Implementation of a Full Optically-Powered 5G NR Fiber-Wireless System

Letícia Carneiro de Souza, Eduardo Saia Lima, and Arismar Cerqueira Sodré Junior

***Abstract*—We report the implementation of a full optically-powered 5G new radio (5G NR) fiber-wireless (FiWi) system based on power-over-fiber (PoF) and radio-over-fiber (RoF) technologies. Our approach enables the simultaneous transmission of a 5G NR signal at 3.5 GHz with bandwidth up to 100 MHz and a 2.2-W optical power signal employing dedicated fiber-optics links. The optical-wireless data link consists of a 12.5-km single-mode fiber (SMF) optical fronthaul followed by a 10-m wireless propagation environment, which is the longest wireless reach reported in literature up to now, regarding optically-powered FiWi systems. The proposed PoF system is able to deliver stable electrical power up to 475 mW, by means of using a 100-m multimode fiber (MMF) link, with the purpose of optically powering a 5G NR remote antenna unit (RAU). An overall power transmission efficiency (PTE) of 23.5% is experimentally demonstrated in a real 5G NR system. Furthermore, the FiWi system performance is investigated in accordance with the 3$^{\text{rd}}$ generation partnership project (3GPP) Release 15 requirements, in terms of root mean square error vector magnitude ($\mathrm{EVM_{RMS}}$). The proposed optically-powered 5G NR FiWi system provides 500 Mbit/s throughput with $\mathrm{EVM_{RMS}}$ as low as 3.9%, employing 64-quadrature amplitude modulation (QAM) without using optical amplification.**

***Index Terms*—5G NR, fronthaul, MMF, PoF, and RoF.**

I. INTRODUCTION

THE fifth generation of mobile networks (5G) has been conceived as a promising solution for addressing the challenges that arise from the massive data traffic growth [1]. In parallel, the sixth-generation of mobile networks (6G) has been gaining attention worldwide and is expected to enhance the performance of information transmission with peak data rates up to 1 Tbps and ultra-low latency of microseconds [2]. In particular, a centralized radio access network (C-RAN) architecture has been proposed to enhance performance and cost-effectiveness of 5G and future mobile networks [1], [3].

In general, a C-RAN architecture consists of optical backhaul and fronthaul connecting the central office (CO) to the core network and remote antenna units (RAUs) or remote radio units (RRUs), respectively [4]. In this context, analog radio-over-fiber (A-RoF) or simply, radio-over-fiber (RoF), represents a key enabler for overcoming bandwidth and flexibility limitations of previous mobile fronthaul technologies [5]. Moreover, RoF is considered a potential technology to achieve optical-wireless convergence, simplifying control, management and allowing resource sharing [1], [6]–[8]. Our research group has intensely contributed to the optical and wireless techniques towards novel 5G new radio (5G NR) fronthauls and access architectures [6], including free-space optics (FSO)- and fiber-optics-based fronthauls [4], a digital signal processing (DSP)-based flexible-waveform and multi-application 5G fiber-wireless system [5] and a 5G NR RoF system based on a monolithically integrated circuit [7].

One of the main challenges of future mobile networks is improving coverage and system capacity. This can be achieved by reducing the cell size and increasing the number of deployed RAUs. However, a large number of RAUs also involves high energy consumption, high cost and contribution to the global carbon footprint [1], [9]. Therefore, it is crucial to provide solutions to properly supply the required power to the RAUs [10]. In particular, energy harvesting has been considered for powering RAUs in future mobile networks, by means of exploiting the ambient radio-frequency (RF) energy and converting it into DC power [11]. However, energy availability and stability are essential to ensure network quality of service (QoS) and can not be guaranteed in RF energy harvesting systems due to significant fluctuations in energy transfer caused by the high sensitivities of the receivers [1], [12].

Power-over-fiber (PoF) has been considered another promising approach to supply the RAUs required power and improve the C-RAN energy efficiency. This technique, firstly reported in 1978 [13], employs a high-power laser diode (HPLD) that emits light through an optical fiber to a photovoltaic power converter (PPC), which performs the optical-to-electrical (O/E) conversion, aiming to transport electrical power to remote locations. PoF provides excellent electrical isolation and immunity to RF, magnetic fields, sparks and interference. As a consequence, it has become a very attractive solution to several application fields, such as high-voltage installations [14], hazardous environments [15], [16] and Internet of Things (IoT) [17]–[19]. In PoF systems, the power transmission efficiency (PTE) is defined as the ratio between the HPLD output power and total electrical power delivered by PPC. Although the PoF technology typically provides lower PTE compared to the conventional power lines, it can be easily integrated with short-range RoF

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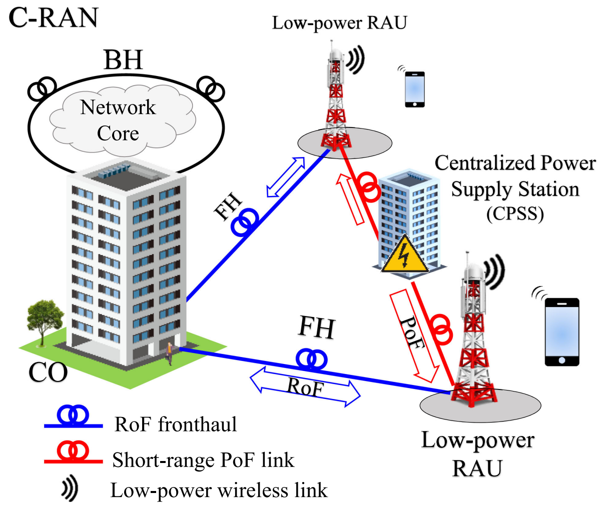

