Optically Powered Radio-Over-Fiber Systems in Support of 5G Cellular Networks and IoT

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***Abstract*—We propose using power-over-fiber (PoF) in some part of future 5G cellular solutions based on radio access networks considering currently installed front-haul solutions with single mode fiber to optically power communication systems for 5G new radio (NR) data transmission. Simulations addressing design parameters are presented. Radio-over-fiber (RoF) transmission over single mode fiber (SMF) is experimentally implemented and tested for link lengths ranging from 100 m up to 10 km with injected PoF signals up to 2 W. 64QAM, 16QAM and QPSK data traffic of 100 MHz bandwidth are transmitted simultaneously with the PoF signal showing an EVM compliant with 5G NR standard, and up to 0.5 W for 256QAM. EVM of 4.3% is achieved with RF signal of 20 GHz and QPSK modulation format in coexistence with delivering 870 mW of optical power to a photovoltaic cell (PV) after 10 km-long SMF link. Using PoF technology to optically powering remote units and Internet-of-Things (IoT) solutions based on RoF links is also discussed.**

***Index Terms*—5G, chromatic dispersion, error vector magnitude, power-over-fiber, radio access network, radio-over-fiber, small cell.**

I. Introduction

POWER-OVER-FIBER (PoF) is now seen as a realistic option to feed some reconfigurable elements in optical access networks with single mode fibers (SMF) [1], and to optically powering remote antenna units (RAUs) through specialty fibers such as double-cladding fibers for high power levels [2] or multicore fibers for high data rates demands in future mobile front-haul with analog RoF (ARoF) [3], [4] and space division multiplexing (SDM). The reduction of the cell size of RAUs boosted to support the bandwidth demands of RF signals targeted by the upcoming 5G technology will mean a dramatic increment in the number of RAUs installed. Affordable deployments require simplified low power consumption RAUs as those described in [5] that require less than 100 mW. This scenario opens up new application niches for PoF technology [6] thus allowing dynamic control of RAUs powering based on specific strategies using energy optimization algorithms, driving the required significant reduction of power demands of future 5G-based RAUs with massive antenna deployments [7]. The use of passive optical networks (PONs) for wireless data convergence has been investigated and trialled so far even for future 5G optical network deployments [8]. With the recent growth in the deployment of optical access networks, optical fiber is almost ubiquitous and found very close to the customers, exactly where it is required for small-cell access networks that are based on RoF techniques. On the other hand, ARoF is a promising candidate for the future 5G mobile front-haul due to its important advantages like low transmission loss and the simplicity required at the RAU, also providing the bandwidth requirements demand by 5G. So that ARoF-based centralized radio access networks (C-RANs) can face all challenges addressed by the upcoming 5G technology like high data rates, low latency and energy consumption [9]. Some experiments of analog transmission of 5G NR signals over SMF were reported in [10].

In this scenario, from the point of view of operators, there is a considerable interest in the reuse of the already deployed broadband fiber networks, being SMFs the most popular and widely used mean for these optical fiber-based infrastructures. While introducing remote powering capabilities via optical fiber means, the PoF technique also allows a simple way to simultaneously transmit optical data and power into optical fibers beyond employing a dedicated fiber channel to perform the PoF feature [11].

Moreover, in future 5G networks, envisaging a huge number of RAUs deployed in densely populated areas or events, the coexistence of PoF and data signals over the same single-channel may lead to important installation savings and simplifying the entire broadband access network. Additionally, it can be cost-effective solution. SMF fiber small core area limits the maximum optical power launched [12] into a single channel in PoF applications. And similar considerations should be applied for any single mode individual core of a multicore fiber (MCF) [13]. However, in future low power consumption femtocells or in energy optimized scenarios using PoF to provide sleep-mode RAU operation as an added-value PoF functionality those power levels can be enough. The evolution to a broadband access networking architecture compliant with a cost-effective network operation envisions the coexistence of PoF and data traffic signals over the same SMF-based channel. Then the simultaneous injection

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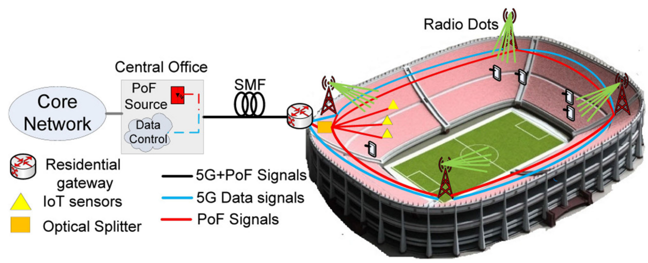

Fig. 1. Proposed configuration of SDM-based (SMF bundles) optical front-hauling integrating different optically feeding technologies.

of high-power laser (HPL) signals for PoF purposes in a fiber channel requires analysing the impact of the latter on the data traffic signal quality as well as a discussion about the PoF requirements to assure a negligible data traffic penalty. Hence in this work, we propose the use of SMF to implement a C-RAN front-haul architecture connecting the central office (CO) to the RAUs for future 5G cellular networks based ARoF together with possibility of optically powering RAUs or other components in the transmission system. We present a simulation study for the design parameters of ARoF transmission following 5G New Radio (NR) numerology [14]. We experimentally address the impact on Error Vector Magnitude (EVM) when introducing a PoF signal over SMF for remote feeding purposes on different carrier frequencies of radio data transmission. The EVM performance and evolution for different modulation formats and link lengths for different PoF power levels is analyzed. Safety power levels for coexistence of data and energy with negligible impact are derived. The potential of using PoF technology in RoF systems for future 5G front-haul is also discussed. Limiting factors like the chromatic dispersion of the fiber, non-linear effects and HPL instabilities are also analyzed.

