Photonics Breakthroughs 2024: Advances in B5G Radio-Power Over Fiber Fronthaul

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***Abstract*—Specific demands of providing power to equipment in remote areas or hazardous environments, including populated areas, requiring high throughputs and ultra-low latency in beyond 5G (B5G) mobile communications that are based on Radio over Fiber (RoF) have made Power over Fiber (PoF) attractive. This paper reviews a breakthrough of a long-distance hollow core fiber (HCF) fronthaul (up to 11.1 km) able to meet the requirements of B5G optical mobile networks, where the transmission medium is common to both 5G NR and PoF signals. This work is placed in context and compared with results provided by other authors, showing the relevance of the outcomes and subsequent future possibilities. It also creates a discussion in which the performance of other fiber technologies may be compared, as new B5G fronthauls with special attention paid to transmission in a single fiber, avoiding noise transfer between high power laser PoF source and 5G-NR data that affects the signal quality. PoF energy delivery efficiencies are also analyzed, achieving up to 9.9 % efficiency (from launched optical power to electrical power on the load) for a 3.1 km HCF and 0.9 % for a 11.1 km HCF. The PoF signal is used to supply a Bluetooth Low-Energy load.**

***Index Terms*—High Power laser, hollow core fiber, photovoltaic power converter, power over fiber, radio over fiber, wireless communications, 5G-NR, optical fiber networks, BLE.**

I. Introduction

A. Background

THE rapid deployment of Fifth-Generation (5G) New Radio (NR) technology in mobile networks and the challenging requirements regarding latency and energy efficiency, make it necessary to evolve quickly [1] to beyond 5G (B5G) networks and towards the Sixth Generation (6G) of mobile technology, which aim to achieve transfer rates around Tbps with ultra-low latency across extensive 3D coverage. This will require high-capacity mobile networks capable of linking a great number of nodes [2] and using small cells with greater throughput and reduced individual power requirements per cell for keeping power consumption/OPEX within reasonable limits. All this presents a significant challenge to current transport infrastructures, which may lead to major changes in the radio access network (RAN) architecture, with greater centralization and reallocation of processing functions. To that respect, the main proposal is the Cloud/Centralized Radio Access Network (C-RAN). In this architecture, there are three main entities: the Central Unit (CU), in charge of controlling the resources of the network; the Distributed Unit (DU), which is controlled by the CU and processes data within the network; and the Radio Unit (RU), which controls the physical and digital layer of the network. The Fifth Generation Fixed Network initiative shows how fiber is ubiquitous in its support of increasing bandwidth + connectivity demands of mobile networks. In terms of bandwidth and weight as part of the back/front haul infrastructure for transmitting radio–over-fiber (RoF) signals, the initiative presents performance improvements. Typical C-RANs operate with Digital Radio over Fiber (DRoF), which relies on transmitting digital high-speed signals through optical fibers. These signals require large bandwidths and sampling frequencies, leading to low spectral and power efficiency. However, the alternative Analog Radio over Fiber (ARoF) would help to maximize the spectral and power efficiency of C-RANs, as digitization is not required with this alternative [3] and does not demand as much processing time as DRoF. Therefore, ARoF would enable higher throughputs with reduced power consumption, lower latency and good scalability [4]. Currently, studies are being conducted to estimate and minimize the installation cost of these architectures. Among these, combinations of high fidelity DRoF and high spectral efficiency ARoF are under study [5].

The proliferation of small cells with reduced power consumption is critical for enabling the large-scale deployment of 6G networks. The traditional electrical power distribution scheme comprises a power supply bureau or central power cabinet and direct power distribution through a copper wire for each small cell [6]. However, such a scheme raises concerns regarding power reliability, as copper wires are highly susceptible to electromagnetic interference, short circuits, and sparks. Alternatively, power-over-Ethernet (PoE) has been considered for powering small cells, providing data and electrical power transmission. This solution can suffer from electromagnetic interference and voltage fluctuations. Additionally, the transmission loss is high and IEEE 802.3bt limits the maximum cable length for PoE

