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Effect of Nonlinear Phase Variation in Optical Millimetre Wave Radio over Fibre Systems

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ABSTRACT

In this paper, we propose an optical millimetre wave radio-over-fibre (mm-wave RoF) system that uses a dual drive Mach Zehnder modulator (DD-MZM), which is biased at the maximum transmission biasing point, to generate an optical double sideband-suppressed carrier. The input to the DD-MZM are binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 8-phase shift keying (8-PSK) and 16-qaudrature amplitude modulation (16-QAM) schemes at a carrier frequency of 5 GHz with a rate of 2 Gsym/s and a local oscillator of 15 GHz obtain an mm-wave RoF signal at 30 GHz. We evaluate the generation and performances of the proposed system in terms of the power penalty, the error vector magnitude and the bit error rate (BER). Impairments including the self-phase modulation, chromatic dispersion and attenuation are considered when modelling the single mode fibre (SMF) based on the symmetrical split step Fourier method. We show that the power efficiency improves in the optimum region on average by ~11 dB, ~11 dB, ~12 dB and ~18 dB for BPSK, QPSK, 8-PSK and 16-QAM, respectively for the same optical launch power over 10, 30 and 50 km of SMF compared to the linear and non-linear regions.

1. Introduction

Existing radio frequency (RF) based wireless communication systems use the frequency range of 0.7 - 2.6 GHz with a maximum achievable distance of over a few kilometres (over 200 m in urban areas at 2.6 GHz, and up to 5 km at 870 MHz) [1].During heavy rain, the coverage distance is rather limited with a typical attenuation of~7 dB/km [1].

In future wireless access networks based on 5G, radio over fibre (RoF) techniques are seen as a reliable and cost-effective solution for the distribution of data [2,3]. In such scenarios, the unlicensed millimetre (mm)-wave frequency band for signal generation and distribution over a fibre link offer increased capacity. In [4] a single-input single-output photonic wireless link operating at 237.5 GHz with 100 Gbps data transmission over a 20 m of free space channel has been demonstrated. Generation of the mm-wave signal in the optical domain has attracted attention in recent years [5-8]. The wide bandwidth available in the optical domain and the non-linear characteristics of the electro-optic modulators, namely the dual drive Mach Zehnder modulator (DD-MZM) enables the generation of optical mm-wave signal for transmission over a long span. Optical mm-waves can be generated in a number of ways including (i) direct modulation of a laser, which is the simplest method for data rates below several Gb/s with a transmission span <100 km. However, laser chirping degrades the quality of transmitted signal particularly in long haul transmission spans [9,10]; (ii) harmonic generation, which uses frequency modulation – intensity modulation (FM-IM) to generate a wide range of optical mm-wave frequencies [11]. However, the latter scheme is rather complex to implement requiring several electro-optic devices and modulators [11]; (iii) the optical heterodyne method, which is mostly used with wavelength division multiplexing (WDM) with a wavelength spacing equivalent to the optical mm-wave frequency and requiring two lasers with identical linewidths [12]. However, the heterodyne method is strictly limited to the optical mm-wave frequency band and it requires synchronisation of the laser sources; and (iv) the external modulation (EM) technique, which is seen as one of the simplest for generating the optical mm-wave at high frequencies up to 40 GHz with lower phase noise[13]. In [14], the X-cut DD-MZM was proposed for optical mm-wave generation where the optical waveguide is in an equal distance from the RF ports, thus cancelling out the chirping effect. Unlike optical heterodyne systems, there is no requirement for the optical phase locking at EM.

In the literature, most research on optical mm-wave schemes are focused on generation with very little on the evaluation of performance metrics such as power penalty (PP), the error vector magnitude (EVM) and the bit error rate (BER) performance for different modulation schemes and a range of transmission spans [15]. The data modulated onto the optical mm-wave carrier is the major source of concern since it requires sufficient signal to noise ratio (SNR) at the receiver. The required SNR of course depends on the system being adopted and will have a direct effect on the performance metrics. In [8], the generation of optical mm-wave based on the optical heterodyne method over a 42 km of SMF was reported. However, limitations of the optical heterodyne method and PP associated with the system were not investigated.

In [16], a bidirectional optical mm-wave RoF utilising two MZMs to generate the optical mm-wave was reported. In [8] and [16], no analysis on the system performance metrics (i.e., the maximum link span, and EVM or PP) were provided. A tuneable phase shift method using a notch filter and a polarisation-maintaining fibre Bragg grating (PM-FBG) was introduced in [17] with no supporting data analysis.

