Designing WDM-RoF Concept-Based Full-Duplex MMW Fiber Fronthaul Microcell Network

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Abstract—**In the paper, we propose, highlight, and discuss a new approach to design full-duplex fiber fronthaul microcell network for a next-generation mobile communication system, for example, incoming 5G NR, using wavelength division multiplexed Radio-over-Fiber concept. During the proof-of-concept simulation experiments using well-known computer software VPI Photonics Design Suite, the feasibility and effectiveness of the proposed access network architecture are confirmed, as well as the acceptable limits for high-quality simultaneous transmission of a digital radio-signal package containing a high-speed millimeter-wave information signal with a multi-position QAM and a high-speed centimeter-wave service signal with ASK are quantified.**

I. INTRODUCTION

Today, the global telecommunications industry is experiencing a stage of violent development associated with the becoming of fifth-generation mobile communication networks (5G NR) [1]-[5] and it is planned that the revolutionary milestone for 5G NR in compare to available 4G LTE should be millimeter-wave (MMW) communication with mobile radio terminals in access networks [6], [7]. However, the propagation distance of MMW signals is greatly limited for wireless communication due to high atmospheric attenuation and the poor diffraction [3], [7]. In this direction, well-known Radio-over-Fiber (RoF) approach [8]-[10] combining fiber optics and wireless communication to effectively solve limited coverage of MMW signals, which has the advantages of low loss, wide bandwidth, long-distance transmission, strong anti-interference ability with low cost and easy maintenance, is considered as the most promising concept. In order to further gain the communication capacity and flexibility of a RoF-based mobile communication system and reduce its construction cost, so-called WDM-RoF system was proposed by combining the RoF concept and widespread in fiber optics communication wavelength division multiplexing (WDM) technique [10], [11]. This approach is able to achieve seamless connection between wired and wireless networks and meet the needs of high-speed, large-capacity transmission.

Following the tendency, we have contributed some works referred to computer-aided design of RoF-based access network [12]-[17] using a well-known software tool such as VPI Photonics Design Suite. Elaborating the direction, in this paper we review shortly the distinctive features of small cell scenario of access network and an acceptable for 5G NR MMW-band frequency allocation. After that, we propose, highlight, and validate a new schematic of WDM-RoF-based full-duplex MMW fiber fronthaul microcell network for an access network of 5G mobile communication systems.

II. SMALL CELL SCENARIO OF ACCESS NETWORK

In general, a MMW fiber-wireless fronthaul network (FWFN) of RoF architecture represents the further development of mobile communication networks of the previous generation [2]. The peculiarity of its configuration is in much smaller area of cells down to micro-cells with service area about 500-600 m and pico-cells for mobile user terminals (UT) with service area not more than 200-300 m [3], [17]. Due to the relatively small number of UTs inside a pico-cell, it is critical to reduce cost of its remote base station (RBS), in fact, representing an interactive interface between the optical and RF sections of the transmission system. The most promising solution to this problem is to simplify extremely the layout of a pico-cell RBS (pRBS), which could be done by shifting all the main processing procedures to the higher stage of the access network that is a micro-cell RBS (μRBS). Analyzing the diagram of a MMW FWFN from the functional viewpoint, one can realize that it consists of one μRBS and a set of pRBSs interactively connected with the μRBS by a fiber fronthaul microcell network (FFMN). The above design principle is clearly illustrated in Fig. 1.

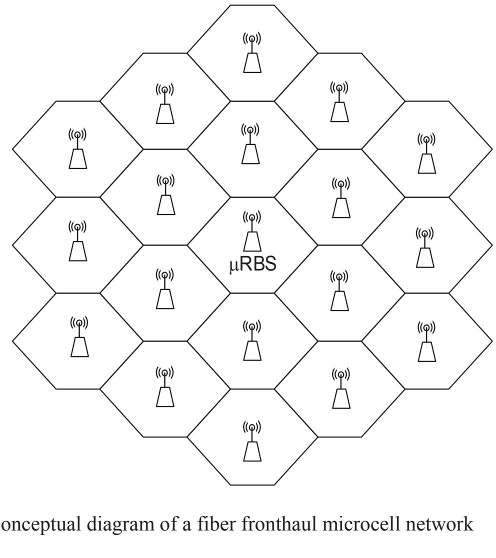
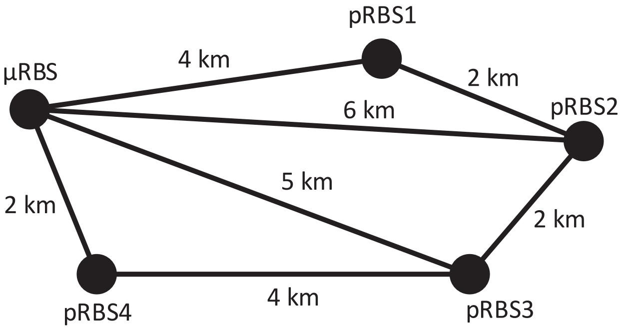


