Studying Optical Frequency Comb-Based Fiber to Millimeter-Band Wireless Interface

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***Abstract*—Using off-the-shelf photonic computer-aided design tool VPIphotonics Design Suite, a detailed analysis of optical-frequency-comb-based fiber to millimeter-band wireless interface in actual base station for emerging 5G access networks of fiber-wireless architecture was carried out. The simulation experiments to study fiber transmission of 1.25-Gbit/s, 64-QAM signals in the bandwidth 37-43.5 GHz predict that the needed transmission quality is supported at a distance of optical cable between Central Office and Base Station up to 40 km, which is quite acceptable for an access network.**

Keywords-radio-over-fiber; base station; optical frequency comb; recirculating loop; suppressed carrier single sideband modulator.

I. INTRODUCTION

Within the recent decades, an explosion of researches and developments referring to the next-generation communication networks known as 5G New Radio (NR) has been observed [1]-[5]. Based on 4G Long-Term Evolution (LTE) progress [6], 5G NR is in principle a novel stage of unprecedented technological innovation with ubiquitous speed connectivity. As a result, it is expected that 5G NR will radically transform a number of industries and will provide direct, super-speed connections between any users and any sensors and devices.

At the present time, several reviews to analyze significant changes in the 5G NR approaches as compared to the existing 4G LTE networks have been published [7][8] denoting a series of milestones. Developing this topic, Table I summarizes the results of the advanced analysis adding the investigations of the last 5 years.

A review of the current Research and development (R&Ds) in 5G NR area convincingly demonstrates the consistent achievement of the milestones indicated in Table I, which is reflected in a vast number of publications and the emergence of commercial products. Among them, much attention is paid to radically expanding the available spectral bands (see point 1 of the Table I), which is associated with the absorption of the Millimeter Wavelengths (MMW). Following this tendency, currently, the local telecommunications commissions of various countries are proposing and harmonizing the plans of frequency allocation in MMW-band, which will be reviewed this year at the World Radio Conference (WRC-2019) [9]. Another milestone of great importance is the development of access networks (see point 3 of the Table I). In this direction, well-known Radio-over-Fiber (RoF) technology [10]-[12] is considered as the most promising approach, which is implemented based on Fiber-Wireless (FiWi) architecture.

TABLE I. THE MILESTONES IN THE WAY TO TRANSFORM 4G LTE TO 5G

No	Designation	Short Description
1	Radically expanding the available spectral bands	Some super-wide bandwidth cases in 5G access networks will require contiguous carrier bandwidths. To support them, additional carrier frequencies (below 6 GHz), as well as millimeter wave (mmWave) RF carriers will be required.
2	Increasing user densification	The answer is to use small-cell technology (from macro-cells to femto-cells) that enables carriers to provide more users with lower latency, better mobile device battery life, and expanded cellular coverage
3	Establishing optimized access network architecture	Following the milestones of the points 1 and 2, it is necessary to optimize the access network architecture so that at the same time provide high-quality communication with fixed and mobile users and low charges for the building and maintenance of networks. A promising candidate for solving the problem is a fiber-wireless architecture, already tested in 4G LTE systems.
4	Providing More Options with Fixed Wireless Access	Fixed Wireless Access provides users with more alternatives for connecting to the cloud using wireless broadband data communication to connect two or more fixed locations. In particular, the introduction of this type of service will be very feasible for the broad development of telemedicine.
5	Using a Mobile Phone as a Hub	A future people life is able to revolve around a new 5G smartphone. With high-speed mobile broadband access and truly ubiquitous coverage, it will enable devices to communicate directly with each other, without routing the data paths through a network infrastructure.
6	Using active antenna systems in mm-Wave communication	Following the tendencies of expanding the available spectral bands and increasing user densification, mm-Wave 5G wireless network infrastructure can be erected with a lot of small cell sites controlled by the corresponding remote (base) station (RS). In order to avoid inter-interference inside these cells, one of the promising approaches is to equip the RS with beam-steerable phased array antennas using hundreds of antenna elements to form directional beams.
7	Providing low latency	Mission-critical services requiring very high reliability, global coverage, and very low latency, which may be more important than throughput in some applications, will become more native to support 5G infrastructure.

