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Converging optical-to-MMW wireless links in fiber-wireless access network of 5G communication system

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Abstract

This paper reviews the principles and ways to advanced design of an access network with millimeter-wave wireless distribution using Radio-over-Fiber approach. To validate the concept, the results of simulating experiment on transmission of 16-, 64-, 256-, and 1024-position quadrature amplitude modulated RF signals at 15 or 40 GHz through optical distribution network are demonstrated and discussed. It is shown that due to fiber dispersion the standard error vector magnitude limit is achieved when the maximum length of the fiber-optic link is more than 4 times shorter at 40 GHz compared to the transmission at 15 GHz.

Keywords: Access network, Radio-over-Fiber, optical distribution network, fiber-wireless interface, millimeter-wave wireless communication

1. Introduction

As known, the basic requirements in the field of telecommunications for the worldwide community in the 21st century are higher data rate, reduced latency and continuous connection to the end user. The first two requirements are met mainly through the development of fiber-optic technologies, and at present, the throughput of digital fiber-optic communication systems (FOCS) has exceeded 1 Tbit/s. The latter need can be effectively solved by the development of wireless technologies. However, fundamental problem of the existing wireless communication systems lies in insufficient bandwidth. Thus, fiber-optic and wireless access networks are at the center of the scientific community's attention as the most relevant and significant technologies over the past two decades (Effenberger, 2016).

The above-mentioned bandwidth makes FOCS a leading technology not only for transport networks, but also for next-generation access networks. Unfortunately, an important drawback for the implementation of the access networks lies in the complexity and high cost associated with the need to lay the optical cables up to user terminals. Although traditional wireless access networks provide a flexible communication with a relatively simple infrastructure, they cannot meet a growing need to increase the capacity of communication systems. The most promising way to enhance data rate, which is actively discussed in recent publications, is to raise the operating frequency band up to millimeter waves (MMW) and to apply multi-position digital modulation format of the radio-frequency (RF) carrier. Thus, the convergence of optical and MMW wireless access networks into a hybrid fiber-wireless (FiWi) architecture, which is a distinctive feature of the 5th generation (5G NR) communications systems, is an obvious solution in the context of both capacity and high mobility (Andrews, 2014).

In this way, well-known Radio-over-Fiber (RoF) technology (Al-Raweshidy, 2002) is considered as the most promising approach, which is implemented based on FiWi architecture. Its key advantages for the cellular communication networks are the following (Andrews, 2014; Chen, 2014; Munn, 2016; Frenzel, 2017):

1. Higher noise immunity, since data streams are mainly delivered through fiber-optic links.
2. Small attenuation of signal power in fiber-based transmission path due to the fact that the losses in the fiber optic cable are four orders of magnitude smaller than in the coaxial one.
3. A lower cost of construction and operation that simplifies the structure and reduces the power consumption of Radio Access Units (RAU) due to using in the access networks the principle of transmission of digital streams on the subcarriers of the RF band.

Based on the benefits noted above, this paper reviews the principles, features, and ways to advanced design of 5G access network with MMW wireless distribution using RoF approach. To validate the concept, the results of simulating experiment on transmission of multi-position quadrature amplitude modulated RF signals through optical distribution network are demonstrated and discussed.

2. Design Principles of MMW Fiber-Wireless Access Network

To implement effective cellular communication within a small cell scenario (Boccardi, 2014; Dat, 2015), 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 (World Radiocommunication Conference, 2019). Figure 1 demonstrates these MMW bands.

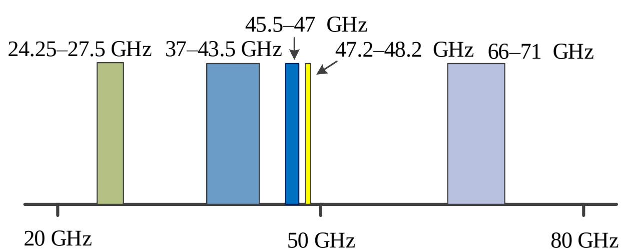


Figure 1. 5G's MMW spectrum allocation of WRC-19 assignation.

In general, a MMW fiber-wireless access network (FWAN) of FiWi architecture represents the further development of mobile communication networks of the previous generation (Rappaport, 2013). The peculiarity of its configuration is in a much smaller area of cells down to pico-cells for mobile user terminals (UT) with service zone diameter not more than 200-300 m (Belkin, 2019a). Due to the relatively small number of UTs inside the cell, it is critical to reduce cost of RAU, in fact, representing an effective interface between the optical and RF sections of the interactive transmission system. The most promising solution to this problem is the ultimate simplification of the RAU layout, which could be done by shifting all the processing procedures to the Central Station (CS). Analyzing the diagram addressed to FWAN from the functional viewpoint, two sub-systems are separated that consist of optical distribution network (ODN) including CS hardware and fiber-optics link (FOL), as such as fiber-MMW wireless interface including a RAU hardware and the same FOL. The above design principle is clearly illustrated in Fig. 2.

