International Journal of Microwave and Wireless Technologies, 2016, 8(3), 597–602.
doi:10.1017/S1759078715000586

RESEARCH PAPER

Direct and external modulation of IF over fiber systems for 60 GHz wireless applications

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Wireless domestic applications involving high data rates are required to work on millimeter wave band. Signal propagation at this frequency range is affected by walls and oxygen absorption which limits communication distances to few meters in one room. Radio coverage can be extended to other rooms by optical links. Performances of such photonic systems are dependent on optoelectronic devices, electrical driving, and receiver circuits. In this paper, radio-over-fiber (RoF) links based on the intensity modulation and direct detection technique are investigated for transmission of a broadband OFDM signal. Direct and external modulations are exploited to analyze system performances according to the ultra wideband (UWB) millimeter-band standard. To avoid component tolerances at high frequencies, an intermediate frequency modulation of the optical transducers is chosen. Optoelectronic and optical components of RoF links are modeled by equivalent electrical circuits with consideration of noise and nonlinearities. These models are validated in system simulation by error vector magnitude evaluation with a measurement setup according to the UWB centimeter-band standard.

Keywords: Microwave photonics, Modeling, Simulation and characterizations of devices and circuits

Received 10 October 2014; Revised 10 March 2015; Accepted 11 March 2015; first published online 16 April 2015

I. INTRODUCTION

The unlicensed millimeter band at 60 GHz is nowadays a solution to offer multi-gigabits/s wireless data [1]. However, communication distances are limited to few meters due to walls, obstacles, and oxygen absorption [2]. These short coverage ranges can be extended by means of radio-over-fiber (RoF) technology [3, 4]. This solution offers the advantage of the high bandwidth of optical fibers and removes signal-processing functions in transceivers. Various RoF systems were proposed to cancel local oscillators in receivers by optical generation of millimeter-wave signal making thus an expensive solution [5]. Another alternative is direct detection followed by complementary metal oxide semiconductor (CMOS) circuits which can be more competitive solution for domestic applications [6]. The data transmission through the optical fiber can be realized by direct modulation (DM) at an intermediate frequency (IF) of lasers, electro-absorption modulated lasers (EMLs) or Mach–Zehnder modulator (MZM). DM of distributed feedback (DFB) lasers is a simple technique but it has a bandwidth limitation. The EML is attractive in short-reach networks because it offers an easy integration, low-driving voltage, and power dissipation [7]. The MZM offers low chirp and higher performances that is why it is widely used in the long-haul transmission system [8]. However, the nonlinear effects induced by optical modulators cause intermodulation distortion and result in signal degradation.

In this paper, we present performance analysis of orthogonal frequency-division multiplexing (OFDM) signal transmission over two RoF links: DM of a DFB laser and external modulation (EM) with an electro absorption modulator. The OFDM signal matches with the specification given by the IEEE802.15.3c standard for the ultra wideband (UWB) millimeter-band. System simulation is performed with the developed electrical circuit models of photonic and optical components [9, 10]. These models have realistic characteristics and include noise sources and nonlinearities. To validate the simulation, we used a simple measurement setup having a direct solution to perform the error vector magnitude (EVM) of the first band (3.1–4.6 GHz) of UWB centimeter-band standard (ECMA-368). The EVM is a good performance metric to analyze degradation of such complex signal [11]. Then, signal broadband and data rate effects on the EVM are also discussed.

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II. ROF SYSTEMS MODELING

The photonic components of the RoF systems are modeled with equivalent electrical circuits by using an analogy between the optical power and a current or voltage. As the optical phase noise is eliminated in the direct detection, the power consideration of these models is appropriate to represent the optical signal. The fiber is a standard single-mode fiber with a length lower than 100 m which is typical for home area network applications. Chromatic dispersion effect and attenuation are incorporated in the model but the influence in the system performance is neglected. For the optical/electrical (O/E) part, the photodiode model includes noise and is linear due to the case here where the received optical power is much lower than its saturation level. With the realistic characteristics of E/O and O/E modules, gain compression, intermodulation distortions, and noise power of the RoF links can then be investigated by simulation.

