Influence of frequency mapping on intermodulation distortion in an SOA-based optical fronthaul C-RAN architecture for 5G communications

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ABSTRACT

In this paper, three orthogonal frequency division multiplexing (OFDM) bands of 400 MHz are successfully transmitted over 20 km of single-mode fiber (SMF). The framework is that of a fifth generation (5G) centralized radio access network (C-RAN) architecture including semiconductor optical amplifier (SOA), using analog intermediate frequency signal over fiber (AIFoF) technology. An error vector magnitude (EVM) enhancement is observed by adopting an optimized intermediate frequency (IF) configuration that minimizes the system nonlinearities by avoiding second-order intermodulation distortions (IMD2) caused by the optical modulator, SOA and photodiode association.

Keywords: Analog Radio-Over-Fiber, 5G, OFDM, Semiconductor Optical Amplifier, nonlinearities, IMD.

1. INTRODUCTION

In order to meet 5G requirements in terms of data rate and latency, there has been an architectural evolution from the distributed RAN (D-RAN) to the C-RAN, where distant remote radio heads (RRHs) are connected to the baseband unit (BBU) pool, placed at the central office. This fronthaul (FH) architecture is based on the digital radio over fiber (D-RoF) technology using the common public radio interface (CPRI) standard, which imposes a high penalty in terms of bandwidth and latency. For this reason, new alternatives have been proposed such as the analog RoF (A-RoF) [1], where analog radio frequency (RF) or IF signal is transmitted through the FH link. Indeed, A-RoF enhances the spectral efficiency by avoiding the digitization process and enables cost reduction and energy savings by having much simplified RRHs, designed to perform only the RF function, without the need for expensive and power-hungry analog to digital/digital to analog converters (ADC/DAC) at each RRH. With increased carrier frequency, analog-domain radio frequency signal over fiber (ARFoF) becomes more vulnerable to nonlinear distortions. To overcome this problem, AIFoF is usually used for the signal transmission at high RFs, such as in the 5G millimeter wave band, since the frequency up/down-conversion process becomes more flexible and allows the use of optical components with lower bandwidth (BW) than ARFoF. However, despite these advantages, AIFoF still suffers from nonlinearities coming from the channel. Therefore, researchers have investigated techniques in order to mitigate IMD2 and IMD3 [2]. Fig. 1 shows the block diagram of an AIFoF system. First, the signal is up-converted to an IF ($f_{IF} < f_{RF}$), which is further converted to the target radio frequency by a local oscillator ($f_{RF} = f_{IF} + f_{LO}$), before being transmitted to the user equipment (UE) through the wireless link. To extend the maximum reach of our OFDM multiband (MB) system over the FH link, we investigate in this work to use the SOA as a booster amplifier in the C-RAN architecture since it presents attractive features including large optical BW, low cost and small size.

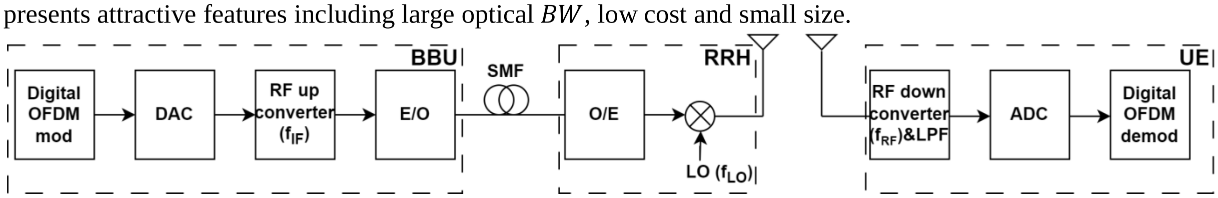

Figure 1. Block diagram of an AIFoF system for the downlink transmission in the 5G C-RAN architecture (E/O: electrical-to-optical; O/E: optical-to-electrical; LPF: lowpass filter).