The paper is divided into four sections. Section II describes the challenges to design power by light systems for different applications targeted by next generation access networks. We also propose a case study for these future 5G networks. In Section III, firstly we provide a simulation study for the design parameters of the RoF systems and address the main limiting factors. Then experimental and simulation results evaluating the PoF impact are performed and discussed. Scalability issues for remote feeding are also addressed. Section IV concludes the paper.

II. Integration Of Power-Over-Fiber In The Front-Haul Of Future Mobile Communication Perspectives

Fig. 1 shows the configuration of the proposed C-RAN network where radio transmission between base band units (BBUs) at CO and variety of RAUs is done in a centralized way. The possibility of optical powering is added by the PoF source located in the CO as well. A detailed study about the state of the art of PoF technology being applied to RoF systems is presented in our previous study [13]. However, this work present for the first time to the best of the authors' knowledge the integration of PoF in 5G NR signals in standard single mode fibers. It also represents a first approach towards SDM solutions based on MCF [13].

As a use case we consider a football stadium where high connectivity is required for different events that might be held in such places. Stadiums have been already considered as launching events by the 5G pan-European trials road map [15]. Different services can be provided like virtual reality applications, live sport streaming and other entertainment applications inside, around and in the fans zone of the stadium. For that we propose a solution that can integrate medium-range links of mm-wave transmission following 5G requirements. This study may help in the design of future RoF systems supporting 5G services in such environments and applications where 10 km-long SMF links connecting the BBUs and the RAUs in a centralized fashion can be quite enough for the expected coverage area and type of scenario. SMF can provide an optimal solution for this type of access network, as the first step to expand the capacity in future 5G front-haul solutions tends to exploit the existing infrastructure of SMF by adding bundles of SMF fiber.

On the other hand, PoF technology is advantageous as it may help to improve the flexibility and reliability of the system. The use of fiber bundles allows the possibility of considering different PoF scenarios i.e shared or dedicated [13]. Additionally, this can partially solve the problem of the small core area of SMF fibers as aforementioned that limits the maximum energy delivered to the remote side by consider more fibers for feeding purposes. PoF technology can be used isolated or in combination with standard electrical power supplies. PoF can be utilized in the different services that C-RAN can support as integrating in a centralized way multiple IoT devices with its massive deployment requirements [16]. Different RAUs in the network can transmit and receive information from IoT devices while its processing is done in the BBU after sending back the information via the fiber backbone.

IoT in near future represents a massive number of low power devices connected to the internet with the need of being frequently updated. The current network standard like LTE cannot support efficiently this technology as it is mainly developed for mobile broadband [17]. For that 5G NR can address all the limitations to enable IoT with good functionality. In compliance with the proposed scenario, IoT smart stadium can be easily integrated with the physical infrastructure of a 5G front-haul based on SMF fiber bundles. Thanks to the current low power IoT ecosystems, PoF can be an option to power wireless IoT sensor networks.

Table I gives an example of the small radio cells and smart IoT nodes with its low power consumption where PoF can be optimal solution for powering. Emerging radio dot systems represent energy and cost effective solution with ideal network performance [18]. These small cells can be distributed and installed even under fans seats of the stadium [20]. In our scenario, we propose these Dots to cover specific areas in the stadium where a high Quality of Service (QoS) is required, for instance in premium or VIP areas; as a first migration step towards future deployments. It can provide redundancy or independent connectivity to prevent failures in case of blackout for security reasons. They can also connect multiple IoT sensor nodes distributed in the stadium

TABLE I
LOW POWER CONSUMPTION DEVICES FOR COMMUNICATION AND IOT SENSING FOR STADIUM SCENARIO

Device	Function	Consumption
Radio Dot System [18]	Small radio cell for Wi-Fi connectivity	< 200 mW**
OV9655 camera	Monitor people in specific areas	90 mW
Vison Sensor [19]	Monitoring Fans activities, Gates entrance, Parking	17.9 µW
BME280 Sensor	Temperature, Humidity, Pressure	1.32 mW

**Depending on the operation mode.

to monitor different environmental conditions like temperature. Low power vision systems, based IoT nodes, can sometimes replace the traditional concept of cameras [19] in those specific areas covered by Radio Dots and such systems can be employed for different applications within the stadium where very high resolution is not important or low power schemes are preferred. From Fig. 1, the residential gateway houses the optical demux device which splits data traffic and PoF signal. Afterwards data signals are received by different radio dots using SMF in ring topology by exploiting network switches. The residential gateway can also distribute energy to IoT nodes and radio dots in a star topology by employing asymmetric power splitters for energy distribution [21]. Optically powering such systems can be cost effective and ensure service continuity [22]. As shown from Fig. 1, the PoF technology can be utilized for different applications depending on the delivered energy.

As general concept, the stadium is taken as representative example but the deployed system can have potential in other areas where 5G is required for mission critical services. The most important aspect in the paper is to ensure that this technology can be integrated with the infrastructure of the next generation access networks based RoF following 5G NR numerology for different RF carrier frequencies beyond 6 GHz frequency band with acceptable penalty (no impact in the ideal case) on the data traffic signal quality. For instance, the proposed system can be integrated within the architecture proposed in [23] where a Fiber-Wireless (Fi-Wi) hybrid approach is considered to support IoT networks with a network power saving design based on turning into sleep mode some phases of the Optical Network Units (ONUs) in cooperation with the Optical Line Terminals (OLTs) thus bringing additional power economy to the network.

