Received: 20 December 2022 | Revised: 10 May 2023 | Accepted: 30 June 2023

DOI: 10.1002/mop.33829

RESEARCH ARTICLE

WILEY

Optimized MSA DPD method for improving 5G multiband optical fronthaul performance

Muhammad Usman Hadi[1] | **Ghulam Murtaza**[2] | **Shafaq Kausar**[3]

[1]School of Engineering, Ulster University, Belfast, United Kingdom

[2]Department of Electronic and Information Engineering, University of Bologna, Bologna, Italy

[3]Department of Electrical Engineering, Boise State University, Boise, Idaho, USA

Correspondence
Muhammad Usman Hadi, School of Engineering, Ulster University, 2-24 York Street, Belfast, BT15 1AP, United Kingdom.
Email: usmanhadi@ieee.org and m.hadi@ulster.ac.uk

Abstract

A modified optimized magnitude-selective affine (OMSA) model-based digital predistortion (DPD) is presented that introduces the weighting function into our earlier proposed magnitude-selective affine (MSA) method with an aim to further reduce the complexity overheads without affecting performance compared to the MSA method. This model utilizes a power-reliant weighted function rather than the summation of MSA quantities for improving the multiband 5G new radio (NR) analog radio over fiber system performance. The OMSA-DPD method is tested using 5G NR signals which are transmitted over a 10-km fiber length. The performance of the OMSA-DPD method is assessed in comparison to MSA and generalized memory polynomial (GMP) methods in terms of adjacent channel power ratio, error vector magnitude, and complexity. The experimental results show that the OMSA-DPD method achieves better performance with lower complexity compared to the MSA and GMP models, meeting the 3GPP limits.

KEYWORDS

digital predistortion, error vector magnitude, optimized magnitude-selective affine, radio over fiber

1 | INTRODUCTION

Radio over fiber (RoF) technology is gaining growing interest in the framework of next-generation 5G and 6G systems, due to its ability to support high-speed and high-capacity wireless communication.[1] The use of optical fibers for transmitting radio signals allows for much greater bandwidth and distance compared to traditional wireless systems, which can help to meet the growing demand for data transmission in 5G and 6G networks.[2]

Additionally, RoF systems can provide better isolation between different wireless users, which can improve the overall performance and reliability of the network. RoF systems can also be easily integrated with existing optical fiber infrastructure, which can help to reduce the cost and complexity of deploying 5G and 6G networks.[3,4]

Furthermore, RoF systems can support a wide range of wireless technologies, including millimeter wave, terahertz, and other emerging technologies that are anticipated to play a key part in 5G and 6G networks.[3,4] By leveraging the capabilities of RoF technology, 5G and 6G networks can provide improved coverage, higher data rates, and lower latency for a wide range of applications.

One major challenge in RoF systems is the presence of various impairments that can degrade the quality of the transmitted signal. These impairments include the nonlinear effect of laser, optical fiber dispersion, and noise, which can severely limit the performance of the system.[5,6]

Digital predistortion (DPD) is a significant technique to counterfeit the nonlinear effects, dispersion, noise, and other signal impairments for improving the performance of systems.[5–8] DPD mitigates the impairments in the RoF link, leading to an overall improvement in the overall performance of RoF systems; DPD treats all these impairments in a RoF system as a black box and finds the inverse nonlinear response to that black box. When cascaded together, the overall response is linear, which results in the removal of all these impairments.[7,8]

Several different DPD architectures can be applied to RoF systems. One of the techniques is generalized memory polynomial (GMP). The GMP architecture is a model-based approach that uses a polynomial model to represent the nonlinear behavior of the RoF system.[4,9] It was shown previously that this architecture can provide good performance but requires accurate modeling of the system, which can be challenging.[4,9] Similarly, the memory polynomial (MP) is a simplified version of the GMP architecture, which uses a fixed polynomial model to represent the nonlinear behavior of the RoF system. This architecture can provide good performance but is less flexible than the GMP architecture.[9,10] Canonical piece-wise linearization (CPWL) architecture can be used for DPD as a way to approximate the nonlinear transfer function of a radiofrequency (RF) for RoF systems. The linear functions are chosen such that they are "canonical," meaning that they can be used to approximate the original nonlinear transfer function of the RoF link. This architecture has a good performance as compared to GMP or MP architectures. However, the complexity of the CPWL is very high and it makes the usage questionable.[10] Recently, we proposed the use of the magnitude-selective affine (MSA) method to mitigate the impairments in the RoF system.[10] This architecture provided good performance, but the complexity is still high (low as compared to CPWL) and may require more hardware resources compared to the other architectures. However, it can provide good performance and improve the overall performance of the RoF system. One potential way to reduce the complexity of the MSA architecture is to combine the different stages into a single stage, using a more flexible and powerful DPD technique such as the GMP approach. On the contrary, in the context of nonlinear compensation, machine learning (ML) has been explored extensively, with numerous models and techniques proposed.[11,12]

