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COMPARATIVE COMPUTER-AIDED DESIGN OF MILLIMETER-WAVE-TO-OPTICAL CONVERTERS FOR FIFTH-GENERATION COMMUNICATION NETWORK

M. E. Belkin[a], T. Bakhvalova[a], and A.S. Sigov[a]

[a]Scientific and Technological Center "Integrated Microwave Photonics" MIREA - Russian Technological University Moscow, Russian Federation

[a]belkin@mirea.ru

ABSTRACT
Using well-known off-the-shelf optoelectronic software, we compare in detail three most prospective types of external optical modulators as millimeter-wave-to-optical converters in fiber-optics link of fiber-wireless fronthaul network for fifth-generation communication network based on Radio-over-Fiber technology. In all cases, the same 1.25 Gbit/s 16-position quadrature amplitude modulated signal at the radio-frequency carrier in intermediate-band (15 GHz) or millimeter-wave band (40 GHz) propagates over fiber-optics link under study. In the result, it is shown that the use of a signal transmission scheme at the radio frequency of intermediate band (between "Low Range" and "High Range" of 5G network) allows a significant increase in the length for the fiber-optics section of a fiber-wireless fronthaul network. However, this leads to a complication of the base station scheme, since additional up/down-conversion of the radio-frequency carrier is required.

Keywords: 5G communication network, quadrature-amplitude-modulation signal transmission, electro-optical modulator

1. INTRODUCTION

In the last decade, the global telecommunications industry is experiencing a stage of violent development associated with the becoming of fifth-generation mobile telecommunications networks (5G NR) (Andrews, Buzzi, Choi, Hanly, Lozano, Soong and Zhang 2014; Browne 2018; Chen and Zhao 2014; Munn 2016; Waterhouse and Novak 2015). The serious activity of the world telecommunication community in this direction began in the first half of the current decade. This statement is easily confirmed by the world's largest scientific database IEEE Xplore. In particular, when typing the keywords "5G" and "communication" in the search box, the number of publications increased 210 times from 2010 to 2018. Table 1 lists the search results in more detail.

One of the key distinctive feature of 5G NR in comparison with the previous generations is to overcome the 5 GHz ceiling in a mobile network (5G Americas 2017). Following this tendency, which is reflected in a vast number of publications, currently, the local telecommunications commissions of various countries are proposing and harmonizing the plans for mobile communication in millimeter-wave (MMW) band (24.5-86 GHz), which will be reviewed this year at the World Radio Conference (WRC-2019) (Resolution 238 2017).

Table 1: Publications Referred to 5G Communication

Year	Number of publications
2010	23
2011	30
2013	680
2015	1332
2018	4831 including 3321 in conference proceedings, 1409 in journals and magazines, and 58 in monographs

Another milestone of great importance is the development of access network. In this direction, well-known Radio-over-Fiber (RoF) technology (Al-Raweshidy and Komaki 2002; Novak, Waterhouse, Nirmalathas, Lim, Gamage, Clark, Dennis and Nanzer 2016; Sauer, Kobyakov and George 2007) is considered as the most promising approach, which is implemented based on fiber-wireless architecture. A typical configuration of a RoF-based communication network includes central office (CO), set of base stations (BS), which are a key element of a RoF-based fiber-wireless fronthaul network (FWFN) that interactively (using downlink and uplink) connects the CO and each BS using fiber-optic links (FOL), and microwave or millimeter-wave band user radio terminals. As is known, for the transmission of signals through a FOL, direct and inverse electro-optical conversions are required. The first one in the RoF-based communication system is usually performed with the help of an external electro-optical modulator (EOM), and the second with a photodetector.

Taking part in the studies recently we have proposed and previously investigated photonics-based beamforming networks for ultra-wide MMW-band antenna arrays (Belkin, Fofanov, Golovin, Tyschuk and Sigov 2018), optimal approaches to design next-generation combined fiber-wireless telecom systems (Belkin, Golovin, Tyschuk and Sigov 2018; Bakhvalova, Belkin, Fofanov 2018), and to distribute signals through FWFN (Belkin, Bakhvalova, Sigov 2019), as well as have studied fiber distribution networks with direct and external modulation in the “Low Range” of 5G NR system (Bakhvalova, Fofanov, Alyoshin and Belkin 2019). Nevertheless, in the cited, as well as in the works of other authors referred to this direction, there is no specific consideration related to the choice of the optimal frequency range for signal transmission over the FOL included in the FWFN. This choice, in principle can be made on the basis of one of three transmission options (Belkin, Bakhvalova, Sigov 2019): in the baseband, in the intermediate frequency (IF) band, and in the millimeter-wave radio frequency (RF) band. Meeting this shortcoming, the remainder of the paper is organized as follows. Section 2 presents the reference data for the further simulation. Section 3 demonstrates the models and setups for simulation of a FOL with three types of EOM using well-known software tool VPIphotonics Design Suit™. Leveraging the application of these EOMs for a realistic case in Section 4 the results of the simulation experiment by the same computer tool imitating transmission of quadrature amplitude modulated RF signals of 40 GHz (“High Range” of a wireless cell) or 15 GHz (IF-band) through a FOL connected CO and BS, are discussed. Section 5 concludes the paper.