III. POWER-OVER-FIBER AND RADIO-OVER-FIBER SYSTEM DESIGN AND PERFORMANCE

A. Chromatic Dispersion Induced Power Fading

For addressing the impact of chromatic dispersion in 5G NR transmission over SMF, simulations based on Virtual Photonic Instrumentation software tool (VPI) are done for different carrier frequencies, link lengths and dispersion parameters. We analyse the frequency band that can be selected for the desired link length depending on the final application. The 5G NR waveform format considered in this study is based on CP-OFDM (Cyclic Prefix – Orthogonal Frequency Division Multiplexing) with adaptive modulation including QPSK, 16QAM, 64QAM and 256QAM. The RF signal is optically modulated with an optical signal carrier at 1532 nm using a Mach-Zehnder modulator (MZM) where the CP-OFDM signal is up-converted on the RF carrier frequency to emulate the transmitted data. EVM of data signal is used in this section as figures of merit to evaluate the performance of the designed system. Fiber chromatic dispersion is one of the most important parameters in the design of any RoF link, especially for high carrier frequencies, that can lead to power losses in the received RF signal after O/E conversion [24]. An increase in either the dispersion or carrier frequency, significantly limits the obtainable transmission distance. The transmission distance at which the first extinction (signal fading) occurs is found to be [24]:

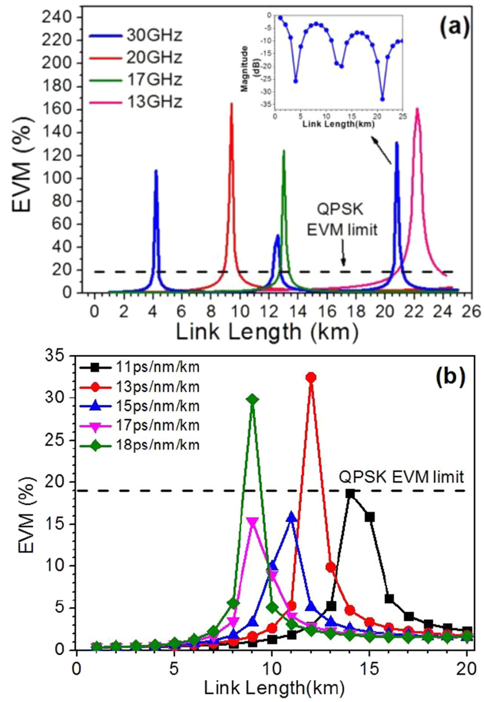

Fig. 2. Simulation results α=0.2 dB/km, QPSK signal: (a) EVM vs. link length for different carrier frequencies with link length up to 25 km (step 100 m), D =17 ps/nm/km. (b) EVM vs. link length with L swept every 1 km, RF= 20 GHz.

$$L_1 = \frac{C}{2D\,\lambda^2 {f_c}^2} \tag{1}$$

where c is the speed of light, λ is the optical wavelength and f_c is the carrier frequency, respectively. Therefore, it is of prime importance to address all these parameters in the system design depending on the final application. We simulate the EVM for different cases. Results are shown in Fig. 2(a) for a QPSK modulated signal with 20 GHz RF carrier frequency and +10 dBm of optical power injected into the system. As expected EVM is dramatically degraded at the estimated link length (L_1) for different carrier frequencies due to the RF power fading where inset photo in Fig. 2(a) shows the penalty induced in recovered

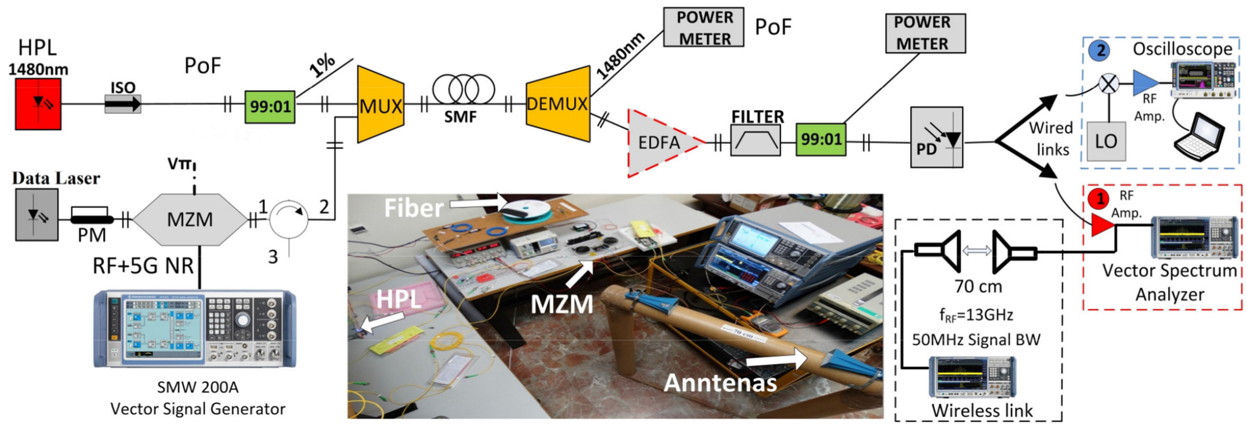

Fig. 3. Experimental setup for the evaluation of the 5G RoF data transmission in coexistence with the PoF signal. Inset: Picture of the real testbed implementation. HPL: High-Power Laser, ISO: Optical Isolator, PM: Polarization Maintaining Fiber, LO: Local Oscillator.

