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Experimental validation of a 64-QAM LTE radio-over-fiber and free-space optics link at the 2000 nm band

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Abstract—Radio over fiber (RoF) transmission systems have been developing rapidly, especially for applications in 5G networks. In scenarios unsuitable for fiber-optics, radio over free-space optics (RoFSO) presents a suitable solution. Nevertheless, free-space optics (FSO) suffers from atmospheric conditions. The use of the 2000 nm band offers several advantages over the commonly used 1550 nm region. We focus on proof-of-concept evaluation of such a 2000 nm RoFSO transmission system. Measured characteristics are compared with a similar 1550 nm RoFSO system. We demonstrate both systems for QPSK and 64-QAM LTE formats, at 5 GHz and 10 GHz with a 20 MHz bandwidth.

I. INTRODUCTION

With the upcoming 5th generation (5G) networks and beyond, the transmitted data capacity has arisen significantly. Current predictions expect the total mobile data load to reach 77 exabytes per month by 2022 [1]. Two technologies converge to provide sufficient data throughput, the millimeter-wave (mmW) and the fiber-optics.

On one side, higher radio-frequency (RF) bands have been exploited, e.g., the K-band of 24-28 GHz [2], [3], and the extremely high frequency (EHF) region of 60 GHz band, which has attracted a lot of attention [4] for short connections. However, these mmW frequencies are designed to work in small-cell network architectures, such as pico- and femto-cells, and their main purpose is to deliver the required signal from the base station (BS) to the end users. Integrated photonics is often discussed once speaking of small cell architectures [5].

To overcome longer transmission distances, fiber optics can provide the required bandwidth for the 5G networks as well as accessibility to the high-speed backbone networks. A very high data capacity of over 10 Pbit/s was already demonstrated using a 19-core single optical fiber [6]. Nevertheless optical fibers may also be used for transmission of RF signals [7], [8], thus replacing coaxial cables at frequencies higher than 10-20 GHz due to their lower attenuation. Note, optical fibers have a typical attenuation of 0.2 dB/km at any proposed 5G band, compared with

~0.5-0.6 dB/m loss of coaxial cables in the K-band. In dense urban areas the installation of optical cables is often limited or even prohibited due to installation cost and right of access. Therefore, in such scenarios free-space optics (FSO) technologies present a viable solution while maintaining almost the same data throughput as the optical fiber and bridging the gap between the central office and BS. In recent years, numerous studies [9], [10], [11] have shown the possibilities of RoF transmission using FSO (denoted as RoFSO).

However, FSO links are strongly affected by the weather conditions, i.e. fog, snow, turbulence, etc. as discussed in [12], [13]. It is generally known that, moving the transmission carrier to longer wavelengths makes the transmitted signal more resilient to Mie scattering. Therefore, within the context, the 2000 nm band is a promising candidate to increase the RoFSO system reliability since critical components have emerged during the last few years, specifically Mach-Zehnder modulators [14] and high bandwidth photodiodes [15]. The 2000 nm band offers a number of other advantages such as significantly lower atmospheric attenuation and higher transmit optical power levels not effecting eye safety. This year's first demonstration of data transmission over an FSO link at 1 Gbps and 2 Gbps was presented in [16].

In this paper, we present a first demonstration of RoFSO at 2000 nm. We provide a back-to-back (B2B) system evaluation using quadrature phase-shift keying (QPSK) and 64-QAM (quadrature amplitude modulation) signals with a 20 MHz bandwidth at the carrier frequencies of 5 GHz, which corresponds to wireless communication in this frequency band and of 10 GHz, which presents the highest possible frequency of analyzed electro-optical components (modulator and photodetector). Next, we evaluate the RoFSO system performance to compare the results with a 1550 nm RoF system demonstrating very similar results, thus confirming the great potential of the 2000 nm RoFSO system.

II. MEASUREMENT CONFIGURATION

Our measurement configuration is designed as similar as possible for both 2000 nm and 1550 nm and based on the same building blocks which are envisioned as the 5G RoF enablers. The experimental setups are depicted in Fig. 1. Continuous-wave laser sources (denoted as LS1550 - 1550 nm Thorlabs distributed-feedback laser, model MCLS1-1550DFB, and LS2000 - 2000 nm Eblana Photonics Fabry-Perot laser with suppressed side modes, model EP2004-0-DM) were used to generate the optical carriers, which were then externally modulated by mmW signals in 10 GHz Mach-Zehnder LiNbO₃ modulators (MZM1550 - Thorlabs model LN81S-FC, and MZM2000 - IxBlue model MX2000-LN-10). MZM1550 and MZM2000 had the quadrature point voltages of 1.0 V and 2.7 V, respectively. For 1550 nm system we also included a polarization controller (PC), whereas for 2000 nm PC was not required as both MZM2000 and LS2000 are equipped with polarization-maintaining fibers. The RF signal was then generated using Rohde&Schwarz SMW200A, providing long-term evolution advanced (LTE-A) format [17] according to the E-UTRA test models [18], i.e., a signal with 20 MHz bandwidth. We used test models 3.1 and 3.3 for 64-QAM and QPSK, respectively.