This paper proposes a 5G new radio (NR) multiband for RoF link, equipped with an optimized MSA (OMSA) method for enhanced mobile broadband (eMBB) scenarios at 1.14 and 12 GHz, respectively. The OMSA method is shown to further reduce complexity while delivering a performance that is at least as good as that of MSA. This is accomplished by using a weighted function as a nonlinear operator to accurately capture the system's nonlinear behavior, which reduces the number of segments and coefficients required, resulting in a more efficient and user-friendly model.

Experimental results demonstrate that the OMSA model has lower complexity than the MSA model while achieving slightly better performance, as assessed in terms of computations, error vector magnitude (EVM), or adjacent channel power ratio (ACPR). The remainder of the paper is structured as follows: Section 2 provides a theoretical explanation of the proposed DPD methodology, Section 3 describes the experimental setup, Section 4 presents the experimental results, and Section 5 concludes the paper.

2 | DPD INTEGRATION BASED ON OPTIMIZED MSA

In this context, we are discussing the fundamental modeling for DPD. The MSA function, which was previously suggested, can be presented in its efficient form as[10,13,14]

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

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

In Equation (1), the linear model coefficients for each zone of the MSF function $u^{(1)}_{m,k}(.)$ are represented by $A^{(1)}_{m,k,l}$ and $B^{(1)}_{m,k,l}$. In Equation (2), the input baseband signal is represented by $x(n)$, and the output baseband signal is characterized by $y(n)$. The dimension of the finite impulse response filter is characterized by K, and the memory depth is symbolized by M. The number of partitions is represented by L, and the threshold is represented by β_l. The model coefficients are embodied by $c^{(1)}_{m,k,l}, c^{(2)}_{m,k,l}, c^{(3)}_{m,k,l}, c^{(4)}_{m,k,l}$.

The input power terms in Equation (1) are compared to thresholds for the offset and linear gain selection for the MSA function, eliminating the need for a square root calculation. The overall model of Equation (1) in terms of the MSA function can be expressed as follows:

$$\begin{aligned} y(n) = &\sum_{m=0}^{M} c_m x(n-m) \\ &+ \sum_{m=0}^{M} \left(A^{(m)}_{k,1}\, |x(n-m)|^2 + B^{(m)}_{k,1}\right) e^{j\theta(n-m)} \\ &+ \sum_{m=0}^{M} \left(A^{(m)}_{k,21}\, |x(n-m)|^2 + B^{(m)}_{k,21}\right) \\ &e^{j\theta(n-m)}|x(n)| + \cdots \beta_{k-1} \le |x(n)| \le \beta_k. \end{aligned} \tag{3}$$

The coefficients for each zone of the MSF linear model function $u^{(i)}_{m,k}(.)$, namely, $A^{(i)}_{m,k,l}$ and $B^{(i)}_{m,k,l}$, are defined in Equation (4). These coefficients are determined through a least-squares algorithm.

By referring to Figure 1, it is apparent that the MSA paradigm can achieve higher precision by minimizing the number of segments. The input waveform is divided into multiple zones based on β values in the MSA model, and each zone has its own set of model parameters. Collectively, the segments can be regarded as a group of affine functions. On the other hand, the OMSA model partitions the input signal with a predetermined threshold based on β and replaces the affine functions with subjective functions that are contingent upon the input power. These subjective functions in the OMSA model can be represented as

$$\prod\nolimits_s (x(n)) = \frac{1}{2}\left[1 + \tan h\left(S(|x(n)|)\left(\frac{(1-k)}{k}k\right)\right)\right], \tag{4}$$

$$\prod\nolimits_D (x(n)) = \frac{1}{2}\left[1 + \tan h\left(S(|x(n)|)\left(\frac{1}{k^2}i\right)\right)\right]. \tag{5}$$