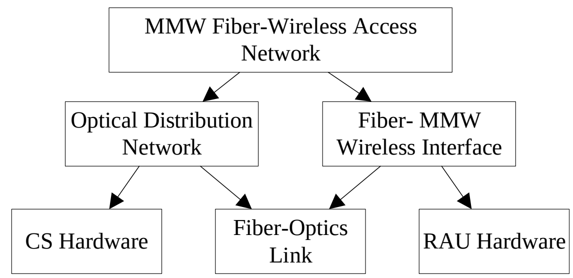


Figure 2. The design principle of MMW Fiber-Wireless Access Network.

3. Proof-of-Concept Computer Design of Optical Distribution Network

As known (Dat, 2015), the key function of the CS is to realize efficient electro-optical conversion and intensity modulation of an optical carrier. Correspondingly, the goal of the study is to examine a CS layout so to determine maximum allowable distance of FOL propagating multi-position quadrature amplitude modulation (M-QAM) signals over a RoF-based ODN using advanced electroabsorption modulated laser (EML) (Salvatore, 2002). To realize this goal, we compare in detail the simulation results for transmitting four versions of M-QAM signal of 16, 64, 256, and 1024 positions modulating RF carrier in intermediate or MMW band. The main advantages of an EML as compared to the standard configuration of a separate semiconductor laser and a Mach-Zehner modulator consist in a lower power consumption and a much wider modulation band (Salvatore, 2002). On the contrary, the key disadvantages in terms of transmitting an intensity-modulated signal over a distant optical fiber are in a larger linewidth and a greater parasitic frequency modulation (chirp), which, when transmitting QAM-signals, should lead in principle to a significant reduction in the maximum length of the FOL. The quality is analyzed in terms of error vector magnitude (EVM) limit provided that the bottom of EVM value determined by European Telecommunications Standard Institute corresponds to 12.5% for 16-QAM, 8% for 64-QAM, 3.5% for 256-QAM, and 2.5% for 1024-QAM (ETSI TS, 2018).

In all cases, the M-QAM digital signal modulates the RF carrier in so called Intermediate (IM) band that allocates between the 5G's Low and High ranges (Belkin, 2019a) or MMW band (see Fig. 1) and propagates over FOL. A tool for the computer simulation is well-known commercial software VPIphotonics Design Suite™. 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. Table 1 lists the common reference data for the ODN under study. In addition, Tables 2 and 3 list the reference data for continuously emitting laser source and EAM, correspondingly, due to the lack of the library model for EML in the tool.

Table 1. Common reference data for the ODN under study.

Parameter		Value
Length of PRBS		2^{15}–1
Bitrate		2.5 Gbit/s
RF Carrier Frequency		15, 40 GHz
Input RF Power		-11 ...-26 dBm
Type of RF modulation		M-QAM
Number of M		16, 64, 256, 1024
Type of optical modulation		Intensity
PIN-Photodiode	Responsivity	0.9 A/W
	Dark current	100 nA
	3dB Bandwidth	50 GHz
Post-amplifier	Gain	30 dB
	Noise Spectral Density	$20 \cdot 10^{-12}$ A/$Hz^{1/2}$
Optical Fiber	Type	SMF-28e+
	Length	up to 7 km
	Attenuation	0.2 dB/km
	Dispersion	$17e^{-6}$ s/m^2
	Dispersion Slope	80 s/m^3

Table 2. Reference data for laser source.

Parameter	Value
Operating current	40 mA
Average Power	8 mW
Optical Carrier	C-band (193.3 THz)
Linewidth	1.5 MHz
Relative intensity noise	-150 dB/Hz
Threshold current	8.5 mA

Table 3. Reference data for electro-absorption modulator.

