

# An OFDM-based radio over fiber system with channel estimation denoising and digital linearization

Luis Carlos Vieira, Paulo de Tarso Neves Junior, and Alexandre A. P. Pohl

**Abstract**—This work presents experimental results for a 20.3 km fiber-optic link operating at 3.5 GHz for potential Radio-over-Fiber (RoF) applications. The system employs OFDM together with denoising-assisted channel estimation and digital polynomial linearization based on a Least Squares (LS) training algorithm. To evaluate the minimum input power required to satisfy 5G EVM specifications and the resulting dynamic range enhancement, the EVM versus RF input power is characterized for both 64-QAM and 256-QAM signals. The experimental results show that the proposed compensation scheme reduces the EVM from 8.2% to 1.9% for 64 QAM and from 6.6% to 1.8% for 256 QAM.

**Keywords**—Radio over fiber, channel estimation, linearization, OFDM.

## I. INTRODUCTION

Radio-over-fiber (RoF) technology has emerged as a key enabler for the deployment of 5G and 6G networks [1]–[3]. Compared to digital mobile fronthaul, analog transmission in conventional RoF offers advantages such as higher spectral efficiency, simpler remote antenna units (RAUs), lower installation and maintenance costs, and centralized control functionality [1]. However, analog optical transmission is highly sensitive to link noise and nonlinear distortion, and the inherently high peak-to-average power ratio (PAPR) of orthogonal frequency-division multiplexing (OFDM) signals further aggravates these nonlinear effects.

Several compensation schemes have been proposed to mitigate nonlinearity in RoF and intermediate-frequency-over-fiber (IFoF) systems, including digital predistortion [4]–[7] and nonlinear equalization [8], [9]. Digital predistortion is a well-known linearization technique that has demonstrated significant performance improvements in RoF systems. However, because predistortion is implemented at the transmitter, it requires a feedback link to adapt to variations in the nonlinear characteristics of RoF/IFoF links. In contrast, nonlinear equalization concentrates digital signal processing (DSP) functionalities at the receiver, eliminating the need for a feedback link in RoF/IFoF systems and reducing implementation cost.

Channel estimation in OFDM is typically performed in the frequency domain using either comb-type or block-type

approaches [10]. Comb-type methods use sparsely inserted pilot subcarriers within each symbol and apply estimators such as least squares (LS) or minimum mean square error (MMSE), followed by interpolation to obtain the channel response across all subcarriers. In contrast, block-type estimation employs full pilot symbols occupying all subcarriers, enabling direct estimation of the complete channel frequency response. This estimate is then reused for subsequent data symbols until the next pilot block. Block-type methods are especially suitable for optical OFDM systems, where the channel varies slowly and can be considered quasi-static over multiple symbols [11].

In this work, we experimentally demonstrate an OFDM-based RoF system operating in the 5G frequency band at 3.5 GHz, employing channel estimation denoising (CED) combined with a polynomial-based digital linearization approach. This compensation scheme is implemented after the RoF link. Such a post-compensation approach is particularly suitable for the uplink of analog RoF systems, as all DSP processing can be centralized, thereby preserving the simplicity of remote antenna units (RAUs). The proposed scheme can also be applied to the downlink by placing the compensation stages in mobile devices or in DSP-assisted RAUs. System performance is evaluated for different input power levels using both 64-QAM and 256-QAM signals, with excellent results achieved over a 20.3 km RoF link.

## II. SIGNAL MODEL AND COMPENSATION APPROACH

In OFDM systems, the available channel bandwidth is partitioned into  $N$  orthogonal subchannels, allowing the data stream to be transmitted in parallel across these subchannels. This parallel transmission increases the symbol duration, thus reducing the sensitivity of the signal to channel impairments such as intersymbol interference (ISI). The discrete-time OFDM signal is generated using an  $N$ -point inverse fast Fourier transform (IFFT) and can be expressed as

$$s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi nk/N}, \quad n = 0, 1, \dots, N-1 \quad (1)$$

where  $X(k)$  denotes the complex data symbols mapped onto the  $N$  subcarriers, with  $k = 0, 1, \dots, N-1$ .