2. PROPOSED SOA-BASED C-RAN ARCHITECTURE AND SYSTEM MODELLING

In this paper, we consider the proposed setup shown in Fig. 2. This figure also presents the power spectral density (PSD) of the OFDM signal at different points of the transmission chain. At the MB transmitter (Tx), three cyclic-prefix OFDM bands are generated. Each one is composed of 16 symbols with 1024 subcarriers which 330 are modulated using 16-QAM, corresponding to a BW of 400 MHz. The rest of subcarriers are nulled. We use an oversampling factor of 16 and a cyclic prefix equivalent to 1/16 of each OFDM symbol duration. Afterwards, the 3 bands are up-converted to the desired intermediate carrier frequencies (i.e. f_1, f_2, f_3). Note that the frequency of second and third bands are calculated as follows: $f_i = f_{i-1} + BW + GB$, where the guard-band (GB) is 40 MHz (10% of the BW). After the digital to analog conversion, the resulting analog signal is transformed to the optical domain, by means of a laser operating at 1540 nm (P_{in_laser}=-10 dBm) and a Mach-Zehnder modulator (MZM) which is quadrature biased (V_{DC}=1.5V_{π}; V_{π}=6 V). The output is amplified by a SOA, supplied by a 200 mA bias current, and transmitted through 20 km of SMF (D=16.7 ps/(nm.km); α=0.2 dB/km). At the receiver (Rx), the optical signal is transformed to electrical domain by the photodiode (PD) and down-converted in order to recover the three Rx independent filtered signals which will be finally demodulated. In order to focus on the nonlinearities arising from the FH network between the BBU and the RRH, we simulate the MB transmission over SMF by neglecting the effect of the wireless link, between the RRH and the UE, which is assumed to be ideal. The Tx and Rx are implemented in MATLAB®. The SOA is simulated using Keysight Advanced Design System (ADS), according to a numerical method that has already been experimentally validated in [3].

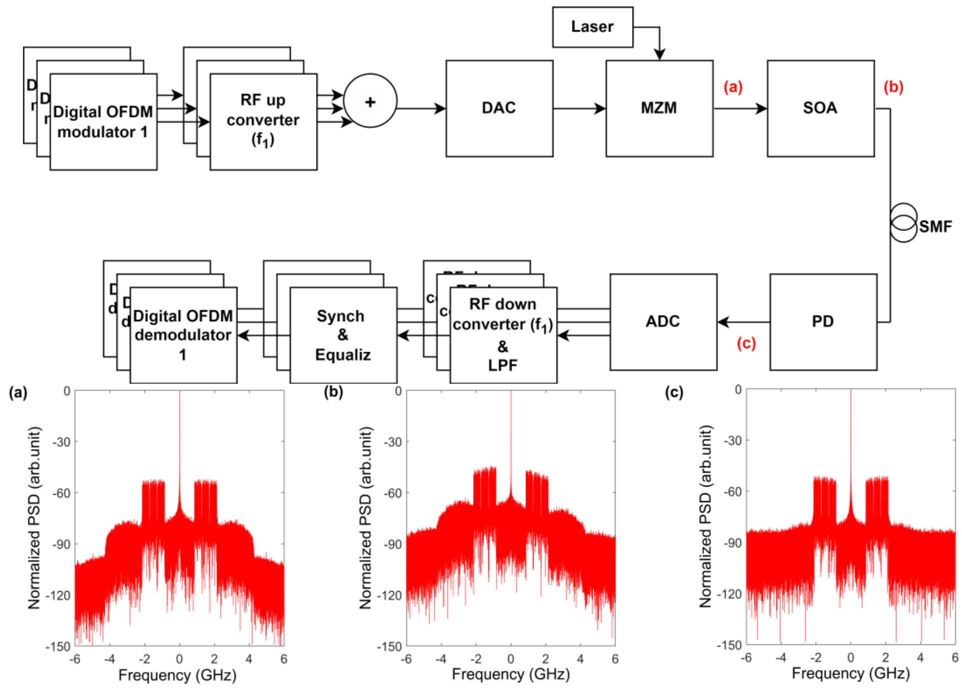

Figure 2. Matlab/ADS co-simulation setup (Synch: synchronization; Equaliz: equalization). PSD of the OFDM MB signal at the output of (a) MZM, (b) SOA, and (c) PD (V_{pp}/V_{π} =0.5, $P_{in\ SOA}$ =-10 dBm).