Investigation of the generated frequency harmonics in an optical mm-wave RoF systems is essential. This is because the presence of higher order frequency harmonics (i.e,. 1st and 2nd order harmonics) affects the magnitude of the spectral response of the RF component. Thus, the need for characterisation of RF components in terms of PP, EVM and BER is required. In addition, the fibre linear impairments such as the chromatic dispersion (CD), the fibre attenuation and the non-linear fibre impairments such as the self-phase modulation (SPM) are not studied. Mm-wave generation using EMs based on different modulation techniques such as double-sideband (DSB), single-sideband (SSB), and optical carrier suppression (OCS) have been reported [18-20], but there is a lack of experimental comparison and investigation at the system level, especially for multiple-channel and ultra broad-band systems up to 2.5 Gb per channel. In EM schemes the modulator is biased at a particular operating point. By appropriately selecting the biasing point it is possible to suppress the optical carrier with the majority of the power (>60 %) being transferred to the sideband components, thus resulting in an optical double sideband suppressed carrier (ODSB-SC).

In [21], the nonlinearity of SMF, namely SPM and cross-phase modulation (XPM) were simulated for a subcarrier multiplexed (SCM) RoF system. In the simulated SCM-RoF model [21], the variation of optical modulation index (OMI) changes the magnitude response of the detected RF signal due to SPM and XPM effects. However, in this approach no optical mm-wave carriersignal is generated and no investigation of the SPM effect has been carried out. The optical XPM compensation for a coherent optical orthogonal frequency-division multiplexing (CO-OFDM) scheme for a WDM system has been simulated in [22] using the electrical low-pass filter (LPF), phase modulator (PM) and analogue-to-digital convertor (ADC). However, the EVM or PP and BER of the system are notinvestigated for a range of transmission spans. In [23], the stimulated Brillouin scattering (SBS) effect, but not the SPM effect, has been studied for the optical mm-wave RoF system using the EM method.

In this paper, we propose an optical mm-wave RoF system by using EM operating at 30 GHz. DD-MZM is biased at the MATB point to generate ODSB-SC from a local oscillator at 15 GHz. For the first time, we investigate the relation between PP and SPM and verify it by comparing the non-linear phase variation obtained from simulation with the predicted non-linear phase. We simulate the effect of SPM on the RF component at 5 GHz for the optical mm-wave RoF system and investigate a number of performance metrics including PP, EVM and BER for BPSK, QPSK, 8-PSK and 16-QAM schemes at a rate of 2 Gsym/s. The remaining of the paper is organised as follows; in section 2 the system description is discussed and simulated impairments are highlighted. In section 3 the non-linear phase analysis is presented. In section

4, simulation results are presented. Finally, section 5 concludes the findings of the investigation

2. System Description

The fibre impairments in RoF systems are seen as serious challenges in terms of the received signal quality and the maximum achievable transmission distance. The linear fibre impairments are CD, which results in pulse extension and inter-symbol interference (ISI), and attenuation [24]. Whereas the non-linear fibre impairments such as SBS [25, 26], stimulated Raman scattering (SRS) [27], four wave mixing (FWM) [28], and SPM and XPM [29]are transmission link span and power dependent. In this work we are focusing on CD under linear impairments and, SPM and SBS under nonlinear impairments, since the proposed scheme is not RoF WDM.

Fig. 1 depicts the schematic diagram of proposed optical mm-wave RoF system, which is adopted for simulation in the MATLAB® domain. All the system parameters adopted for simulation are depicted in Table I.

Here DD-MZM EM is adopted to generate the most stable optical mm-wave signal and achieve the most compact topology [30,31].

A distributed feedback (DFB) laser is used to generate a continuous wave (CW) signal Ei(t) at 1550 nm with 0 dBm (1 mW) of optical power, which is then applied to the DD-MZM with an output given by [32]:

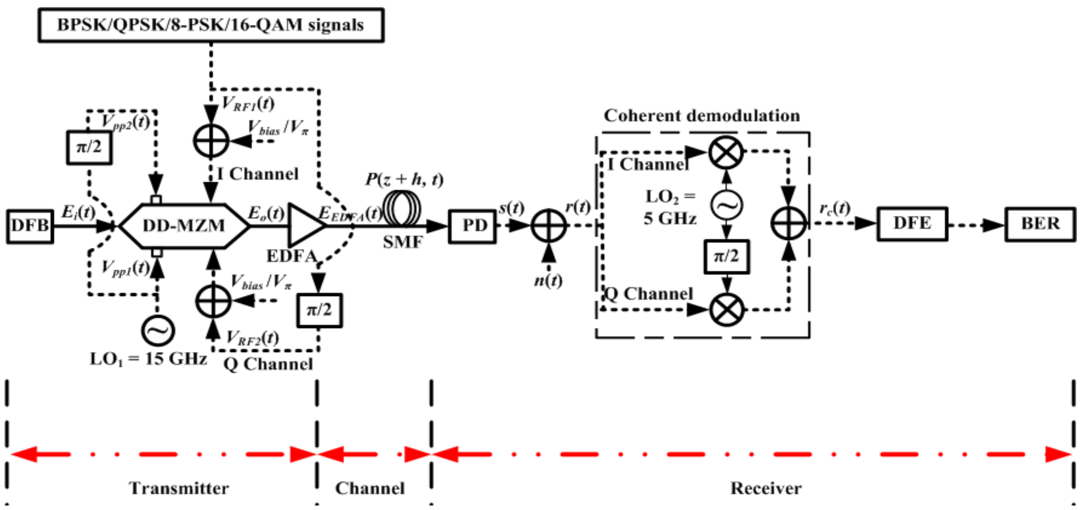

Figure 1: A block diagram of the simulated model. Abbreviations, DFB: Distributed feedback laser, DD-MZM: Dual-drive Mach-Zehnder modulator, OLP: Optical launch power, LO: local oscillator, SMF: Single mode fibre, PD: Photodetector, DFE: Decision feedback equaliser, BER: Bit error rate, Optical signal: ——►, Electrical signal:- - - -►

TABLE I

INCLUDEDQUANTITIESIN THE SIMULATION

PARAMETER	SYMBOL	VALUE
Data rate	R_s	2 Gsym/s
DFB operating wavelength	λ	1550 nm
DFB optical output	Ei(t)	1 mW
Local oscillator	LO_1, $V_{pp}(t)$ and $-V_{pp}(t)$	15 GHz, 1 V
Electrical modulated data	$V_{RF1}(t)$, $V_{RF2}(t)$	5 GHz, 1 V
Bias voltage	V_{bias}	3.6 V
Switching voltage	V_π	4.6 V
Optical launch power	EDFA, P(z,t)	-15 dBm to 15 dBm (0.0316 mW to 31.6227 mW)
Single mode fibre	SMF	10 km, 30 km and 50 km
Attenuation	α	0.2 dB/km
Dispersion	D	17 ps/km×nm
SMF non-linear refractive index	n_2	2.2 × 10-20 m2/W
Photodetector responsivity	R	0.6 A/W

$$E_o(t)=\frac{E_i(t)}{2}\left[\begin{array}{l}\exp\left(j\pi\left(\dfrac{V_{pp1}(t)+V_{bias}+V_{RF1}(t)}{V_\pi}\right)\right)\\+\exp\left(j\pi\left(\dfrac{V_{pp2}(t)+V_{bias}+V_{RF2}(t)}{V_\pi}\right)\right)\end{array}\right] \quad (1)$$

where $V_{PP1}(t)$ and $V_{PP2}(t)$ are the local oscillator (LO_1) signal and its 90^0 version, V_π is the switching voltage at 4.6V that introduces π radian phase shift in DD-MZM, and $V_{RF1}(t)$ and $V_{RF2}(t)$ at 1V, respectively represent the in-phase and the quadrature components of BPSK, QPSK, 8-PSK and 16-QAM RF signals.

In order to achieve V_π the bias voltage V_{bias} must be set at 3.6 V when using a 1 V_{pp} signal at the LO_1.

As a consequence, the MATB point is achieved for DD-MZM, which is essential for generating ODSB-SC.

In Eq.(1), the ideal transfer function of the DD-MZM excludes the optical insertion loss.

Values of V_{bias} and V_π are adopted from the data sheet for Thorlabs LN86S-SC-40 Gb/s MZM.

This commercially available X-cut DD-MZM can be considered chirp free due to the symmetrical locations of waveguides with respect to the RF electrodes.

The optical spectrum at the output of DD-MZM Eo(t) is depicted in Fig. 2, which shows the ODSB-SC at wavelengths (frequencies) of 1549.88 nm (193.485 THz) and 1550.120 nm (193.515 THz) with 30 GHz spacing.

The RF components are modulated on both sides of the optical carrier.

The erbium doped fibre amplifier (EDFA) is modelled as a gain to provide OLP at the output of DD-MZM, which is fed into the SMF as depicted in Fig. 1.

In our simulation, we have not considered the noise due to EDFA since the main focus of the investigation in the proposed setup is the effect of the SPM and the non-linear phase variation on the 5 GHz RF component.

In this work, we have adopted the well-known symmetrical split step Fourier method for SMF, (see the flow chart in Fig. 3).

