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Investigation of a WDM M-QAM RoF-RoFSO System

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Abstract- *The radio over fiber (RoF) technology combines the advantages of radio frequency (RF) and optical communication systems. Hybrid RoF and radio over free space optics (RoFSO) is a solution for the last mile access networks in urban areas and in areas where installation of RoF links is impractical and costly. In this work we introduce a 4-, 16- and 64- quadrature amplitude modulation (QAM) hybrid RoF-RoFSO communication system and investigated the inter-channel interference and the effects of atmospheric turbulence on the FSO section of the link.*

Keywords: *radio over fiber (RoF), radio over free space optics (RoFSO), inter-channel interference*

I. INTRODUCTION

During the last two decades, we have seen considerable growth in the number of users requiring access to high data rates [1]. Such an increase in the volume of the data rates is putting pressure on the existing radio frequency (RF) based communication networks, which has resulted in spectral congestions. In order to meet this challenge and ensure sufficient telecommunications networks resources for all at any times and any places, the services providers have considered the use of millimeter-wave (mmW) RF combined with optical fiber technologies, this option is one of the most attractive methods for fifth-generation (5G) wireless networks because of the huge bandwidth for high-speed mobile communications [2,3]. In radio over fiber (RoF) systems, the light carrier signal is modulated by the high-frequency RF signal for transmission over an optical fiber [4]. In RoF systems, modulation of the light sources is carried out internally or externally. The former is for low to medium data rates. The letter, which uses an external Mach-Zehnder modulator (MZM) or an electro-absorption-based modulators are intended for medium to high data rates [5].

The RoF technology offers a number of advantages including lower propagation loss (i.e. fiber), which is independent of the RF signal [6], a large bandwidth, immunity to the RF induced interference, low complexity and low power consumption. The RoF technology, is therefore, suitable for applications such as base-station to base-station, base station to mobile switching center, central hubs to home/offices for high quality video distributions and mobile broadband services [4,7]. However, the installation of RoF systems in urban areas is time consuming, costly and impractical in some situations due to geographical constraints and physical obstacles. Therefore, one possible solution to this would be the use of all-wireless radio over free space optics (RoFSO) technology, where the FSO section is compatible with optical fiber transmission in terms of all available bandwidth. In addition, RoFSO is more flexible than RoF with significantly reduce installation costs in urban areas, see Fig. 1 [8,9].

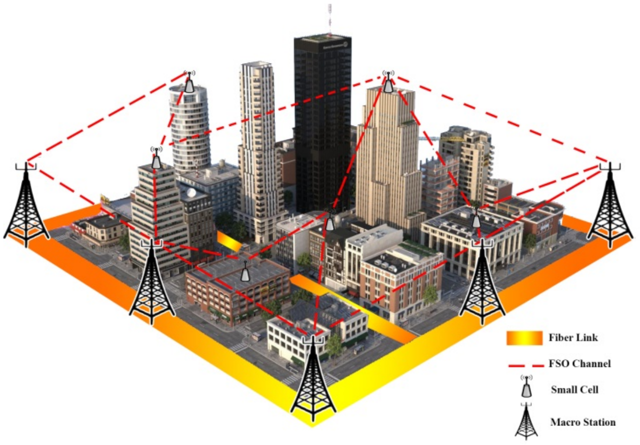


Figure 1: Schematic of RoF-RoFSO system in urban areas

There are a number of challenges in RoF-RoFSO systems that need addressing including fiber dispersion, laser and fiber nonlinearity, data rates, transmission spans and interference in multi-channel systems. In [10], the effects of weather conditions on the FSO link employing 4- and 16- quadrature amplitude modulation (QAM) with Orthogonal frequency-division multiplexing (OFDM) modulation was reported. They showed that a hybrid mmW and FSO link offer improved error vector magnitude (EVM) by 3% compared with mmW or FSO. In [11], a 16-QAM parallel RF-FSO link under a dust condition was experimentally investigated showing that the EVM for FSO is higher than the acceptable range for the visibility of < 50 m. Note, dust has no effect on the RF links because the longer wavelength, which is significantly longer than dust particle size. The effects of atmospheric turbulence on hybrid optical fiber and FSO systems have been studied. In [8], it was shown that higher power degraded the link performance because of nonlinear distortion and higher bit per symbol are more susceptible to the atmospheric turbulence. In addition, higher-order QAM is more susceptible to turbulence [8]. The narrower signal bandwidth leads to improved EVM values under turbulence. As per Nguyen et al. [12] results, the EVM of a 64-QAM hybrid RoF-RoFSO link under moderate turbulence for 5, 20 and 50 MHz signal bandwidths is 2.7, 4.1 and 9%, respectively. Both optical bandpass filters and electrical equalizers have been used in hybrid RoF-RoFSO to improve system performance. Bandpass filter reduced the EVM about 2% and the electrical equalizer decreased log(BER) about 0.7 [9,2,13]. An adaptive equalizer (AE) can improve system performance by removing the linear errors from the modulated signal using a finite impulse response filter [14].