RF power due to chromatic dispersion for RF 30 GHz. Also from this figure we can see the EVM cyclic behaviour (especially for RF 30 GHz) with a period length given by [24]:

$$\Delta L = \frac{c}{D\lambda^2 {f_c}^2} \quad (2)$$

being $\triangle$L the link length period between two notches. In Fig. 2(b) the effect on EVM with a varying D is depicted showing how the transmission distance can be increased (i.e shifting L_1 to longer distances) as D is decreased. EVM is sensitive even with D variations of 0.1 ps/nm/km. From these results its clearly seen the importance of considering the chromatic dispersion in the design of future cellular networks based on RoF technology. The link length and the RF carrier frequency have to be carefully selected too.

B. Experimental Testbed

The analog RoF (ARoF) system implemented is depicted in Fig. 3, where an inset picture of the experimental setup is included. A laser diode (LD) at 1532 nm generated a continuous wave externally modulated through a Mach-Zehnder modulator (MZM). The SMW200A Vector Signal Generator provided the RF carrier signal modulated with a baseband signal defined in the 5G NR standard. This signal drives the MZM and emulates the 5G user data. Tests include 256QAM, 64QAM, 16QAM and QPSK modulation formats with 30 kHz subcarrier spacing and 100 MHz bandwidth. The modulated optical carrier (data traffic) is then multiplexed with the HPL PoF signal at 1480 nm (PoF power delivery purposes).

The HPL source linewidth is around 3 nm. High-power handling multiplexer (MUX) and demultiplexer (DEMUX) devices are used to combine and separate both the PoF and data traffic signals to be transmitted and received, with losses $\leq$ 1 dB for both of them, and different ARoF-based SMF link lengths (100 m, 5 km, and 10 km) are tested. An Erbium Doped Fiber Amplifier (EDFA) is employed, only if data signal amplification is required. Amplified Spontaneous Emission (ASE) is filtered out by a bandpass optical filter. A 99:1 coupler is used for monitoring the data traffic power at reception. The data traffic signal is then detected using a 20 GHz high-speed photodiode (PD). A RF power amplifier stage is employed to amplify the electrical signal prior to the reception stage where two methods are used to detect and analyse 5G transmission performance. In the first one, signal feed directly to the signal spectrum analyzer with 20 GHz of bandwidth. In the second, an oscilloscope with 2 GHz bandwidth is used. Mixer and local oscillator (LO) are added to receive the signal within the oscilloscope bandwidth range. The highest link length chosen to be tested experimentally is 10 km that can be enough to deploy the main scenario proposed in Section II. Depending on the simulation results discussed in the previous section, different RF carrier frequencies up to 20 GHz are launched and experimentally tested.

C. EVM Characterization

The quality of the data traffic signal is evaluated through the EVM figure of merit. The measured values are compared with the EVM requirements for downlink transmission signals from base stations provided within the 5G NR standard [14]. Fig. 4 shows the EVM results for different modulation formats, for an input RF power ($P_{RF\cdot IN}$) of +12 dBm, a RF frequency carrier of 13 GHz and two link lengths (100 m and 5 km), using the wired set-up reported on Fig. 3 (i.e., without the wireless link). Those experimental results showed no relevant impact on the system performance for PoF injected power levels below 0.5 W, as EVM keeps under the limits allowed by the 5G NR standard (dashed lines), for both link lengths. This performance is also verified for all HPL powers tests (up to 2W of HPL output, 1.62 W injected in the fiber) for a 100 m-long link (see Fig. 4(a)). Meanwhile at 5 km, the EVM measurements showed a degradation beyond 0.5 W, especially for a 1 W optical power output from the HPL (0.82 W injected in the fiber). The measured values follow the standard apart from the 256QAM modulation test.

Fig. 5 shows that up to a 0.5 W PoF input for a link length of 10 km, there is negligible impact for the two cases we choose (16-QAM signal at RF 17 GHz and QPSK signal at RF 20 GHz). However, at 1 W of HPL input power the EVM is significantly degraded for both experiments, being especially dramatic for

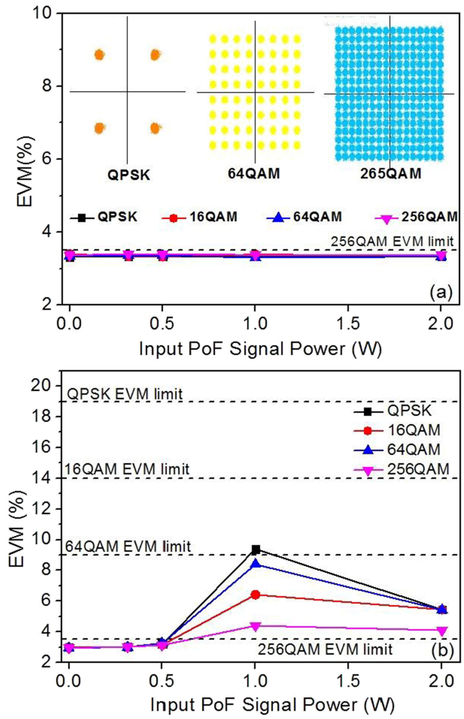

Fig. 4. EVM measurements vs input PoF signal of power levels (0, 0.3, 0.5, 1, 2) W. $P_{RF\cdot IN} = +12$ dBm, $f_{RF} = 13$ GHz. Link length range: (a) 100 m, (b) 5 km.