A) E/O and O/E transducers models

The DFB laser is from 3S Photonics Company having a wavelength of a 1.56 μm, a modulation bandwidth of 16.8 GHz and an efficiency of 0.087 W/A. The EML is from III–V Laboratory and integrates a 1.53 μm DFB laser with a threshold current of 10 mA and a slope efficiency of 0.16 W/A, and an electro-absorption modulator. The electrical model of DFB lasers is based on two rate equations for carriers and photons including Langevin noise sources to consider the random nature of carrier recombination and photon generation [9]. The physical parameters of the laser equivalent circuit are obtained from the known data of its heterostructure layers and some of system parameters extracted from measurements of static curve and relative intensity noise (RIN). A matching circuit and parasitic elements due to a laser packaging are also added to the model. The EML circuit is formed by the DFB laser model and Electro-Absorption Modulator (EAM) model constituting of a single RC low-pass filter and nonlinearities behavior of the electro-optical effect describing the dependence of the optical output power with the reverse bias voltage [10].

The measured and simulated characteristics of the static curves and RIN of these devices are presented in Fig. 1. The RIN values of both DFB lasers are almost equal in the working frequency range from 2 to 5 GHz. The same photodetector is used for both RoF systems. It includes a PIN photodiode with a 3 dB bandwidth of 20 GHz and a responsivity of 0.83 A/W followed by a low-noise amplifier (LNA). The photodiode model includes a current source for optical to electrical conversion, a resistor–capacitor (RC) circuit for the frequency response and packaging parasitic elements. This model considers the thermal noise and the shot noise linked to the photodetected. The LNA with a gain of 33 dB and a noise figure of 3.5 dB has a flat response which does not introduce amplitude and phase distortions in the working frequency bandwidth.

B) Noise power and compression point

The thermal noise, laser RIN and shot noise are the different noise sources in the RoF link. At the output of the LNA, the total noise power NP_{out} of the RoF systems is given by (1).

$$\begin{aligned} NP_{out} = &((kT\,BG_{RoF} + kT\,B)_{th} \\ &+ (RIN\,I_{ph}^2 R_l B)_{RIN} + (2q\,I_{ph} R_l B)_{shot})_{RoF} G_{LNA} \\ &+ (kT\,B(NF_{LNA} - 1)G_{LNA})_{LNA}, \end{aligned} \quad (1)$$

where indices (th, RIN, and shot) refer to thermal, laser, and shot noises, k the Boltzmann's constant, T the standard temperature in Kelvin, B the noise bandwidth, G_{RoF} the link gain, I_{ph} the photodetected DC current, q the electron charge and R_l the load impedance, and G_{LNA} and NF_{LNA} are the LNA available gain and noise figures. For B equals to 1 Hz, the noise calculations at the LNA output at a frequency of 4 GHz are represented in Fig. 2. For DM, noise powers estimated with a laser bias current from 30 to 80 mA show a dominant laser noise for low bias current and both laser and shot noises when bias current increase. For EM, noise powers are calculated for EAM bias voltage from -3.2 to -1 V and for a laser bias current of 50 mA. Laser and shot noises decrease when the EAM absorbs strongly the light due to the low photodetected current levels.

The 1 dB compression point (P_{1dB}) depends on the bias conditions as shown in Fig. 3. Measured and simulated input power compression point ($P_{in,1dB}$) at a carrier frequency of 4 GHz without the LNA for DM increases with bias current and has a value of -13, 14.5, and 21 dBm for 30, 50, and 80 mA, respectively. For the external modulation, $P_{in,1dB}$ increases with the EAM bias voltage and is equal to 13 and 18.9 dBm for -2 and -2.6 V, respectively.

