Received: 20 October 2021

DOI: 10.1002/mop.33169

WILEY

RESEARCH ARTICLE

Enhancing 5G multi-band long haul optical fronthaul links performance by magnitude-selective affine digital predistortion method

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Abstract

This paper presents a novel magnitude-selective affine (MSA) based digital predistortion (DPD) method for the performance investigation of multiband 5G new radio (NR) based analog radio over fiber link. The proposed MSA-DPD method is derived from the canonical piecewise linear (CPWL) based model by employing MSA functions, which can result in reduction of the number of multiplication operations and the model complexity. The 5G NR standard at 20 GHz with 50 MHz bandwidth and flexible-waveform signal at 3 GHz with 20 MHz bandwidth is used. A dual drive Mach Zehnder modulator having two distinct RF signals modulates a 1310 nm optical carrier using distributed feedback laser for 22 km of standard single mode fiber. The proposed MSA-DPD method is compared with the CPWL and generalized memory polynomial method. The experimental results are presented in terms of adjacent channel power ratio, error vector magnitude, number of estimated coefficients and multiplications suggesting that MSA-DPD method achieves a better performance as compared to CPWL and GMP models with much lesser complexity meeting the 3GPP Release 17 requirements.

KEYWORDS

adjacent channel power ratio, digital predistortion, error vector magnitude, generalized memory polynomial, magnitude-selective affine, radio over fiber

1 | INTRODUCTION

With recent advances in 5G and beyond, the accelerating growth of base stations (BS) has led to the centralization of radio access networks (C-RAN),[1] which decreases the capital expenditure as it leads to simplifications in network management.[2] To facilitate C-RAN, a fronthaul (FH) connects base band units (BBU) to remote radio heads (RRH) (see Figure 1). With 5G roll out stage accelerating in most of the developed world, the microwave photonics-based solutions like radio over fiber (RoF) have a higher significance for connecting the BBUs with RRUs[3] owing to advantages such as cost-effectiveness, immunity to electromagnetic disturbance, broader bandwidth and increasing the wireless links reach for all type of distances ranging from short to long.

There have been various versions of RoF such as analog RoF (A-RoF),[4,5] digital RoF (D-RoF),[6,7] sigma delta RoF (SD-RoF)[8,9] and other variants that have been. Up to an extent, A-RoF links are the uncomplicated and economical solution, however, it suffers from signal nonlinearities. The other solutions comprise of other versions such as D-RoF or SD-RoF, however, the legacy infrastructure of A-RoF deployed and its simplest noncomplex implementation still makes it a strong candidate as an optical front haul (OFH)[10] (see Figure 1).

However, the nonlinearities in A-RoF variants are of significance and needs to be addressed. Mitigation of the impairments of the RoF system has been studied previously.[10,11] For 5G applications, the digital predistortion (DPD) technique is regarded as one of the promising linearization solutions due to ordinary hardware requirements and cost. In the recent past, indirect learning architecture (ILA) based DPD has been widely employed using volterra methods[10–13] and canonical piece-wise linearization (CPWL) methods.[14] Moreover, the concept of using machine learning (ML) for DPD that reduces the link nonlinearities is a recent addition. Use of K-nearest neighbor algorithms, support vector machine[15] and deep learning methods were also