Here

$$S(x(n)) = \left(1 - \frac{|x(n)|}{x_{\text{threshold}}\, |x|_{\max}}\right). \tag{6}$$

The OMSA model employs two subjective functions, namely, functions $\prod_s(.)$ and $\prod_D(.)$, which are responsible for mapping the absolute value of the input signal to their respective weighting functions for the dynamic and static terms. The input signal is split into $k = 2$ segments based on a threshold value β in this study. The |.| operator calculates the absolute value of the input signal. By utilizing these weighting functions, the model's accuracy can be improved by reducing the number of segments and considering the power of the input signal. With the updates

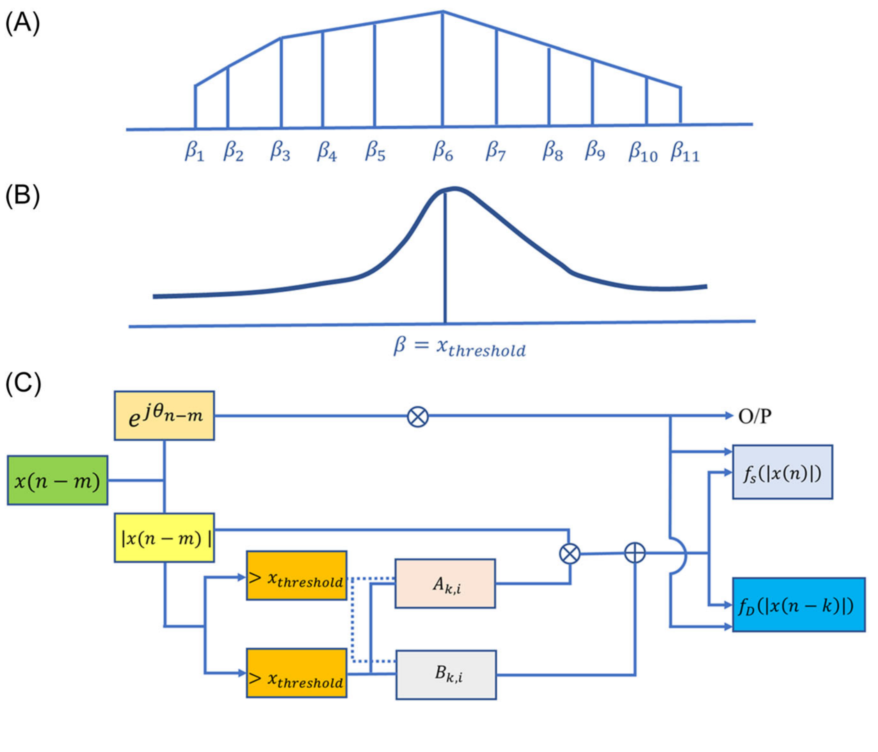

FIGURE 1 Illustration of: (A) magnitude-selective affine (MSA) model, (B) optimized MSA (OMSA), and (C) OMSA model structure.