Multi-channel systems are used to increase the system bandwidth (i.e. data throughput). In RoF, the two most widely adopted multiplexing schemes are wavelength division multiplexing (WDM) and subcarrier multiplexing (SCM). In SCM, a single optical carrier is used for transmission and is more sensitive to the noise [15]. In this work, WDM is adopted in a multi-channel M-QAM RoF-RoFSO system and we investigate the effect of atmospheric turbulence (on FSO link) and the inter-channel interference.

The rest of the paper is organized as follows. Section II provides a brief description of turbulence modeling and in section III system structure is explained. Section IV describes the simulation parameters and results and finally, section V provides concluding remarks.

II. Turbulence Modeling

Turbulence is due to the refractive index variation of air, which affects both amplitude and phase of the optical wave-front thus resulting in fluctuation of the received optical intensity level and dispersion [16]. The most important predictor of the turbulence effect is the refractive index structure parameter (C_n^2), which describes the variation of refractive index [17]. Gamma-gamma distribution model is most widely used for weak to strong turbulence conditions with the probability density function (PDF) of the received light intensity given by [18]:

$$P(I) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{I}{< I >}\right)^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta\left(\frac{I}{< I >}\right)} \quad (1)$$

$$\alpha = \left\{\exp\left[\frac{0.49\sigma_l^2}{(1+1.11\sigma_l^{\frac{12}{5}})^{\frac{7}{6}}}\right]-1\right\}^{-1} \quad (2)$$

$$\beta = \left\{\exp\left[\frac{0.51\sigma_l^2}{(1+0.69\sigma_l^{\frac{12}{5}})^{\frac{5}{6}}}\right]-1\right\}^{-1} \quad (3)$$

where Γ is the Gamma function, K_n is the modified Bessel function of the 2nd kind of order n, α and β are the Gamma-Gamma distribution parameters describing large and small scale scintillation respectively.

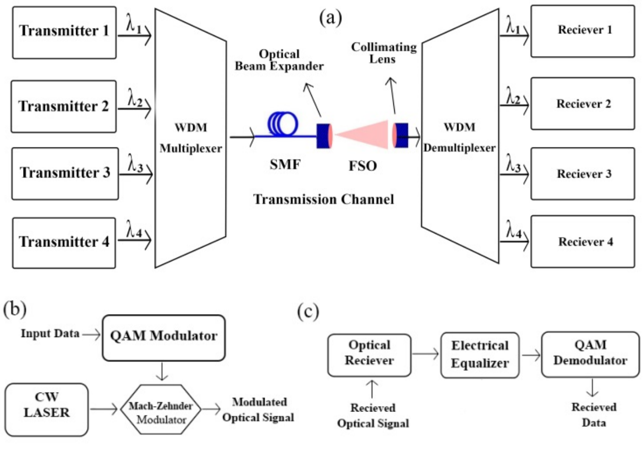


Figure 2: Block-diagram of hybrid RoF-RoFSO system: (a) a 4-channel WDM RoF-FSO system, (b) transmitter and (c) reciever

III. Proposed System

The schematic diagram of the proposed WDM M-QAM RoF-RoFSO system is shown in Fig. 2. It is composed of three parts of the transmitter, channel and the receiver. In each transmitter, the binary data streams are converted to M-QAM prior to external modulation of the laser beam using MZM, see Fig. 2(b). The outputs of the MZMs are multiplexed in the wavelength domain using a WDM for transmission over a single mode fiber (SMF). The output of the SMF is launched into a FSO channel using an optical beam expander. At the receiver, a combination of collimating lenses and WDM demultiplexer are used to separate different optical wavelengths. An optical receiver with a decision feedback equalizer and QAM demodulators are used to recover the transmitted data stream. Note, in order to reduce the system cost no optical amplifiers are used.