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A typical configuration of an RoF-based communication network including Central Office (CO), set of Base Stations (BS), and microwave or millimeter-wave band user radio terminals, have been discussed in detail in numerous publications (for example, in [10]-[13] and the papers cited there), so it is not considered in this paper. An important element of this network architecture is a base station, through which an interactive fiber-wireless interface is implemented. Taking part recent studies, we have proposed and previously investigated two design concepts of cost- and power-efficient base station for emerging FiWi networks [14][15], in which for a multi-frequency conversion of a Radio-Frequency (RF) carrier, an Optical Frequency Comb Generator (OFCG) based on microwave-photonic technology was used. Namely, it was designed on a long-wavelength Vertical Cavity Surface Emitting Laser (VCSEL) operating in the period doubling state in the first case, and on an Optical Recirculation Loop (ORL) technique using two Suppressed Carrier Single Sideband (SC-SSB) optical modulators in the second one.

Nevertheless, in the cited papers, as well as in the works of other authors referred to this direction, there is no analysis of the efficiency of the OFCG-based actual base station for emerging FiWi networks that supports high-speed multichannel digital RF-signal transmission. Meeting this shortcoming, the remainder of the paper is organized as follows. Section II demonstrates the models and setups for simulation of a recirculation-loop-based OFCG and fiber to MMW-band wireless interface using the well-known software tool VPIPhotonics Design Suit [16]. Leveraging the application of this OFCG for a realistic case, the simulation results by the same computer tool imitating multi-wavelength optical frequency comb generation and transmission of quadrature amplitude modulated RF signals through OFCG-based fiber-wireless interface of a FiWi-architected base station are discussed in Section III. Section IV concludes the paper.

II. Describing the Models and Setups for Simulation

A. Optical Frequency Comb Generator

Generally, the outstanding performance of OFCG has led to a revolution in a lot of radio-engineering fields, from radio-frequency arbitrary waveform generation to coherent optical communications. The key R&D achievements in this direction are summarized in [17]. In the paper, four layouts of OFCG suitable to achieve a comb with a spectrally flat envelope are reviewed consisting of cascaded intensity and phase modulators, dual-drive Mach Zehnder modulator (another name for the SC-SSB modulator), two-cascaded phase modulators with linearly chirped fiber Bragg grating, and three cascaded modulators: two intensity and one phase. As a result, it was concluded that the ideal optical frequency comb must be well conceived to target a particular application. Nevertheless, the above-mentioned paper does not consider the option of OFCG based on an optical recirculation loop, which has been studied for more than 10 years as a good candidate for designing microwave-photonics multichannel oscillators and frequency converters [18][19]. The undoubted advantages of this technique include simplicity of the scheme, stability, robustness, tunability, low RF driving voltage, etc. However, its important disadvantage is the relatively short comb length. For example, as follows from [18], the output comb of the device under study consists of only 5-9 teeth, that is, not enough for a realistic 5G application in MMW-band. The obvious way to create a multichannel fiber-to-wireless interface in such environment is to “compact” the comb by narrowing down the interval between frequency teeth.

Following this concept, Fig. 1 shows the VPI model and setup for simulation of the OFCG scheme under study. There are four units depicted in Fig. 1: the composed model of ORL includes library models of optical X-coupler, SC-SSB modulator, Optical Amplifier (OA), Optical Band-Pass Filter (OBPF), as well as library models of Continuous-Wave Semiconductor Laser (CW-SL) emitting at the frequency ν_0 as an optical source, RF Generator (RFG) as a RF signal source and library instrumental model of Optical Spectrum Analyzer (OSA). In order to close the ORL, output of OBPF through the service unit T and input of SC-SSB are connected to X-coupler's port 'input2' and port 'output2', correspondingly. During the simulation, RFG acts as a source of the reference RF signal (f_{ref}), while using the OSA, the output optical spectrum is recorded.