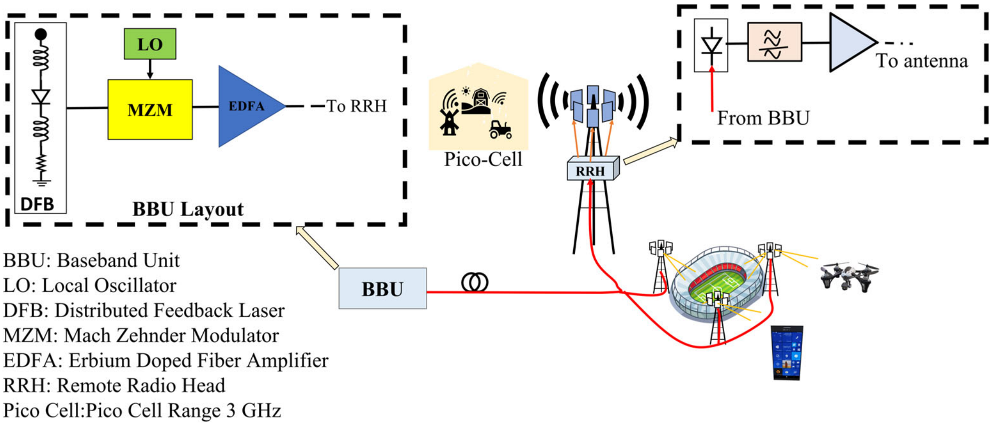

FIGURE 1 Centralization of radio access networks based scenario, OFH, Backhaul, Central Office highlighting indoor and outdoor scenarios like stadiums, buildings, and small cell scenarios. connects base band units and remote radio heads architecture is also shown

employed.[16] However, the complexity of training in ML-based solutions is relatively quite high, making the utilization of this method time and power consuming.[16]

Recently, it was shown in[15,17] that out of all the possible architectures, CPWL method outperforms the other models such as memory polynomial (MP) and generalized memory polynomial (GMP). CPWL is an obvious choice due to the performance enhancement that it brings; however, it has a lot of complexity and overheads. Extending the previous work, the objective of this work is to further reduce the overheads and complexity of the CPWL method by proposing a magnitude selective affine (MSA) function-based model. The advantage of this method is that it requires only a single linear operation for the selected zone leading to a lower complexity and simpler structure. The contribution of nonlinearities from the laser and to some extent, the photodiode part is important as transmission quality decreases and the interference with channels nearby is triggered. However, while considering the long-range networks, the nonlinearities due to the combination of fiber chromatic dispersion and laser frequency chirp are usually the main cause of signal impairment.[7] However, the non-idealities owing to laser and possibly to photodiode are of paramount importance as discussed in.[18–23]

for 3 and 20 GHz, respectively. A dual drive Mach-Zehnder modulator (MZM) is used with a 1310 nm distributed feedback (DFB) laser for a fiber link length of 22 km. Moreover, the MSA-DPD are compared with GMP and CPWL DPD techniques to assess the complexity reduction and performance improvements. The rest is structured as follows. The DPD methodology and theoretical explanation is given in Section 2, while Section 3 covers the experimental setup while the experimental outcomes are shown in Section 4. Real time implementation discussion is presented in Section 5. Finally, conclusions are presented in Section 6.

2 | MSA BASED DPD ARCHITECTURE

The basic modeling for DPD technique is discussed in this section. The simplest and efficient form of feedback structure is obtained by the error between normalized output and input to the system as the new input. Here, as shown in Figure 2A, the input signal in the previous succession is considered.

The basic modeling for MSA-DPD technique is discussed in this section. The CPWL model can be expressed as[24]:

$$
\begin{aligned}
y(n) = {} & \sum_{m=0}^{M}\sum_{k=0}^{K}\sum_{l=1}^{L} c_{m,k,l}^{(1)}\left|\,|x(n-k)|^2-\beta_l\right| x(n-m-k) \\
& +\sum_{m=1}^{M}\sum_{k=0}^{K}\sum_{l=1}^{L} c_{m,k,l}^{(2)}\left|\,|x(n-k)|^2-\beta_l\right| x^2(n-k)x^*(n-m-k) \\
& +\sum_{m=1}^{M}\sum_{k=0}^{K}\sum_{l=1}^{L} c_{m,k,l}^{(3)}\left|\,|x(n-k)|^2-\beta_l\right| x(n-k)\,|x(n-m-k)|^2 \\
& +\sum_{m=1}^{M}\sum_{k=0}^{K}\sum_{l=1}^{L} c_{m,k,l}^{(4)}\left|\,|x(n-k)|^2-\beta_l\right| x^*(n-k)\,x^2(n-m-k).
\end{aligned} \tag{1}
$$