Parameter	Value
Operating voltage	-0.6 V
Extinction ratio	14 dB
Slope efficiency	0.14 W/V
Linewidth enhancement factor (α)	1.0
Adiabatic chirp factor	0

3.1. CAD Model and Setup

Figure 3 shows VPIphotonics Design Suite's ODN model and setup for the simulation experiments. The ODN model consists of the library models of EAM optically injected by C-band DFB laser, FOL, and photodiode following by electrical amplifier. One can see their relevant parameters in Tables 1-3. The rest of the Fig. 3 includes the library models of measuring instruments consisting of M-QAM Transmitter Module and M-QAM Receiver Module. The first one imitates 2.5 Gbit/s, M-QAM RF transmitter containing library models of QAM generator, output unit for power control, and an element setting 30-dB signal-to-noise ratio (SNR). This module generates an electrical M-QAM signal up-converted at a given RF carrier frequency. The second one detects RF signal, decodes an electrical M-QAM signal and evaluates the error-vector magnitude (EVM) of the received M-QAM signal. The model of Numerical 2D Analyzer is used for two-dimensional graphical representation of the data from the M-QAM Receiver output.

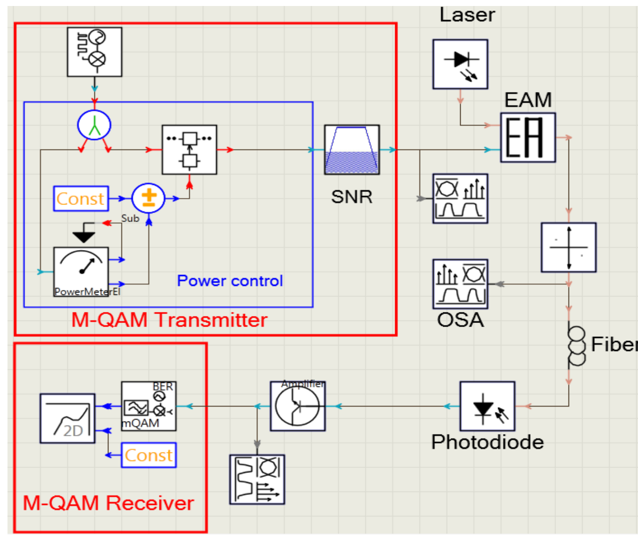
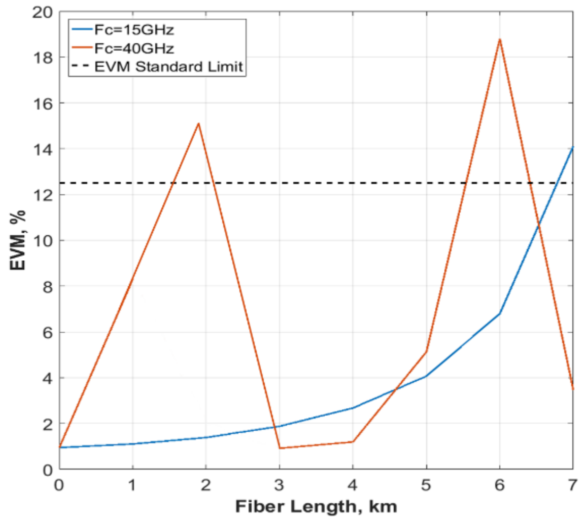


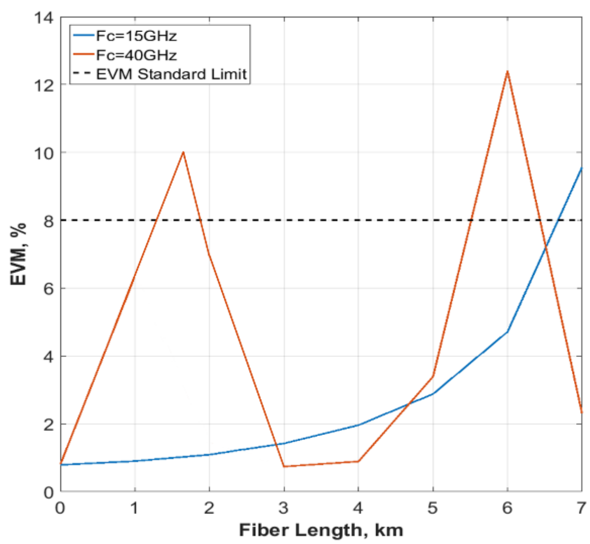
Figure 3. VPIphotonics Design Suite's ODN model and setup for the simulation experiment.