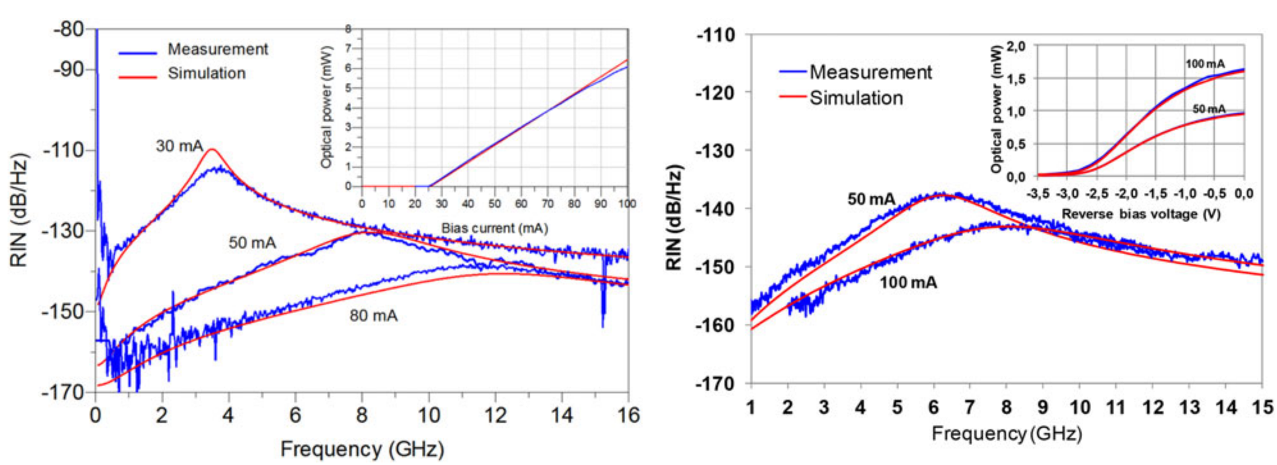

Fig. 1. Measured and simulated static response and laser RIN with DM (left) and EM (right).

https://doi.org/10.1017/S1759078715000586 Published online by Cambridge University Press

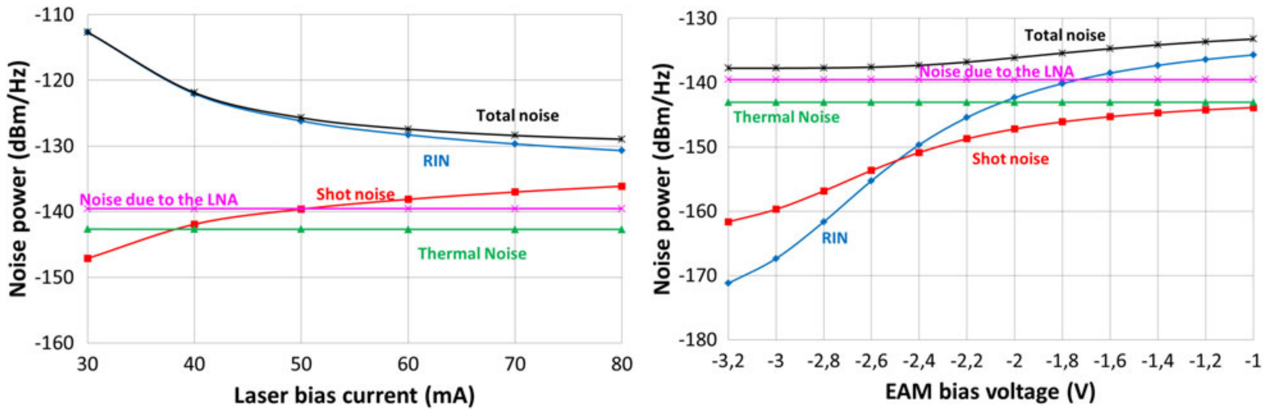

Fig. 2. Calculated noise powers with DM (left) and EM (right). $G_{RoF,\ DM} = [-24, -30, -31]$ dB for [30, 50, 80] mA, $G_{RoF,\ EM} = [-48, -49.5, -59.5]$ dB for $[-2, -2.4, -2.8]$ V, $G_{LNA} = 33$ dB and $NF_{LNA} = 3.5$ dB.