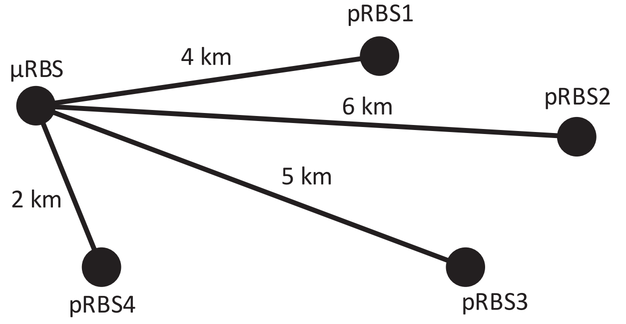
Fig. 1. Conceptual diagram of a fiber fronthaul microcell network

Introducing a smaller partition, Figure 1 shows a probable configuration containing 19 pico-cells inside one micro-cell. Each of peripheral pico-cell is controlled by a corresponding pRBS, which is an interface between fiber and wireless network sections. In the center of FFMN a μRBS is located, which simultaneously operates as a pRBS of the central cell.

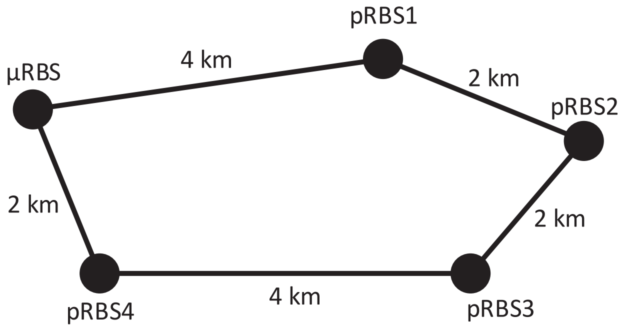
In the framework of RoF concept, all RBSs have to connect through fiber-optics links. This raises the issue of the optimal network topology in terms of the minimum cost of its air or underground installation, which, as known, is the main item of capital expenditure for the construction of a wired communication network. For this purpose, there are various options, and Figure 2 depicts the three most commonly used that are called fully-connected (a), radial (b), and ring (c) topologies. Let's compare these three topologies in the design based on an example of an arbitrary micro-cell. Suppose that it is necessary to interactively distribute the data signals from the μRBS to four pRBSs with their positional relationship shown in Figure 2. As one can see, the topology of variant (a) is the most reliable, since all RBSs are interconnected and there are workarounds in case of failure of any of them. However, it is the least economical, since the maximal length of the optical path is required. The topology of variant (b) is the simplest and the more economical, since the lower length of the optical path is required. Nevertheless, it is not reliable enough, because the break of one of the links leads to termination of the traffic for the corresponding pRBS. The ring topology of Figure 2(c) is the best and most economical choice, since the minimal length of fiber-optics links is guaranteed. In addition, it has sufficient survivability, since if one of the connecting links is broken, communication can be carried out in the opposite direction.



(a) Fully-connected topology (the overall length is 25 km)



(b) Radial topology (the overall length is 17 km)



(c) Ring topology (the overall length is 14 km)

Fig. 2. Variants for the topologies of FFMN under study

To implement effective 5G cellular communication within the small cell scenario, a number of leading countries developed prospective spectra including MMW-bands up to 100 GHz. This trend gained legal status at the last World Radiocommunication Conference (WRC-19), where additional bands for International Mobile Telecommunication (IMT) were assigned [18]. Figure 3 demonstrates these MMW bands.

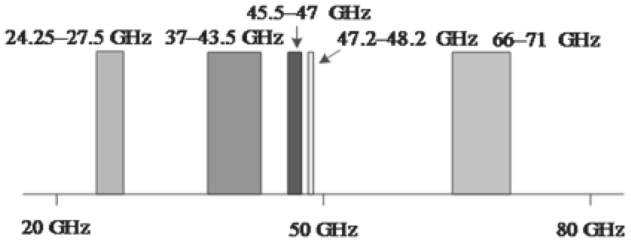


Fig. 3. 5G's MMW spectrum allocation of WRC-19 assignation

III. PROPOSED DESIGN PRINCIPLES OF MMW FIBER FRONTHAUL MICROCELL NETWORK

Figure 4 demonstrates generalized block diagram of the proposed WDM-RoF concept-based full-duplex MMW FFMN for an access network of 5G mobile communication systems. In according to Fig. 1 the block diagram contains a μRBS and a set of pRBSs interconnected by FFMN of ring topology, the optimal application of which was confirmed in the previous section. Each of RBSs includes downlink and uplink channels. In particular, downlink channel of μRBS consists of n-outputs WDM laser source, n optical modulators (OM), each of them is controlled by the corresponding transmitting downlink (TDL) unit forming digitally modulated radio-frequency (RF) signal. All optical channels are combined in wavelength division multiplexer. Output multichannel optical signal is input to port 1 of the optical circulator, which implements the ring topology of the FFMN that starts at its port 2 and finishes at the port 3. Micro-cell distribution network contains a corresponding number of pRBSs, each of which includes receiving downlink (RDL) unit for duplex wireless communication with UTs.