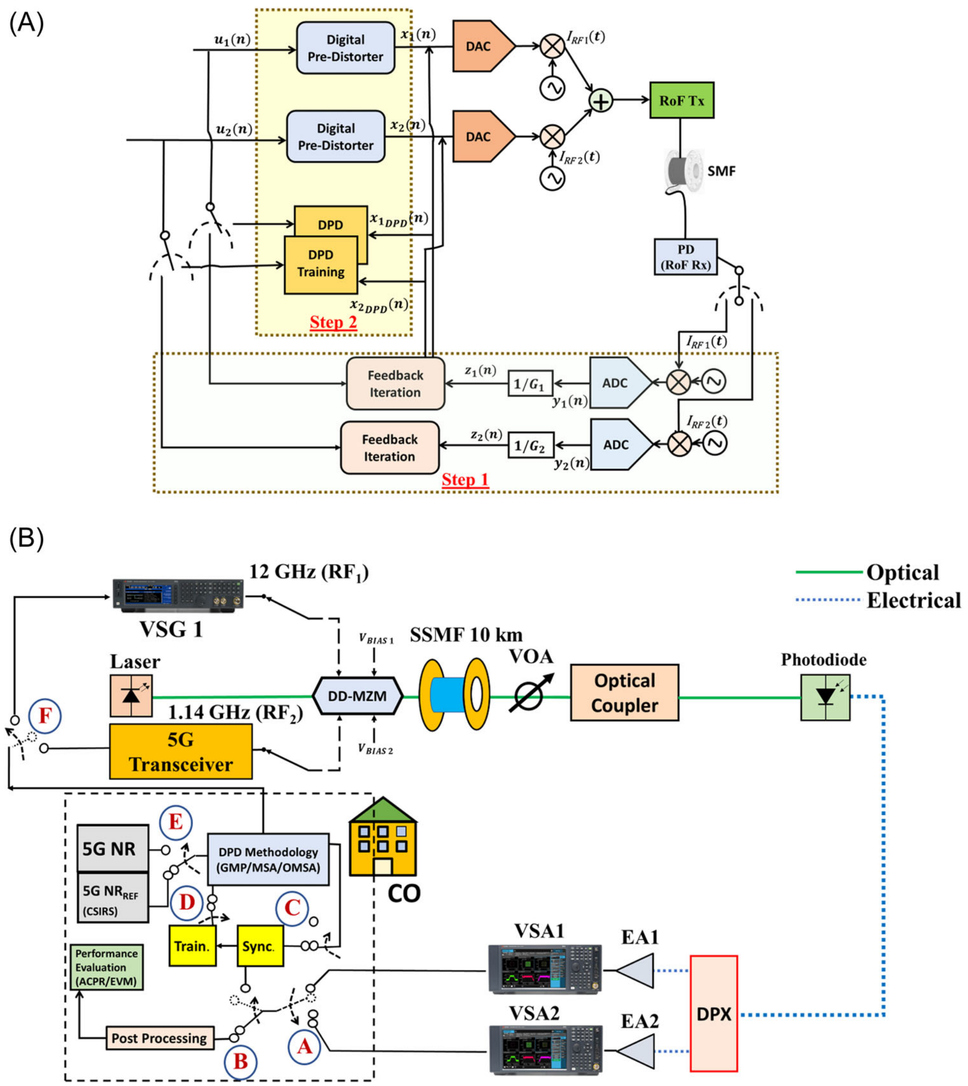

FIGURE 2 Block diagram of: (A) the radio over fiber digital predistortion training and modeling methodology; (B) the experimental bench for the radio over fiber (RoF) digital predistortion (DPD) implementation methodology. GMP, generalized memory polynomial; MSA, magnitude-selective affine; MZM, Mach-Zehnder modulator; NR, new radio; OMSA, optimized magnitude-selective affine; SSMF, standard single-mode fiber; DAC, digital to analog converter; DD, dual drive; DPX, diplexer; Rx, receiver; Tx, transmitter; VOA, variable optical attenuator; VSA, vector signal analyzer; VSG, vector signal generator.

explained in Equations (5)–(7), the OMSA with the updates will become

$$\begin{aligned} y(n)_{\mathrm{OMSA}} = &\sum_{m=0}^{M} c_m x(n-m) \\ &+ f_s(x(n))(A_{k,i}|x(n)| + B_{k,i})e^{j\theta(n)} \\ &+ \sum_{m=1}^{M} f_D(x(n-m))(A_{k,i}|x(n-m)| \\ &+ B_{k,i})e^{j\theta(n-m)} + f_s(x(n))(A_{k,i}|x(n)| \\ &+ B_{k,i})e^{j\theta(n)}|x(n)| + \sum_{m=1}^{M} f_D(x(n-m)) \\ &(A_{k,i}|x(n-m)| \\ &+ B_{k,i})e^{j\theta(n-m)}|x(n)|, \end{aligned} \tag{7}$$

where $x(n)$ and $y(n)$ show the corresponding input and output at the baseband. The proposed OMSA structure is shown in Figure 1C.

3 | EXPERIMENTAL BENCH

In this technique, we would like to check the efficacy of the proposed OMSA method and compare its performance with our previous methods. For this, a multiband 5G NR setup for eMBB environments operating at 1.14 and 12 GHz is used, with a DPD block added for enhancing the performance via linearization. The setup shown in Figure 2B includes a Mach-Zehnder modulator from iXblue dual drive, a 1550-nm laser, a 10-km standard single-mode fiber, and an R402 PIN

TABLE 1 Optical link parameters.