3. IMPACT OF SYSTEM NONLINEARITIES ON PERFORMANCE

In the considered chain, the nonlinearities arise from the MZM/PD and also from the SOA. First, we evaluate the effect of MZM/PD nonlinearities on performance, without considering the SOA. By raising the peak-to-peak voltage V_{pp} from 0.3V_{π} to 0.7V_{π}, Fig. 3(a) shows that the EVM rises for the three studied bands. Indeed, higher values of V_{pp} introduce IMDs with higher amplitude levels at the output of MZM. The photo current is proportional to the output optical power of the MZM which has a nonlinear power transfer function expressed as [4]

$$P_{out_{MZM}}(t) = P_{in\_laser}\cos^2\left(\frac{\pi}{2V_{\pi}}\left(V_{DC} + V_{pp}S_{OFDM}(t)\right)\right), \tag{1}$$

where $S_{OFDM}(t)$ represents the normalized OFDM signal, with maximum amplitude of 0.5. Hence, the electrical Rx OFDM signal is affected by odd order IMDs generated at the output of the PD, which become more important with a greater V_{pp} value, causing an increase of the EVM. Due to inter-band interference with the first and third bands, we also notice a slight degradation of the EVM on the second band. The average EVM of the three bands is then evaluated in the presence of SOA for different input powers P_{in} at various values of V_{pp}. Although the SOA operates within its linear regime at P_{in}= -20 dBm, a high EVM (e.g. EVM =25.33% for V_{pp}=0.3V_{π}) is observed in Fig. 3(b) for all V_{pp} values due to the significant effect of amplified spontaneous emission (ASE) noise in this region. We also remark an EVM loss by reducing $\frac{V_{pp}}{V_{\pi}}$ from 0.7 to 0.3, at -20 dBm. Indeed, smaller V_{pp} generates a lower power of the modulating OFDM signal, which leads to a reduced signal to noise ratio (SNR) value. Hence, the optical output signal becomes more vulnerable to the SOA ASE noise. However, by raising P_{in} values to a certain limit, an EVM decrease is observed as the optical SNR (OSNR) performance is improved. Finally, at high P_{in} values, the SOA enters its nonlinear region.

For this reason, the EVM starts to increase from 7.76% to 8.43% with -5 and 0 dBm respectively at V_{pp}=0.5V_π, but remains below the considered forward error correction (FEC) limit of 12.5 % for 16 QAM. By applying larger $\frac{V_{pp}}{V_\pi}$, the EVM attains even larger values (i.e. 10.13 % at 0 dBm with V_{pp}=0.7V_π) as the nonlinearities effects of the SOA become more pronounced. Indeed, the four-wave mixing (FWM) [3] represents the prominent nonlinear effect generated by the SOA at high powers, when it is used with a multicarrier modulation technique, like the OFDM in our case. We choose to conduct the rest of our simulations with a fixed value of $\frac{V_{pp}}{V_\pi}$=0.5 as it offers the best compromise between having acceptable OSNR and reducing nonlinearities caused by the MZM/PD and the SOA.