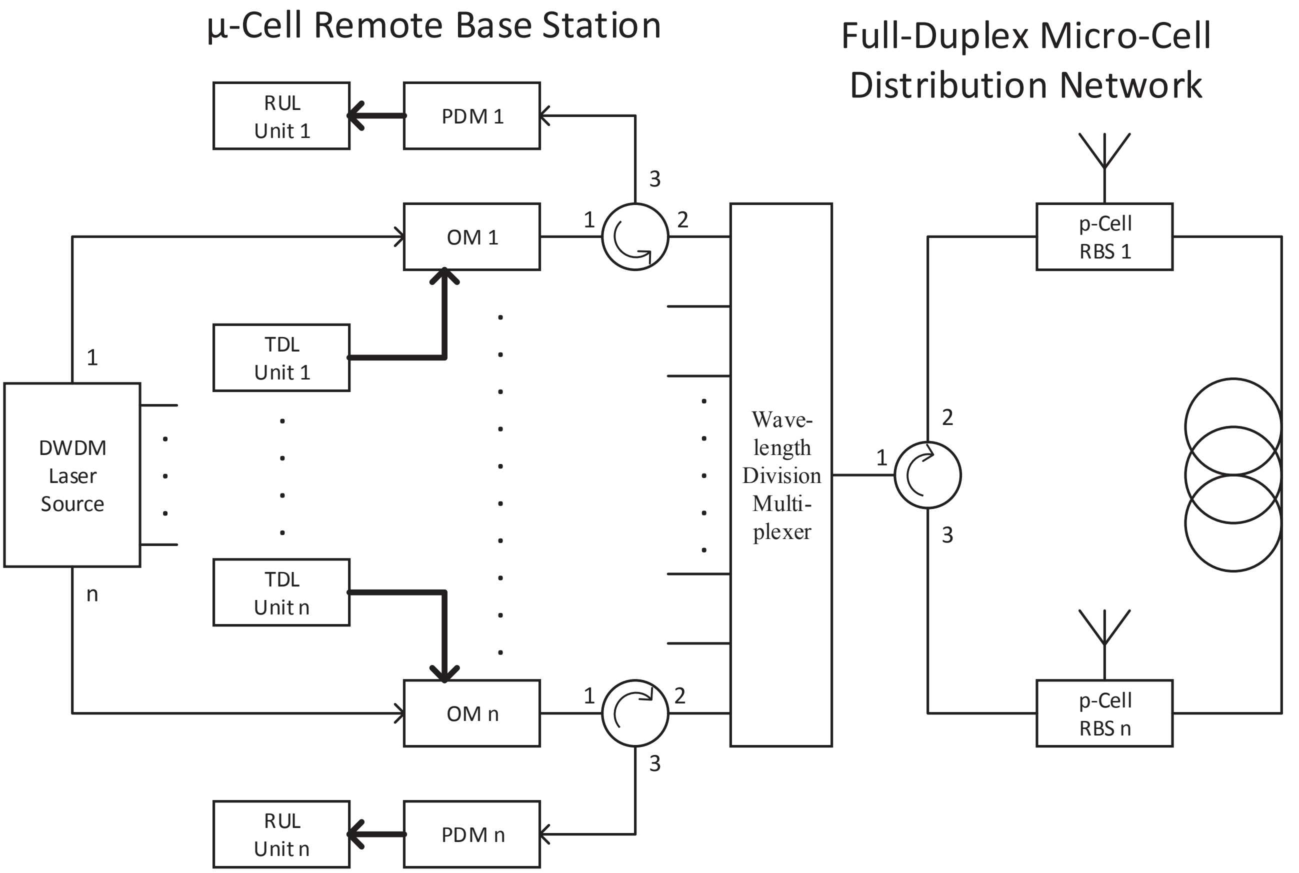


Fig. 4. The generalized block diagram of the proposed WDM-RoF concept-based full-duplex MMW FFMN (Thin line means optical connection, thick line means RF connection)