In this paper, multiband 5G NR based Radio over Fiber link equipped with MSA-DPD is presented as an OFH solution to cover enhanced mobile broad band (eMBB) scenarios

Here, the baseband input is represented by $x(n)$ and the output baseband signal is represented by $y(n)$, K is the FIR length filter, M is represented by memory depth, L is the

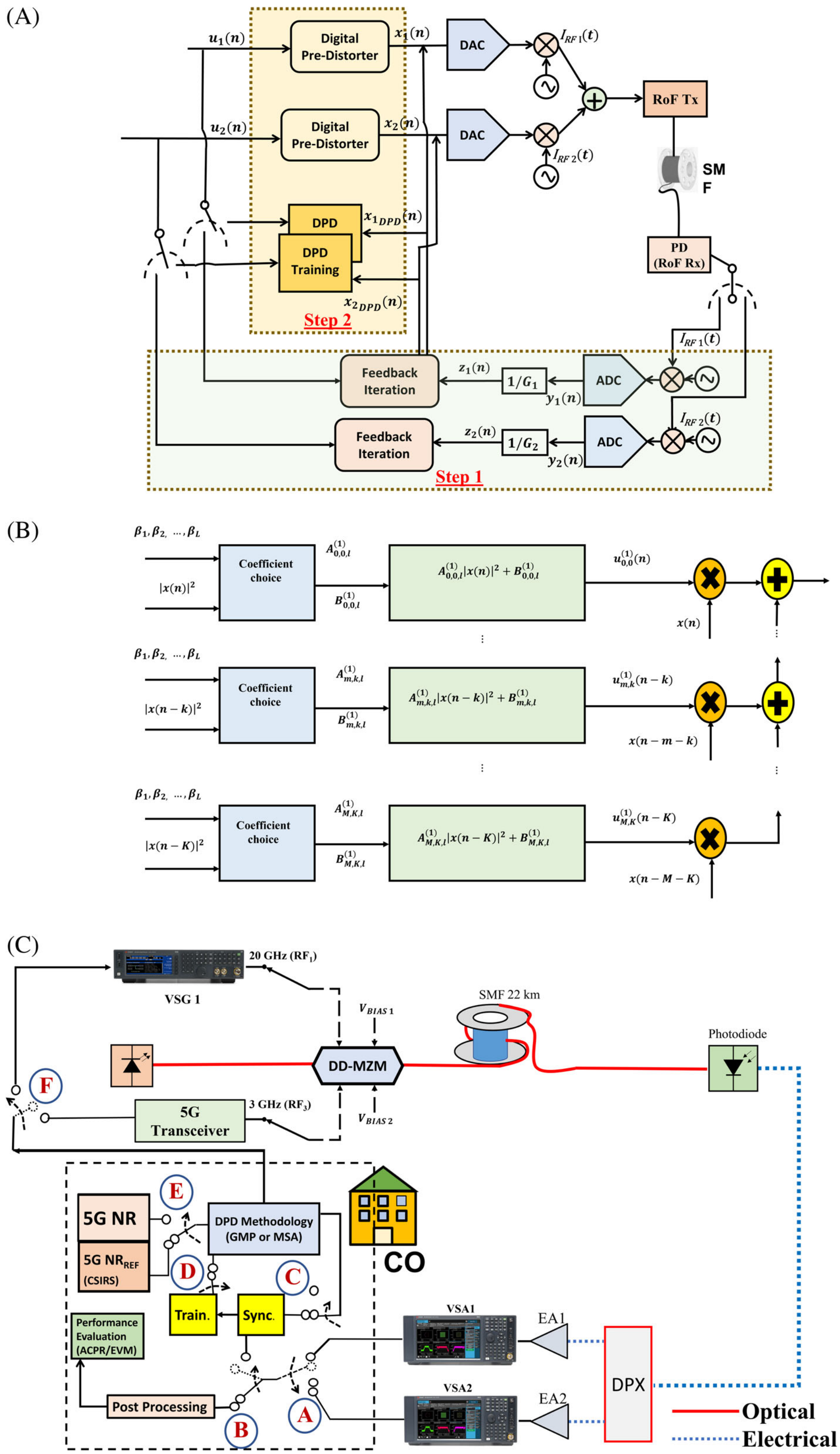

FIGURE 2 Block diagram of (A) RoF digital predistortion (DPD) modeling methodology. (B) Hardware implementation example using magnitude-selective affine. (C) Analog multi band 5G-NR-OFH RoF. The following switches have following functionalities: A: Selection between VSA 1 and 2. B: Selection between post processing block for performance or synchronization block. C: Connected to synch. Block for performing synchronization followed by DPD training. D: DPD blocks connection with training DPD block. E: Required for time synchronization (TS) procedure. F: Required for performing validation to launch DPD inputs to the vector signal generators

number of partitions in the CPWL, β_l shows the threshold while $c^{(1)}_{m,k,l}, c^{(2)}_{m,k,l}, c^{(3)}_{m,k,l}, c^{(4)}_{m,k,l}$ presents the model coefficients.

In the Equation (1), there are many orders of multiplications and additions which will add a lot of overhead in terms of complexity and utilization if hardware resources during DPD implementation, the most important of them is dedicated hardware adders and multipliers. In order to optimize the operations, the coefficients in the zone that have similar magnitude can be coupled.