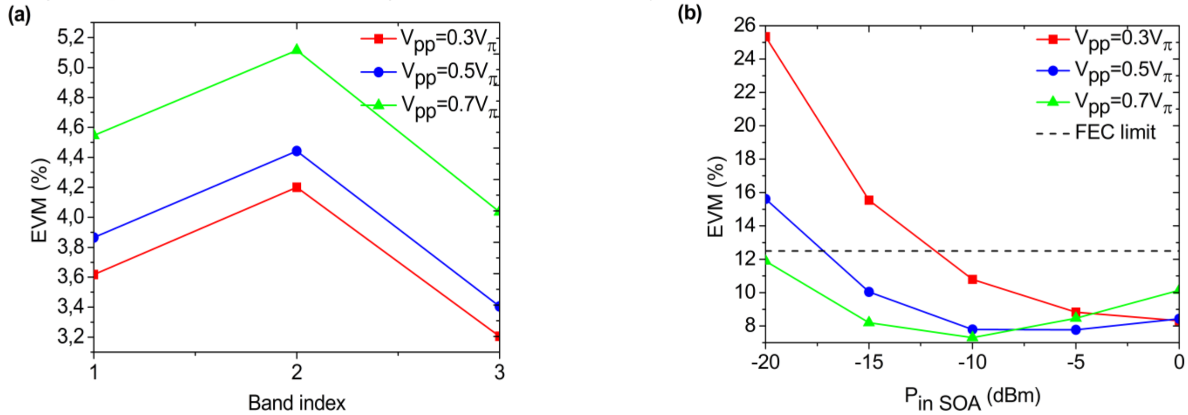

Figure 3. EVM performance for 3 OFDM bands in AIFoF system (a) w/o SOA; (b) w SOA

4. INFLUENCE OF IF MAPPING ON THE SYSTEM PERFORMANCE

Not only odd but also even order IMDs could be located near the user bands when they are generated at the output of the MZM which is associated with the optical field transfer function that is not symmetric with respect to the operating point V_{DC} (set at the quadrature point). IMD2 are particularly important since they are high in power. Fortunately, they could not be considered at the output of the PD which generates only odd nonlinearities as the power transfer function (Eq. (1)) is symmetric to V_{DC}. However, in the presence of SOA, IMD2 become much stronger and also subjected to the nonlinearities related to the SOA. Thus, they remain present at the output of PD and introduce spectral components which are close to the desired signals in case of 5G systems with bands of potentially high BW values. In the considered scenario with 400 MHz of BW, if the bands are located at f_1= 1.06, f_2=1.50, f_3=1.94 GHz, the second harmonic (2f_1=2.12 GHz) and the second IM product (f_3-f_1=0.8 GHz) impact first and third bands respectively (Fig. 4(a)). For this reason, in the presence of SOA at P_{in}=0 dBm, we observe in Fig. 5 higher EVM values for the first and third band in comparison with the second one, which is the opposite of what we obtained when only the MZM/PD association is considered (Fig. 3(a)). Thus, the choice of IFs in an AIFoF system is crucial because it determines the presence of IMDs that affects significantly the system performance. To overcome this problem, digital predistortion (DPD) may be used. However, it increases the system complexity, particularly with MB transmission. Therefore, we propose here a numerical method to find out an optimized IF configuration that allows to eliminate the impact of IMD2 and harmonics. Our approach is being focused on moving particularly (f_3-f_1) and (2f_1) IMDs away from the considered carrier frequencies. By doing that, we prevent as well all the other IMD2 products (i.e. f_2-f_1, f_3-f_2, f_1+f_2, 2f_2, f_1+f_3, f_2+f_3, 2f_3) since they represent the closest components to f_1 and f_3. Thus, in the case of a MB transmission with n bands centered at (f_1, f_2, ..., f_n) and considering that $f_i = f_{i-1} + BW + GB$, we need to resolve the following system of inequalities

$$f_n - f_1 + BW \leq f_1 - \frac{BW}{2} - \frac{GB}{2} \qquad \text{and} \qquad 2f_1 - BW \geq f_n + \frac{BW}{2} + \frac{GB}{2}, \tag{2}$$

which gives us the unique solution describing the condition of the IF f_1 that should be met in order to avoid the IMD2:

$$f_1 \geq \left(n + \frac{1}{2}\right) BW + \left(n - \frac{1}{2}\right) GB\ . \tag{3}$$

In our case, by setting n=3, BW=400 MHz and GB=40 MHz, f_1 should be greater than or equal to 1.50 GHz. To validate our result, we reevaluate again our system performance with a second IF configuration that satisfies the constraint related to f_1 (i.e. f_1= 1.50, f_2=1.94, f_3=2.38 GHz). An EVM decrease, for the first (from 12.06% to 5.33%)

and the third (from 7.54% to 4.57%) bands is actually obtained, as seen in Fig. 5. This EVM improvement is attributed to the fact of choosing a certain value of the first IF f_1 that allows keeping the second harmonic ($2f_1$) and the second IM product (f_3-f_1) far enough from our band of interests (Fig. 4(b)). Fig. 5 depicts also the 16-QAM constellations on the Rx side for these two considered IF configurations.