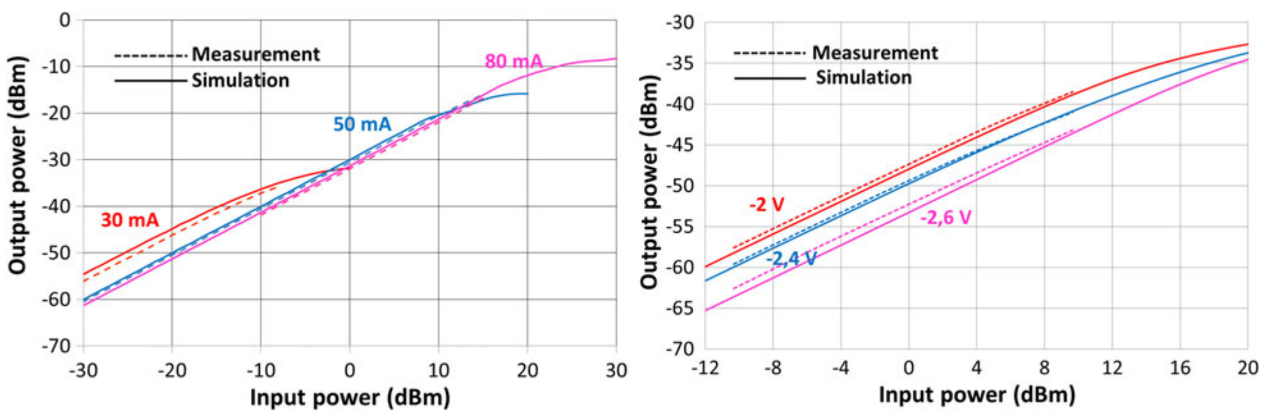

Fig. 3. Compression points of the RoF links with DM (left) and EM (right).

III. ROF SYSTEM PERFORMANCES

The transmission efficiency of an OFDM signal is evaluated by the EVM from the received constellation and the ideal one. The EVM of UWB centimeter-band standard is measured and simulated for the first band group with a Time Frequency Codes number 1 following the ECMA-368 standard. This standard exhibits a signal bandwidth of 528 MHz for each sub-band with total subcarriers of 128 and a data rate up to 480 Mb/s. For the UWB millimeter-band, the IEEE 802.15.3c standard is used which deals with a 512 total sub-carriers, a bandwidth of 1815 MHz and a data rate up to 6.16 Gb/s. The schematic blocks of RoF systems are described in Fig. 4. The measurement was performed only for the centimeter-band due to the setup simplicity. The OFDM signal is generated directly at an IF by an arbitrary wave generator (AWG). A variable attenuator and a broadband Radio Frequency amplifier were used to control the OFDM signal power. The EVM was calculated with a digital storage oscilloscope having a vector signal analysis solution.