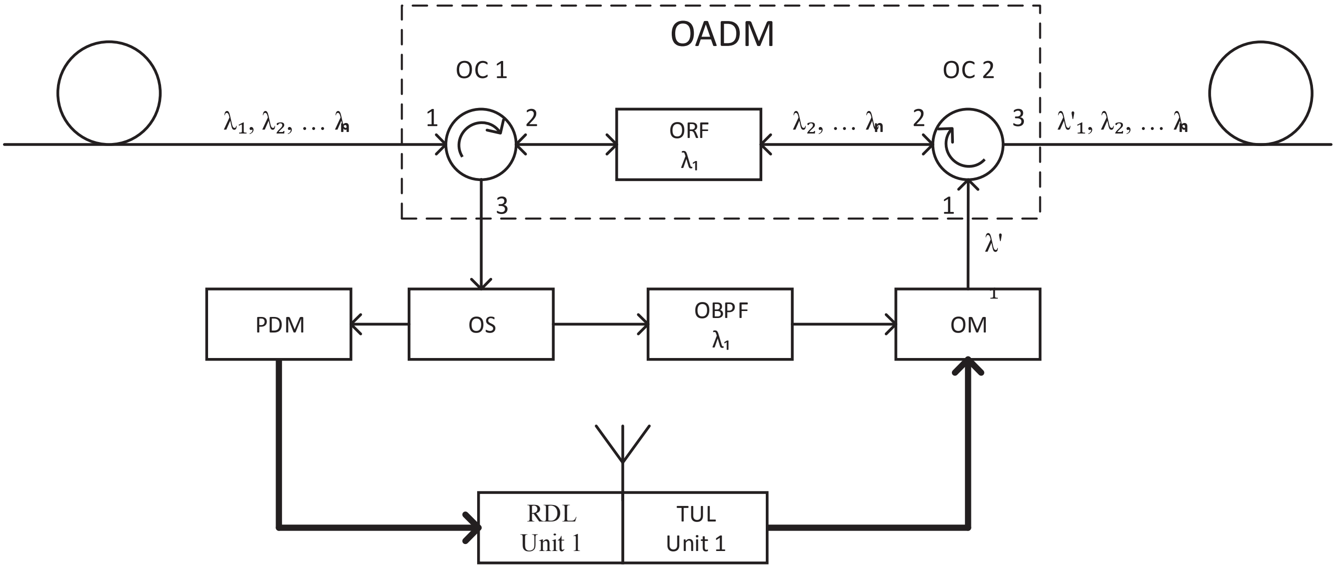


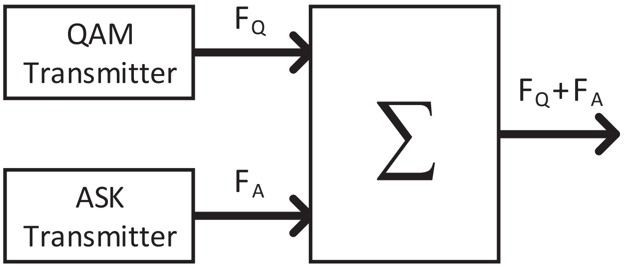
Fig. 5. The block diagram of a pRBS (Thin line means optical connection, thick line means RF connection)

Fig. 5 demonstrates the block diagram of a pRBS included in micro-cell distribution network of Fig. 4. To make the consideration concrete, we took the pRBS1 operating at a wavelength of optical carrier λ_1. Otherwise, this scheme is no different from other pRBSs in the distribution network. In the Figure, to select the corresponding optical channel in the downlink direction and the subsequent input of the optical channel of the uplink direction on the same optical carrier, a passive optical add-drop multiplexer (OADM) is used, including two optical circulators (OC1, OC2) and optical reflective filter (ORF) tuned on λ_1.

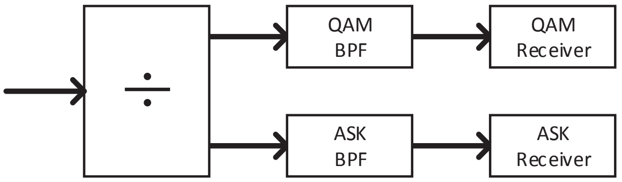
In the downlink direction, the modulated optical signal from port 3 of the OC1 enters the optical splitter (OS). The optical signal from the left port of the OS is converted into the RF band using a channel photodetector module (PDM), after which it is fed to the input of the RDL unit 1 for subsequent wireless transmission to the corresponding UT. Moreover, the signal from the right port of the OS enters a narrow-band optical bandpass filter (OBPF) that selects an unmodulated optical carrier λ_1.

In the uplink direction, the RF signal received from the UT is processed in the TUL unit 1, converted into the optical range using an optical modulator (OM), which is pumped by optical carrier from the OBPF output. The modulated optical signal enters the OADM, which introduces it into the multi-wavelength optical stream propagating over the micro-cell distribution network. Further, following Fig. 4, the combined optical signal from all pRBS is fed to port 3 of the optical circulator and distributed over the channels in the Wavelength Division Multiplexer, making advantageous of its bi-directionality. The channel optical signal from each output of the multiplexer through the corresponding optical circulator is fed to the input of the photodetector module (PDM), which converts it into the RF band, and then is processed in the corresponding RUL unit.

Figure 6 exemplifies the layouts of transmitting (a) and receiving (b) downlink and uplink RF units for the case when in each channel in both directions an informational digital RF (IDRF) signal with multi-position quadrature amplitude modulation (QAM) and a service digital RF (SDRF) signal with amplitude shift keying (ASK), are simulcasted. Through IDRF signals, high-speed duplex communication with network users is carried out according to the requirements for the 5G NR. The purpose of the SDRF signals is to ensure the effective reciprocal functioning of network and terminal devices, such as assignment and reuse of RF carriers in UTs, remote control of the pRBS's phased array antenna radiation patterns [19], coordinated multipoint transmission for mobile users [20], and so on. We propose to exploit a frequency division of RF carriers when transmitting IDRF signals in MMW band and SDRF signals in centimeter band. Thus, the TDL and TUL units have a simple circuitry consisting of QAM and ASK transmitters and a power combiner, while RDL and RUL units include a power divider, corresponding bandpass filters (BPF) as well as QAM and ASK receivers.