The time-domain digital linearization scheme is depicted in Fig. 1. It employs a third-order memoryless polynomial at the receiver for post-compensation of nonlinear distortion. Compared to models based on memory polynomials [12], the

Luis C. Vieira, Department of Electronics (DAELN-CT), Federal University of Technology-Parana (UTFPR), Curitiba, Brazil, e-mail: vieira@utfpr.edu.br; Paulo de Tarso Neves Jr., Graduate Program in Electrical Engineering and Computer Science (CPGEI), UTFPR, Curitiba, Brazil, e-mail: pn-eves@utfpr.edu.br; Alexandre A. P. Pohl, Graduate Program in Electrical Engineering and Computer Science (CPGEI), UTFPR, Curitiba, Brazil, e-mail: pohl@utfpr.edu.br. This work was partially supported by the project approved under the bid MCTI/FINEP/FNDCT - Infraestrutura de Pesquisa - Proinfra 2023.

proposed approach requires fewer coefficients and does not rely on delayed input samples for nonlinear compensation. The number of coefficients of a memoryless polynomial increases linearly with the polynomial order  $P$ , whereas that of a memory polynomial is proportional to  $P(M + 1)$ , where  $M$  is the memory depth. Consequently, the proposed approach has lower computational complexity than memory polynomial-based methods. In Fig. 1, the polynomial linearizer is designed to approximate the inverse of the link nonlinearity. Its coefficients are estimated during a training phase using known signals and a linear least-squares algorithm. An offline training strategy is adopted, in which the coefficients are computed in a single step. Following training, the linearizer coefficients are updated and applied to the received signal, producing the linearized output  $y_{lin}$ , which is then forwarded to subsequent processing stages. The update interval is determined by the stability of the nonlinear characteristics of the RoF link.

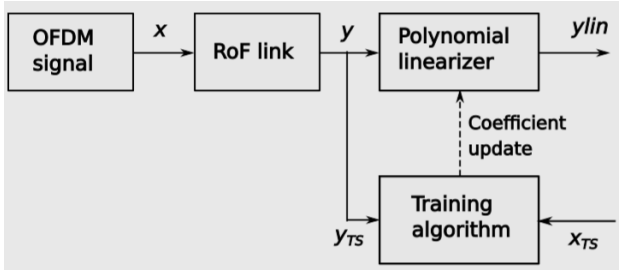


Fig. 1. The digital linearization approach.

After linearization, the received signal is transformed into the frequency domain using a fast Fourier transform (FFT), and the channel estimation is then performed. The resulting channel response is subsequently used for OFDM equalization. In this work, block-type channel estimation based on the LS algorithm is employed. To mitigate noise in channel estimates, a sequence of training symbols (TSs) is transmitted within each OFDM frame, and the resulting channel responses are averaged across all TSs.

Specifically, the channel response  $H(k)$  for each subcarrier  $k$  is first obtained as

$$H(k) = \frac{y_{TS_{Lin}}(k)}{x_{TS}(k)} \quad (2)$$

where  $x_{TS}(k)$  denotes the known transmitted training symbol and  $y_{TS_{Lin}}(k)$  is the corresponding received signal after linearization. This estimate is computed independently for each TS. The final channel response used for equalization is then obtained by averaging these estimates over the sequence of TSs.

It is worth noting that the performance of the proposed channel estimation approach is further improved by applying linearization prior to the FFT operation, thereby reducing distortion effects before frequency-domain processing.

### III. EXPERIMENTAL SETUP

The experimental setup of the proposed OFDM-RoF system is shown in Fig. 2. Two 64-QAM OFDM signals with bandwidths of 50 MHz and 100 MHz are generated in MATLAB

for transmission over the 3.5 GHz RoF link. In addition, the transmission performance of a 256-QAM OFDM signal with 50 MHz bandwidth is also investigated. The 100 MHz 64-QAM OFDM signal uses an IFFT size of 1024 with 418 data subcarriers and cyclic prefix (CP) size of 64, while both 50 MHz OFDM signals use an IFFT size of 512 with 210 data subcarriers and CP size of 32. The corresponding sampling rates are 245.76 MS/s and 122.88 MS/s for the 100 MHz and 50 MHz signals, respectively. All OFDM signals are generated with a subcarrier spacing of 240 kHz. Binary phase-shift keying (BPSK) training signals are utilized for both polynomial linearizer training and OFDM channel estimation. In this work, each OFDM frame consists of 120 data symbols and up to 8 TSs.