Parameter	Value
5G NR waveforms	f_c = 1.14 and 12 GHz
	Flexible G/F-OFDM
	Constellation type = 256 QAM
Laser	Wavelength = 1550 nm
	iXblue Mach-Zehnder modulator
Optical fiber	Type = SSMF
	Fiber dispersion = 16 ps/nm km
	Fiber distance = 10 km
	Attenuation = 0.32 dB/km
R402 PIN photodiode	Responsivity = 0.84 A/W
	Bandwidth = 40 GHz

Abbreviations: NR, new radio; SSMF, standard single-mode fiber.

photodetector to convert the received wave back to the electrical domain. The signals are separated by a diplexer and then sent to distinct vector signal analyzers. The phase and amplitude responses are ensured to be opposite to those produced from electrical amplifiers EA1 and EA2 by using the DPD operation in Figure 2A for training until the error converges. Time synchronization is performed using a 20-MHz channel state information reference signal. The DPD validation phase uses real-time 5G NR frames to confirm the effectiveness of the DPD process.

Table 1 provides details of the experimental bench.

4 | EXPERIMENTAL FINDINGS

We used $K = L = 4$, $M = 3$ for the proposed OMSA and MSA methods. Also, we have used the GMP method previously used by Hadi et al.[10] with similar

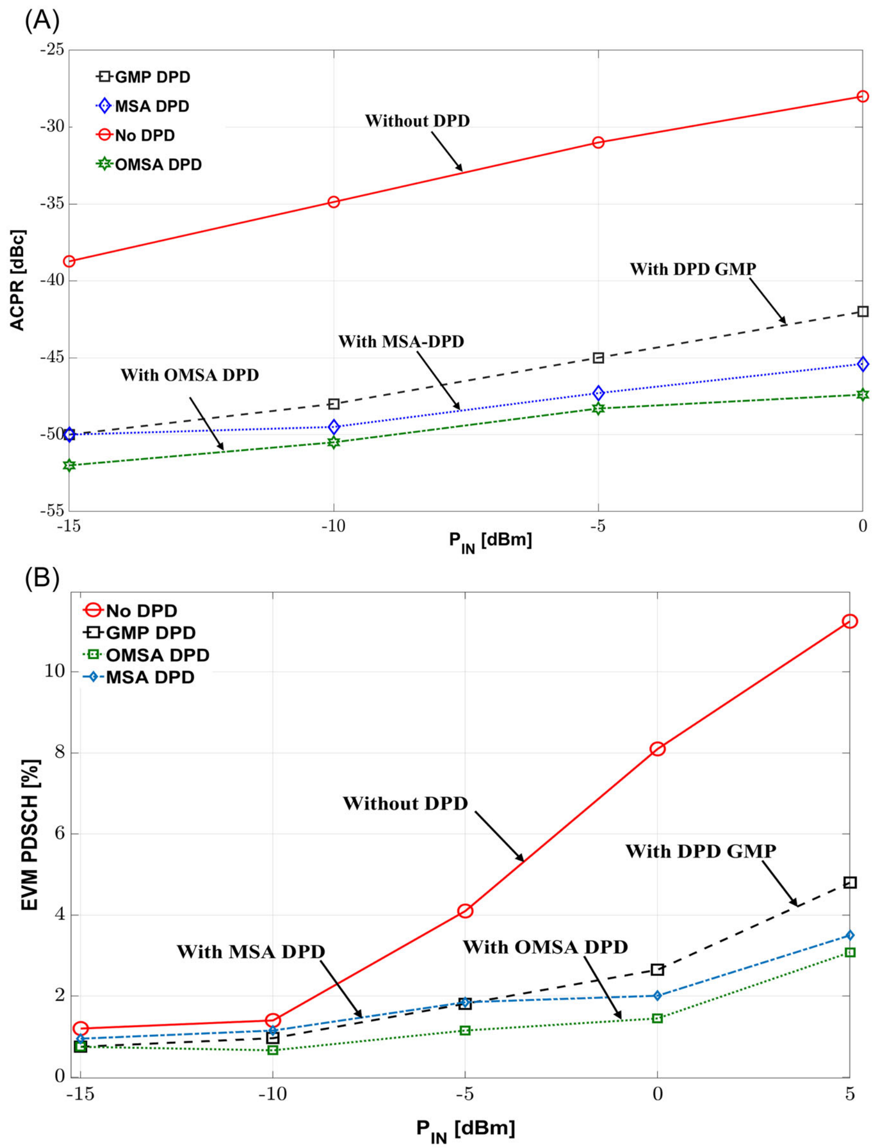

FIGURE 3 Digital predistortion (DPD) performance for changing radiofrequency (RF) input power with reference to: (A) adjacent channel power ratio (ACPR) and (B) error vector magnitude (EVM). GMP, generalized memory polynomial; MSA, magnitude-selective affine; OMSA, optimized magnitude-selective affine.

TABLE 2 Computational (coefficients, multiplications, and time consumption) complexity comparisons.

Method	Coefficients	Condition number	Estimated multiplications	Time consumption (s)
GMP	156	8.14×10^7	19 140	185
MSA	$2(4M+1)\ (K+1)\ L = 520$	3.2×10^{13}	$(14M+2)\ (K+1) = 220$	103
OMSA	$k(4M+1)(K+1)x_{th}\vert_{x_{th}=\beta} = 271$	2.1×10^4	$(14M+2)(K+1)\ x_{th}\vert_{x_{th}=\beta} = 114$	87

Abbreviations: GMP, generalized memory polynomial; MSA, magnitude-selective affine; OMSA, optimized magnitude-selective affine.

parameters ($K = Q = 3$) for a justified comparison. The experimental findings are described in the form of EVM and ACPR.[15]