[25,26] The comparison between threshold function and magnitude of input samples can select which zone the samples will be falling and which affine functions can be utilized. This simplification will result in the reduction of the CPWL complex operation. Therefore, we can rewrite the first term of CPWL function in Equation (1) in a simplified way in terms of MSA function that can be expressed as:

$$\begin{aligned}&\sum_{m=0}^{M}\sum_{k=0}^{K}\sum_{l=1}^{L}c_{m,k,l}^{(1)}\left||x(n-k)|^2-\beta_l\right|x(n-m-k)\\ &=\sum_{m=0}^{M}\sum_{k=0}^{K}x(n-m-k)\left(\sum_{l=1}^{L}c_{m,k,l}^{(1)}\left||x(n-k)|^2-\beta_l\right|\right),\\ &=\sum_{m=0}^{M}\sum_{k=0}^{K}u_{m,k}^{(1)}(n-k)x(n-m-k)\end{aligned} \tag{2}$$

$$u_{m,k}^{(1)}(n-k)=\sum_{l=1}^{L}c_{m,k,l}^{(1)}\left||x(n-k)|^2-\beta_l\right| =\begin{cases}A_{m,k,1}^{(1)}|x(n-k)|^2+B_{m,k,1}^{(1)}, 0\le|x(n-k)|^2<\beta_1\\ \vdots\\ A_{m,k,L}^{(1)}|x(n-k)|^2+B_{m,k,L}^{(1)}, \beta_{L-1}\le|x(n-k)|^2<\beta_L\end{cases}. \tag{3}$$

Here in Equation (2), $A_{m,k,l}^{(1)}$ and $B_{m,k,l}^{(1)}$ are the linear model coefficients defined for each zone of the MSF function $u_{m,k}^{(1)}(.)$.

The example of hardware implementation is shown in Figure 2B. The simplification shown in Equation (2) leads to this realization that input power terms without any magnitude are compared with the thresholds for the offset and linear gain selection for the MSA function. This leads to removal of square root calculation operation. The overall model of Equation (1) in terms of MSA function can be written as:

$$\begin{aligned}y(n)&=\sum_{m=0}^{M}\sum_{k=0}^{K}u_{m,k}^{(1)}(n-k)x(n-m-k)\\ &+\sum_{m=1}^{M}\sum_{k=0}^{K}u_{m,k}^{(2)}(n-k)x^2(n-k)x^*(n-m-k)\\ &+\sum_{m=1}^{M}\sum_{k=0}^{K}u_{m,k}^{(3)}(n-k)x(n-k)|x(n-m-k)|^2\\ &+\sum_{m=1}^{M}\sum_{k=0}^{K}u_{m,k}^{(4)}(n-k)x^*(n-k)x^2(n-m-k),\end{aligned} \tag{4}$$