B. Optical-Frequency-Comb-Based Fiber-to-Wireless Interface

Fig. 2 shows the VPI model and setup for simulation of OFCG-based fiber to MMW band wireless interface while transmission of quadrature amplitude modulated RF signals is supported. The scheme represents the downlink channel of FiWi-architected RoF system and consists of three units imitating the operation of CO, BS, and 2-fiber optical cable between them. The CO includes the same laser model, the radiation of which is divided into two branches using a Y-coupler, library model of SC-SSB modulator with suppressing lower sideband, and library instrumental model of QAM RF Transmitter. The latter contains library models of QAM generator and output unit for power control following by electrical amplifier. This module generates an electrical M-QAM signal up-converted at a given RF carrier frequency. The Optical Cable includes two equivalent library models of single-mode optical fiber. Such a remote optical feed reduces

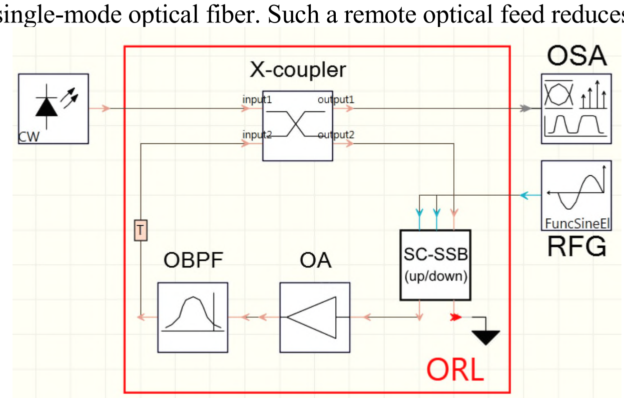

Figure 1. VPI model and setup for simulation of the OFCG.

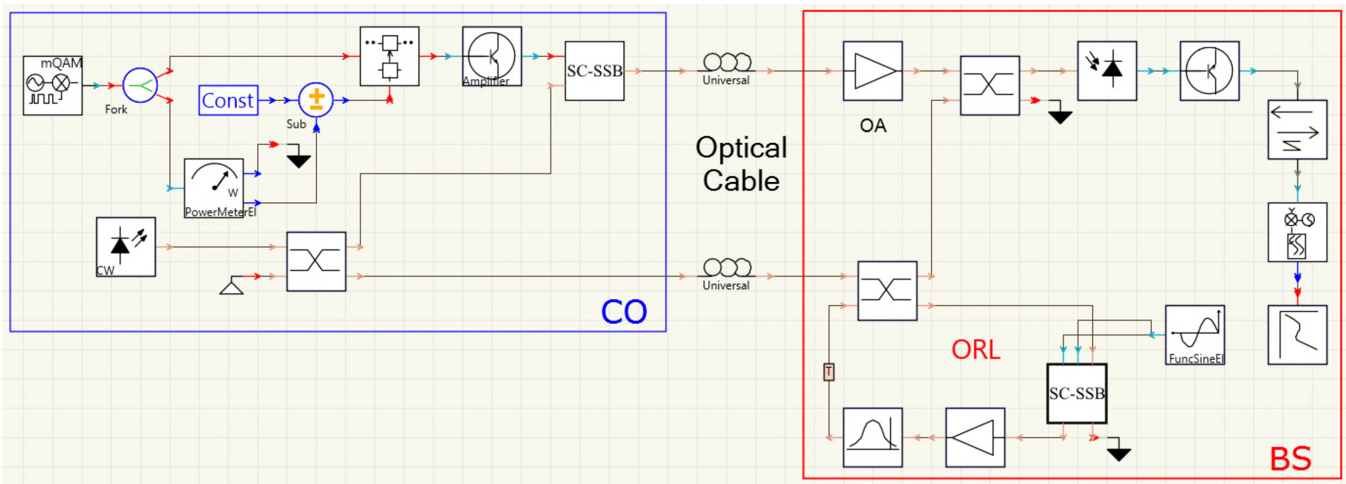

Figure 2. VPI model and setup for simulation of OFCG-based fiber to MMW band wireless interface.

the cost of the BS. Besides the OFCG model (see Fig. 1), the BS includes library models of optical amplifier, X-coupler, photodiode, and electrical post-amplifier outputted to the model of QAM RF Receiver. The latter detects the RF signal, decodes an electrical QAM signal and evaluates quantitatively the Symbol Error Rate (SER) and the Error-Vector Magnitude (EVM) of the output QAM signal. The model of Numerical 2D Analyzer is used for two-dimensional graphical representation of the data from the QAM RF Receiver output.