Figure 3A presents the ACPR for varying RF input power, revealing that the OMSA-DPD method achieves a 20 dB reduction in ACPR (to −47.4 dBc) compared to the case without DPD, keeping it below the −45 dBc threshold set by 3GPP.[16] While the MSA-DPD technique results in a 16 dB reduction in ACPR, the main advantage of OMSA is its reduction in complexity. EVM is also assessed by sweeping the RF input power, as shown in Figure 3B. It is evident that the OMSA-DPD technique results in an EVM reduction of less than 3%, in contrast to the 3.5% obtained with MSA and 5% obtained with GMP, remaining below the 3.5% threshold set by 3GPP.[16] Although OMSA-DPD has a slight improvement compared to MSA, it exhibits a significant improvement compared to GMP. The main contribution of OMSA compared to MSA and GMP is its reduction in complexity. Furthermore, Figure 3B compares the DPD and no DPD results in terms of EVM for 5G NR flexible waveforms, demonstrating that MSA-DPD achieves a better reduction than the other methods.

Although the results in Figure 3 show that OMSA has a slightly better performance than MSA, the actual gain with OMSA is the lower complexity that this model offers. The OMSA-DPD method is more efficient than the MSA method because it requires fewer multiplications and has lesser complexity, as shown in Table 2. Specifically, the OMSA-DPD method requires 114 multiplications, while the MSA method requires 220 multiplications. Similarly, the condition number, time consumption, and other similar statistics of OMSA-DPD methods also signify that it is a better optimized, less complex, and efficient method as compared to MSA and GMP. These can be compared with our previous work where we used DPD based on ML methods.[17,18] The proposed OMSA performs efficiently but its actual gain is in terms of complexity reduction, which is very high in case of ML DPD. The OMSA architecture achieves EVM values consistent with the EVM limit of 3.5% specified in 3GPP TR 21.916 V16.2.0 (2022-06)16 and the latest version 17 of 3GPP TS 36.141, release 17, version 17.5.0.

5 | CONCLUSION

The proposed letter introduces a novel method for optimizing the MSA method to linearize a multiband 5G NR-based RoF link for eMBB applications. The proposed method, known as OMSA-DPD, is experimentally tested for transmitting 5G NR waveforms at 1.14 and 12 GHz over a 10-km fiber distance. The OMSA-DPD method achieves better performance compared to MSA and GMP methods by reducing signal impairments such as ACPR and EVM. Furthermore, it requires fewer multiplication operations, making it more efficient and less complex than the previous MSA method. To the best of the authors' knowledge, this is the first instance of improving the performance of multiband 5G NR-based optical fronthaul using the proposed OMSA-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.