Each generated baseband OFDM signal is uploaded to a vector signal generator (Keysight M9484C VXG), where it modulates a 3.5 GHz RF carrier with a power level ranging from  $-6$  dBm to  $14$  dBm. The resulting OFDM signal is transmitted over the RoF link, which consists of a Mach-Zehnder modulator (MZM) biased around its quadrature point, a 20.3 km standard single-mode fiber (SMF), and a 10 GHz PIN-TIA photodetector (PD). A 1550-nm laser with an output power of  $12$  dBm is used as the optical source, and a polarization controller is placed between the laser and the MZM. After photodetection, the received signal is digitized using a signal analyzer (Keysight N9021B MXA) at sampling rates of  $122.88$  MS/s or  $245.76$  MS/s. The digitized data are then processed offline in MATLAB.

At the receiver side, the DSP functionalities are implemented as illustrated in Fig. 2. First, the received signal is time-aligned by the symbol synchronization block to identify the start of each OFDM symbol. The aligned signal is then linearized using the polynomial-based approach, followed by serial-to-parallel conversion and FFT processing. Next, frequency-domain channel estimation and zero-forcing equalization are performed. Finally, the equalized signal is converted back to serial form and QAM demodulated.

### IV. EXPERIMENTAL RESULTS

This section presents the error vector magnitude (EVM) results and constellation diagrams for the proposed OFDM-RoF system. Performance is evaluated for three signal configurations: 100-MHz 64-QAM OFDM, 50-MHz 64-QAM OFDM, and 50-MHz 256-QAM OFDM. For each case, three approaches are compared: a conventional OFDM-RoF system, a linearized system based on a third-order polynomial without CED, and the proposed OFDM-RoF system with both CED and linearization. The EVM of the proposed system is evaluated for CED using 2, 4, and 8 TSs.

In Fig. 3, the EVM versus RF input power is presented for the 100-MHz 64-QAM OFDM signal. For the conventional OFDM-RoF system, the minimum EVM of  $3.7\%$  is achieved at an RF input power of  $8$  dBm. The EVM performance degrades at lower power levels, where the link is noise-dominated, and at higher power levels due to the increasing impact of RoF nonlinearities. With polynomial linearization applied without CED, the EVM at higher power levels improves significantly.

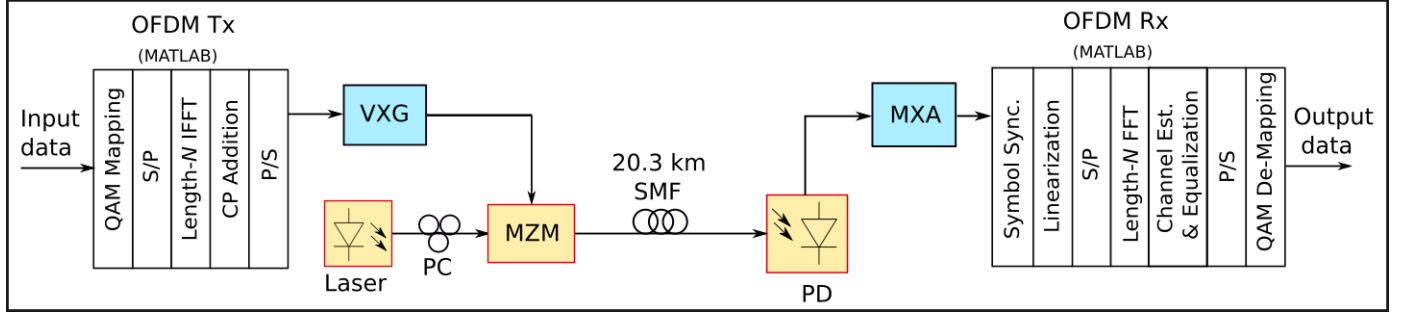


Fig. 2. Experimental setup. PC, polarization controller; PD, PIN-TIA based photo-detector.