Fig. 1. Optically-powered 5G NR FiWi system. CO - central office; BH - backhaul; FH - fronthaul; RAU - remote antenna unit; CPSS - centralized power supply station.

fronthauls, making itself a potential technology to reduce overall network power consumption [20]. Moreover, PoF links could be extremely efficient for contributing with the expected and significant increase in the number of base stations (BS) in the 5G and beyond wireless generations, due to the mm-waves use in the access networks.

In this paper, we present the concept and implementation of an optically-powered 5G NR fiber-wireless (FiWi) system employing the PoF and RoF technologies, aiming at high-throughput short-range 5G NR cells, as presented in Fig. 1. Our implementation is currently based on the 5G NR C-RAN architecture, in which the control functions are centralized at CO. On the other hand, the PoF implementation consists of distributing power by means of optical fibers from a centralized power supply station (CPSS) to each low-power RAU, located at a few hundreds of meters away. Our main contribution is proposing and experimentally demonstrating a low-power 5G NR RAU entirely optically-powered by a PoF system in order to simultaneously power a photodetector and a RF amplifier. In this context, we report a proof-of-concept based on the simultaneous transmission of a 5G NR signal at 3.5 GHz with bandwidth up to 100 MHz and a 2.2-W optical power signal, employing a dedicated fiber topology. The transmission and analysis of the 5G NR standard is performed in accordance to the 3rd Generation Partnership Project (3GPP) Release 15 [21].

This paper is organized as follows. Section II summarizes the state-of-the-art PoF solutions for mobile fronthauls. Section III describes the implementation of our optically-powered 5G NR FiWi system. Section IV reports the experimental results including a performance investigation of the PoF, RoF and FiWi links. Finally, the conclusions and future works are outlined in Section V.

II. RELATED WORKS

Some works employing the PoF technology have been reported in literature for mobile fronthaul applications. In the first experiments, standard multimode fiber (MMF) links were used to feed an RoF unit, which basically consisted of a photodetector, an RF amplifier, and a laser diode for uplink purposes. In particular, Wake *et al.* [22] demonstrated power transmission over a dedicated 300-m MMF link and achieved over 100 mW of delivered electrical power. A 2-W HPLD centered at 834-nm was used, but only 250 mW was required to power the proposed RoF unit. Authors have also implemented a 5-m wireless link operating at 2.5 GHz with data rate of 54 employing the IEEE 802.11g standard with 64-quadrature amplitude modulation (QAM). $[\mathrm{EVM}_{\mathrm{RMS}}]$ root mean square error vector magnitude (EVM) values below 3% were obtained with this configuration. In [23], the experiment was improved by the implementation of a single MMF to transmit three types of signal (digital, RF, and power) supported by coarse wavelength division multiplexing (CWDM) devices. The obtained EVM was around 2% and a transmission efficiency of approximately 6% was achieved with this configuration.

Double-clad fibers (DCFs) have also been employed in PoF solutions for mobile fronthauls. Sato *et al.* [24] presented a technique that enables the transmission of data and high-power signals through the DCF core and inner cladding, respectively. The combination of two 2-W HPLDs and high-power photodetectors resulted in over 400 mW of delivered electrical power. In [25], the same technique was employed to transmit 60 W of optical power. However, PPCs and the required electrical components in the RAU were not implemented. Nevertheless, over 26 W of optical power was delivered to an optical power monitor (OPM) without degrading the RoF system performance. More recently, an optically-powered RoF system employing a multicore fiber (MCF) link has been proposed [26]. A 12-Gbps 16-QAM orthogonal frequency division multiplexing (OFDM) signal with intermediate frequency (IF) of 92 GHz was simultaneously transmitted with a 0.8-W optical power signal to feed an uni-traveling-carrier photodetector (UTC-PD) and an RF amplifier, aiming at 5G applications. Experimental measurements were performed and EVM of approximately 14% was obtained. Moreover, a 1-m wireless link demonstration has been carried out resulting in a bit error rate BER $= 1 \times 10^{-3}$.

MMFs have also been recently investigated as potential candidates for the simultaneous transmission of data and high-power signals. Center- and offset-launching techniques have been implemented to enable the simultaneous transmission of data and 9.7-W optical power signals through a 4-km MMF link [27]. Approximately 6-W optical power was delivered to an OPM. However, PPCs and other electrical components in the RAU were not employed. Regarding high-power delivery, Matsuura *et al.* [28] demonstrated a 150-W optical power transmission over a 300-m DCF link. Four 808-nm HPLDs and 18 PPCs were used for providing 40 W of electrical power, resulting in PTE of approximately 30%. Although it was mentioned the achieved power could be sufficient to feed small to mid-sized RAUs, electrical components such as amplifiers and antennas were not implemented.