ORCID

Muhammad Usman Hadi http://orcid.org/0000-0002-3363-2886

REFERENCES

1. ITU-R. *IMT Vision–Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond, 2015, Recommendation ITU-R M.2083-0*. International Telecommunication Union. 2015:1-19
2. Fernandez EA, Serafino G, Hussain B, et al. Modulation index study of a cost-effective solution for CRAN architecture based on coherent radio-over-fiber backhaul. In: *2018 11th International Symposium on Communication Systems (CSNDSP)*, Budapest, Hungary. IEEE; 2018:1-4. https://ieeexplore.ieee.org/document/8471883
3. Marti J, Capmany J. Microwave photonics and radio-over-fiber research. *IEEE Microw Mag*. 2009;10(4):96-105.
4. Jia S, Zhang L, Wang S, et al. 2 × 300 Gbit/s line rate PS-64QAM-OFDM THz Photonic-Wireless transmission. *J Light Technol*. 2020;38(17):4715-4721.
5. Hadi MU, Murtaza G. Enhancing distributed feedback-standard single mode fiber-radio over fiber links performance by neural network digital predistortion. *Microw Opt Technol Lett*. 2021;63:1558-1565.

6. Hadi MU, Nanni J, Polleux JL, Traverso PA, Tartarini G. Direct digital predistortion technique for the compensation of laser chirp and fiber dispersion in long haul radio over fiber links. *Opt Quantum Electron*. 2019;51:205. doi:10.1007/s11082-019-1923-8
7. Zhang X, Zhu R, Shen D, Liu T. Linearization technologies for broadband radio-over-fiber transmission systems. *Photonics*. 2014;1:455-472.
8. Hadi MU, Kantana C, Traverso PA, et al. Assessment of digital predistortion methods for DFB-SSMF radio-over-fiber links linearization. *Microw Opt Technol Lett*. 2020;62:540-546.
9. Hekkala A, Hiivala M, Lasanen M, et al. Predistortion of radio over fiber links: algorithms, implementation, and measurements. *IEEE Trans Circ Syst I*. 2012;59(3):664-672.
10. 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;64:827-834. doi:10.1002/mop.33169
11. Liu S, Xu M, Wang J, et al. A multilevel artificial neural network nonlinear equalizer for millimeter-wave mobile fronthaul systems. *J Light Technol*. 2017;35:4406-4417.
12. Vagionas C, Ruggeri E, Tsakyridis A, et al. Linearity measurements on a 5G mmwave fiber wireless IFoF fronthaul link with analog RF beamforming and 120° degrees steering. *IEEE Commun Lett*. 2020;24(12):2839-2843. doi:10.1109/LCOMM.2020.3019733
13. Li Y, Cao W, Zhu A. Instantaneous sample indexed magnitudes elective affine function-based behavioral model for digital predistortion of RF power amplifiers. *IEEE Trans Microw Theory Tech*. 2018;66(11):5000-5010.
14. Cao W, Li Y, Zhu A. Magnitude-selective affine function based digital predistorter for RF power amplifiers in 5G small-cell transmitters. In: *IEEE MTT-S International Microwave Symposium*, Hawaii, United States of America. IEEE. 2017:1539-1541. https://researchrepository.ucd.ie/entities/publication/a894e992-959b-4a3e-83fb-8f131afc2d0e/details
15. Hadi MU, Traverso PA, Tartarini G, Venard O, Baudoin G, Polleux JL. Digital predistortion for linearity improvement of VCSEL-SSMF-based radio-over-fiber links. *IEEE Microw Wirel Compon Lett*. 2019;29:155-157. doi:10.1109/LMWC.2018.2889004
16. 3GPP TS 38.215 version 15.4.0 Release 15; 5G; NR; Physical Layer Measurements.
17. Hadi MU. Experimental demonstration of transport over fiber using 5G NR with performance enhancement using DPD. *Opt Commun*. 2023;531:129226.
18. Hadi M, Awais M, Raza M, Khurshid K, Jung H. Neural network DPD for aggrandizing SM-VCSEL-SSMF-based radio over fiber link performance. *Photonics*. 2021;8:19.

How to cite this article: Hadi MU, Murtaza G, Kausar S. Optimized MSA DPD method for improving 5G multiband optical fronthaul performance. *Microw Opt Technol Lett*. 2023;1-7. doi:10.1002/mop.33829