2. REFERENCE DATA FOR THE SIMULATION

In this work, the subject of the study is the FOL of FWFN; the devices of test are three widespread types of electro-optic modulators for an external modulation of optical carrier including double-sideband Mach-Zehnder modulator (DSB MZM), carrier suppressed single-sideband Mach-Zehnder modulator (CS-SSB MZM), and electro-absorption modulator (EAM), and standard single-mode fiber (SMF). A tool for the computer simulation is well-known commercial software VPIphotonics Design Suit™. The study took into account two key distortion sources of the transmitted signal: a chirp of modulators and chromatic dispersion of the fiber. To eliminate the influence of nonlinear effects during modulation and signal transmission through the fiber, RF and optical signal levels were selected so that the modulation index did not exceed 40%, and the optical power in the fiber was not more than 5 mW. Table 2 lists the common reference data for the FOL under study. In addition, Table 3 lists the reference data for the modulators under test.

Table 2: Common Reference Data for the FOL under Study

Parameter		Value
Length of pseudo-random bit sequence		2^{15}-1
Bitrate		1.25 Gbit/s
RF Carrier Frequency		15 or 40 GHz
Input RF Power		-10…0 dBm
Type of RF modulation		16-QAM
Optical Carrier		C-band (1552.52 nm)
Type of optical modulation		Intensity
PIN-Photodiode	Responsivity	0.7 A/W
	Dark current	100 nA
	3dB Bandwidth	50 GHz
	Optical Input Power	<5 mW
Post-amplifier	Gain	30 dB
	Noise Spectral Density	20•10-12 A/Hz1/2
Optical Fiber	Type	SMF-28e+
	Length	up to 70 km
	Attenuation	0.2 dB/km
	Dispersion	$17e^{-6}$ s/m^2
	Dispersion Slope	80 s/m^3

Table 3: Reference Data for the Modulators under Test

Parameter	DSB MZM	CS-SSB MZM	EAM
Optical Insertion Loss	4 dB	6 dB	3 dB
Optical Extinction ratio	20 dB	20 dB	14 dB
Slope efficiency	-	-	0.14 W/V
RF π-Bias Voltage	5.5 V	7.5 V	-
Electro-Optical Bandwidth	40 GHz	40 GHz	40 GHz
Linewidth enhancement factor (α)	0 (X-cut)	0 (X-cut)	1.0

3. CAD MODEL AND SETUP

Figure 1 shows VPIphotonics Design Suite’s externally modulated/direct detection FOL model and setup for the simulation experiments that consist of the library models of unmodulated continuous-wave laser, EOM under test, single-mode optical fiber and photodiode followed by the electrical amplifier model. One can see their relevant parameters in Tables 2 and 3. Besides, there are two instrumental library models in the setup. The first one imitates 1.25 Gbit/s, 16-QAM RF transmitter containing library models of QAM generator, output unit for power control, electrical amplifier, and a device setting the desired signal-to-noise ratio (SNR). This module generates an electrical M-QAM signal up-converted at a given RF carrier frequency. The second one is the

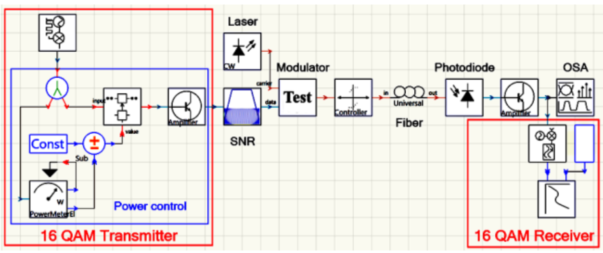

Figure 1. VPIphotonics Design Suite’s Setup for the FOL with External Modulation by QAM-signals

16-QAM RF Receiver. This module detects RF signal, decodes an electrical 16-QAM signal and evaluates the error vector magnitude (EVM) of the QAM signal. The model of Numerical 2D Analyzer is used for two-dimensional graphical representation of the data from the Receiver output.

4. SIMULATION RESULTS

In preparation for the simulation experiments, the intensity-modulation index of each modulator under test was optimized in such a way as to ensure the maximum output RF carrier-to-noise ratio while maintaining the linear-signal mode of the modulators at all modulating frequencies. Figures 2, 3, and 4 depict examples of simulating EVM vs fiber length characteristics for the modulator under test during optical modulation by 1.25 Gbit/s, 16-QAM, 15 GHz (transmission in IF-band) or 40 GHz (transmission in MMW-band) RF signal, correspondingly. For the best vision, there are some insets in the Figures showing constellation diagrams in specific points. In addition, in the Figures, the dotted lines indicate the standard limit of the EVM during transmission of the 16-QAM signal, which is 12.5% (ETSI 2017).