A PoF system capable of delivering roughly 2-W of electrical power over a 100-m MMF link was reported in [29]. A remote radio head (RRH) control board was developed and different

TABLE I
STATE-OF-THE-ART POF SOLUTIONS FOR MOBILE FRONTHAULS

Reference/ Year	**Goal**	**HPLD: Power (W)/ Wavelength (nm)**	**Fiber Optics: Length (m)/ Type/Core (μm)**	**PPC Efficiency (%)**	**Output Electrical Power (W)**	**PTE (%)**	**Wireless Standard/ Reach (m)**	**Throughput (Mbps)/ EVM$_{\text{RMS}}$ (%)**
[22]/2008	Feeding RoF unit (LD/PD/RF amp.)	0.25/834	300/MMF/62.5	56	0.112	44.8	IEEE 802.11g/ 5	54/3
[23]/2012	Feeding RAU (LD/PD/RF amp.)	1/980	100/MMF/50	50	0.06	6	IEEE 802.11g/ 5	54/2
[24]/2013	Transmitting power/ data using DCF	4/830	100/DCF/105	44	0.4	10	Not applicable	Not applicable
[25]/2015	Improving output optical power	60/808	300/DCF/105	-	-	-	Not applicable	Not applicable
[26]/2018	Feeding PD/RF amp. using MCF	0.8/1549.3	-/MCF/-	-	0.05	6.25	OFDM/ 1	12000/14
[27]/2018	Improving output optical power	9.7/1550	4000/MMF/62.5	-	-	-	Not applicable	Not applicable
[28]/2020	Improving output electrical power	150/808	300/DCF/125	54	43.7	30	Not applicable	Not applicable
[29]/2021	Feeding RRH control board/RF amp.	5.4/808	100/MMF/200	45.8	2.343	43.4	Not applicable	0.0066/17.8
[30]/2021	Feeding RRH control board	2.24/1480	14430/SMF/9	30	0.226	10	Not applicable	Not applicable
[31]/2021	Evaluating impact of PoF over SMF	2/1480	100/SMF/9	-	-	-	5G NR/ 0.7	Not applicable
[32]/2021	Transmitting power/ data using SMF	10/1064.8	1000/SMF/8.2	35	2.51	25.1	Not applicable	Not applicable
[33]/2021	Feeding control board	1.26/1480	10000/MCF/-	30	0.133	10.5	5G NR/ 9	Not applicable
This work	**Feeding 5G NR RAU (PD/RF amp.)**	**2.2/975**	**100/MMF/100**	**30**	**0.516**	**23.5**	**5G NR/ 10**	**500/3.9**

sleep mode configurations were implemented intending efficient 5G C-RAN fronthauls. In addition, an RF amplifier was optically-powered by the PoF link, resulting in throughput and EVM of 6.6 kbps and 17.8%, respectively, in the worst-case scenario. In [30], the experiment was modified by the implementation of a 14.43-km single-mode fiber (SMF) link to transmit a 2.24-W optical power signal. Approximately 200 mW of electrical power was delivered, resulting in PTE of 10%. Al-Zubaidi *et al.* [31] reported the use of a SMF link for optically powering RAUs in 5G systems. However, PPCs were not employed in the experiment and optical power was delivered to an OPM, resulting in 870 mW. Moreover, they have implemented a 13-GHz wireless link of 0.7 m employing 5G NR-based cyclic prefix orthogonal frequency division multiplexing (CP-OFDM) waveform format and 16-QAM. EVM of approximately 9% and 14% were obtained for 100 m and 10 km SMF link lengths, respectively, at 1 W of input PoF signal power. Most recently, a 5G fronthaul scenario has been exploited in [32], in which 10-W optical power and 1.5-Gbit/s 5G NR 64QAM-OFDM signal centered at 3.5 GHz with a bandwidth of 100 MHz were simultaneously transmitted over a 1-km SMF link. Over 7 W electrical power was delivered to an OPM, resulting in PTE of 25.1%. In addition, Lopéz-Cardona *et al.* [33] reported a PoF-based 5G NR network employing RoF technology and a MCF link. A main board, basically composed of a microcontroller, was powered by the PoF system. However, its authors do not report the implementation of optically-powered RF amplifiers, RF transceivers and/or photodetectors.

Table I summarizes the main parameters of the state-of-the-art PoF solutions described in this Section. One may note that most works were focused on improving the delivered power and/or evaluating one specific aspect of the PoF system. For instance, [24], [25], [27], [28], [31] and [32] did not investigate optically powering a RAUs or any other BS equipment; only an OPM was employed to measure the delivered electrical power. In addition, [29], [30] and [33] reported the implementation of PoF systems to only power control boards, whereas the photodetectors and RF amplifiers, which are crucial components of a conventional RAU, have been energized in a conventional way, i.e. using electrical power supplies. Completely, only a few papers report experiments of using PoF system for powering a RAU [26][29]. In any case, only [26] presented a RAU fully powered by a PoF link, however, using a generic digital signal, instead of applying a real 5G NR signal, as in our case. In this context, the last column of Table I displays the throughput and EVM results from optically-powered systems for comparison purposes. Finally, Table I demonstrates optically-powered FiWi systems are still unexplored in literature.