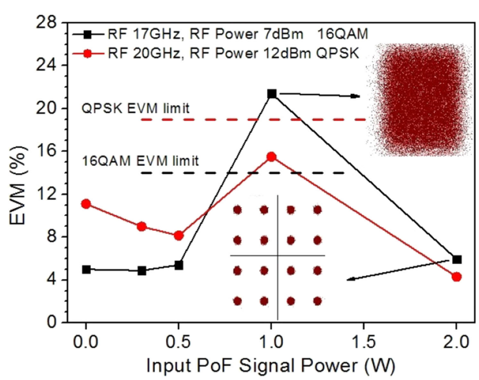

Fig. 5. EVM measurements vs input PoF signal of power levels (0, 0.3, 0.5, 1, 2) W black line: $P_{RF\cdot IN} = +7$ dBm, $f_{RF} = 17$ GHz for 16-QAM signal, red line: $P_{RF\cdot IN} = +12$ dBm, $f_{RF} = 20$ GHz for QPSK signal.

16QAM modulation as the resulting EVM exceeds the limit value. As the HPL is still increased to 2 W, the EVM is then improved for both cases.

The measured EVM peak values mean that we might be operating this transmission link near a RF signal fading as concluded from Section III A. This behaviour will be further discussed in a following section.

Furthermore, a 13 GHz ARoF wireless link up to 70 cm with 50 MHz of signal bandwidth is later implemented with the same setup. The output from the high-speed photodiode is connected to a transmitting horn antenna where the modulated data traffic propagated to a receiving horn antenna, the latter is connected to the test equipment. The EVM performance of the received signal is then evaluated for different fiber link lengths with simultaneous PoF signal injection. Fig. 6 shows the experimental results for a 16QAM modulation.

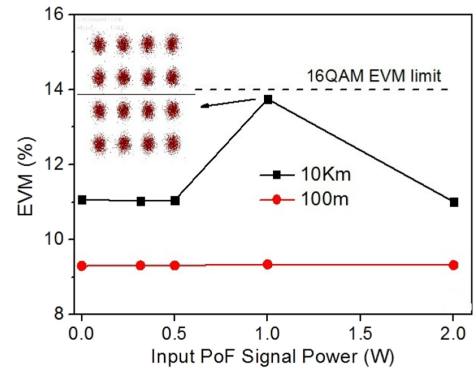

Fig. 6. 16QAM EVM after a 70 cm-long ARoF wireless transmission in coexistence with PoF for different injected powers and fiber link lengths $P_{RF\cdot IN} = +12$ dBm, $f_{RF} = 13$ GHz.

Comparing 16QAM results obtained from both Fig. 4(b) and those from Fig. 6 the EVM degradation for longer link lengths, same testbed conditions but 5 km in Fig. 4(b) vs 10 km in Fig. 6, is also observed due to the higher received power attenuation, in accordance with the results provided in [25]. In all the experimental measurements reported and for link lengths of units of km, the EVM showed negligible impact for PoF signals up to 0.5 W while significantly degraded within a range that could be defined around 1 W. However, it is worth mentioning that beyond 1 W of HPL output power (around at 2 W) EVM results showed a slight improvement in most of the cases considering the different RF power, carrier RF frequency and modulation formats investigated. Thus the PoF signal may additionally contribute to enhance the data traffic signal quality.

D. Experimental EVM Performance Discussion

In this section, we discuss the performance of the implemented RoF link and its EVM figure of merit behaviour in coexistence with the PoF signal, especially for longer distance links. As a general trend the EVM suffers a noticeable (negligible or not) penalty when a PoF signal is injected into the system compared to the HPL OFF status. The HPL has a wide spectrum not only at 1480 nm, where some small additional signals are found around the C-band. The HPL also exhibits some instabilities increasing the noise source. Moreover, the transmission of such high-power levels in the small core area of a SMF arises different nonlinear effects. Being relevant Stimulated Raman Scattering (SRS), and Kerr nonlinearity as Stimulated Brillouin Scattering (SBS) can be neglected due to the linewidth of the HPL. SRS effect in optical fibers has been widely discussed in the literature [26]. For a specific threshold power and an effective transmission distance [13], power transfer from higher to smaller frequencies is expected as a result of the frequency shift which can be around 13.2 THz due to SRS. Depending on the HPL wavelength (1480 nm) and data channel (1532 nm) as well as the high HPL power levels used in the proposed setup, SRS can have great impact as it can increase the optical power and noise of data channel. The noise associated to HPL instabilities is also transferred by SRS. The increased power also induces Self Phase

Modulation (SPM) that may arise from the fiber refractive index (n) dependence on the optical power as:

$$n = n_o + n_2|E|^2 \tag{3}$$

where n_o is the linear refractive index, n_2 is the non-linear index coefficient, and E is the electric field intensity, respectively. SPM causes a phase shift in communication systems which can degrade EVM and it can be expressed as [27]:

$$\Phi_{NL}\ (z,T) = -\frac{1-\exp(-\alpha z)}{\alpha}\ \frac{2\pi}{\lambda}\ n_2|A(0,T)|^2 \tag{4}$$

where α is the fiber attenuation parameter, z is the transmission distance and $|A(0,T)|^2$ is the field envelope at fiber input.