$$u_{m,k}^{(i)}(n-k)=\sum_{l=1}^{L}c_{m,k,l}^{(i)}\left||x(n-k)|^2-\beta_l\right| =\begin{cases}A_{m,k,1}^{(i)}|x(n-k)|^2+B_{m,k,1}^{(i)}, 0\le|x(n-k)|^2<\beta_1\\ \vdots\\ A_{m,k,L}^{(i)}|x(n-k)|^2+B_{m,k,L}^{(i)}, \beta_{L-1}\le|x(n-k)|^2<\beta_L.\end{cases} \tag{5}$$

Here in Equation (4), $A_{m,k,l}^{(i)}$ and $B_{m,k,l}^{(i)}$ are the linear model coefficients defined for each zone of the MSF function $u_{m,k}^{(i)}(.)$ that is estimated by least squares (LS) algorithm.

TABLE 1 Optical link parameters

Parameter	Value
5G NR waveforms	$f_c = 3$ and 20 GHz
	Flexible G/F-OFDM
	Constellation type = 256 QAM
Laser	Wavelength = 1310 nm
	Transmitter type = Mach Zehnder modulator
Optical Fiber	Type = SSMF
	Fiber dispersion = 16 ps/nm km
	Fiber distance = 22 km
	Attenuation = 0.42 dB/km
Photodiode	Responsivity = 0.71 A/W
	Bandwidth = 40 GHz

3 | EXPERIMENTAL TESTBED

For the validation of this technique, a multiband 5G NR scenario for out/in-door environments working at 3 GHz (20 MHz bandwidth) and 20 GHz (50 MHz bandwidth), which was discussed in our previous work,[27,28] but no DPD was implemented. As an upgradation of this architecture, the setup is integrated with a multiband MSA-DPD block to this setup for enhancing the performance of this link. The setup shown in Figure 2C comprises of a 1310 nm optical carrier is modulated by a MZM working with two distinct RF-driven signals and a 1310 nm DFB laser. Vector signal generator (VSG) labeled as VSG1 provides RF1 which is a 5G NR waveform at 20 GHz while 5G transceiver provides RF2 which is a 3 GHz flexible (O/G/F-FDM) signal.

The modulated waveform which is in optical domain is carried through 22 km of Standard Single-Mode Fiber (SSMF) and photodetector (0.71 A/W and 40 GHz bandwidth) receives the signal and converts the received signal back to electrical domain. Since the multiband needs to be isolated separately, an amplification stage is added. Followed by a diplexer (DPX) that separates the 20 and 3 GHz signals. The signals then go to distinct vector signal analyzers (VSA). Here each VSA outputs is fed to the DPD training phase. The DPD operation depicted in the Figure 2A is utilized in this section and training is employed unless the error converges. In simple words, DPD ensures that the phase and amplitude responses are inverse to that obtained at electrical amplifiers EA1 and EA2, respectively.

For time synchronization (TS), 20 MHz channel state information reference signal (CSIRS) has been used to perform accurate TS. The procedure is based on the first path of arrival suggested by 3GPP.[29,30] For the DPD validation phase, general 5G NR frames in real time are fed through the optical link.

The details of experimental bench are given in Table 1.