The proposed system is simulated and its performance is evaluated in terms of the BER as a function of the EVM, which is given by [12]:

$$BER_{M-QAM} = \frac{2}{log_2(M))}\left(1-\frac{1}{\sqrt{M}}\right) \times erfc\left(\sqrt{\frac{3}{2(M-1)}\times\frac{1}{EVM^2}}\right) \quad (4)$$

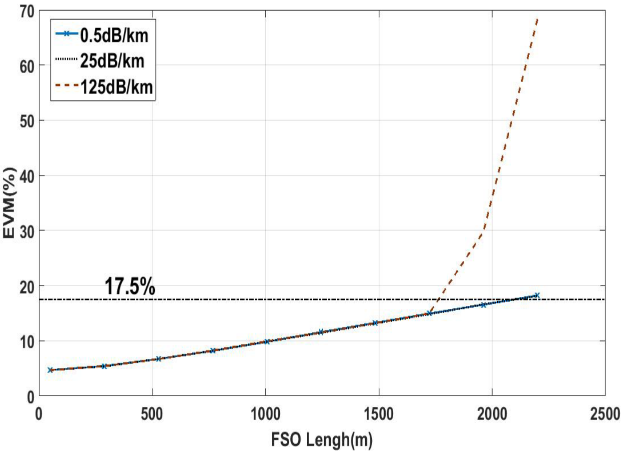
IV. Simulation Results

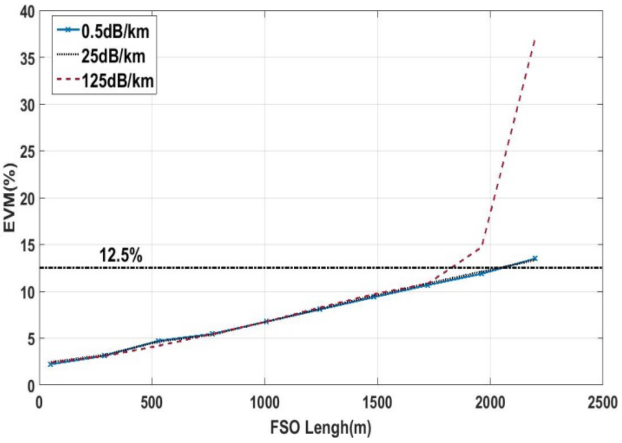
In this section, a 4-channel 25GHz RoF-RoFSO system is simulated for 4-, 16- and 64-QAM at a bit rate of 10 Gbps. The key system simulation parameters are shown in Table 1. Fig. 3 shows the EVM as a function of the FSO link span under turbulence i.e., $C_n^2 = 1.5 \times 10^{-15}\, m^{-\frac{2}{3}}$ for the M-QAM with various FSO loss. Also shown are the EVM levels for the 3rd generation partnership project (3GPP) specifications. At EVM values of 17.5, 12.5 and 8% the maximum link spans for the FSO are 2100, 2050 and

1050 m for 4-, 16- and 64-QAM (with 0.5 or 25 dB/km FSO loss), respectively.

Table 1 Simulation parameters

Parameter	Value
Bit rate	10 Gbps
RF carrier frequency	25 GHz
Laser output power	0 dBm
FSO channel length	800 m
FSO loss	25 dB/km
FSO Tx/Rx aperture diameters	24mm
FSO beam divergence	2 mrad
refractive Index structure parameter (C_n^2)	$1.5 \times 10^{-15}\mathrm{m}^{-\frac{2}{3}}$
SMF length	10 km
SMF loss	0.2 dB/km
SMF dispersion	16.75 ps/nm/km
WDM filter type	2nd order Bessel
WDM bandwidth filter	10 GHz
PD responsivity	1 A/W
number of DFE taps	9