The linear and non-linear fibre impairments in the SMF are modelled based on the following equations [33-35]:

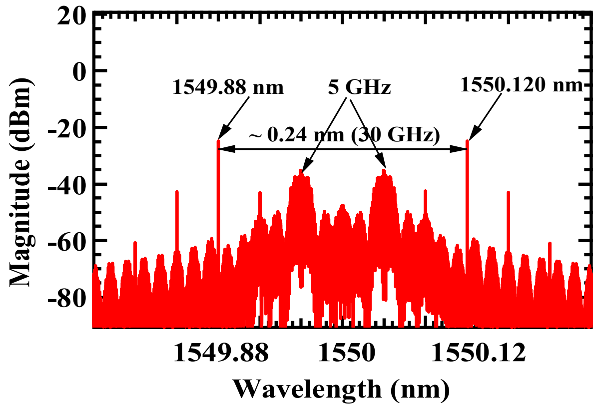

Figure 2: Optical spectrum of the DD-MZM output presenting ODSB-SC to generate 30 GHz OMMW carrier, E0(t)

$$\frac{\partial P(z,t)}{\partial z}-\check{D}(z,t)=-\check{N}(z,t) \quad (2)$$

$$\check{D}(z,t)=-\frac{j}{2}\beta_2\frac{\partial^2 P(z,t)}{\partial T_o^2}+\frac{\alpha}{2}P(z,t) \quad (3)$$

$$\check{N}(z,t)=j\frac{2\pi}{\lambda}n_2\left|P(z,t)\right|^2 P(z,t) \quad (4)$$

where P(z,t) is the electric field amplitude, z is the fibre length, t is propagation time, Ď is the linear operator for the 2nd order SMF dispersion and attenuation, Ň is the nonlinear operator for SPM, β2 is the second order dispersion coefficient, To is the initial propagation time, α is the SMF attenuation coefficient of 0.2 dB/km, λ is the optical wavelength and n2 = 2.2 × 10-20 m2/W [36] is the non-linear refractive index of SMF. In Eq. (2) the evolution of linear operator representing dispersion Ď and the non-linear operator Ň representing SMF impairment in which SPM are included. In Eq.(3) and (4) the linear and the non-linear operators are determined separately and are assumed to be statistically independent. The model for the SMF can be improved by including the effect of the fibre nonlinearity at the middle of the segment rather than at the segment boundaries, which is given as [35, 37, 38]:

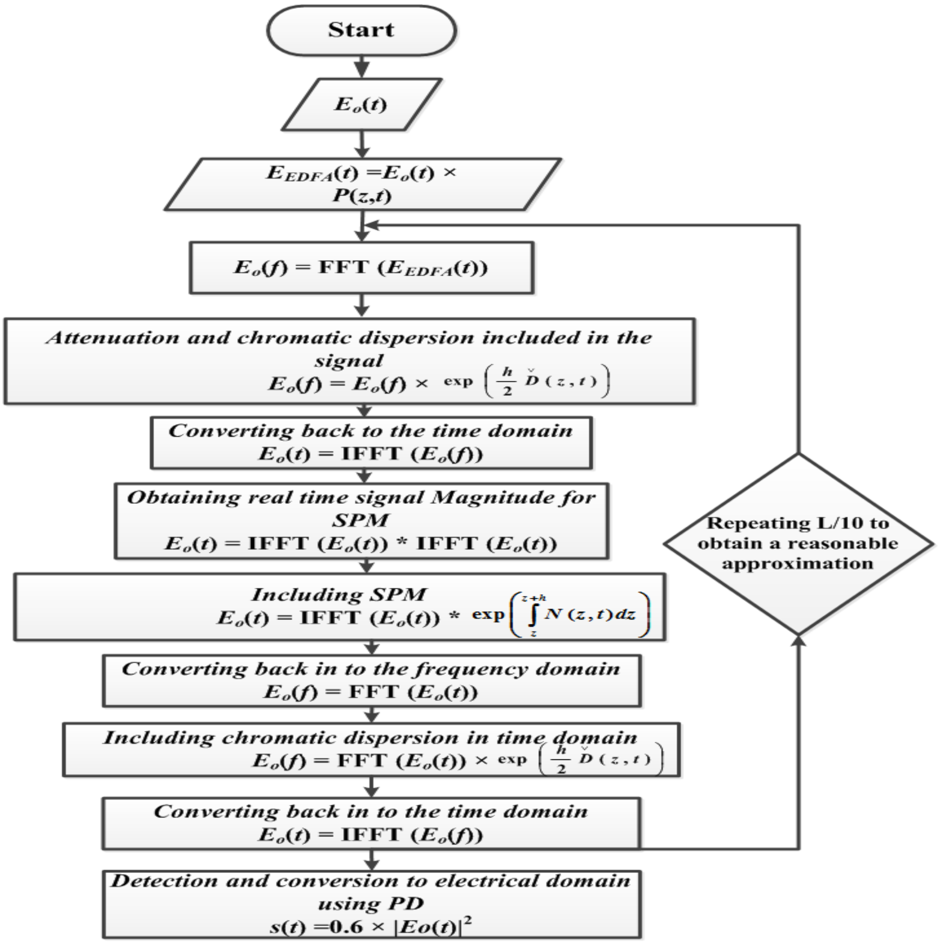

Figure 3: Flow chart of the simulated split step Fourier method for SMF

$$P(z+h,t) = \left[\exp\left(\frac{h}{2}\right) \quad (z,t) \times \exp\left(\int_z^{z+h} N(z,t)dz\right) \times \exp\left(\frac{h}{2}\right) \quad (z,t)\right] P(z,t) \qquad (5)$$

where h is the step size. Using Eq.(5), we could achieve the closet possible results to the experimental data as given in [34]. In the simulated model, the optical loss due to the fibre splicing is not included. Therefore, a power difference of ~2 – 3 dB is expected in comparison to the practical setup. The output of the SMF is then applied to the PD using the square law detection scheme. The magnitude response of the PD output s(t) is illustrated in Fig. 4.

The additive white Gaussian noise (AWGN) n(t) due to the PD, DD-MZM and the LO1is added to s(t). The AWGN channel is given as [39]:

$$\frac{E_s}{N_0} = 10\log_{10}\left(0.5\left(\frac{T_{sym}}{T_{samp}}\right)\right) + SNR$$
$$= -3\text{ dB} + 10\log\left(\frac{T_{sym}}{T_{samp}}\right) + SNR$$

$$\left(\frac{E_b}{N_0} + \log_{10}(N)\right) = \frac{E_s}{N_0} \qquad (6)$$

where E_s is the energy per symbol, N_0 is the noise figure, T_{sym} is the symbol period, T_{samp} is the sampling period, E_b is the energy per bit and N is the number of bits in the simulation.

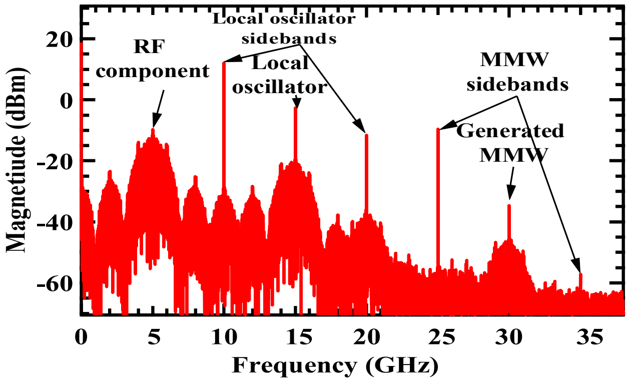

Figure 4: Electrical spectrum at the output of the PD, s(t), Output illustrating RF components, local oscillator and the generated mm-wave for BPSK at 30 km SMF, OLP = 0 dBm at 30 km.

The output of the AWGN channel r(t) is then coherently demodulated by a local oscillator (LO2) operating at 5 GHz with an amplitude of 1 V, (see Fig. 1). Following coherent demodulation at 5 GHz the phase of the data $r_c(t)$ is measured in radians and its average value corresponding to a particular OLP is obtained. The coherently demodulated signal is equalised using a decision feedback equaliser (DFE) by adopting the least mean square (LMS) algorithm with the 5-tap delay. Finally, the recovered data bits are passed through a BER tester (BERT) symbol-by-symbol.

3. Non-Linear Phase Analysis

The non-linear phase variation in the proposed optical mm-wave RoF system is the result of the SPM effect. Such non-linear phase variations obtained from the simulated model is illustrated in Fig. 5, which shows the simulated average non-linear phase variation at $r_c(t)$ just after the coherent demodulation. The plot shows that the non-linear phase decreasing with increasing the launch power reaching the minimum region and then increasing with the launch power for BPSK and all three SMF spans.