Although PoF-based RoF 5G NR systems have recently been proposed, we contribute by entirely powering a low-power 5G NR RAU, composed of a photodetector and RF amplifier, by means of a PoF system. To the best of our knowledge, we report the longest wireless reach from literature (10m) regarding optically-powered 5G NR FiWi systems, compared to [31] and [33], which achieved 0.7m and 9m, respectively. Another outstanding advantage of our setup is the absence of optical amplification, as opposed to [26] and [31]. Regarding energy efficiency, our PoF system overall PTE is 23.5%, which is comparable to most of the state-of-the-art works from Table I, including [32] with a record on the overall optical power transmission efficiency (OPTE). Furthermore, we report, for the first time in literature, an experimental digital performance investigation of a PoF-based system using the 5G NR standard for two distinct modulations (16-QAM and 64-QAM) in the 3.5 GHz regulated 5G frequency band, in accordance to the 3GPP Release 15 [21]. EVM of 3.9% have been achieved, outperforming the previous works [26] and [29], which obtained 14% and 17.8%, respectively. Finally, an unprecedented power stability investigation has been performed in a PoF system and compared to a conventional DC power

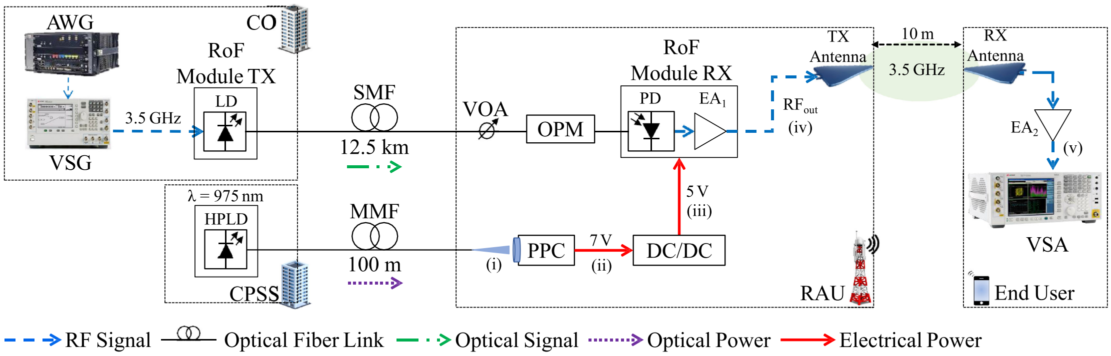

Fig. 2. Block diagram of the proposed optically-powered 5G NR FiWi system: AWG - arbitrary waveform generator, VSG - vector signal generator; LD - laser diode; SMF - single mode fiber; VOA - variable optical attenuator; OPM - optical power monitor; PD - photodetector; EA - electrical amplifier; VSA - vector signal analyzer; HPLD - high-power laser diode; MMF - multimode fiber; PPC - photovoltaic power converter; CO - central office; RAU - remote antenna unit.

supply, with the purpose of validating the applicability of the proposed optically-powered 5G NR FiWi system.

III. IMPLEMENTATION OF THE OPTICALLY-POWERED 5G NR SYSTEM

Fig. 2 depicts a block diagram of the proposed experimental setup based on RoF, PoF and 5G NR standard. Our current implementation exploits the downlink path, i.e., data transmission from CO to RAU. Regarding the RoF option, we have employed A-RoF instead of digital RoF (D-RoF) solution, due to its higher spectral efficiency and RAU simplification, reducing the RAU tasks to a minimum. A-RoF eliminates digital-to-analog converter (DAC), analog-to-digital converter (ADC), up- and down-conversions at RAU. Thus, the RAU energy consumption drastically reduces, favoring the coexistence with PoF.

An arbitrary waveform generator (AWG) (M8190A, Keysight) generates the baseband 5G NR signal and a vector signal generator (VSG) (PSGE8267D, Keysight) has been used to perform up-conversion, providing a 5G NR signal at 3.5 GHz and bandwidth up to 100 MHz, in accordance to the 3GPP Release 15 [21]. Regarding the 5G NR configuration, the downlink shared channels (DL-SCHs) have been properly set with two distinct modulations (16- and 64-QAM) for emulating a 5G NR multi-service application. In addition, we have also included primary synchronization signal (PSS) and secondary synchronization signal (SSS), which enable the user equipment to acquire the cell identity as well as the frame timing. The RoF link consists of commercial RoF transmitter (TX) and receiver (RX) modules, connected via an optical fiber link. The RoF TX module (OZ101 mini TX, Optical Zonu Corporation) is composed of an RF input, a low-noise amplifier (LNA), a 4-dBm distributed-feedback (DFB) laser centered at 1551 nm and an optical output. At CO, the RoF TX module amplifies the RF signal, performs the electrical-to-optical (E/O) conversion and generates a modulated optical carrier by direct modulation. It is driven by an external +5V power supply. The modulated optical carrier was transmitted through a 12.5-km standard SMF optical fronthaul link. Conventional A-RoF systems could experience fading effect [34], due to the fiber chromatic dispersion, since the side-bands beating causes periodic destructive interference depending on the operating frequency, fiber length, dispersion value and carrier wavelength. Specifically for a 12.5-km standard SMF with chromatic dispersion D = 17 ps/nm.km, fading nodes are expected for frequencies higher than 17 GHz. Since the frequency of our 5G NR FiWi system implementation is 3.5 GHz, there was no noticeable degradation due to the fading effect.