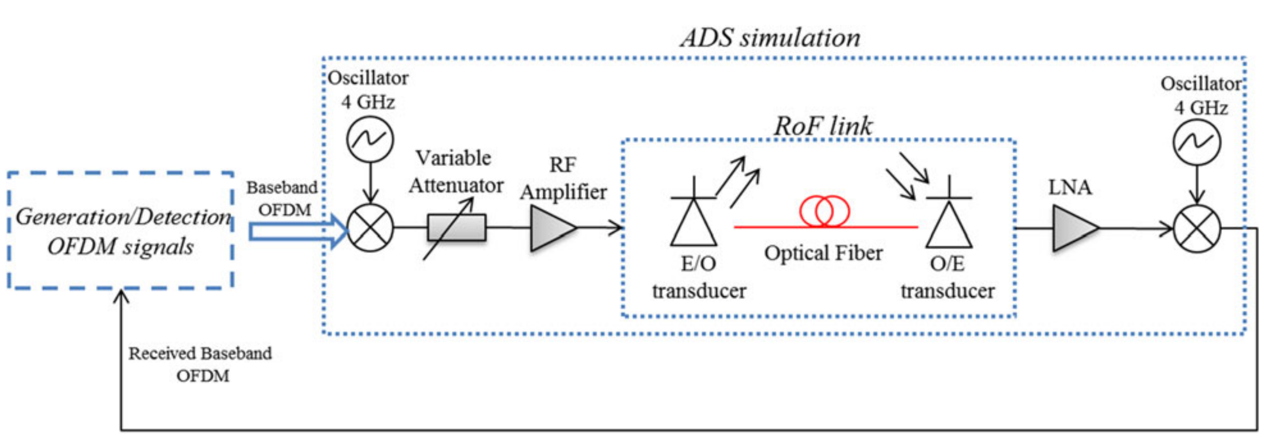

Fig. 4. Schematic blocks for OFDM signal transmission over fiber systems.

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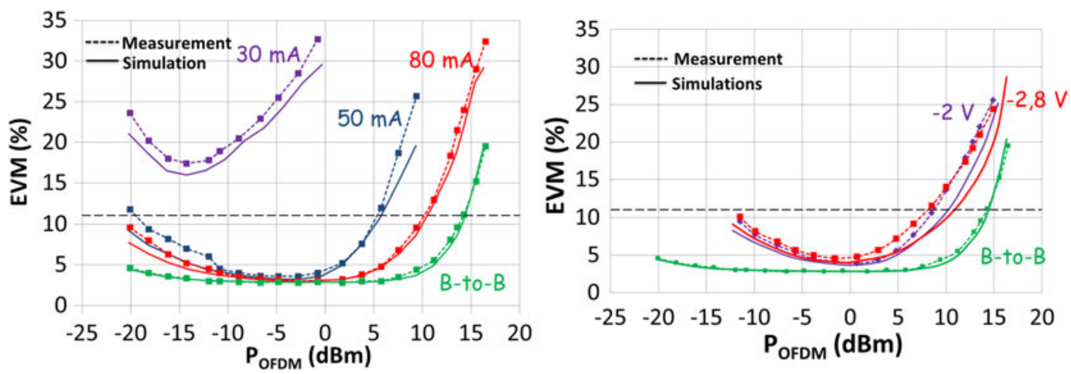

Fig. 5. Measured and simulated EVM versus P_{OFDM} for the B-to-B connection, DM (left) and EM (right) RoF systems – UWB OFDM signal of the centimeter band according to ECMA-368 standard.

The simulation is done within Advanced Design Systems (ADS) with the developed photonics models and with the existing modules of generation and processing of OFDM signal for the UWB centimeter-band. For the millimeter-band, ADS interface with Matlab is used for these functionalities.

The simulation is performed by envelope simulation for analog signal and data flow controller for digital part. Amplifiers were also characterized in frequency, noise and non-linearities, and implemented with ADS modules for simulations.

A) UWB centimeter-band standard

The band group 1 of the UWB OFDM spectrum is used with a data rate of 480 Mb/s and a 16QAM constellation. The spectrum is thus centered at a frequency of 3.96 GHz and constituted of three bands of 528 MHz. In this case, only one sub-band modulates the laser or EML. Before evaluation of the EVM with the photonic links, the reference EVM was determined for a back-to-back connection (B-to-B) consisting of the attenuator and input amplifier. This EVM is reported in Fig. 5 for measured OFDM power (P_{OFDM}) from −20 to 16 dBm (at the amplifier output). For power levels higher than 10 dBm, the EVM increases due to the amplifier gain compression. The realistic parameters of these attenuator and amplifier are used for simulation giving thus the same measured EVM values.