4 | EXPERIMENTAL RESULTS AND DISCUSSION

The proposed MSF-DPD technique and CPWL without modification is used with $M = 3$ and $K = L = 4$. Similarly, for comparison, we have used GMP method previously used in.[15,17] The parameters are $K = Q = 3$. The experimental results are presented in form of adjacent channel leakage or power ratio (ACLR/ACPR) and error vector magnitude (EVM).[17]

The aim of the MSA-DPD technique is to further reduce the complexity and implementation of the DPD methodology and enhance the performance of the link as compared to CPWL, GMP and when no DPD is applied. In Figure 3A, the measured electrical spectra are shown at the PD output. There are two main components that show the carrier signals

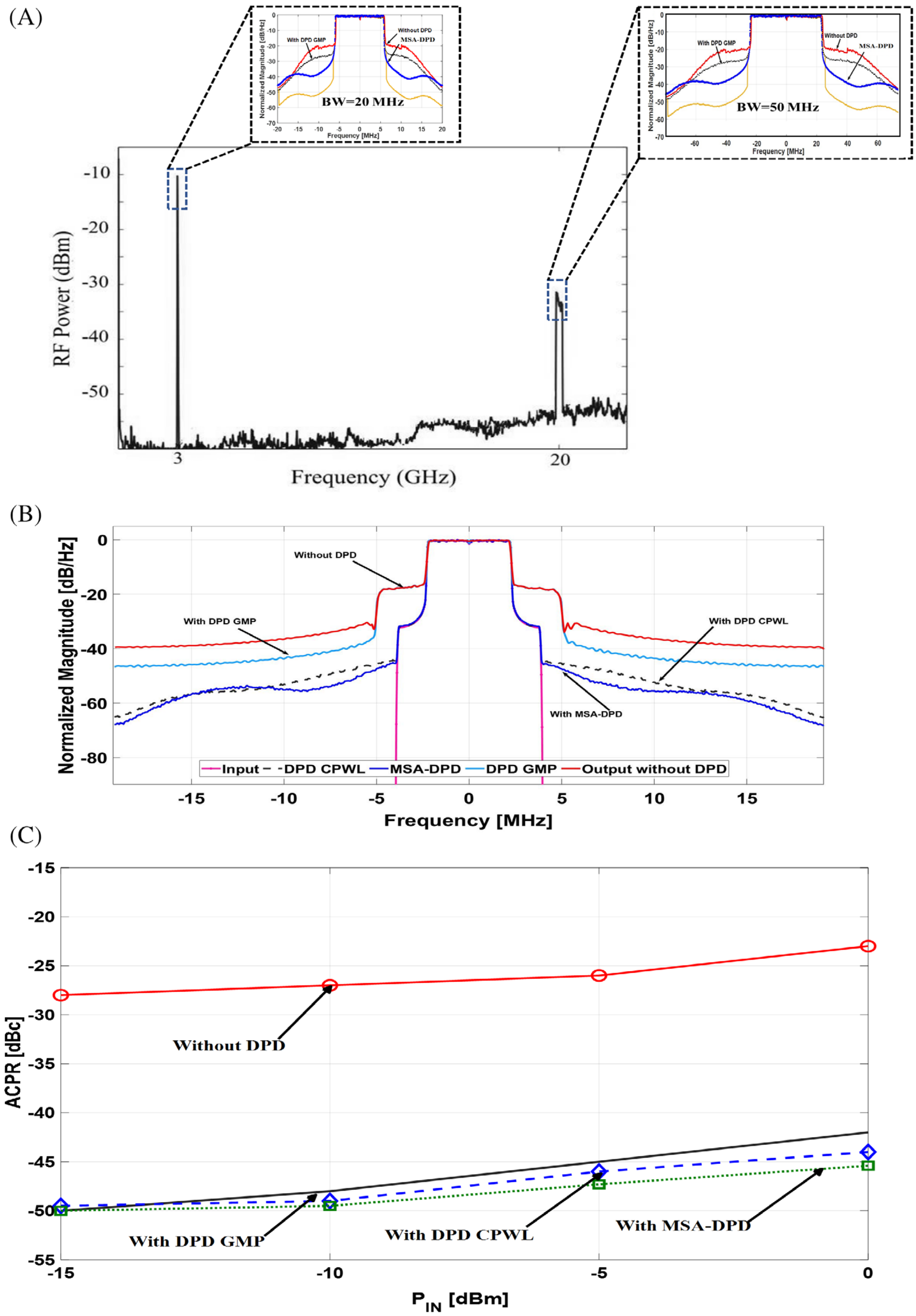

FIGURE 3 5G transceiver performance as a function of adjacent channel leakage ratio (ACLR). (A) The electrical spectra. (B) Spectral density (PSD) for O/F/G-FDM waveforms. (C) adjacent channel power ratio versus varying radio frequency input power at 3 and 20 GHz respectively. Figure 3B shows the power spectral density with and without DPD at 3 GHz. It is observable that MSA-DPD technique results in ACPR reduction of 17 dBs, CPWL results in reduction of 13 dBs and GMP results in reduction of 10 dBs. Indeed, Figure 3C shows the ACPR for the varying RF input power. It is observable that ACPR is reduced with the proposed MSA-DPD methods as compared to CPWL and GMP method by a good proportion of 7 dBs keeping the ACPR below −45 dBc set by 3GPP.