(a) TDL/TUL Unit



(b) RDL/RUL Unit

Fig. 6. Layouts of transmitting (a) and receiving (b) downlink and uplink RF units

In the diagram of Fig. 4, a multi-channel WDM laser source is included in the µRBS schematic. We propose to realize this unit in an unconventional form using an optical recirculating loop (ORL), which greatly simplifies its circuit by using only a single laser emitter. Layout of the proposed WDM laser source is shown in Fig. 7. As one can see, an optical signal from a Master Laser with a frequency of ν_0 using an X-coupler is output either directly or through an ORL based on a suppressed carrier single-sideband (SC-SSB) OM, an optical amplifier (OA) compensating the losses in the ORL, and an optical bandpass filter (OBPF) that limits the overall passband. The frequency of the optical carrier increases with each pass through the ORL by the amount of ν_0+nF_{ref}, where F_{ref} is a frequency of a reference input RF signal at SC-SSB OM, n is a number of optical channels. The n-channel optical filter is installed at the output of the unit, which distributes the optical carriers into the corresponding channels of the µRBS. Earlier we successfully applied this approach in design of optical frequency comb-based fiber to MMW wireless interface [15], having obtained a spectral comb containing more than 20 teeth of approximately the same level.

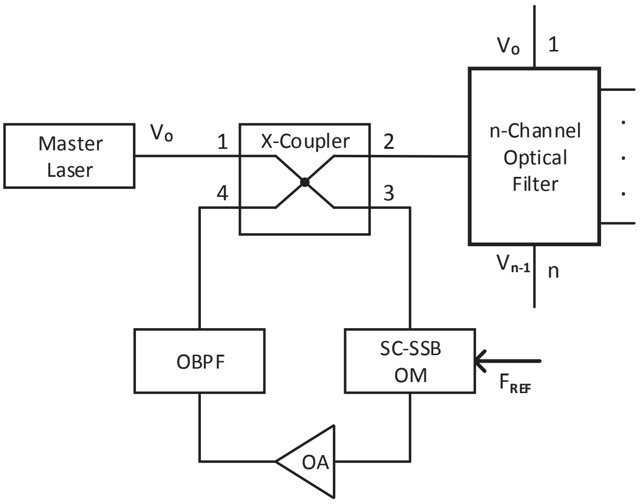


Fig. 7. Layout of the multi-channel WDM laser source

The key distinctive features of the proposed FFMN are:

- Using the small cell scenario, which provides feasible sequential partitioning of the access network into microcells and picocells.
- Full duplex wireless distribution of radio signals in the millimeter wave range, which significantly increases the throughput of communication links with user terminals.

- Using the power- and cost-efficient optical recirculating loop-based for designing WDM laser source at micro-cell remote base station.
- Cost-effective topology of single-fiber bidirectional transmission between μRBS and pRBSs.
- Economy ring architecture of micro-cell fiber distribution network.
- Efficient joint transmission in both directions of a high-speed informational digital RF signal with multi-position quadrature amplitude modulation and a service digital RF signal with amplitude shift keying.

IV. PROOF-OF-CONCEPT COMPUTER SIMULATIONS

To confirm the feasibility and effectiveness of the proposed micro-cell network block diagram, a series of initial simulation experiments was performed. A tool for the computer-aided design is well-known commercial software VPIphotonics Design Suite^{TM}. The study took into account two key distortion sources of the transmitted signal: a chirp of the modulator and a chromatic dispersion of the fiber. The quality of signal transmission during the simulation is determined based on standard telecommunication criteria: Error Vector Magnitude (EVM) for QAM-signals and Bit Error Rate (BER) for ASK-signals. Quantitative criteria are standard threshold values for mobile communications with these types of digital modulation, which are 3.5% for 256-QAM and 10^{-5} for ASK [21].

A. Reference data for the further simulation experiments

As known [10], the key function of the WDM-RoF concept-based FFMN is to realize full-duplex transmission between μRBS and pRBS using intensity modulation of an optical carrier. Correspondingly, the goal of the study is to examine initially the proposed block diagram of Fig. 4 so to determine quality-of-service (QoS) parameters of micro-cell distribution network while simultaneously propagating high-speed digital RF signals with multi-position QAM and ASK over a WDM-RoF-based optical distribution network. To realize this goal, we compare in detail the simulation results for optical transmitting 256-QAM signals in the lower band of 5G's MMW spectrum allocation (see Fig. 3) and ASK signals in CMW band. Table I lists the reference data for the simulation experiment.