At RAU, a variable optical attenuator (VOA) and an OPM have been used to manage and measure the optical power at the photodetector input, respectively. Subsequently, the RoF RX module (OZ101 mini RX, Optical Zonu Corporation) performs the O/E conversion by direct detection and amplifies the RF signal using a photodetector and a 22-dB integrated electrical amplifier, respectively. The recovered and amplified 5G NR signal fed a 5-dBi gain commercial antenna from AARONIA (HyperLOG 7040), giving rise to 10-m reach indoor wireless link under line-of-sight (LOS) condition. The indoor scenario is a research laboratory environment furnished with computers, tables, pieces of equipment and desktops. It is worth mentioning the wireless measurements have been performed at non-business hours, aiming to reduce human-induced shadowing. At the receiver side, the received 5G NR signal has been amplified by a 20-dB gain amplifier (ZX60-83LN12+, Mini-Circuits). Finally, a vector signal analyzer (VSA) (N9020A, Keysight) has been used for evaluating the system performance in terms of $\mathrm{EVM_{RMS}}$ and in accordance with 3GPP Release 15 specifications [21].

The proposed PoF system aims to optically-power a low-power RAU operating on "sleep mode," which offers up to 60% of energy saving in the network [28], [35]. Therefore, our current implementation is based on a CPSS, responsible for centralizing and distributing optical power provided by HPLDs to supply RAUs by means of optical fibers. A PPC, located at RAU, converts the delivered optical power into electrical power. Table II lists the detailed PoF system specifications. In PoF systems, MMFs are generally preferred over SMFs due to the higher power threshold. In addition, non-linear effects, such as stimulated Brioullin scattering (SBS) and stimulated Raman scattering (SRS), might arise at SMFs owing to the smaller core effective area, limiting the transmitted power. When a shared topology is considered, in which data and power are simultaneously transmitted through a single optical fiber, SBS and SRS can also degrade signal quality. On the other hand,

TABLE II
PoF SYSTEM SPECIFICATIONS

Component	Specifications
Fiber-coupled HPLD	Center wavelength: 975 nm Maximum output power: 30 W
Optical Fiber	Type/Length: MMF/100 m 100 μm/140 μm core/cladding diameters
PPC (YCH-L300 with Passive Heatsinking)	Operating wavelength: 915 - 980 nm Output voltage: up to 7 V Maximum incident power: 3 W Conversion Efficiency: 30%
DC/DC converter step-down (LM2596)	Input voltage: 3.2 - 40 V Output voltage: 1.5 - 35 V Conversion Efficiency: up to 92%
RoF Module (OZ101 mini RX)	Operating frequency: 30 MHz - 3 GHz Supply voltage: 5 V Supply current: 95 mA

the large core area of MMFs limits data transmission speed, which might also cause modal dispersion and crosstalk between the data and optical power signals. In this context, our current implementation is based on a dedicated topology, in which data and high-power signals are individually transmitted through dedicated fibers, as shown in Fig. 2.

In this experiment, a 30-W HPLD centered at 975 nm was employed, but only 2.2 W was required to feed the RoF RX module. The optical power signal is then transmitted from CO through a MMF link with core and clad diameters of 100 μm and 140 μm, respectively. The link length was limited to 100 m, mainly due to the MMF high attenuation at shorter wavelengths, i.e. 4 dB/km at the HPLD center wavelength. The maximum PoF MMF link length reported in literature is around 4 km [27], whereas 14.4 km have been achieved employing a SMF link [30]. In case a higher optical power was employed, we could significantly increase the fiber-optics PoF link. However, the overall system PTE would have been drastically reduced. For instance, in [30] the PoF link distance was 14.4 km, however, the achieved PTE was only 10%. Therefore, the trade-off between PoF link length and PTE is also a concern. Consequently, we focused on maximizing the PoF system PTE by implementing a CPSS-based architecture in order to demonstrate its feasibility and potential for remotely powering a low-power RAU. Nonetheless, the 100-m link length implementation is comparable to most works available in literature and is considered practical, considering a CPSS-based architecture. Accordingly, we have employed a 100-m SMF RoF link for attaining the same distance for the PoF and RoF systems, as a first implementation. However, we opted for a 12.5-km SMF link to demonstrate the feasibility of the proposed RoF system in conjunction with the PoF approach. It is worth mentioning the fronthaul distance is limited to 20 km in low latency applications [36]. Since our experimental implementation does not evaluate latency, extending the optical fronthaul link to 12.5-km only impacts on 2.5-dB optical attenuation. Subsequently, two XYZ micropositioners have been used to properly couple the optical energy into the PPC, avoiding additional losses. In addition, a step-down DC/DC converter was necessary to regulate and reduce the voltage, as the RoF RX module operates at 5V and the PPC delivers 7 V output DC voltage.