3.2. Simulation Experiments

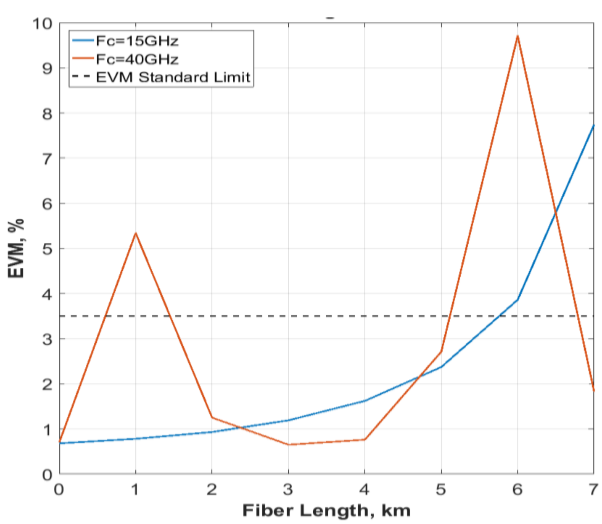
In preparation for the simulation experiment, the intensity-modulation index of EAM under study was optimized in such a way as to ensure the maximum RF carrier-to-noise ratio while maintaining the low-signal mode at all modulating frequencies. Figure 4 depicts examples of simulating EVM vs fiber length characteristics for the ODN under study during modulation by 2.5 Gbit/s, M-QAM, 15 or 40 GHz test signal. As one can see from the Figure, EVM value for any number of QAM positions grows with increasing FOL length. Nevertheless, this growth is smooth at a carrier of 15 GHz and wavy with peaks and dips at a carrier of 40 GHz due to the influence of the combined effect of the modulator chirp and fiber dispersion, which corresponds to the known data (Rappaport, 2013; Belkin, 2019a).



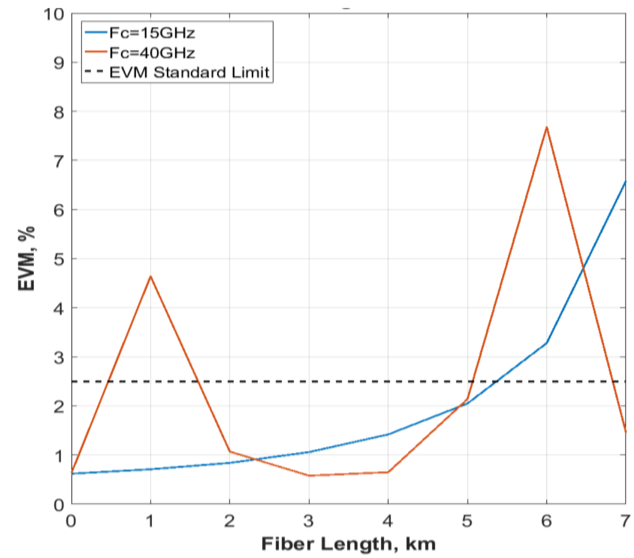
a) 16-QAM



b) 64-QAM



c) 256-QAM



d) 1024-QAM

Figure 4. Examples of simulating EVM vs fiber length characteristics.

The results of the simulation for the ODN under study within MMW fiber-wireless access network of 5G system are summarized in Table 4.

Table 4. The results of the simulation

RF carrier (GHz)	Number of QAM positions	Allowable Distance of FOL (km)
15	16	6.8
	64	6.6
	256	5.8
	1024	5.3
40	16	1.7
	64	1.3
	256	0.6
	1024	0.4

4. Results and Discussion

The following outputs can be derived from our study:

1. With both RF carriers, the allowable distance of FOL gradually decreases as the number of positions of the QAM signal increases.
2. Even in the relatively lower part of the MMW-band, the standard EVM limit is achieved when the maximum length of the FOL is more than 4 times shorter compared to transmission in IM-band, which corresponds to the known data (Belkin, 2019b).
3. The hard fluctuations of the EVM values (see Fig. 4) in MMW band are mainly characterized by the effect of dispersion in an extended optical fiber.
4. The way to significantly increase the allowable distance is in using a dispersion corrector at the far-end of a FOL (Bakhvalova, 2019).

5. Conclusions

To select an optimal way of converting optical-to-millimeter wave wireless links in fiber-wireless access network of 5G communication system we checked by simulation in the established commercial software VPIphotonics Design Suite™ two variants of transmitting 16-, 64-, 256-, and 1024-position quadrature amplitude modulated radio frequency signals at 15 or 40 GHz over a standard single mode fiber-optic line. The results of the simulation experiments showed that the transmission quality in millimeter-wave band are mainly characterized by the effect of dispersion in an extended optical fiber. This effect reduces the maximum allowable transmission length of fiber part up to 0.4-0.6 km that is not enough for a number of 5G applications. To remedy the state we proposed two ways. The first one is in transmission at the radio frequency below millimeter wave (for example at 15 GHz) with subsequent up-conversion at the base station. The second one is in using a dispersion corrector at the far-end of a fiber-optic link, which is the standard approach for super-high speed fiber-optic communication. Our further research will be aimed at experimental confirmation of the obtained simulation results and approaches.

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