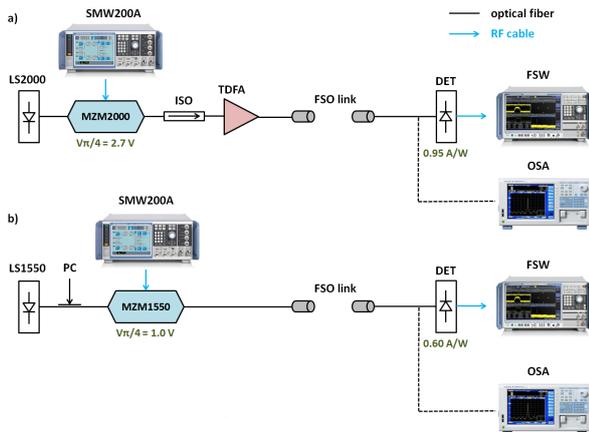


Fig. 1. Measurement configuration for the back-to-back evaluation at: a) 2000 nm and b) 1550 nm; LS - laser source, MZM - Mach-Zehnder modulator, PC - polarization controller, TDFA - Thulium-doped fiber amplifier, DET - photodetector, OSA - optical spectrum analyzer.

An RF signal with a total power of 8 dBm was generated for all tests carried out. In case of the 2000 nm setup, we experienced 7 dB higher optical losses once MZM2000 was set to the quadrature point, therefore for proper comparison we decided to set the same optical power levels. We used therefore a low-noise in-house built Thulium-doped fiber amplifier (TDFA) with an isolator (ISO) to prevent amplified spontaneous emission from propagating in the backward direction. The responsivity of the InGaAs photodetector used was identical for both 1550 nm and 2000 nm (DET, EOT Photonics model EOT5000F with the responsivity of 0.60 A/W at 1550 nm and 0.95 A/W

at 2000 nm). The RF signal was processed in an RF LTE analyzer (Rohde&Schwarz model FSW). An optical spectrum analyzer (OSA, Yokogawa AQ6375B) was used to measure LS2000 and TDFA output spectra. Table I summarizes all key parameters of the 2000 nm RoFSO system.

TABLE I
KEY PARAMETERS OF THE 2000 NM ROFSO SYSTEM

Parameter	Value
RF frequency	5 and 10 GHz
RF bandwidth	20 MHz
RF total power	8 dBm
LTE test model	TM 3.1 and 3.3
Optical carrier wavelength	2000 nm
Laser output power	3.2 dBm
MZM quadrature voltage	2.7 V
FSO link length	1 m
FSO link loss	2.4 dB

III. BACK-TO-BACK PERFORMANCE

First step was to ensure that we preserve optical signal to noise ratio (OSNR) of the 2000 nm signal when using TDFA as illustrated in Fig. 2. We measured the optical spectra of the LS2000 and then the signal after TDFA. Figure 2 shows that OSNR of LS2000 is 53 dB and is well maintained after amplification, where the noise floor given by ASE is relatively low, providing OSNR of 38 dB after TDFA.

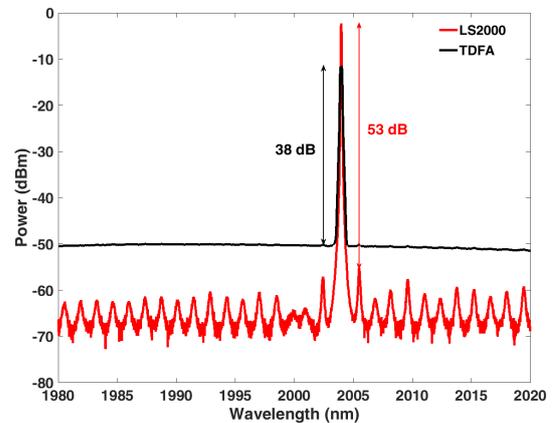


Fig. 2. Output spectra of LS2000 (red) and at the output of TDFA (black) with their OSNR values.