Fig. 3. Photographs of the experimental setup: (a) RoF transmitter; (b) RoF receiver and PoF link; (c) 10-m wireless indoor link; (d) indoor receiver side.

IV. EXPERIMENTAL RESULTS

This section reports the experimental performance investigation of the proposed demonstrator of an optically-powered 5G NR FiWi system. Figs. 3(a) and Figs. 3(b) display experimental setup photographs of the RoF transmitter, PoF link and RoF receiver, whereas Figs. 3(c) and Figs. 3(d) display the 10-m indoor wireless link and receiver side, respectively. The system investigation has been divided into three steps, namely: PoF system performance in terms of efficiency and stability; optically-powered RoF system; PoF-assisted 5G NR FiWi system performance.

A. PoF System

An efficiency analysis has been carried out to demonstrate the PoF system applicability for mobile fronthauls. First, we measured the incident optical power to the PPC. Over 1.7 W of optical power was injected into the PPC, which presents a conversion efficiency of approximately 30%. Total PoF link loss of approximately 1 dB could be estimated, by considering fiber and splice losses. The delivered electrical power was measured at the PPC output, resulting in 516 mW. We have also measured the RoF module consumed current at the DC/DC converter output, which resulted in 95 mA. The employed PPC provided 7V, which was converted to 5V by the DC/DC converter. Therefore, the RoF module total power consumption was 475 mW. Subsequently, we calculated the system electrical PTE, which is defined as the ratio between the HPLD output power and total electrical power delivered by the PPC [20]. Thereby, considering the laser output approximately 2.2 W, PTE of around 23.5% could be achieved, which is comparable to the state-of-the-art works presented in Table I. The overall PoF PTE can be improved by employing laser diodes and PPCs with higher conversion efficiencies.

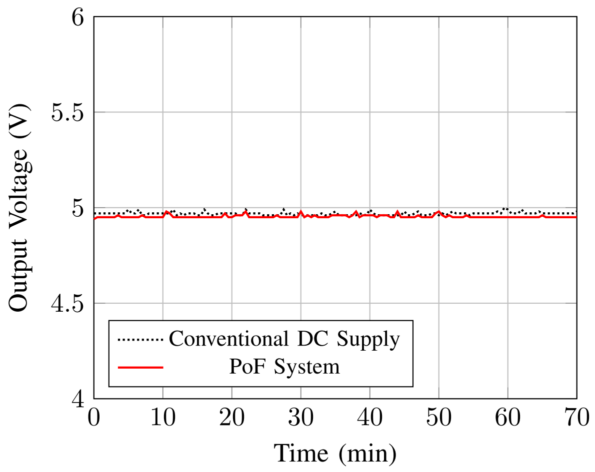

Fig. 4. Comparison of the PoF system with a conventional DC supply over 70 minutes.

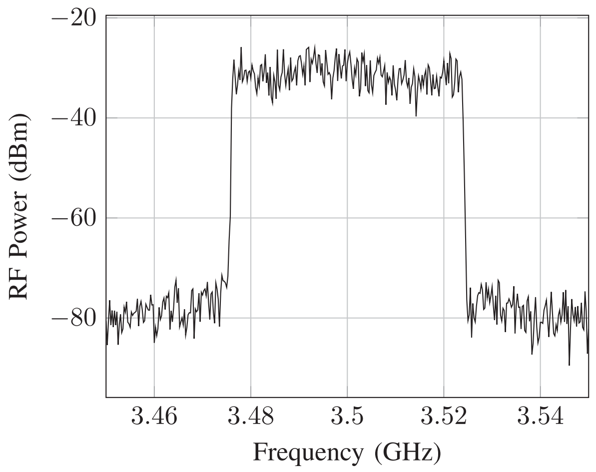

Fig. 5. Measured electrical spectrum at the RoF RX module output.

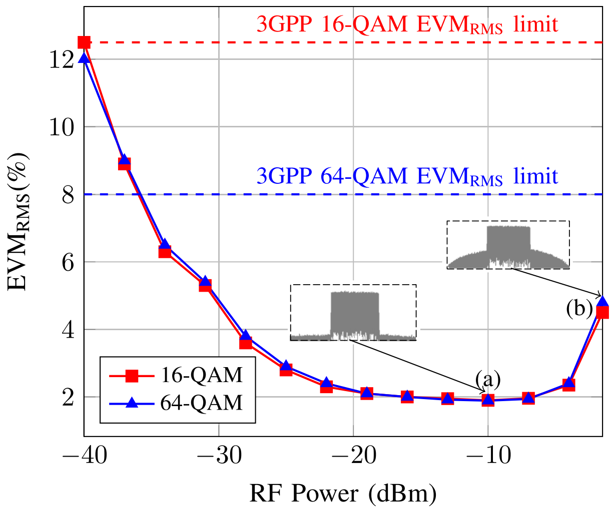

Fig. 6. $\mathrm{EVM}_{\mathrm{RMS}}$ measurements as a function of the RF input power of the RoF TX module for a 50-MHz bandwidth 5G NR signal centered at 3.5 GHz.