The frequency chirping generated from SPM has negative sign as shown in Eq. (4) which is increased as the transmission distance increases. From that point of view and as the chromatic dispersion induced phase shift has an opposite impact with respect to the SPM induced phase shift counterpart, then SPM can partially mitigate the dispersion effect in microwave optical systems [27]. From our experimental results, we can see that HPL higher power levels enhance the resulting EVM value as it is very sensitive to the phase change induced by Kerr non-linear effects resulted from the HPL injection. Cross Phase Modulation (XPM) is a similar effect to SPM, but it involves two optical beams instead of one, in our case the HPL and data. Because the total intensity is the square of a sum of two electric-field amplitudes, the nonlinear phase shift, Φ_{NL}, caused by XPM is twice as large as in SPM [28]:

$$\Phi^{w_1}{}_{NL}(z) = \frac{2\pi n_2}{\lambda A_{eff}}\left(|E_1|^2 + 2|E_2|^2\right) \tag{5}$$

where w_1 and E_1 refers to the data channel and E_2 to the HPL. A_{eff} is the effective area of the fiber. The phase of data signal can be directly affected by HPL signal due to XPM.

For supporting the above analysis, some additional measurements on non-zero dispersion shifted (NZDSF) fibers are implemented. NZDSF fiber shows a different non-linear behaviour compared to SMF due to its large effective area and different dispersion profile. According to NZDSF data sheet, its dispersion parameter is +2 to +6 ps/nm/km over the range of 1530–1560 nm with an attenuation of $\alpha \leq 0.22$ dB/km and an effective core area of 72 µm^2, whereas for standard SMF-28 are 17 ps/nm/km at 1550 nm, $\alpha \leq 0.18$ dB/km and 80 µm^2, respectively. The results for the same test conditions of simultaneous PoF and RoF transmission over a 5 km-long link for both fiber types (SMF and NZDSF) are shown in Fig. 7. As depicted, and for the HPL injected optical powers tested, EVM values for both fibers are increasing as HPL level increases due to additional noise in the C-band from the HPL source. However, the large effective area of the NZDSF fiber reduces the SRS effect that implies a reduction of the SPM phase-shift contribution, thus not leading to a dispersion-induced power penalty compensation. For the SMF case, higher HPL levels tend to compensate for the frequency chirping result from the chromatic dispersion thus leading to a EVM enhancement as seen at 2 W of HPL input levels, if we compare the measured EVM at 1 W of HPL. Also XPM can have more impact to distort the signal in the case of NZDSF compare to SMF due to their low chromatic dispersion.

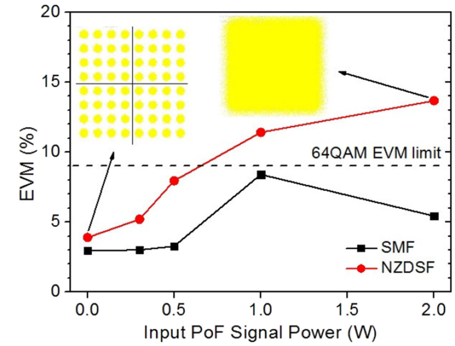

Fig. 7. EVM measurements vs input PoF signal of power levels (0, 0.3, 0.5, 1, 2) W. $P_{RF\cdot IN} = +12$ dBm, $f_{RF} = 13$ GHz, 64QAM modulation format. Link length of 5 km for both SMF and NZDSF fiber tested.

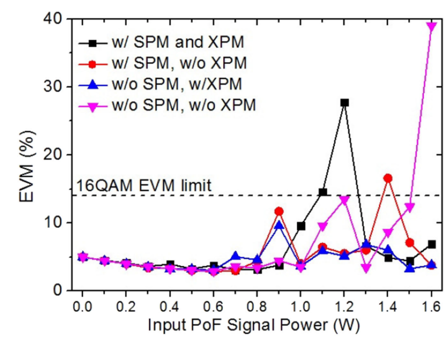

Fig. 8. EVM vs PoF signal. Simulations results: $f_{RF} = 17$ GHz, 16QAM modulation format, 10 km-long SMF link.

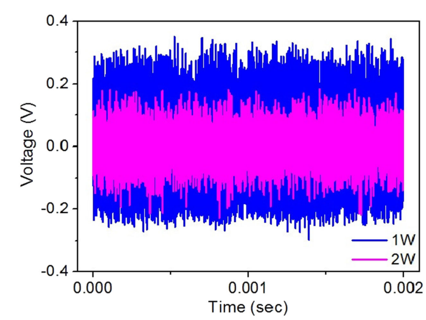

Fig. 9. Noise fluctuations of the HPL output at different power levels for 1 W and 2 W.

VPI simulations are performed to further investigate the HPL impact on the non-linear effects. Simulation results are shown in Fig. 8 for SMF, being in good agreement compared to our experimental EVM values (black curve in Fig. 5). We examine the impact of SPM and XPM. The results show that when both SPM and XPM are considered, there is an increment in the temporal broadening of the signal due to fiber dispersion so EVM degrades at lower PoF level.

Finally, we analyse the HPL instabilities effect. The temporal signal of the HPL output power at different power levels is measured with an oscilloscope (see Fig. 9). It can be seen how fluctuations increase around 1 W. Those fluctuations are transferred to the C-band after a certain link length because of SRS as previously shown in our measurements.

As a conclusion, we show for the first time that PoF technology can be used with RoF, particularly analog RoF systems not only for powering purposes but also to enhance signal quality by taking advantage of fiber non-linearities and overcoming dispersion-induced power penalties in the link. But, the HPL instabilities and noise transfer have also to be taken into account to avoid EVM degradation.