Next, we recorded the phase noise floor for both wavelengths at the carrier frequencies of 5 GHz and 10 GHz with the results for phase noise (dBc/Hz) presented in Table II. The phase noise floor was acquired using a FSW built-in tool. We observe only a small difference at both frequencies, which correlates well with the measured signal performance in terms of the error-vector magnitude (EVM). The EVM results as a function of the RF signal power for carrier frequencies of 5 GHz and 10 GHz at

the wavelengths of 1550 and 2000 nm for 20 MHz QPSK and 64-QAM are depicted in Fig. 3. Also shown are the EVM limits of 18.5 and 9% for QPSK and 64-QAM, respectively, defined by [18].

TABLE II
PHASE NOISE (IN dBc/Hz) OF THE 1550 nm AND 2000 nm CONFIGURATIONS.

Wavelength and carrier frequency	Frequency offset from carrier		
	1 kHz	10 kHz	100 kHz
1550 nm, 5 GHz	-92.9	-115.5	-116.9
2000 nm, 5 GHz	-92.6	-115.4	-117.3
1550 nm, 10 GHz	-87.0	-109.0	-110.5
2000 nm, 10 GHz	-89.9	-112.8	-113.4

For 64-QAM, EVM values better than 1% are achieved only at 2000 nm for 5 GHz and below the RF power higher of -52 dBm. The difference in EVM between 2000 nm and 1550 nm at 5 GHz is most evident at the highest RF power and slowly decreases towards the RF power level of -65 dBm, where the EVM values for both wavelengths are the same. At 10 GHz, the difference in EVM between the two wavelengths is less evident. For QPSK the observed trends are identical to 64-QAM, where again only at 2000 nm and for 5 GHz we can see EVM below 2% for RF powers higher than -55 dBm.

Surprisingly, we can observe that the RoF system offers slightly better performance at 2000 nm for both carrier frequencies and both modulation formats/test models. This may be attributed to the better DET responsivity at 2000 nm and the high-quality of LS2000 having over 50 dB side-mode suppression, where even after amplification the OSNR value is still over 35 dB.

IV. FREE-SPACE OPTIC LINK EVALUATION

After the B2B validation we added a 1 m long FSO link after TDFA in order to make a complete RoFSO system. The FSO link was composed of two collimators (Thorlabs, F810APC-2000) providing a 2.4 dB insertion loss at the 1 m distance. Both collimators were placed on 5D stages (3D + pitch and yaw) as the angular alignment is critical for minimizing the overall loss of the FSO link. Figure 4 shows the laboratory experimental setup of the RoFSO system.

First we analyzed the phase noise levels of the 2000 nm RoFSO system and observed 3 dB lower values compared to the B2B measurement. Then we have carried out an identical EVM measurement for QPSK and 64-QAM at both carrier frequencies for the 2000 nm RoFSO with the results illustrated in Fig. 5.

As shown, EVM decreases with the increase in the RF power levels for both modulation cases, with the QPSK offering better values compared with the 64-QAM. Interesting is to observe the difference between QPSK and 64-QAM to grow as the RF power decreases. Nevertheless, both QPSK and 64-QAM at both carrier frequencies reach the EVM limit at similar RF powers.

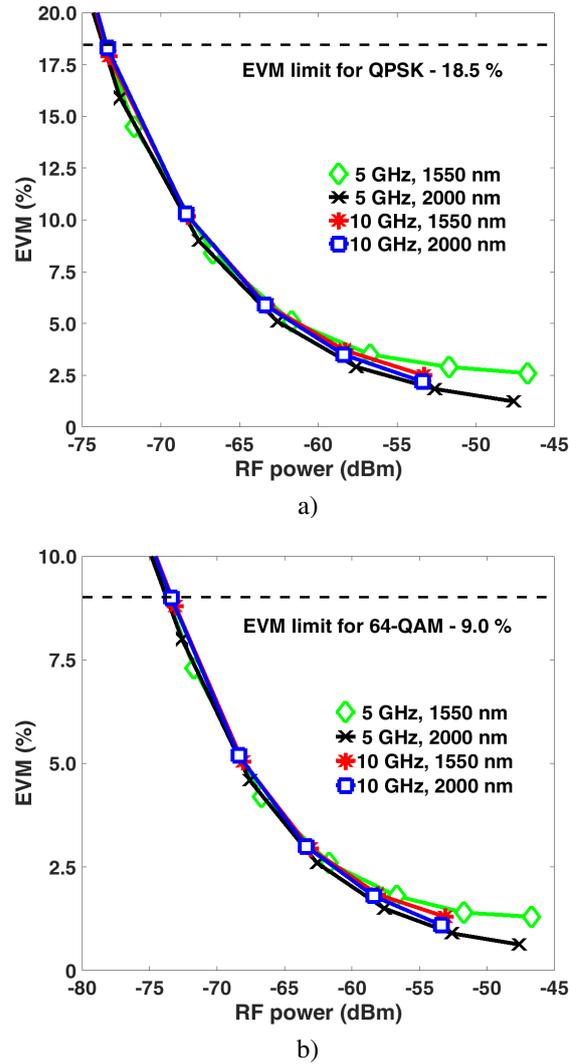


Fig. 3. Error-vector magnitude of a) 20 MHz QPSK signal and b) 20 MHz 64-QAM signal at 1550 and 2000 nm at carrier frequencies of 5 and 10 GHz