B. The setups for modeling

Figure 8 shows VPIphotonics Design Suite's one-channel FFMN model and setup for the simulation experiments. The model consists of the library models of OM optically injected by C-band DFB laser, fiber-optics link (FOL), and photodiode following by electrical amplifier. One can see their relevant parameters in Table I. The rest of the Fig. 8 includes the library models of measuring instruments consisting of M-QAM and ASK Transmitter Modules as well as M-QAM and ASK Receiver Modules. The first transmitting module imitates 1.25 Gbit/s, M-QAM RF transmitter containing library models of QAM generator, output unit for power control. The second one imitates 1.25 Gbit/s ASK RF transmitter containing library models of Pseudo Random Bit Sequence generator, the filtered output of which is transferred to the RF carrier by means of the library model of a sinusoidal signal generator "FuncSineEl" and is filtered using a RF band-pass filter. The both modules are output by a library element setting SNR. In addition, the first receiving module detects RF signal, decodes an electrical M-QAM signal and evaluates the error-vector magnitude (EVM) of the received M-QAM signal. In the second one, FFMN model's output signal is down-converted to baseband using the same "FuncSineEl" library model, filtered, and detected using the library model of BER analyzer. The models of Numerical 2D Analyzer are used for two-dimensional graphical representation of the data from the M-QAM and ASK receiver outputs. To be able to monitor the quality of transmission of optical and RF signals at various points of the setup, library models of spectrum analyzers were introduced.

TABLE I. THE REFERENCE DATA FOR THE SIMULATION EXPERIMENT

Parameter		Value
Length of Pseudo Random Bit Sequence		2^{15}-1
Bitrate		1.25 Gbit/s
RF Carrier Frequency		
- For IDRF signals		24.25-27.5 GHz
- For SDRF signals		4-10 GHz
Type of RF modulation		
- For IDRF signals		256-QAM
- For SDRF signals		ASK
Optical Carrier		C-band
Space between WDM optical carriers		100 GHz
RF Output Signal-to-Noise Ratio (SNR)		20-40 dB
Type of optical modulation		Intensity
Semiconductor laser source	Operating current	40 mA
	Average Power	8 mW
	Optical Carrier	C-band (191…196.1 THz)
	Linewidth	0.4 MHz
	Relative intensity noise	-150 dB/Hz
Optical modulator	Type	Electro-absorption
	Operating voltage	-0.6 V
	Extinction ratio	14 dB
	Slope efficiency	0.14 W/V
	Linewidth enhancement factor (α)	1.0
	3-dB modulation bandwidth	30 GHz
PIN-Photodiode	Responsivity	0.7 A/W
	Dark current	100 nA
	Optical Input Power	<3 mW
	3-dB passband	up to 30 GHz
Post-amplifier	Gain	40 dB
	Noise Spectral Density	$20 \cdot 10^{-12}$ A/Hz$^{1/2}$
Optical Fiber	Type	SMF-28e+
	Length	up to 20 km
	Attenuation	0.2 dB/km
	Dispersion	17e^{-6} s/m^2
	Dispersion Slope	80 s/m^3

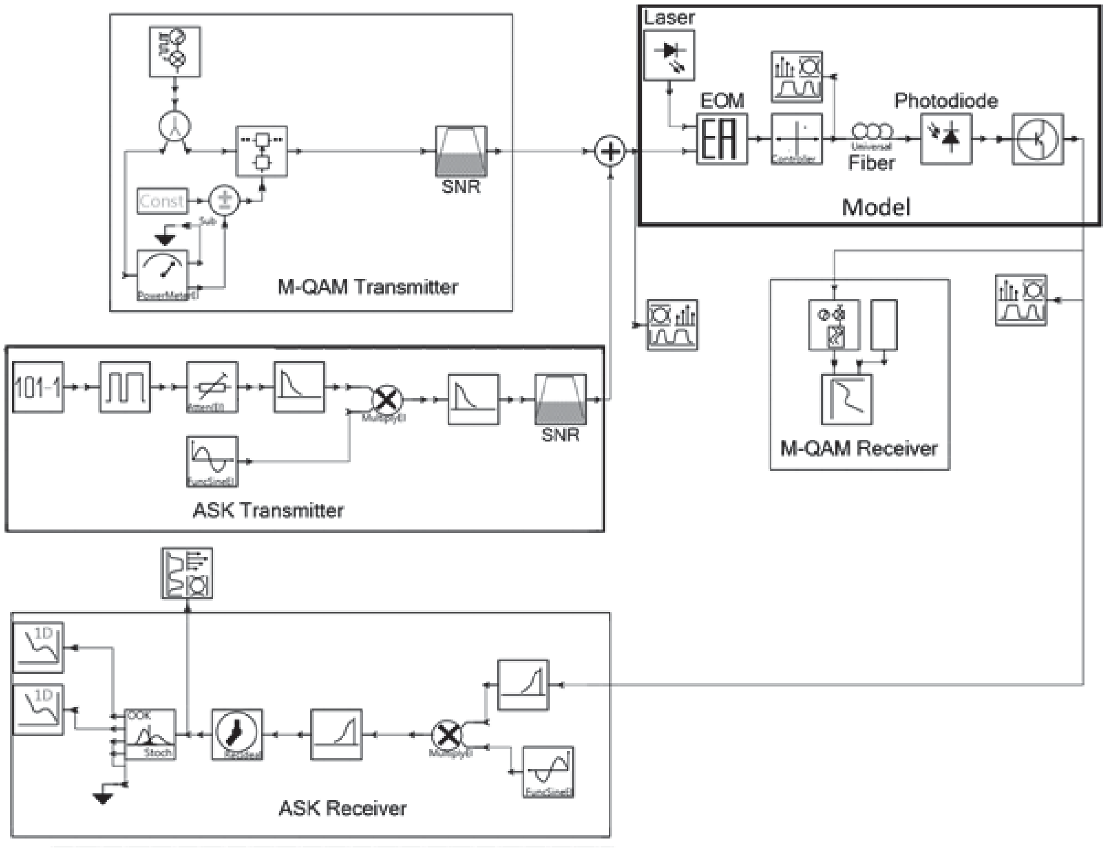
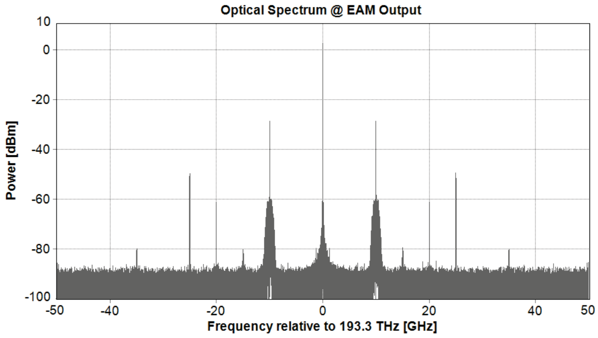