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to approximately 100 m. Regarding data transmission, media converters are needed to enable the integration of Ethernet-based communication with the high-speed mobile fronthauls (MFH). An alternative solution to electrical distribution is power over fiber (PoF), which is practically immune to electromagnetic interference, compatible with high-speed mobile fronthauls RoF and can eliminate the need for an external power supply for the RU when deploying mobile networks avoiding the need to construct electric power facilities and install electric power lines. In remote areas where supplying electrical power is difficult, solar power supply systems, including solar panels, controllers, batteries, and inverters, can become an alternative choice. However, the performance of the solar power supply system is highly dependent on weather conditions and unavailable in tunnels or mines where specific power supply systems are designed [7]. Therefore, it is highly desirable to explore an efficient and centralized-management solution for the electrical power supply of B5G small cells, including a combination of solar power and PoF supply as suggested in [8]. Finally, it is also attractive in case of a power outage at a RU in the event of a natural disaster or sabotage, where PoF could provide resilience to the network. Even when setting up temporary networks with high traffic demands [9] (such as for sports events or festivals), PoF can simplify the logistics of laying down the much bulkier and heavier copper power cables.

B. Challenges

One of the first experiments of a completed optically powered antenna optical fiber link was a hybrid system using 8 multimode fibers (MMF), with 200 μ m core diameter, deployed in parallel for powering optical transmitters coupled to single mode fibers (SMF) that delivered the signals to perform analog beam forming at a distance of tens of meters [10]. A single fiber to perform data and energy delivery has the benefits of being a compact and flexible solution but has some challenges. One of them relates to the nonlinear effects that occur in standard optical fibers, as the noise transfer from the high-power source to the data signal directly derives from Stimulated Raman Scattering (SRS). This mostly affects spatially shared configurations, where PoF and data signals travel through the same core of the optical fiber. High power lasers (HPLs) used to generate PoF signals present instabilities that limit their performance. Tapered gain lasers with varying longitudinal mode area can help in decreasing these instabilities [11]. However, it is still important to take into account these effects in shared configurations. Chromatic dispersion is another important impairment in ARoF links. Chromatic dispersion can cause power fading at certain carrier frequencies depending on the fiber characteristics. The impact of these effects has already been studied in [12], where chromatic dispersion-induced and noise transfer effects over 5G NR ARoF signals were studied for different 5G-compliant signals. Also, a number of mitigation strategies for the elimination of the power fading effect such as Optical Single Sideband or Optical Carrier Suppression has been proposed [13] but necessitate the use of more complex configurations. When trying to reach longer distances, higher power signal levels can be used or for increasing the throughput, multichannel transmission using Wavelength Division Multiplexing (WDM) can be a solution but transmission can be affected when increasing the power, reducing channel separation or increasing the number of channels as nonlinear effects, such as Four Wave Mixing can affect the propagation. To avoid nonlinear effects when combining PoF and RoF in dedicated configurations, using a single fiber, would require the use of one medium for data delivery and another for energy delivery. This can be achieved using a double cladding fiber (DCF), using the core for data transmission and the inner cladding for power delivery. But coupling to the inner core and cladding can be complex, having high losses. On the other hand, the HPL wavelength of preference for power delivery is 808 nm with a higher conversion efficiency of photovoltaic power converters (PPC) used in the remote node. But this limits the maximum distance to just a few hundreds of meters due to the high absorption of silica at that wavelength, having achieved 43 W electrical power at 300 m and a throughput of 54 Mbps [14]. Another possibility is to use multicore fibers (MCFs) increasing the energy delivered by increasing the number of cores and avoiding Fresnel reflections that can reduce the maximum power per core due to SRS as proposed in [15] reporting 1 W electrical power delivered at 14 km while transmitting 10 Gbps, but no ARoF signals. They used a 4-core MCF in a shared configuration (all cores transmitting data and delivering power) with a proper selection of wavelengths for long distance, nevertheless energy is delivered at 1550 nm where PPC efficiency is smaller than at 1480 nm and the system cannot be upgraded to deliver greater powers. Better values of power and ARoF transmission were achieved providing energy and data transmission in dedicated cores, as in [6] achieving 9 Gbps 5G-NR ARoF while delivering 11.9 W electrical power, using a 1 km 7-core MCF with HPL at 1064 nm, but the power delivery will greatly degrade at longer distances due to higher absorption at this shorter wavelength.

An even greater throughput of 39.5Gbps (including 5G NR ARoF signal of 15Gbps and 25Gbps digital communication signals) while delivering 0.7 W electrical power using a 7-core MCF at 0.25 km was reported in [16]. However, the nonlinear impediments to data transmission are restricted to the properties of solid silica core fibers (SCFs) in all cases for longer distances and data rates.