The non-linear phase variation can be measured at any particular fibre distance z independent of the simulated model presented in Fig. 6 as given by [37, 39]:

$$\phi_{\mathrm{NL}}(z,t) = -\frac{1-\exp(-\alpha z)}{\alpha}\frac{2\pi}{\lambda} n_2 \left|P(z,t)\right|^2 \tag{7}$$

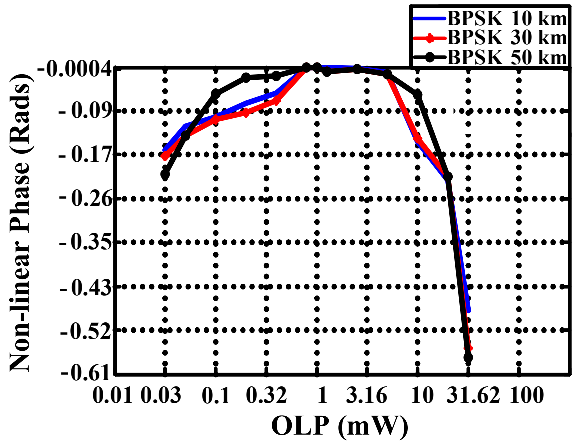

Figure 5: Average nonlinear phase variation in OMMW-RoF system with BPSK modulation scheme using nonlinear phase equation

Equation (7) indicates that the magnitude of the non-linear phase is directly proportional to the square of the OLP. The negative measured phase, due to the exponential term in Eq. (7), which is always a positive value and less than 1, results in negative non-linear phase variation. Note that the non-linear phase cannot be zero as long as |p(z,t)|2 ≠ 0. Fig. 6 illustrates predicted and simulated non-linear phase variations from Eq. (7) as a function of OLP for BPSK at a 30 km SMF span, showing a good agreement with a maximum difference of ~0.035 – ~0.05 rad. For fibre spans of 10, 30, and 50 km, the minimum non-linear phase values were obtained at a power range of ~0.30 mW to ~3.14 mW. Increasing the OLP level using EDFA to ~3.14 mW will result in reduced non-linear phase. However, beyond OLP of 3.14 mW the non-linear phase variation is due to the fibre non-linear Kerr effect which will result in increased SPM effect.

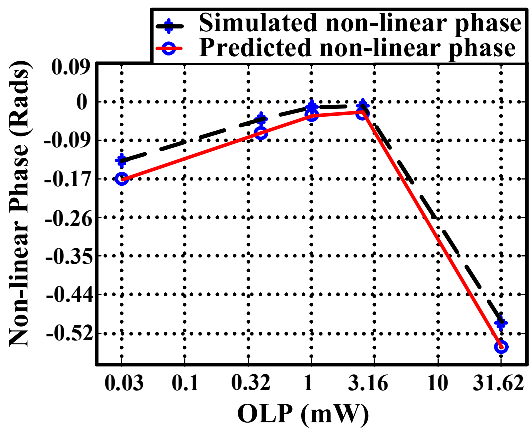

Figure 6: Predicted and simulated average nonlinear phase variations in OMMW-RoF system with BPSK modulation scheme using nonlinear phase equation.

4. Results

Fig. 7 shows the PP against the OLP for BPSK, QPSK, 8-PSK and 16-QAM for a range of SMF length for 30 GHz OMMW. The plots show three distinct regions; linear, optimum and the nonlinear (as labelled), are identified based on the PP for a given OLP. The PP values presented in Fig. 7(i), (ii), (iii) and (iv), obtained at a BER of 10^{-5}. The PP values were calculated against back-to-back model which refers to the simulated system without the SMF. In linear regions, PP decreases with increasing OLP for all modulations schemes and transmission spans. In the linear regions, Kerr effect is not significant since OLP is low, thus resulting in reduced SPM effect, however CD is the dominant fibre linear effect. The intermixing effect between SPM and CD is mainly contributing to the optimum regions, which corresponds to the SNR range where PP is at its minimum. In non-linear regions, PP increases with OLP due to the SPM. This is because of Kerr effect and is dependent of the light intensity.

Fig. 7(i) depicts PP variations against OLP for BPSK for a range of FMF spans, showing the lowest PP compared to other modulation schemes. The average rate for PP improvement at the optimum region for BPSK is ~11 dB compared to the linear and nonlinear regions. This is a significant result highlighting that the system can operates at the optimum OLP level. In Fig. 7(ii) the PP for QPSK in the optimum region illustrates an average improvement of ~11 dB compared to the linear and nonlinear regions. QPSK exhibits similar PP performance over the same fibre spans compared to BPSK. Such close performance can be related to the Euclidean distance between the constellation points, which is the same for BPSK and QPSK modulation schemes.

Fig. 7(iii) illustrates the performance of 8-PSK showing higher PP compared to BPSK and QPSK since the Euclidean distances dramatically decreases. 8-PSK shows ~12 dB PP average improvements over the linear and the non-linear regions. Finally, Fig. 7(iv) depicts PP for 16-QAM with the highest power penalty observed in all three identified regions compared to other modulations. This is because the Euclidean distance between the constellation points are smaller than other modulation schemes. However, at the optimum OLP level, up to ~18 dB PP improvement can be achieved, thus confirming the lowest possible PP over the three transmission fibre spans at 10, 30, and 50 km, respectively.