The EVM evaluations with the photonic links are represented in Fig. 5 and show a good agreement between measurement and simulation. These EVM are the average values of the three sub-bands. For the direct modulation, the results indicate a strong dependence of the EVM with laser bias current. A minimum EVM value of 17% is obtained for a bias current of 30 mA at P_{OFDM} of −14 dBm. This EVM value increases for lower P_{OFDM} due to the contribution of the different noise sources. As the DFB laser is biased near the threshold value, the optical signal is clipped causing distortion and EVM increase for higher P_{OFDM}. For bias currents of 50 and 80 mA, EVMs around 3% are obtained over 10 dB range power. The EVM increasing for P_{OFDM} below −10 dBm is related to the noise and for P_{OFDM} above 5 dBm is caused by the system compression. However, the input amplifier has an output P_{1dB} of 17 dBm but its contribution on EVM appears rather linked to a peak-to-average power ratio (PAPR) of the OFDM signal. As the amplifier P_{1dB} value is close to the RoF compression point for a bias current of 50 mA, the EVM degradation is more important due to the common contribution of the amplifier and RoF link nonlinearities.

For the external modulation, the EVM is estimated as a function of P_{OFDM} for a bias current of 50 mA and bias voltages of −2 and −2.4 V. For P_{OFDM} higher than 5 dBm, the EVM increases due to the RF amplifier P_{1dB}. For lowers P_{OFDM}, the EVM increases as much the modulator absorbs the light. Furthermore, increasing the bias current of the EML like in DM can enhance the dynamic range.

B) UWB millimeter-band standard

For the UWB millimeter band, the OFDM signal with the same constellation as before is used but with an analog bandwidth of 1.815 GHz and a data rate of 6.16 Gb/s. The central frequency of the OFDM signal is chosen at 4 GHz. Figure 6

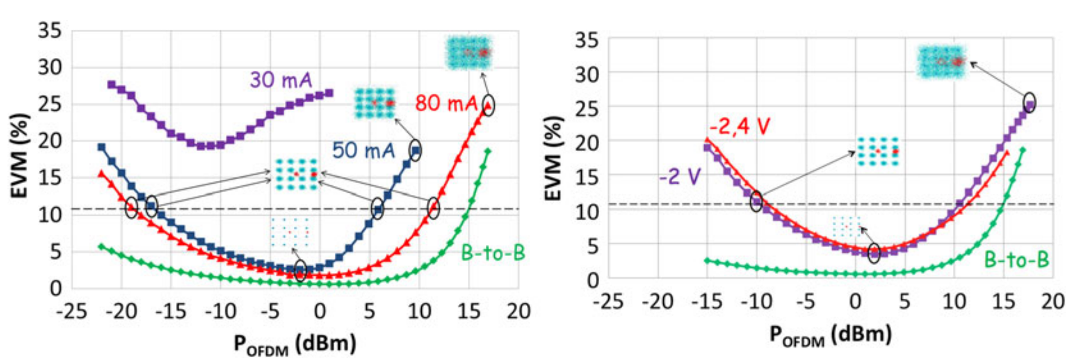

Fig. 6. Simulated EVM and constellations versus P_{OFDM} for DM (left) and EM (right) RoF systems with UWB millimeter-band following IEEE 802.15.3c standard.