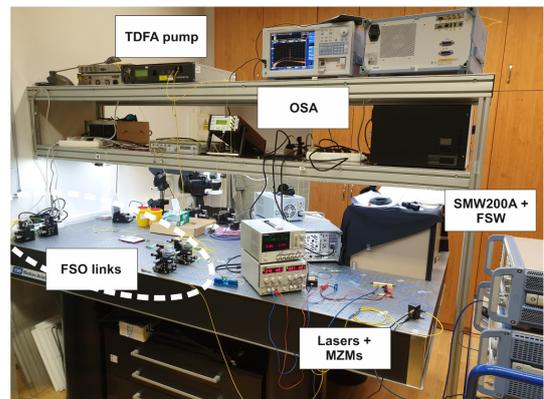


Fig. 4. Laboratory configuration of the 1550 nm and 2000 nm RoFSO systems.

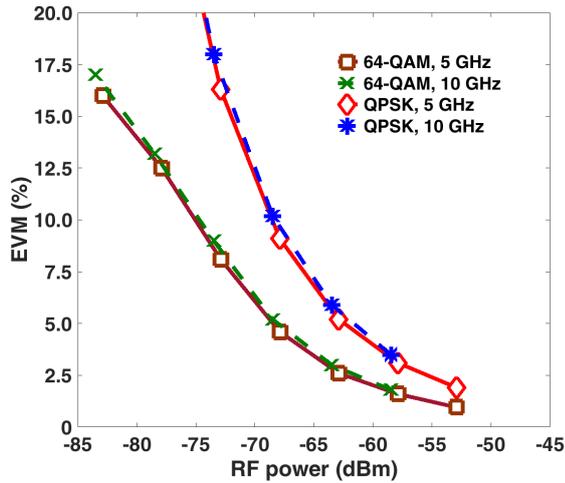


Fig. 5. EVM values for QPSK and 64-QAM formats at 5 GHz and 10 GHz in the 2000 nm RoFSO system.

Last, we show the calculated BER for the RoFSO system at 2000 nm in Fig. 6. We can see that for 64-QAM format RF power levels of more than 5 dB higher are required than for QPSK format, whereas both carrier frequencies differ only marginally.

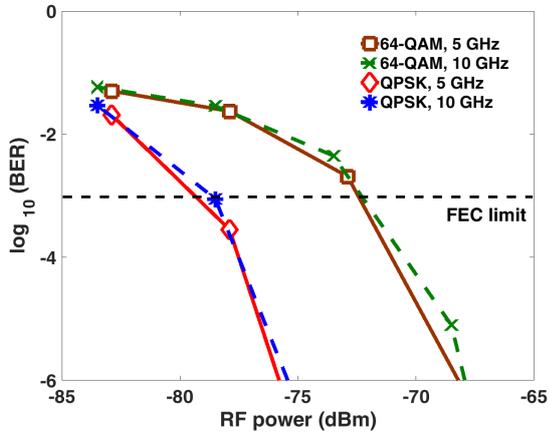


Fig. 6. BER values for QPSK and 64-QAM formats at 5 GHz and 10 GHz in the 2000 nm RoFSO system.

V. CONCLUSION

We have designed and validated a complete 2000 nm RoFSO system. We have achieved slightly better performance in terms of the EVM compared with 1550 nm system. EVM values below 1% were observed for 64-QAM and below 2% for QPSK at the RF power of -53 dBm. Moreover, the 2000 nm FSO link provided only 2.4 dB insertion loss. Furthermore, our in-house built Thulium-doped fiber amplifier allowed us to work at similar power levels as at 1550 nm thus compensating for the higher

insertion loss of the Mach-Zehnder modulator at 2000 nm when biased at quadrature point. The system can transmit multi-carrier signals such as OFDM.

In the future, we will focus on detailed analyses of the atmospheric effects on the 2000 nm RoFSO system, studying turbulence effects and fog/mist impact. Furthermore, higher output optical powers are expected to be used at 2000 nm thanks to the higher eye-safety limits.

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