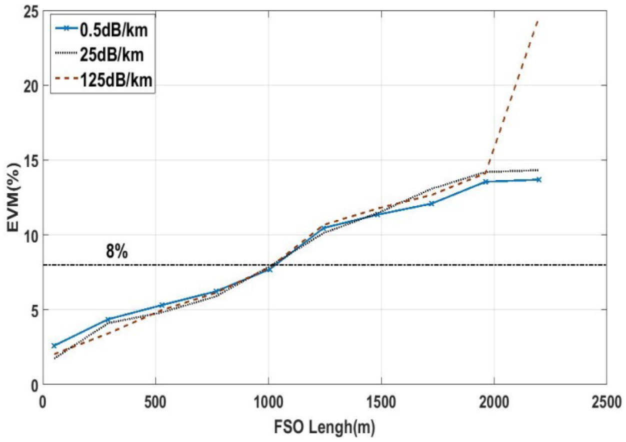
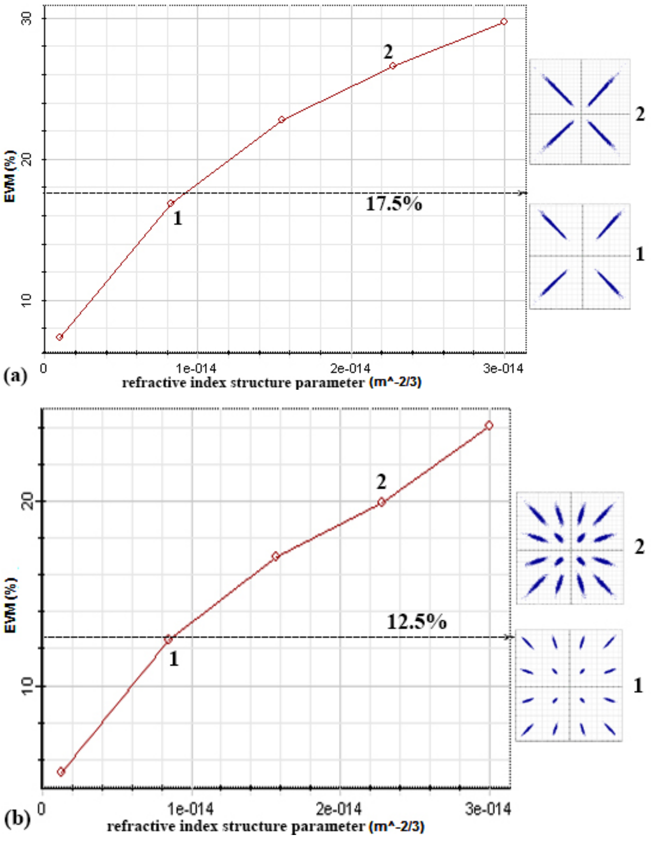


Figure 3: Simulated EVM versus FSO channel length for 10 km long SMF and $\boldsymbol{C_n^2 = 1.5 \times 10^{-15}\, m^{-\frac{2}{3}}}$ for: (a) 4-QAM, (b) 16-QAM and (c) 64-QAM

Fig. 4 shows the simulated EVM against C_n^2 for the proposed system with 800 m and 10 km of FSO and SMF link spans, respectively. As is shown, the EVM values drop with higher orders of QAM, where lower turbulence is tolerated i.e., C_n^2 of $9.2 \times 10^{-15}\, m^{-\frac{2}{3}}$, $8.7 \times 10^{-15}\, m^{-\frac{2}{3}}$ and $5 \times 10^{-15}\, m^{-\frac{2}{3}}$ are for 4-, 16- and 64-QAM at EVMs of 17.5, 12.5 and 8%, respectively. Also shown are the constellation diagrams at the minimum and maximum values of EVM, which illustrates increased impairment due to turbulence at higher orders of QAM.