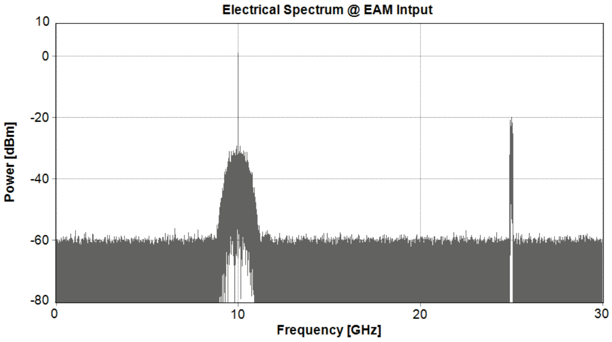
Fig. 8. VPIphotonics Design Suite’s one-channel FFMN model and setup for the simulation experiments

C. Simulation Results

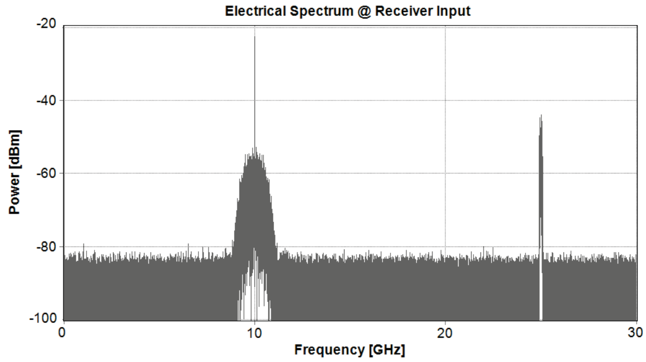
First of all, Fig. 9 highlights optical spectrum at the output of OM (a) as well as combined electrical spectra at the input (b) and output (c) of the FFMN model under study using input SNR=30 dB. As one can see from the graphics, all spectra are of high quality. In particular, the optical spectrum of Figure (a) shows a sufficient output power of the optical carrier of 3 dBm, providing a high SNR. The graph clearly shows the double sideband spectra for the first harmonics of the modulating RF signals, separated from the optical carrier by 10 GHz (ASK) and 25 GHz (QAM), respectively. It is also worth noting the optimal modulation depth of the optical signal, at which the relative level of the second-order harmonic distortions does not exceed -30 dB, and the level of crosstalk at the sum and difference frequencies is less than 50 dB for the ASK-channel and 30 dB for the QAM-channel. The high quality of RF signal transmission is confirmed by the graphs of (b) and (c), the spectra of which are almost identical.