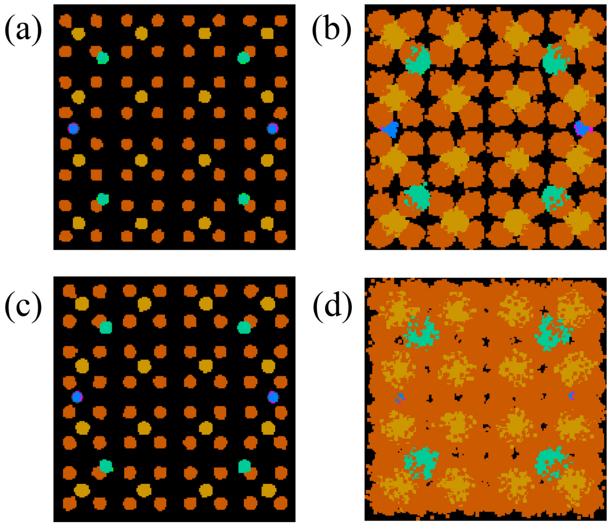

Fig. 7. Received constellations at: (a) RF input power of -10 dBm; (b) RF input power of -1.5 dBm; (c) optical power of -6 dBm; (d) optical power of -15 dBm.

Constant supply voltage and current are crucial parameters to ensure a reliable performance of the RoF module. If not enough power is supplied, the photodetector could be damaged and/or electrical amplifier may not work properly. As a consequence, the RF signal quality could be degraded, compromising the EVM parameter. We have compared the DC/DC converter output voltage stability considering two different scenarios, both providing 5-V DC voltage, namely: conventional DC supply and PoF system. Fig. 4 depicts the DC/DC converter output voltage measurements over a 70-minute period. One can note that the voltage supplied by the PoF system is comparable to the DC supply measurements. In addition, no significant voltage fluctuations are observed, meaning the proposed PoF system is able to properly power the RoF module.

B. Optically-Powered RoF and FiWi Systems

The next characterization step consisted of evaluating the optically-powered RoF system performance. Fig. 5 depicts the measured 50-MHz electrical spectrum at the RoF RX module output. No apparent distortion is observed after the detection and amplification, meaning the RF signal is ready to be radiated. Afterwards, the RoF link performance was evaluated as a function of the $\mathrm{EVM}_{\mathrm{RMS}}$. The 3GPP has specified maximum $\mathrm{EVM}_{\mathrm{RMS}}$ values of 12.5% and 8% for 16-QAM and 64-QAM, respectively [21]. Fig. 6 presents the measured EVM results as a function of the RF input power of the RoF TX module for a 50-MHz bandwidth 5G NR signal centered at 3.5 GHz. The proposed RoF system meets the 3GPP requirements for RF power levels higher than approximately -40 dBm and -36 dBm for 16-QAM and 64-QAM, respectively. The best performance was achieved at -10 dBm, with EVM of 1.9% for both 16-QAM and 64-QAM. Fig. 7(a) presents the received constellations at -10 dBm RF input power. One can note well-defined symbols with no noticeable phase distortions. Overall, throughput of 250 Mbps has been obtained with this bandwidth and modulations. It can be observed that the EVM has increased for RF input power above -8 dBm, decreasing signal quality. This signal degradation may

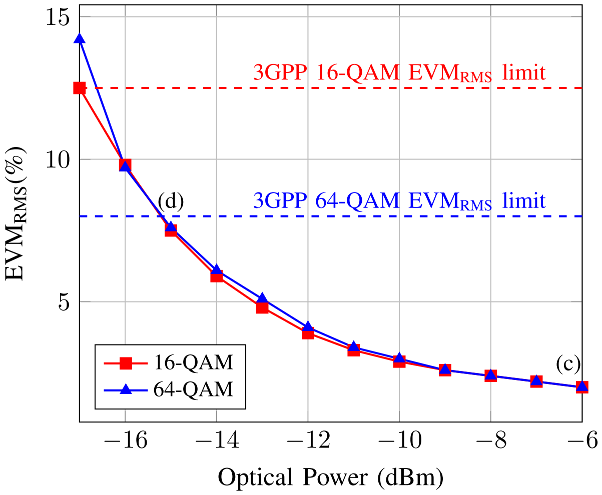

Fig. 8. EVM$_{RMS}$ measurements as a function of the RoF RX module input optical power.

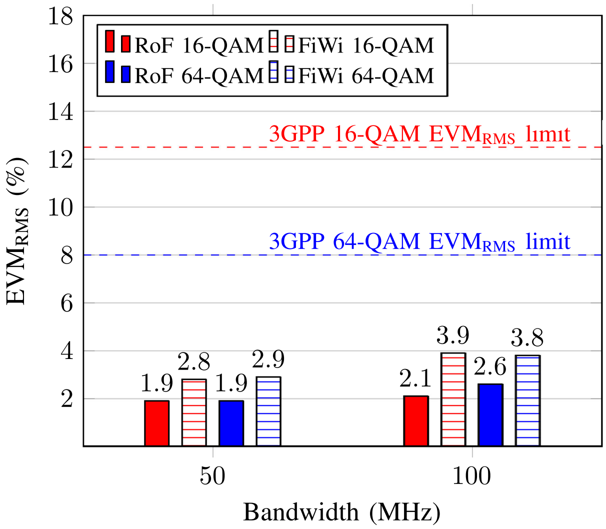

Fig. 9. EVM$_{RMS}$ measurements as a function of bandwidth.

occur due to the RoF TX module electrical amplifier non-linear response, which generates significant inter-modulation products at higher RF power, since the RoF TX module maximum electrical input power is around 0 dBm. The inter-modulation products reduce the signal-to-noise ratio (SNR), which is noted in the electrical spectra insets from Fig. 6, impairing the 5G NR signal in both phase and magnitude, as presented in Fig. 7(b).

