



d) FSO, L = 1 km, V = 500 m, QPSK

Fig. 5. Examples of eye diagrams for transmitted QPSK optical signals using the FBMC model

For the optical fiber communication, a transmission distance can be expressively larger than in presented simulations. The fiber length is set to 10 km by reason of possible comparison with optical wireless communications. Acquired simulation results attest that a single-mode fiber (SMF) is the most profitable transmission medium for high-quality optical signals with the BER parameter around 10^{-8}.

TABLE III
BER VALUES OF TRANSMITTED OPTICAL SIGNALS FOR DIFFERENT INTERNAL MODULATIONS IN THE FBMC MODEL

	L = 10 [km]			*L* = 1 [km]
	SMF	FSO (V = 500 m)	FSO (V = 50 km)	FSO (V = 500 m)
QPSK	6,540.10^{-9}	-	2,823.10^{-7}	8,766.10^{-8}
16-QAM	1,850.10^{-8}	-	1,355.10^{-6}	2,10.10^{-6}
64-QAM	9,254.10^{-8}	-	5,41.10^{-6}	4,93.10^{-6}
256-QAM	7,099.10^{-7}	-	4,495.10^{-5}	1,99.10^{-5}

As seen in Table III, the visibility parameter *V* is the utmost importance for the free space optical (FSO) communication. With small visibility (*V* = 500 m), it is impossible to have successful communication for large path lengths with extreme BER values. After changing this parameter representing improvement of meteorological conditions, optical signals can be successfully transmitted with satisfactory bit error rates. In a case of permanently bad meteorological conditions, a transmission distance must be sufficiently shortened again. This means that communication can only happen with acceptable errors either with higher visibility (V = 50 km) or when using lower path lengths (L =1 km), although in each case the error rates using the FSO system are always much larger than those obtained using the SMF system.

When successful communication is achieved, we can change the simulator parameters to analyze effects of internal modulation techniques (see Table III). Based on simulation results, the QPSK modulation achieves the best BER values also in a case of non-coherent optical receiving. More multi-level QAM variants can achieve slightly worse BER values, but still convenient for high bit rate transmissions.

Based on our simulations, we can confirm that a signal transmission at the optical wireless communication is strongly dependent on meteorological conditions. So, a signal transmission using the single-mode optical fiber is more suitable solution for longer distances in NG-PON networks. For shorter distances when a network infrastructure does not allow utilizing optical fibers, a transmission of optical signals in the wireless environment can be a practical alternative. However, this environment is very sensitive on meteorological conditions and a short transmission distance can be deficient in many cases also.

For reliable and consistent optical fiber and wireless communication, the FBMC modulation format utilizing internal multi-level and multi-state modulations can be effectively incorporated into the optical transmission path with both transmission media. By this way, more effective utilization of the bandwidth can be achieved, resulting in higher transmission rates of optical signals comparing to the common on-off keying (OOK).

VI. CONCLUSION

In this contribution, the current state of the performance analysis of the FBMC modulation format for its possible utilization in optical fiber and wireless communications is presented. The FBMC model is expandable by a simple configuration of functions in the Matlab Simulink program environment. For providing more precise simulations and BER estimations, it is possible to upgrade the presented FBMC model for dynamic and multichannel modelling. The dynamic FBMC model is depending on a time and on a signal propagation through the selected transmission environment and allows utilizing various input transmission channels, respectively signals working on different wavelengths. The FBMC model can be extended for novel and advanced optical and/or electrical signal processing techniques by adding appropriate blocks in the simulation environment.

Ultimately, a program dedicated to the FBMC modulation format can be adapted also for another types of multicarrier modulations using corresponding parameters. Also, other novel and advanced signal processing techniques can be included into the FBMC model.

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