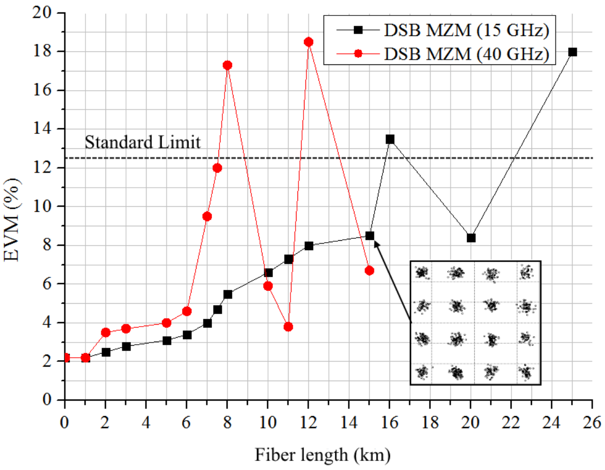

Figure 2. Example of simulating EVM vs fiber length characteristic for a FOL with DSB MZM under test

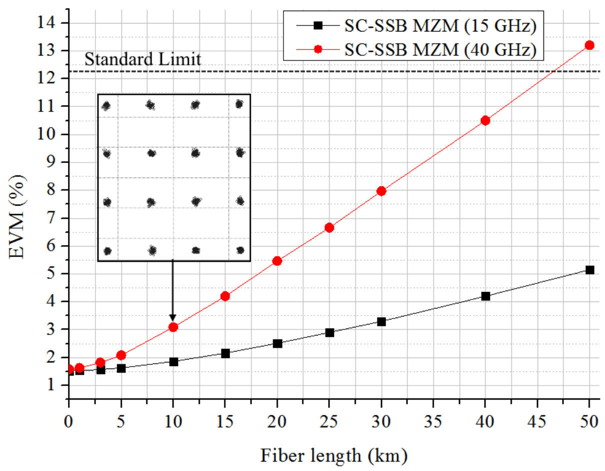

Figure 3. Example of simulating EVM vs fiber length characteristic for a FOL with CS-SSB MZM under test

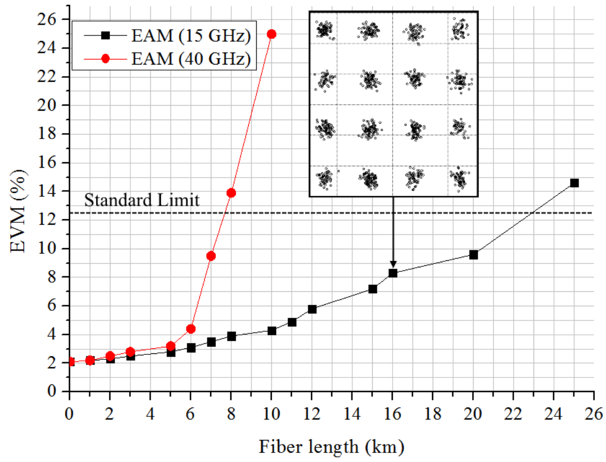

Figure 4. Example of simulating EVM vs fiber length characteristic for a FOL with EAM under test

The results of the simulation for the fiber-optics link under study within fiber-wireless fronthaul network of 5G NR system are summarized in Table 4.

Table 4: The Results of the Simulation

Device under test	RF carrier (GHz)	Allowable Distance of FOL (km)
DSB MZM	15	16
	40	7.3
SC-SSB MZM	15	Much more than 50
	40	47
EAM	15	23
	40	8

The following outputs can be derived from our study:

- the minimum values of EVM were obtained for external modulation using CS-SSB MZM, which, nevertheless, requires the most complex control schematic, accordingly, has the greatest value;
- the slope of the EVM characteristic increases with distance from SC-SSB MZM to DSB MZM through EAM, which corresponds to the known data (Kim, Bae, Kim and Chung 2018; Salvatore, Sahara, Bock and Libenzon 2002);
- the following from Fig. 2 significant fluctuations in the values of the EVM are characterized by the effect of dispersion in an extended optical fiber. To eliminate it in order to increase the length of the FOL, it is required to introduce at its end a dispersion corrector, which is a standard element in fiber-optic communication systems.

CONCLUSION

Using off-the-shelf photonic computer-aided design tool VPIphotonics Design Suite a methodical analysis for the model of fiber-optics link within fiber-wireless fronthaul network with external intensity modulations by 1.25-Gbit/s 16-QAM signal for 5G NR-oriented networks based on analog RoF system, was conducted. For a comprehensive analysis, all prospective electro-optical converting devices including a DSB MZM, SC-SSB MZM, and EAM, were comparatively investigated. The results of simulating the error vector magnitude coincide in trend with the known calculation and experimental data, however, differ quantitatively, which is associated with a large number of device parameters used in the process of transmitting the QAM-modulated radio-frequency signal over the fiber-optic link. The use of a signal transmission scheme at the radio frequency of intermediate band (between "Low Range" and "High Range") allows a significant increase in the length for the fiber-optics section of a fiber-wireless fronthaul network. However, this leads to a complication of the base station scheme, since additional up/down-conversion of the radio-frequency carrier is required. Therefore, to make a final decision, more thorough research in the framework of a specific RoF-based network is needed.

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