Fig. 8 presents the measured EVM results as a function of the RoF RX module input optical power, which was varied from −17 to −6 dBm using a VOA. The RF input power of the RoF TX module was set to −10 dBm. The 16-QAM 5G NR signal meets the 3GPP requirement of 12.5% for optical power levels higher than −17 dBm, whereas EVM below 8% was obtained for optical power levels above approximately −15 dBm for 64-QAM. The best performance was achieved at −6 dBm, with EVM of 2% for both 16-QAM and 64-QAM. Figs. 7(c) and Figs. 7(d) present the measured 5G NR constellations for −6 dBm and −15 dBm optical power, respectively. As the proposed optically-powered RoF system has met the 3GPP EVM requirements with plenty of margin, a wireless link could be successfully implemented with this configuration, giving rise to a 5G NR FiWi system.

The last and most important implementation was the optically-powered FiWi system performance analysis. The PoF technique has been used for remotely powering an RoF module, enabling a 10-m reach 5G NR wireless access point as a proof-of-concept. We have employed the best RoF performance points, namely: −10 dBm electrical input power and −6 dBm optical power. The effective isotropic radiated power (EIRP) was approximately −13 dBm, whereas the estimated path loss was 63 dB. As a consequence, the amplified signal channel power that reaches the VSA input was approximately −60 dBm. In this case, bandwidths up to 100 MHz have been used, which is the maximum allowed for the 3GPP frequency range 1 (FR1). Fig. 9 reports the EVM measurements for 50- and 100-MHz bandwidth 5G NR signals for RoF and FiWi system implementations. One can note the optically-powered RoF implementation does not critically degrade the overall system performance, since the back-to-back (B2B) EVM measurements were around 0.7%. The B2B condition consists of directly connecting the 5G signal generator with the correspondent analyzer, aiming to measure the minimum attainable EVM. The wireless channel imposed only 1% and 1.8% EVM degradation for the 50 MHz and 100 MHz bandwidths, respectively. Nevertheless, the FiWi system met the 3GPP Release 15 specifications with margin, e.g. 4% for 64-QAM and up to 8% for 16-QAM. Such margin could be used for increasing the wireless link, since we employed the maximum standardized bandwidth for FR1. For instance, margin of 26 dB and 30 dB for 64- and 16-QAM modulations, respectively, could be inferred from Fig. 6. We have performed an estimation on the wireless link extension based on the system EVM margin. We concluded the 10-m wireless link impacts only 1% on the EVM figure of merit, as presented in Fig. 9. In addition, we have established a line-of-sight environment by properly aligning the transmitting and receiving antennas and assuring no reflections. Consequently, the wireless link margin was substantially enhanced to 170 m and 270 m, for 64- and 16-QAM modulation schemes, respectively. It is important to mention we have used only −13 dBm EIRP and a unique 20-dB RF amplifier at the receiver. Therefore, the link could be further extended by employing higher transmission powers and higher-gain RF amplifiers at the reception. Overall, the proposed FiWi system has shown potential for integrating the 5G networks by means of enabling a fully optically-powered 5G NR RAU, providing up to 500 Mbit/s throughput in accordance to the 3GPP specifications.

V. CONCLUSION

We have successfully proposed, implemented and characterized a 5G NR FiWi system employing the PoF technique to optically power low-power RAU, which consists of a photodetector and an RF amplifier. A 5G NR signal at 3.5 GHz with bandwidth up to 100 MHz and a 2.2-W optical power signal were simultaneously transmitted using a dedicated fiber topology. Experimental results have demonstrated the PoF link could provide up to 475 mW with PTE of 23.5%, enabling a full optically-powered 5G NR RAU. Aiming to demonstrate the feasibility of the proposed PoF system, a stability analysis has also been carried out, demonstrating no significant voltage fluctuations over a 70-minute period. Furthermore, the optically-powered low-power 5G NR FiWi system performance has been evaluated as a function of $\mathrm{EVM_{RMS}}$ and in accordance to 3GPP Release 15 specifications. We have successfully achieved 500 Mbit/s throughput, accomplishing the recommendations with margin up to 8%. The obtained results demonstrated that PoF might be considered as a potential alternative to power RAUs and enhance energy efficiency of future mobile networks. Future works regard the improvement of the PoF link reach and PTE, as well as increasing the delivered electrical power to support longer-reach wireless links by powering more complex RAUs. Further experimental evaluations concern the implementation of PoF and RoF links with comparable link distances, considering both dedicated and shared scenarios, as well as employing a single hybrid SMF/MMF optical cable.

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