III. SIMULATION EXPERIMENTS

A. *Reference Data for the Simulation*

In this work, the subject of the study is a fiber to MMW-band wireless interface and the device of the study is an OFCG based on a SC-SSB optical modulator. A tool for the computer simulation is the well-known commercial software VPIPhotonics Design Suit™. In the course of the research, first of all, the possibility of creating a multi-frequency OFCG with the closest arrangement of the teeth is checked. Then, the transmission quality of a digital RF signal with multi-position QAM through the downlink channel of the base station using fiber to MMW-band wireless interface is analyzed. Two limiting factors are taken into account during the simulation procedure: fiber chromatic dispersion and RF channel spacing. Table II lists the common reference data for the OFCG under study. In addition, Table III lists the reference data for the fiber to MMW-band wireless interface under study.

TABLE II. REFERENCE DATA FOR OPTICAL FREQUENCY COMB GENERATOR

Parameter	**Value**
Laser Source Frequency (ν_0)	193.3 THz
Laser Linewidth	10 kHz
Reference RF frequency (f_{ref})	0.3 GHz
Type of modulator inside optical recirculating loop	SC-SSB (up/down)
Gain of Recirculating Loop (g)	0.8<g<1
Number of Up or Down Round Trips	Not less than 10
Level Non-Uniformity of Output Comb Teeth	Not more than 5 dB

TABLE III. REFERENCE DATA FOR THE FIBER TO MMW-BAND WIRELESS INTERFACE UNDER STUDY

Parameter		**Value**
Length of PRBS*		2^{15}-1
Bitrate		1.25 Gbit/s
RF Carrier Frequency		40.2 GHz
Type of RF modulation		64-QAM
Optical Carrier		C-band
RF band		37-43.5 GHz
Type of optical modulation		SC-SSB (up)
PIN-Photodiode	Responsivity	0.92 A/W
	Dark current	100 nA
	3dB Bandwidth	50 GHz
	Optical Input Power	Near 3 mW
Post-amplifier	Gain	30 dB
	Noise Factor	2 dB
Optical Fiber	Type	SMF-28e+
	Length	Up to 50 km
	Attenuation	0.2 dB/km
	Dispersion	$16e^{-6}$ s/m^2
	Dispersion Slope	80 s/m^3

* Pseudo Random Bit Sequence

B. *Optical Frequency Comb Generator*

Fig. 3 demonstrates an OSA's spectrum of multi-wavelength optical frequency comb output following the setup of Fig. 1. As one can see from Fig. 3, the OFCG under study includes 21 optical carriers with the spacing of 0.3 GHz and the level non-uniformity of less than 5 dB.

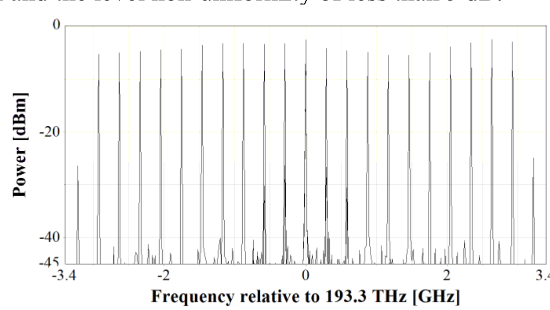

Figure 3. A spectrum of multi-wavelength optical frequency comb output.

C. Optical-Frequency-Comb-Based Fiber-to-Wireless Interface

Our further studies were related to EVM analysis depending on the length of the optical cable and the spacing between the RF channels in the setup of Fig. 2. The results of the simulations are presented in Fig. 4 and Fig. 5, respectively. For a clear view, there are some insets in Fig. 4 showing constellation diagrams in specific points. In particular, as one can see from Fig. 4, due to dispersion in the optical cable, the EVM values increase with a slope of near 0.17 %/km reaching a standard limit for 64-QAM of 8% [20] at the distance of 40 km.