For instance, at an input power of 14 dBm, the EVM decreases from 7.1% in the conventional system to 2.4% in the linearized system. Further improvement is achieved with the proposed compensation approach: an EVM of 1.9% is obtained at 14 dBm when using 8 TSs. At lower power levels, the advantage of the combined compensation scheme is also evident. For example, at  $-2$  dBm, the EVM is reduced from 9.4% for both conventional and linearized systems to 7.3% with the proposed method. This value is well within the 3GPP limit of 8% for 64-QAM.

Fig. 4 presents the EVM results for the 50-MHz 64-QAM OFDM signal. For the conventional OFDM-RoF system, the minimum EVM of approximately 3.2% is achieved at an RF input power of 6 dBm. As observed previously, the EVM at higher power levels improves significantly with both polynomial linearization (without CED) and the proposed combined compensation approach. At an input power of 14 dBm, the EVM decreases from 8.2% in the conventional system to 2.4% with linearization, and further to 1.9% with the proposed method using 8 TSs. Notable improvements are also observed at lower power levels. For example, at  $-4$  dBm, the EVM is reduced from 8.5% for both conventional and linearized systems to 6.5% with the proposed approach using 8 TSs, and to 6.8% when using 4 TSs. Both results are well within the 3GPP limit for 64-QAM.

The performance results for the 50-MHz 256-QAM OFDM signal are shown in Fig. 5. For the conventional OFDM-RoF system, only the EVM values at 4, 6, and 8 dBm fall within the 3GPP limit of 3.5% for 256-QAM. With polynomial linearization applied without CED, the EVM at higher input power levels ( $> 8$  dBm) is reduced to below 3.5%, indicating an extension of the dynamic range of the system by more than 4 dB. When both CED (with 4 or 8 TSs) and linearization are applied, the EVM remains within the 3GPP specification across a wider input power range, from 2 to 14 dBm, while achieving substantial EVM reduction. For example, at 14-dbm input power, the proposed approach with 8 TSs reduces the EVM from 6.6% to 1.8%. The minimum EVM values are 3% at 6 dBm for the conventional system and 1.3% at 12 dBm for the proposed OFDM-RoF system using 8 TSs. These results demonstrate both improved EVM performance and an increase in system dynamic range of at least 6 dB with the proposed compensation scheme.

The received signal constellations after the 20.3-km RoF

link for the conventional and proposed OFDM-RoF systems at an RF power level of 12 dBm are shown in Figs. 6 and 7. The proposed combined compensation scheme significantly improves the constellation quality for both 64-QAM and 256-QAM signals, as evidenced by the clearer and more compact received constellation points.

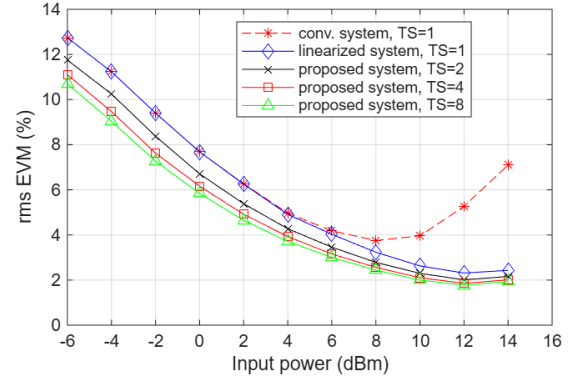


Fig. 3. EVM results for the OFDM-RoF system. 100-MHz signal bandwidth, 64-QAM.