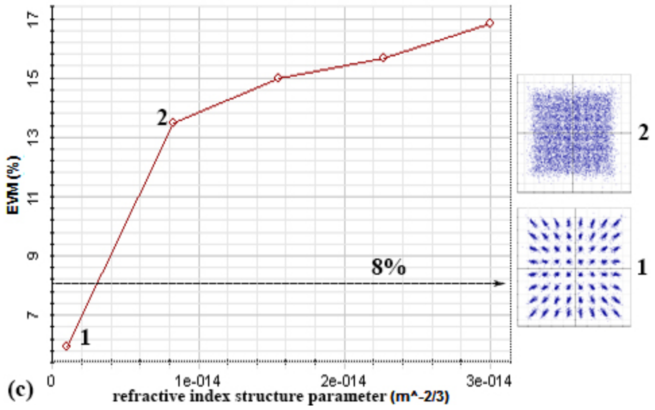
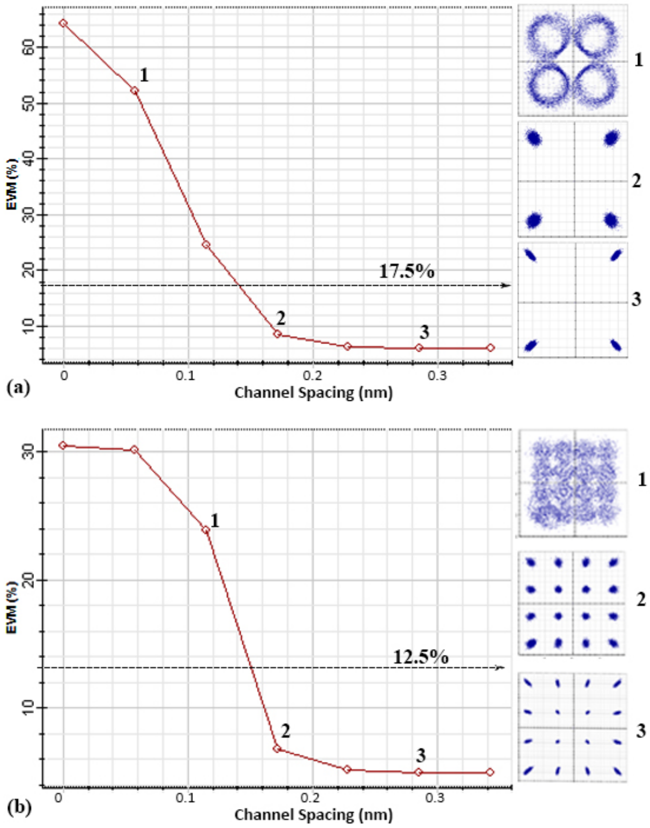


Figure 4: Simulated EVM versus refractive index structure parameter for 800m of FSO length and 10km of SMF for: (a) 4-QAM, (b) 16-QAM and (c) 64-QAM

Finally, Fig. 5 depicts the simulated EVM as a function of the channel spacing (i.e., WDM) for the proposed RoF-RoFSO system. As shown for the EVM limits of 17.5, 12.5 and 8 % the required channel spacing is 0.14, 0.15 and 0.17 nm for 4-, 16- and 64-QAM, respectively. Note, the influence of adjacent channels can be ignored by increasing the channel spacing to 0.23, 0.25 and 0.29 nm for 4-, 16- and 64-QAM, respectively. In this system, the number of channels is not very high and channel spacing can be taken to be sufficiently large and therefore interference can be ignored. Also shown are the constellation diagrams for three values of EVM, which illustrates increased imperilments due to channel spacing at higher orders of QAM.



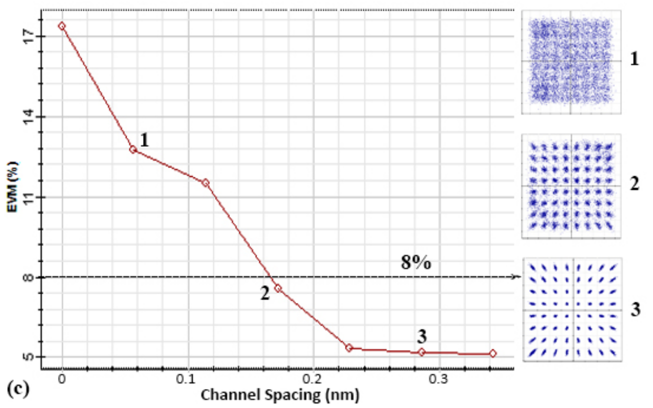


Figure 5: Simulated EVM versus channel spacing for 800m of FSO channel length, 10km of SMF length an $\boldsymbol{C_n^2 = 1.5 \times 10^{-15}\ m^{-\frac{2}{3}}}$d, a) 4-QAM. b) 16-QAM, c) 64-QAM

V. CONCLUSIONS

We introduced a hybrid 4-channel 25 GHz RoF-RoFSO system and investigated the effects of turbulence, FSO channel length and channel spacing for the link with 4-, 16- and 64-QAM at a bit rate of 10 Gbps. EVM was used to compare simulation results with the summary of results shown in Table 2.

Table 2: Simulation result

Parameter	**4-QAM**	**16-QAM**	**64-QAM**
Maximum acceptable C_n^2 $(m^{-\frac{2}{3}})$	9.2×10^{-15}	8.7×10^{-15}	5×10^{-15}
Maximum acceptable FSO range (m)	2100	2030	900
Channel spacing without interference (nm)	0.23	0.25	0.29

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