E. Optical Feeding Capability

In addition to the energy levels that can be delivered at the remote site, one of the key important design parameters in any PoF system is the efficiency of the photovoltaic cell (PV). The PV cell selection should consider the HPL operating wavelength and the fiber attenuation. Although at 1480 nm the currently available PV cell has a low efficiency around 26% [29], [30] compared to other interesting PoF wavelengths, 1480 nm provides the greatest PoF system overall efficiency taking into account the low fiber attenuation coefficient and the link distances evaluated [12]. In our experiment we measure the HPL level that can be delivered at the end of the link (DEMUX output), see Fig. 3. We measured 870 mW of optical power at PV input when the HPL is injecting 2 W into the 10 km-long SMF link. If we consider a 26% PV efficiency [12], then the electrical power (P_{elec}) at the remote site would be 226.2 mW.

Apart from powering small radio cells**,** this power level can drive different electronic components wherein (amplifier, photodiodes, transmitters etc…) or systems as those proposed in [5], [11] which used optical powering. For example, in [5], total electrical power of 80 mW is used to drive a 100 GHz analog photoreceiver while in [11] different remote units configurations are described with maximum electrical power demand of 221 mW at a maximum distance of 1 km. These remote units comprise a VCSEL transmitter, a photodiode and three amplifiers. Moreover, this power (226.2 mW) can be quite enough to feed sensor networks in IoT applications [31], where a low power real time IoT system is used to monitor the structural health of a football stadium which fits with the main scenario proposed in Section II. Also in [23] a PoF solution is proposed in a power saving scheme for C-RAN integrated IoT network. However, in the developed scenario this power can feed two radio dots and some IoT sensors or it can be employed to feed as many as required low power IoT sensors. The feeding capability can be even increased by using higher PoF levels at CO, using SMF bundles or a dedicated fiber scenario without MUX/DEMUX losses or other impairments due to data/power simultaneous transmission [13].

IV. Conclusion

We introduce the integration of PoF in the next generation radio access network. The possibility to exploit the currently existing infrastructure based SMF is discussed. The design of a power by light system that can integrate low power consumption RAU or IoT wireless sensor network is described. The impact of PoF signals on RoF transmission for different modulation formats compliant with 5G New Radio (NR) standard are analysed. SMF ARoF links with different modulation formats are implemented spanning link lengths from 100 m up to 10 km with simultaneous PoF signal injection with maximum of 2 W at the HPL output. For a 100 m-long link no significant EVM penalty is observed for the different PoF signal levels injected. For 5 km and 10 km link lengths we measured that 5G NR signals over different RF carriers can coexist with injected PoF signals up to 0.5 W with negligible EVM penalty. Beyond 0.5 W of PoF power injection values, EVM results showed a significant degradation related to HPL instabilities causing high noise levels that are transferred by SRS. However, for PoF power values greater than 1 W the EVM results are enhanced due to PoF induced SPM, XPM that partially compensate for frequency chirping resulted from chromatic dispersion. The experimental EVM behaviour with the different HPL power levels is analysed too.

Total optical power of 870 mW at the remote side is successfully delivered with EVM values in compliance with 5G requirements. The scalability analysis of the feed power is presented showing the capability of the proposed system to power different electronic component in communication systems and IoT sensor networks. Apart from that, we show that PoF can be applied to improve data signal quality utilizing fiber nonlinearity in HPL high power levels.

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References

[1] Y. Bi, S. Shen, J. Jin, K. Wang, and L. G. Kazovsky, "Remotely powered and reconfigured quasi-passive reconfigurable nodes for optical access networks," in *Proc. J. Elect. Comput. Eng.*, Jan. 2016, Art. no. 2938415.

[2] M. Matsuura and J. Sato, "Bidirectional radio-over-fiber systems using double-clad fibers for optically powered remote antenna units," *Proc. IEEE Photon. J.*, vol. 7, no. 1, pp. 1–9, Feb. 2015.

[3] G. Otero *et al.*, "SDN-based multi-core power-over-fiber (PoF) system for 5G fronthaul: Towards PoF pooling," in *Proc. Eur. Conf. Opt. Commun.*, pp. 1–3, 2018.

[4] C. Vázquez, D. S. Montero, F. M. A. Al-Zubaidi, and J. D. López-Cardona, "Experiments on shared- and dedicated- power over fiber scenarios in multi-core fibers," in *Proc. Eur. Conf. Netw. Commun.*, Valencia, 2019, pp. 412–415.

[5] T. Umezawa *et al.*, "Multi-core based 94-GHz radio and power over fiber transmission using 100-GHz analog photoreceiver," in *Proc. ECOC, 42nd Eur. Conf. Opt. Commun.*, 2016, pp. 1–3.

[6] C. Vázquez, D. S. Montero, P. J. Pinzón, J. D. López-Cardona, P. Contreras, and A. Tapetado, "Integration of power over fiber on RoF systems in different scenarios," in *Proc. SPIE*, 2017, Art. no. 101280E.

[7] J. Wu, Y. Zhang, M. Zukerman, and E. K.-N. Yung, ''Energy-efficient base-stations sleep-mode techniques in green cellular networks: A survey," *IEEE Commun. Surv. Tut.*, vol. 17, no. 2, pp. 803–826, 2015.

[8] J. S. Wey and J. Zhang, "Passive optical networks for 5G evolution," in *Proc. SPIE Broadband Access Commun. Technol. XII 10559*, California, United States, 2018, Art. no. 105590N.

[9] C. Ranaweera, E. Wong, A. Nirmalathas, C. Jayasundara, and C. Lim, "5G C-RAN with optical fronthaul: An analysis from a deployment perspective," *J. Lightw. Technol.*, vol. 36, no. 11, pp. 2059–2068, Jun. 2018.