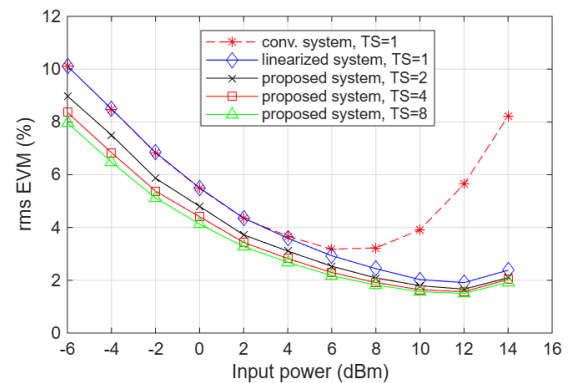


Fig. 4. EVM results for the OFDM-RoF system. 50-MHz signal bandwidth, 64-QAM.

## V. CONCLUSIONS

In this paper, the performance of an OFDM-RoF system employing a time-domain polynomial linearization approach together with a frequency-domain CED method was experimentally investigated. Significant EVM improvements were

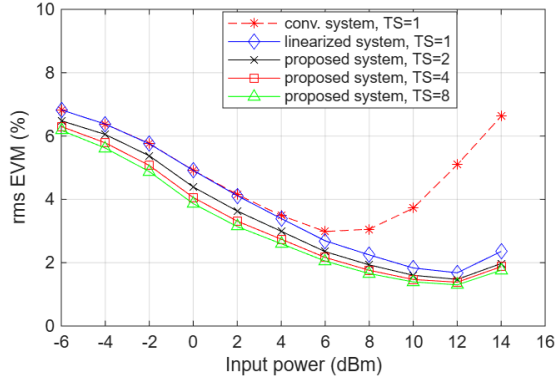


Fig. 5. EVM results for the OFDM-RoF system. 50-MHz signal bandwidth, 256-QAM.

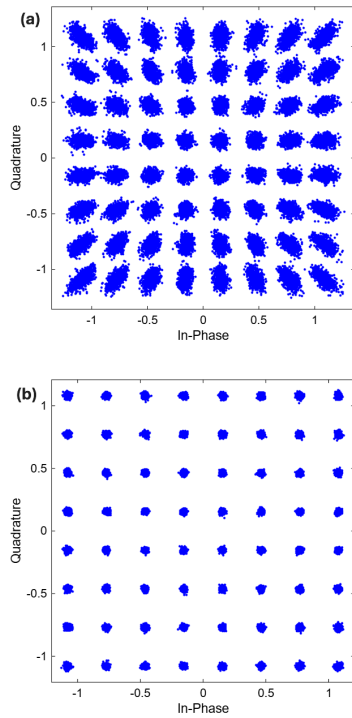


Fig. 6. Received 64-QAM signal constellations after the 20.3-km RoF link: (a) conventional OFDM-RoF; (b) proposed OFDM-RoF using 8 TSs. Input power level of 12 dBm.

achieved using the combined compensation scheme in a 20.3-km OFDM-RoF link operating at 3.5 GHz, considering 50 MHz and 100 MHz OFDM signals modulated with 64-QAM and 256-QAM. A third-order memoryless polynomial model was adopted for linearization, while CED was carried out using 2, 4, and 8 TSs. For both 64-QAM and 256-QAM, the optimal EVM performance was obtained with the combined compensation scheme using 8 TSs. For 50-MHz 64-QAM transmission at an RF input power of 14 dBm, the EVM was significantly reduced from 8.2% in the conventional system to 1.9% with the proposed compensation approach using 8 TSs. Similarly, for the 100-MHz 64-QAM signal at 14 dBm, the EVM decreased from 7.1% to 1.9% when the proposed compensation method with 8 TSs was applied. For the 256-QAM OFDM signal, the proposed compensation scheme em-

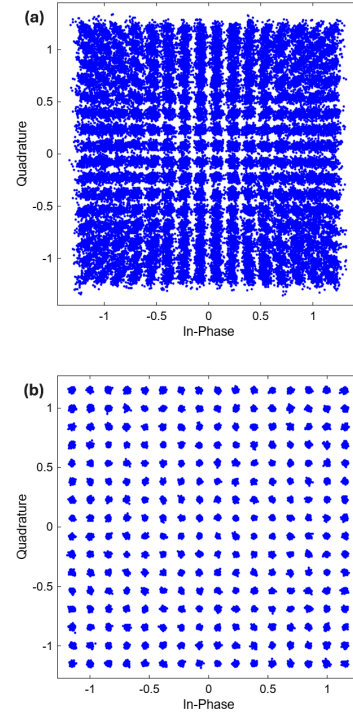


Fig. 7. Received 256-QAM signal constellations after the 20.3-km RoF link: (a) conventional OFDM-RoF; (b) proposed OFDM-RoF using 8 TSs. Input power level of 12 dBm.