(a) Optical spectrum at the OM output



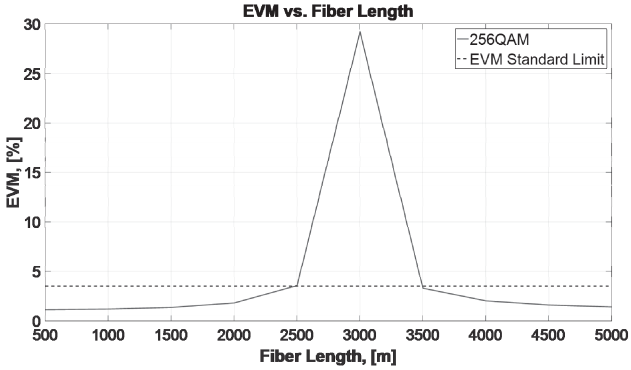
(b) RF spectrum at the input of the model under test



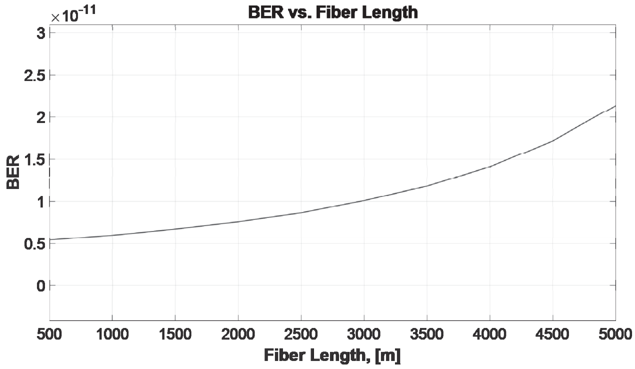
(c) RF spectrum at the output of the model under test

Fig. 9. Optical spectrum at the output of OM (a) as well as combined electrical spectra at the input (b) and output (c) of the FFMN model under study

This qualitative conclusion is confirmed by the results of measuring EVM or BER vs fiber length (see Fig. 10 (a) and (b), correspondingly). In the result, maximum allowable distance for transmitting 256-QAM signal is 2.5 km. However, with such a length, the BER value of ASK signal transmitting is only 10^{-11} and does not exceed $2x10^{-11}$ when it is doubled.



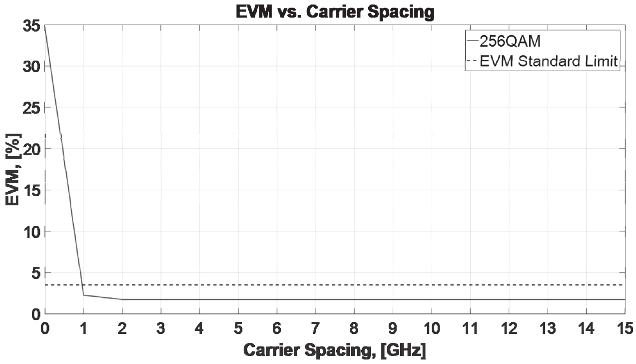
(a) EVM



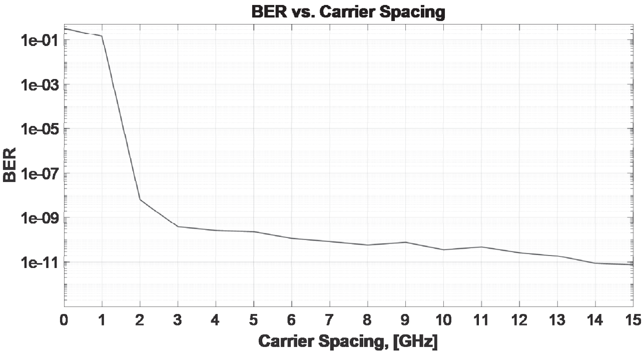
(b) BER

Fig. 10. EVM (a) and BER (b) vs fiber length characteristics

In addition, another simulation experiment relating to calculating EVM or BER vs RF carriers spacing characteristics using fiber length of 2 km is carried out and its results are highlighted in Fig. 11.



(a) EVM



(b) BER

Fig. 11. EVM (a) and BER (b) vs RF carrier spacing characteristic

As one can see from the Figure, the minimum allowable separation between the RF carriers is approximately the same, amounting to 1 GHz when transmitting a 256-QAM signal and 1.5 GHz when transmitting an ASK signal, which also confirms the high achieved quality of their joint transmission.

V. CONCLUSION

In this paper, a new approach to design full-duplex fiber fronthaul microcell network for a next-generation mobile communication system, for example, incoming 5G NR, using wavelength division multiplexed Radio-over-Fiber concept is proposed and discussed. To confirm a feasibility and effectiveness of the proposed access network, a detailed analysis of micro-cell network block diagram and a series of initial simulation experiments were carried out using off-the-shelf computer-aided design tool VPIphotonics Design Suite. The simulation experiments predict that the needed quality to jointly transmit in both directions a high-speed informational digital millimeter-wave signal with multi-position quadrature amplitude modulation and a service digital centimeter-wave RF signal with amplitude shift keying is supported if the distance of fiber-optics link between micro-cell remote base station and a set of pico-cell remote base stations is not more than 2.5 km (see Fig. 10), which is quite acceptable for a realistic access network. In the course of another simulation experiment evaluating the effect of RF co-channel interference, it was shown that the minimum allowable separation between the RF carriers is approximately the same, amounting to minimum 1 GHz when transmitting a 25-GHz signal with 256-position quadrature amplitude modulation (see

Fig. 11(a)) and 1.5 GHz when transmitting a centimeter-wave signal with amplitude shift keying (see Fig. 11(b)), which also confirms the high achieved quality of their joint transmission.

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