The results of PP investigations for all four modulation schemes confirms the optimum range for OLP i.e. - 4 dBm ≤ OLP ≤ 4 dBm for the 5 GHz RF component. In nonlinear regions shown in Fig. 7, PP increases with SNR, with 16-QAM displaying the highest PP due to smallest Euclidean distance between the constellation points compared to BPSK QPSK and 8-PSK. The average rate of PP improvement over 10, 30 and 50 km for BPSK, QPSK, 8-PSK and 16-QAM are ~11 dB, ~11 dB, ~12 dB and ~18 dB, respectively operating at the optimum region compared to the non-linear region. The rates of improvement for all modulation schemes at all distances confirm that at points where the non-linear phase variation is minimum, the PP is at its optimum level. The PP values are more than 10 dB due to the fibre non- linear (SPM) and linear (CD) impairments. In fact, the major reason for high PP values is due to the fibre non-linearity at the PD which results in phase-to-amplitude conversion [40].

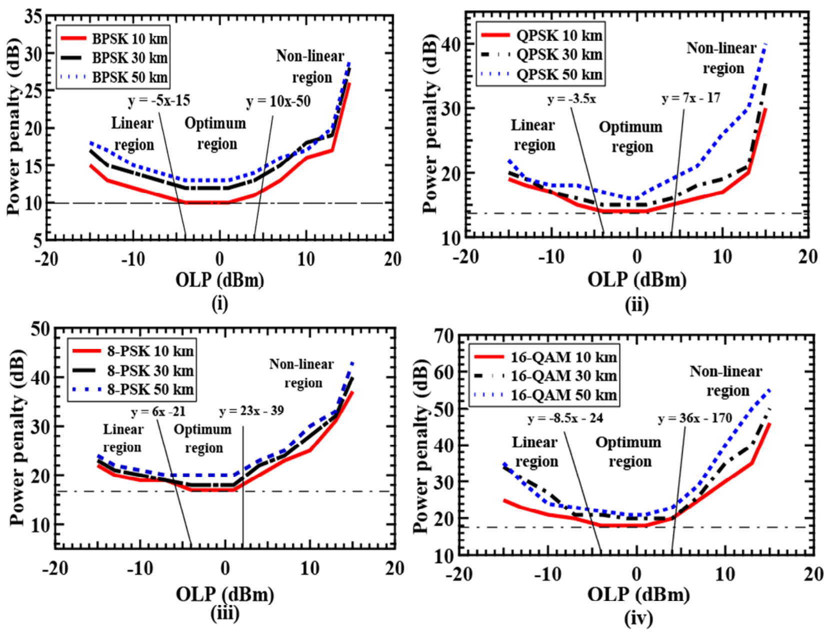

Figure 7: Power penalty against the optical launch power for (i) BPSK, (ii) QPSK, (iii) 8-PSK and (iv) 16-QAM modulation schemes for 30 GHz OMMW.

In [41], the reported EVM at a BER of 10^{-5}(error free communication) for BPSK, QPSK, 8-PSK and 16-QAM are ~33%, ~24%, ~15% and ~7%, respectively, which we will use it as a reference. Fig. 8 illustrates the EVM for all modulation schemes for 30 km and 50 km SMF spans. For BPSK and QPSK at a 30 km of SMF, EVMs are ~33% and ~24 % at SNR of~ 24 dB while at 50 km, the error free EVM happens at SNR of ~ 28 dB and ~ 32 dB, respectively. For 8-PSK at 30 and 50 km of SMF 15 % EVM is achieved at SNR values of ~28 dB and ~32 dB, respectively. For 16-QAM, EVM of ~15% is accomplish at SNR values of ~41 dB and ~48 dB for the 30 km and 50 km SMFs, respectively. BPSK and QPSK require lower SNR values of ~25 dB to achieve an error free communication at a BER of 10-5. The SNR increases drastically for 8-PSK and 16-QAM with the average SNR values of ~30 dB and ~44dB, respectively. This is due to the increased data rate and the reduction in the Euclidean distance between the constellation points for higher order modulations. Hence, higher SNR values are required in order to achieve the transmission spans of 30 km and 50 km.

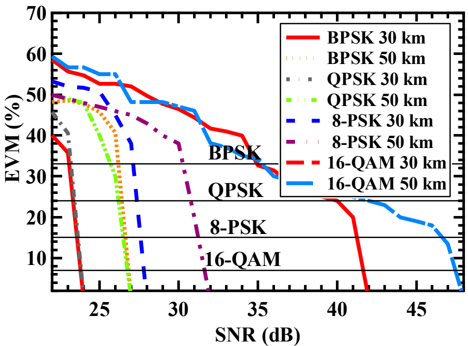

Figure 8: The EVM against SNR for BPSK, QPSK, 8-PSK and 16-QAM for 30 GHz OMMW with the optical power of 0 dB

Optical mm-wave and SMF spans of 10, 30 and 50 km. Also shown is a plot for the reference back-to-back (BTB) link.