ploying 8 TSs improved the system dynamic range by at least 6 dB. The proposed memoryless polynomial-based linearization approach exhibits lower computational complexity than memory polynomial-based methods, thereby providing a more computationally efficient solution for nonlinear compensation.

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#### REFERENCES

- [1] C. Lim and A. Nirmalathas, "Radio-Over-Fiber Technology: Present and Future," *Journal of Lightwave Technology*, vol. 39, no. 4, pp. 881–888, 2021.
- [2] S. Noor, P. Assimakopoulos, and N. J. Gomes, "A flexible subcarrier multiplexing system with analog transport and digital processing for 5G (and beyond) fronthaul," *Journal of Lightwave Technology*, vol. 37, no. 14, pp. 3689–3700, 2019.
- [3] P. Zhu, Y. Yoshida, A. Kanno, and K.-i. Kitayama, "DSP-enhanced radio-over-fiber technologies for 5G-and-beyond wired-wireless convergence," *Journal of Optical Communications and Networking*, vol. 14, no. 8, pp. 595–605, 2022.
- [4] L. C. Vieira and N. J. Gomes, "Experimental demonstration of digital predistortion for orthogonal frequency-division multiplexing-radio over fibre links near laser resonance," *IET Optoelectronics*, vol. 9, no. 6, pp. 310–316, 2015. [Online]. Available: <https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-opt.2014.0160>
- [5] Z. Cheng, X. Zhang, and G. Xu, "Low complexity digital predistortion for multiband radio over fiber systems," *IEEE Microwave and Wireless Technology Letters*, vol. 34, no. 7, pp. 955–958, 2024.

- [6] M. U. Hadi, M. Awais, M. Raza, and S. Kausar, "Performance Enhancement in Multiband 5G NR-Radio-over-Fiber System using DPD," in *2021 International Topical Meeting on Microwave Photonics (MWP)*, 2021, pp. 1–4.
- [7] L. A. M. Pereira, L. L. Mendes, C. J. A. Bastos-Filho, and S. Arismar Cerqueira, "Linearization schemes for radio over fiber systems based on machine learning algorithms," *IEEE Photonics Technology Letters*, vol. 34, no. 5, pp. 279–282, 2022.
- [8] H. J. Park, S.-Y. Jung, D. W. Kwon, S.-H. Cho, H. S. Chung, J. H. Lee, and S.-K. Han, "Distortion Mitigation in Multiband OFDM RoF Transmission Employing Blind Post Equalizer," *IEEE Photonics Technology Letters*, vol. 28, no. 23, pp. 2708–2711, 2016.
- [9] E. Liu, Z. Yu, Y. Song, K. Sun, H. Huang, F. Yin, Y. Zhou, and K. Xu, "TL-ANN based nonlinear equalization for multi-users radio over fiber system," *Journal of Lightwave Technology*, vol. 41, no. 5, pp. 1399–1405, 2023.
- [10] Y. Liu, Z. Tan, H. Hu, L. J. Cimini, and G. Y. Li, "Channel Estimation for OFDM," *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 1891–1908, 2014.
- [11] L. Liu, X. Yang, and W. Hu, "Experimental evaluation of pilot pattern design in direct-detection optical OFDM transmission," *Optics Communications*, vol. 294, pp. 83–87, 2013. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0030401812014514>
- [12] D. Morgan, Z. Ma, J. Kim, M. Zierdt, and J. Pastalan, "A Generalized Memory Polynomial Model for Digital Predistortion of RF Power Amplifiers," *IEEE Transactions on Signal Processing*, vol. 54, no. 10, pp. 3852–3860, 2006.