[10] D. Konstantinou, A. Morales, S. Rommel, T. R. Raddo, U. Johannsen, and I. T. Monroy, "Analog radio over fiber fronthaul for high bandwidth 5G millimeter-wave carrier aggregated OFDM," in *Proc. 21st Int. Conf. Transparent Opt. Netw.*, 2019, pp. 1–4.

[11] D. Wake, A. Nkansah, N. J. Gomes, C. Lethien, C. Sion, and J. Vilcot, “Optically powered remote units for radio-over-fiber systems,” *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2484–2491, Aug. 2008.

[12] J. D. López-Cardona, C. Vázquez, D. S. Montero, and P. C. Lallana, “Remote optical powering using fiber optics in hazardous environments,” *J. Lightw. Technol.*, vol. 36, no. 3, pp. 748–754, Feb. 2018.

[13] C. Vázquez *et al.*, “Multicore fiber scenarios supporting power over fiber in radio over fiber systems,” *IEEE Access*, vol. 7, pp. 158409–158418, 2019.

[14] Base Station (BS) radio transmission and reception, *Eur. Telecommun. Standards Inst.*, 2021. [Online]. Available: https://www.etsi.org/deliver/etsi_ts/138100_138199/138104/15.05.00_60/ts_138104v150500p.pdf

[15] “5G pan-european trials roadmap version 2.0,” *5G Infrastructure Assoc.*, 2021, [Online]. Available: https://5g-ppp.eu/wp-content/uploads//2017/05/5GInfraPPP_TrialsWG_Roadmap_Version2.0.pdf

[16] M. Fiorani, S. Tombaz, J. Martensson, B. Skubic, L. Wosinska, and P. Monti, “Modeling energy performance of C-RAN with optical transport in 5G network scenarios,” *IEEE/OSA J. Opt. Commun. Netw.*, vol. 8, no. 11, pp. B21–B34, Nov. 2016.

[17] G. A. Akpakwu, B. J. Silva, G. P. Hancke, and A. M. Abu-Mahfouz, “A survey on 5G networks for the Internet of Things: Communication technologies and challenges,” *IEEE Access*, vol. 6, pp. 3619–3647, Dec. 2017.

[18] “Superior indoor coverage with 5G radio dot,” *Ericsson*. 2021. [Online]. Available: https://www.ericsson.com/en/ran/indoor-coverage

[19] M. Rusci, D. Rossi, M. Lecca, M. Gottardi, E. Farella, and L. Benini, “An event-driven ultra-low-power smart visual sensor,” *IEEE Sensors J.*, vol. 16, no. 13, pp. 5344–5353, Jul. 2016.

[20] “Connected stadiums,” *Ericsson*, 2021. [Online]. Available: https://www.ericsson.com/en/networks/offerings/urban-wireless/connected-stadium

[21] J. D. López-Cardona, D. Sánchez Montero, and C. Vázquez, “Smart remote nodes fed by power over fiber in Internet of Things applications,” *IEEE Sensors J.*, vol. 19, no. 17, pp. 7328–7334, Sep. 2019.

[22] F. M. A. Al-Zubaidi, D. S. Montero, and C. Vázquez, “SI-POF supporting power-over-fiber in multi-Gbit/s transmission for in-home networks,” *J. Lightw. Technol.*, vol. 39, no. 1, pp. 112–121, 2020.

[23] T. G. R. Miyanabe, Y. Lee, H. Nishiyama, and N. Kato, “An Internet of Things traffic-based power saving scheme in cloud-radio access network,” in *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3087–3096, Apr. 2019.

[24] U. Gliese, S. Norskov, and T. N. Nielsen, “Chromatic dispersion in fiber-optic microwave and millimeter-wave links,” *IEEE Trans. Microw. Theory Techn.,* vol. 44, no. 10, pp. 1716–1724, Oct. 1996.

[25] J. Nanni, J. Polleux, C. Algani, S. Rusticelli, F. Perini, and G. Tartarini, “VCSEL-based radio-over-g652 fiber system for short-/medium-range MFH solutions,” in *J. Lightw. Technol.*, vol. 36, no. 19, pp. 4430–4437, Oct. 2018.

[26] J. Bromage, “Raman amplification for fiber communications systems,” *J. Lightw. Technol.*, vol. 22, no. 1, pp. 79–93, Jan. 2004.

[27] F. Ramos, J. Marti, V. Polo, and J. M. Fuster, “On the use of fiber-induced self-phase modulation to reduce chromatic dispersion effects in microwave/millimeter-wave optical systems,” *IEEE Photon. Technol. Lett.*, vol. 10, no. 10, pp. 1473–1475, Oct. 1998.

[28] J. Toulouse, “Optical nonlinearities in fibers: Review, recent examples, and systems applications,” *J. Lightw. Technol.*, vol. 23, no. 11, pp. 3625–3641, Nov. 2005.

[29] M. Dumke, G. Heiserich, S. Franke, L. Schulz, and L. Overmeyer,“Power transmission by optical fibers for component inherent communication,” *J. Systemic*, vol. 8, no. 1, pp. 55–60, 2010.

[30] X. Xu, S. Yang, C. Zhang, T. I. Yuk, and K. K. Y. Wong, “Optically powered communication system with distributed amplifiers,” *J. Lightw. Technol.*, vol. 28, no. 21, pp. 3062–3069, Nov. 2010.

[31] D. Phanish *et al.*, “A wireless sensor network for monitoring the structural health of a football stadium,” in *Proc. IEEE 2nd World Forum Internet Things*, 2015, pp. 471–477.

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