Fig. 9(a) shows the BPSK BER performance over SMF spans of 10, 30, and 50 km, respectively.

BPSK at 10 km requires a SNR of ~19 dBm to achieve an error free communication at a BER of 10-5.

The SNR increases to ~27dBm at 50 km, which is twice the required SNR at 30 km. QPSK performance is closely match that of BPSK as expected, (see Fig. 9(b)), since the Euclidean distance between the constellation points remains the same in BPSK. The marked changeis observed for 8-PSK, (seeFig.9(c)), where at a BER of 10^{-5}, the SNR values increases to ~24 dBm, ~28 dBm, and ~32 dB mat SMF spans of 10, 30 and for 50 km, respectively.

Finally, for 16-QAM, (see Fig. 9(d)), the SNR values have increased to ~38dBm, ~42dBm and ~48 dB mat 10, 30 and 50 km fibre spans, respectively.

Moreover, for higher order modulations the number of constellation points increases with the data rate. Hence, the average non-linear phase experienced by each constellation points contributes to the overall non-linear phase shift of the modulated data. Thus, higher order modulation schemes are affected more than the lower orders.

Such effects can be observed in the increased PP, EVM and SNR values for particular modulation schemes.

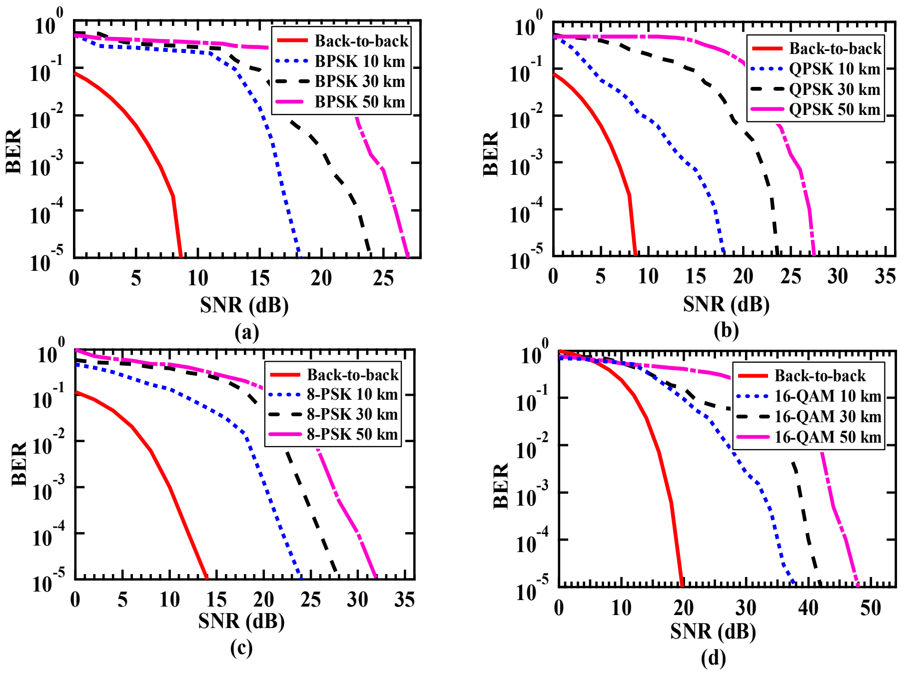

Figure 9: The BER value against SNR for (a) BPSK, (b) QPSK, (c) 8-PSK and (d) 16-QAM modulation schemes over 30 GHz OMMW.

5. Conclusions

In this paper, four different modulation schemes of BPSK, QPSK, 8-PSK and 16-QAM for 30 GHz optical mm-wave RoF at the RF frequency of 5 GHz were investigated. For the optical mm-wav RoF link we have defined an optimum band for the optical launch power where nonlinear phase variation is at its minimum. We identified an optical launch power region where PP is at its minimum value as needed for signal in optical mm-wave RoF systems. We showed that in the optimum OLP region, the PP improved on average by ~11 dB, ~11 dB, ~12 dB and ~18 dB for BPSK, QPSK, 8-PSK and 16-QAM,respectively, for 30 and 50 km SMF spans. To achieve the required EVM for BPSK and QPSK, the average SNR value of ~25 dB is needed for 30 km and 50 km SMF spans increasing to ~30 dB and ~44 dB for 8-PSK and 16-QAM over the same link spam, respectively.

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BIOGRAPHIES

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