Another option to avoid non-linear effects was to use microstructure optical fibers, with a large core that also provides an increased power damage threshold for co-transmission of signal and power [17]. Experiments with simultaneous transmission of 976 nm for laser energy and 1550 nm for data were provided at 1.37 km, but with losses of 2.26 dB/km and 1.44 dB/km, respectively, limiting link length.

C. Breakthroughs

In most conventional optical fibers, light propagates through silica, which in many cases can limit power and data throughput due to nonlinear effects, losses, dispersion and power handling constraints. The innovation of hollow-core fiber (HCF) is the guidance of light in air, which offers many improvements over silica. Beginning in the late 90 s, research into HCFs began with photonic bandgap fibers (PBGFs), which relied on a cladding comprising a periodic lattice of holes that allowed the core to be of lower refractive index than its surroundings and guided light through the photonic band gap effect. Later, designs would feature a pattern of silica tubes axial to the propagation of light, known as antiresonant nodeless fiber (ANF). As fabrication technology improved, double nested ANF (DNANF), exhibiting concentric tubes, was developed and demonstrated to have lower minimum propagation loss than pure SCF [18], enabling longer link lengths. Moreover, compared to silica, signals in air experience over 44 % increase in group velocity, corresponding to 30 % decrease in latency; this and lower chromatic dispersion decrease latency and increase data throughput, respectively. These properties alone make HCF attractive for 5G NR and 6G mobile networks. For PoF, meanwhile, the biggest improvement over SCF is the reduction in nonlinearity. Considering only Kerr effects, the reduction in nonlinear index shift scales with at least 230 times the ratio of HCF to SMF mode area, assuming effective indices of 1 and 1.44 respectively at 1064 nm [19], [20]. As the HCF effective mode area is usually larger than in SMF, reductions in this nonlinearity often exceed 1000x. Noise transfer from HPL to signal is therefore suppressed, enabling at the same time both high throughput and resilient PoF links. HCFs have been demonstrated to have stable performance when carrying high-power optical signals, with 1 kW delivered over a 1 km NANF with total efficiency of up to 80 % [21]. In [22], PoF was used to send an optical power signal of 1.31 W through a 6 m HCF to power a camera. However, no application of HCF in long-distance optical 5G NR mobile networks had been proposed before our work in [23], where the feasibility of using HCF in long-distance fronthauls, sharing the transmission medium between 5G NR ARoF and PoF signals. Comparing HCF, MCF, and SMF links up to 11.1 km, the 5G NR signal in HCF was shown to suffer from minimal SRS-induced noise transfer. Furthermore, the HCF links used mode-matching splices with relatively low losses, demonstrating the fiber's potential for use in the field to drive an electronic load without an external receiver-side power supply.

The rest of the paper is structured as follows. The breakthrough research on MFH with ARoF and PoF based on HCF at long distances is described in Section II, while a comparison with other PoF and ARoF MFH results provided in 2024 are discussed in Section III. A brief summary of MFH integrating PoF and RoF are discussed in Section IV. A discussion on impact, limitations and future vision is reported in Section V. Conclusions follows.

II. Breakthrough Research

Analog Radio-Power over Hollow Core Fiber mobile fronthaul showing co-transmission at several kilometers avoiding noise transfer and other nonlinearities and with potential to increase link length and power delivery was presented in [23]. The whole system elements were considered and tested, from high power delivery to 5G-NR data transmission on an RF carrier, feeding a specific load at the remote node where signals with EVM values in compliance with 3GPP were received. The reported experiments on MFH based on HCF open the path to co-transmission of high PoF signals and 5G-NR high throughput and low latency signals in a single fiber.

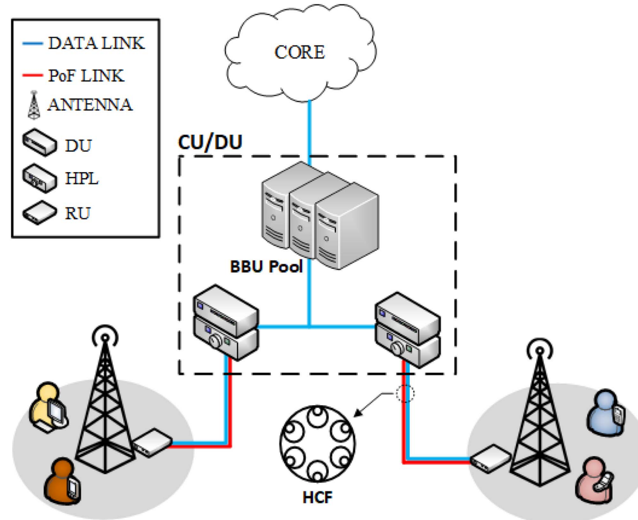

Fig. 1. B5G fronthaul with RoF and PoF with Hollow core Fibers (HCF).