Besides, Fig. 5 demonstrates EVM vs RF channel spacing characteristic at the fiber distance of near 12 km. As a result, as the co-channel spacing shrinks, the EVM remain at about 3% until 240 MHz. With a further reduction in the RF channel spacing, the slope of the EVM curve begins to increase reaching the standard limit at about 215 MHz.

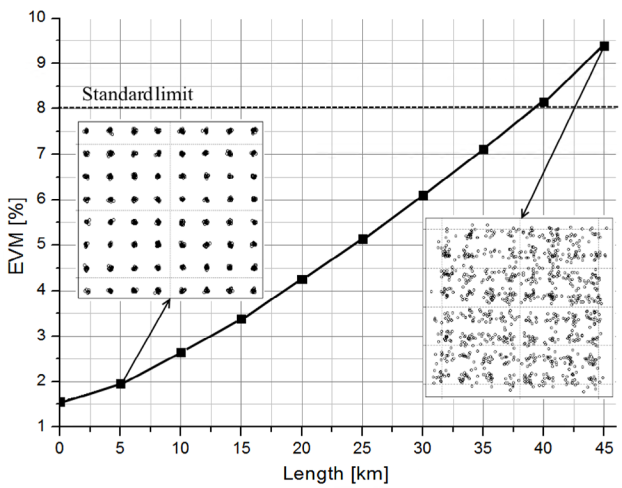

Figure 4. EVM vs Optical Cable Length.

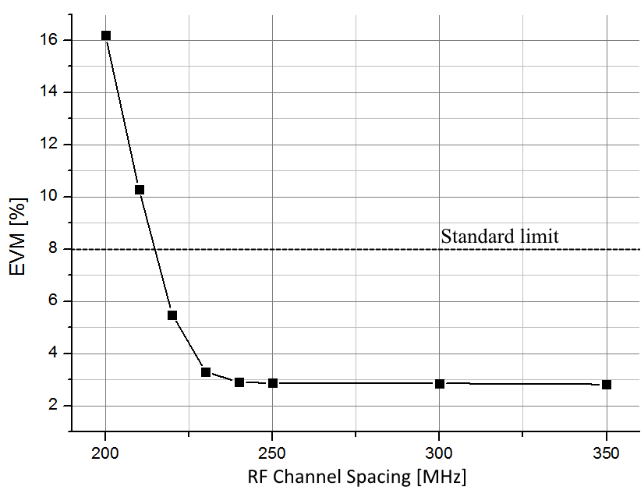

Figure 5. EVM vs RF Channel Spacing.

The following outputs can be derived from our study:

• When transmitting digital radio signals with 64-QAM on millimeter-wave RF carriers (37-43.5 GHz), even when using a single-sideband modulator with a suppressed optical carrier, dispersion in an optical cable has a significant impact on the quality of the received signal. However, the error is within the standard limit up to a distance of 40 km.

• With a fiber-optic link length of up to 12 km, it is acceptable to shrink the interval between RF channels from 300 to 215 MHz.

IV. CONCLUSION

In this paper, a detailed analysis of optical-frequency-comb-based fiber to millimeter-band wireless interface in actual base station for emerging 5G access networks of fiber-wireless architecture was carried out using off-the-shelf computer-aided design tool VPIphotonics Design Suite. The specific goal of the research was to assess the possibility and efficiency of creating a downlink channel of a multi-channel base station using a multi-wavelength optical frequency comb generator with a close arrangement of optical carriers based on a cost- and power-efficient optical recirculation loop including carrier-suppressed single-sideband optical modulator. Following this goal, firstly a computer model and a setup for simulation were proposed and described. Simulation experiment predicts that OFCG including 21 optical carriers with the spacing of 0.3 GHz and the level non-uniformity of less than 5 dB can be realized. Leveraging the application of this OFCG for a realistic case, the model and setup to simulate fiber to millimeter-band RF interface were proposed and described. The simulation experiment predicts that the needed transmission quality is supported at a distance of optical cable between Central Office and Base Station, which is quite acceptable for an access network. In the course of another simulation experiment evaluating the effect of RF co-channel interference, it was shown that the number of RF channels within the same frequency band could be increased 1.4 times.

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