[29] It is important to observe that MSA-DPD performs a little better than CPWL, however, the performance gain is not the only benefit, but the complexity reduction is the most important benefit of the proposed MSA-DPD technique (discussed in Section 5).

In addition to ACPR evaluation, EVM is evaluated depicted in Figure 4A by sweeping the RF input power. It is evident that MSA-DPD results in EVM reduction to <3% as compared to 5% obtained with GMP. The MSA-DPD has a slight improvement as compared to CPWL, but this is not the significant contribution, we expect to have similar improvement but with smaller complexity. In addition to this, Figure 4B compares the DPD and no DPD results in terms of EVM for 5G NR flexible waveforms. Clearly, MSA-DPD has better reduction as compared to other methods.

The complexity reduction that MSA-DPD brings with gaining similar performance as compared to CPWL method is significant contribution. Table 2 presents the complexity computations for the methods used that signifies that MSA DPD (220 multiplications) has much lesser complexity as compared to CPWL (880 multiplications).

TABLE 2 Complexity comparisons

DPD method	Coefficients	Estimated multiplications
GMP	156	19,140
CPWL	$(4M+1)(K+1)$ $L=260$	$(14M+2)(K+1)$ $L=880$
MSA-DPD	$2(4M+1)(K+1)$ $L=520$	$(14M+2)(K+1)=220$