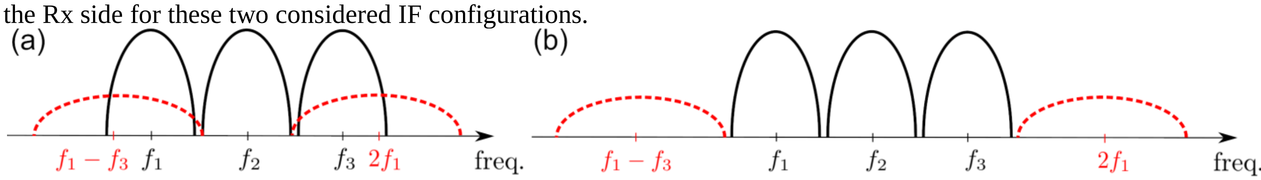

Figure 4. Second harmonic ($2f_1$) and second IM product (f_3-f_1) for different IF configurations (a) IF_1= 1.06, IF_2=1.50, IF_3=1.94 GHz; (b) IF_1= 1.50, IF_2=1.94, IF_3=2.38 GHz

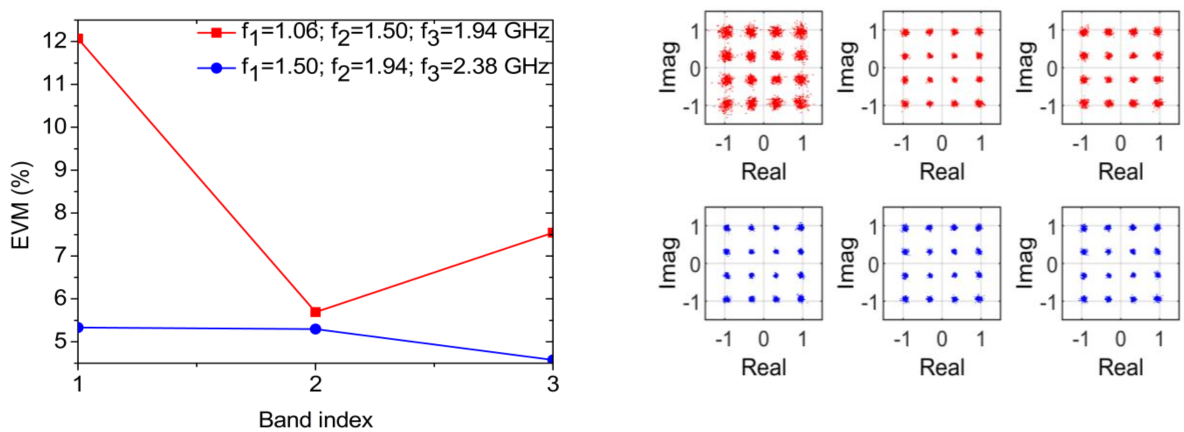

Figure 5. EVM performance for 3 OFDM bands in AIFoF system for different IF configurations at P_{in} = 0 dBm. Constellation diagrams for the first (in red) and the second (in blue) IF configuration.

5. CONCLUSIONS

This paper proposes using the SOA as a booster amplifier through the 5G optical fronthaul network of the C-RAN architecture. By simulating a MB system composed of three OFDM bands of 400 MHz using the AIFoF technology, acceptable performance in terms of EVM are achieved, even at high input powers. Through a numerical study based on avoiding IMD2, we derive an optimized IF configuration that enables not only to reduce the average EVM by 3.3%, but also to flatten the EVM performance for the three user bands, without the need to implement any complex predistortion techniques at the transmitter to mitigate these system nonlinearities.

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