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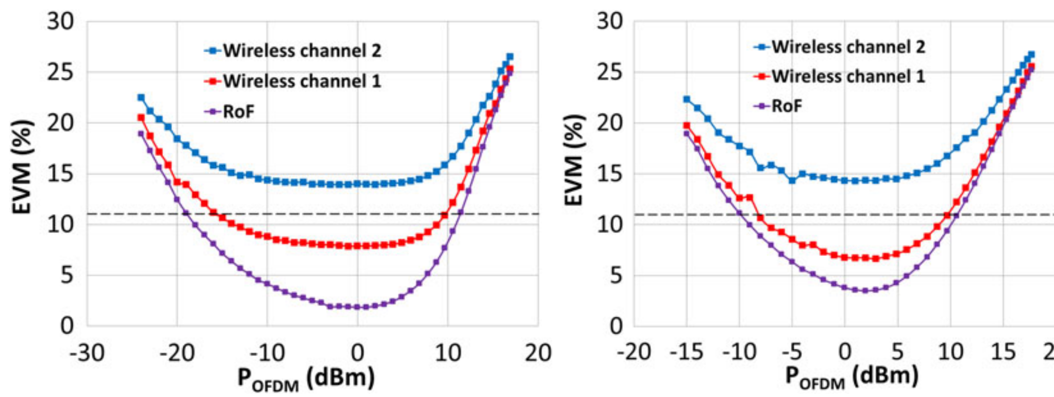

Fig. 7. Simulated EVM with two wireless paths for DM with a bias current of 50 mA (left) and EM with a bias voltage of −2 V (right).

reports the EVM values obtained by simulation for direct and external modulations for different bias conditions. It is shown a similar results than those obtained for a centimeter band standard. The difference is due to the AWG noise, which is not considered here, giving thus a lower value of the minimum EVM.

C) Discussions

The RoF links with DFB laser and EML can present closest performances depending on the bias conditions of the transducers and noise contribution. For direct modulation, the laser RIN and shot noise are the main noise contributions when the laser is biased far from its threshold. As the link gain for EM is low due to the EML attenuation and the insertion losses between the laser and electro-absorption modulator, the principal noise degradation is due to the receiver electronic circuits before −2 V. The use of electronic circuits with better performances permits to enhance the performances of RoF system with EML [12].

The increase of the signal bandwidth and data rate does not affect the EVM of the OFDM signal. This is due to the closed signal PAPR value which is equal to 9 for the centimeter-band standard and 11 for the millimeter-band standard. Then, the nonlinearities appear at the same order of power levels.

IV. WIRELESS CHANNEL EFFECT

The simulation setup is completed by the 60 GHz radio channel for indoor applications. It is characterized by high free-space attenuation and high-energy absorption by walls and obstacles. Thus, the number of significant reflection paths is reduced and the structure of such channel is composed principally by the direct path line-of-sight (LOS) and some low-order reflection paths where first and second orders are generally considered [13]. This clustering approach is based on Saleh–Valenzuela model with coefficients given in [14]. Two scenarios of the office LOS channel configuration are considered here. The difference between these scenarios is the *Tx*/*Rx* antenna orientations, which are 30°/30° for the channel 1 and 60°/60° for channel 2.

After photodetection, the OFDM signal is upconverted to 60 GHz band with ideal circuits. A distance of 5 m is used between antennas and only thermal noise is considered in the front-end receiver. Simulation results for the two scenarios are presented in Fig. 7 and show an increase of the EVM minimum. For channel 1, most of the transmission power is spread between the transmitter and the receiver through the LOS path. While for channel 2, the transmitted power is scattered on higher number of secondary Non-Line-Of-Sight paths, and hence more interferences are presents.

V. CONCLUSION

The developed photonic components coupling to ADS analog/digital co-simulation method are used to analyze performances of RoF to transmit OFDM signals. Modulation of DFB laser and EML with UWB centimeter and millimeter standards is compared by EVM evaluation as function of the signal power. It is shown that both modulation schemes can give the same EVM values depending on the biasing conditions regardless on the dominant noise sources. RIN and shot noise are the contributor sources for DM and the noise receiver front-end electronic circuits for EM. The increase of OFDM signal bandwidth from 528 to 1815 MHz has no effect on the EVM which is due to the closest PAPR value of these signals.

ACKNOWLEDGEMENT

The authors gratefully acknowledge Y. Chatelon from L2E, J-L. Polleux and C. Viana from ESYCOM ESIEE Paris and F. Van Dijk from III-V Lab for their measurement helps.

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