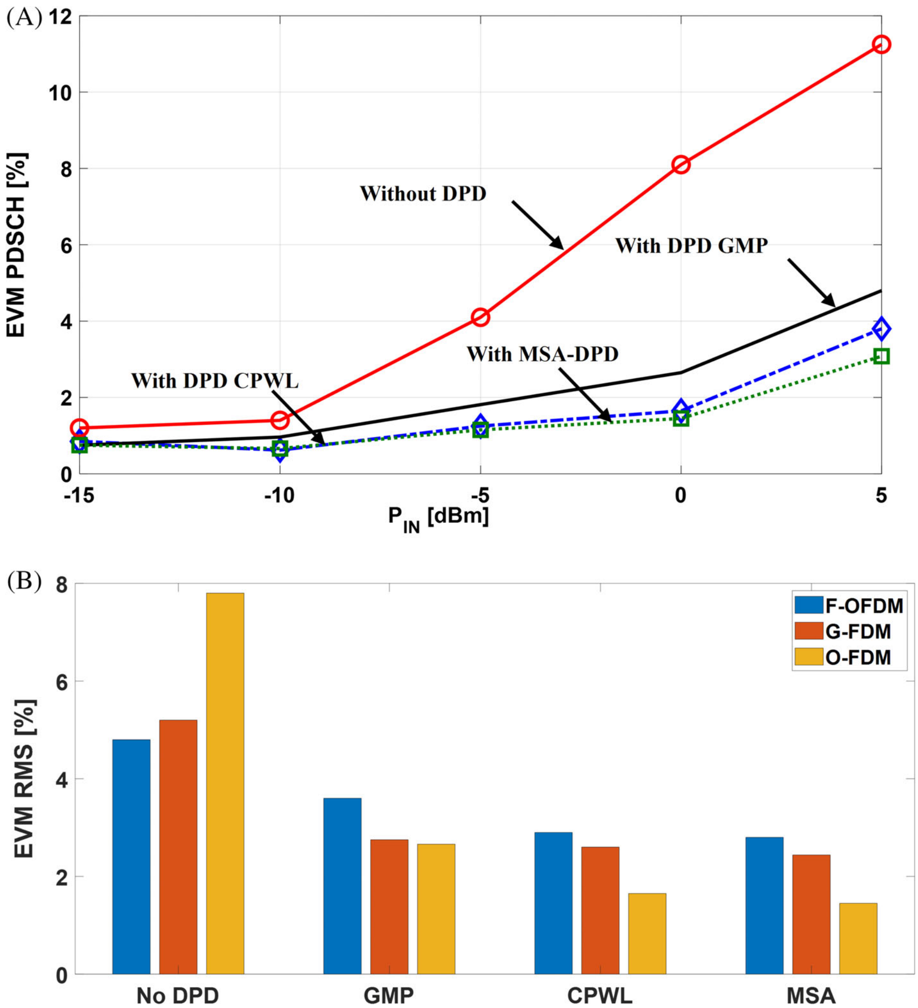

FIGURE 4 5G NR OFH performance (A) shows error vector magnitude versus varying radio frequency input power. (B) Digital predistortion (DPD) efficacy with magnitude-selective affine, canonical piecewise linear, generalized memory polynomial, and without DPD

5 | REAL-TIME IMPLEMENTATION

In a realistic scenario, linearization methodology is carried out at the Central Office (CO) where the BBUs are placed and a periodical re-training of the DPD system is in this case necessary, requiring, however, a negligible time with respect to the time of normal operation of the RoF system. Recently, a Xilinx DPD kit has been developed that can be used for this purpose.[29]

It should be noted that DPD works as a black box, it counter acts the overall nonlinearities of the system including that of MZM (laser), fiber and photodiode. Invariably, the combined effect of laser chirp and fiber dispersion becomes a major nonlinearity issue after tens of kilo meter.[10] Therefore, laser and possibly photodiode are the primary source of nonlinearity which is mitigated in this proposed bench. In future, it will be interesting to increase the length of fiber and linearize the link by mitigating the fiber nonlinearities such as Kerr effect.

Indeed, with the higher modulation format and higher bandwidth similar to multiple LTE carriers or 5G new radio (NR) waveforms as discussed, they would lead to higher complexity of DPD operation due to stronger PAPR. Concomitantly, the elevation in bandwidth will lead to overall increase in the base-band memory of the system model. Nevertheless, the evaluated models are still valid. However, higher values of the Q and K will be indispensable as compared to the considered case.

6 | CONCLUSION

In this paper, a novel unprecedented MSA based DPD architecture has been proposed for RoF links linearization. The successful realization of multiband 5G NR based radio over fiber link addressing long-reach and outdoor eMBB applications with a novel MSA-DPD method which is a simplified version of CPWL method. The 5G NR multiband signals at 3 and 20 GHz are employed to 22 km fiber length. The proposed MSA-DPD method results in reduction of ACPR from -22 to -47 dBc and EVM is reduced from 11% to 2.8% at RF input power of 5 dBm. The results signify that proposed MSA-DPD method reduces the signal impairments in better proportions as compared to GMP method and CPWL. The estimated multiplication operations from CPWL to MSA are reduced from 880 to 220 leading to much less complexity and overheads meeting the standardization requirements set by 3GPP release 17. To the best of our knowledge, this is an unprecedented work where multiband 5G NR based optical fronthaul performance was enhanced using proposed DPD technique.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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How to cite this article: Hadi MU, Soin N, Kausar S. Enhancing 5G multi-band long haul optical fronthaul links performance by magnitude-selective affine digital predistortion method. *Microw Opt Technol Lett*. 2022;1-8. doi:10.1002/mop.33169