A. Concept and Principle

Fig. 1 shows the proposed scenario for long reach HCF as an optical fronthaul link in B5G networks providing high throughput, low latency and leveraging power delivery over fiber. HCF has attractive features such as: high energy transmission is possible, around 1000 times that of normal SCF: low latency, around 15 μ s time delay difference with SMF in 10 km [24]; high linearity reducing nonlinear effects in high transmission and in energy delivery such as noise transfer, SRS and Stimulated Brioullin Scattering (SBS); chromatic dispersion D in the range of 2.5–3.5ps/(nm $\cdot$ km) within the C-band [25] making first frequency of power fading in ARoF transmission higher as being affected by a D value that scales down $\sim$ 2.5 times of that in step index SCF.

The use of a single fiber for providing those features is an advantage over other hybrid topologies considered combining MMFs for energy delivery and other types of fiber supporting a single mode for data transmission [10], [26], [27].

MCF can also provide higher power levels than SMF at long distance with no impact, but overall power is limited by the number of cores, and Fan In - Fan Out (FIFOs) devices to launch/extract the signals to/from the different cores of the MCF increase the losses. Nevertheless, depending on the considered power levels it can be an option, so it was included in the comparative analysis.

These features make HCF an ideal candidate in scenarios integrating PoF and ARoF transmission, so we performed a proof of concept to show the capability of delivering HPL energy through HCF from 3 km to 11.1 km along with ARoF signals in compliance with 3GPP standards for mobile networks. A comparison with SMF and MCF was also provided to reinforce the potential of HCF as a MFH infrastructure.

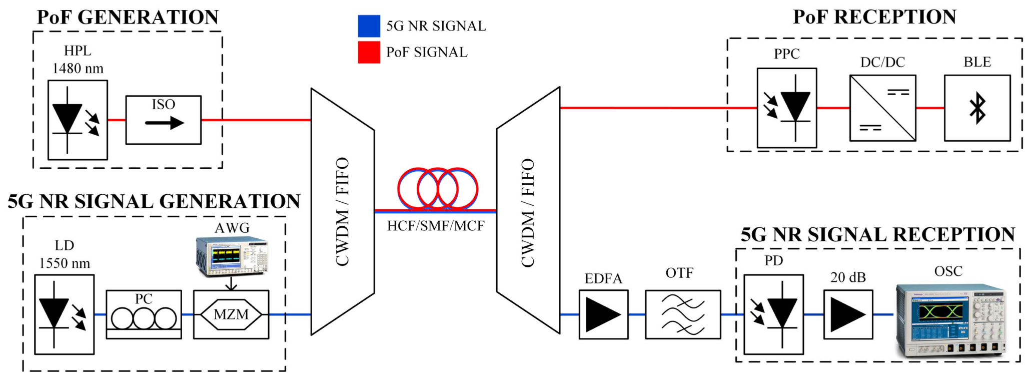

Fig. 2. Set-up for PoF and 5G NR ARoF simultaneous transmission through a single optical fiber. AWG: Arbitrary Waveform Generator, BLE: Blue Tooth Low-Energy. CWDM: Coarse Wavelength Division Multiplexer, EDFA: Erbium Doped Fiber Amplifier, OTF: Optical Tunable Filter, FIFO: Fan-in/Fan-out, HCF: Hollow Core Fiber, MCF: Multicore Fiber, SMF: Single Mode Fiber, HPL: High Power Laser, PPC: Photovoltaic Power Converter, ISO: Isolator, OSC: Oscilloscope, PC: Polarization Controller, PD: Photodetector.

B. Results and Achievements

We performed measurements to test the feasibility of PoF and 5G NR ARoF shared transmission in a single fiber. We compared the same scenario using HCF, MCF and SMF, within optical MFHs. We tested two HCFs lengths of 11.1 km and 3.1 km respectively, two SMF lengths of 9.8 km and 3.3 km and one length of 4-core MCF of 10 km. Details regarding HCFs' and MCF's structure and characterization of the MCF's losses and crosstalk at 1550 nm are given in [23]. We selected nested anti-resonant nodeless fibers (NANFs) because of their good characteristics in terms of attenuation at both bands, 1480 nm and 1550 nm, and good connections to SMFs.

Fig. 2 shows the set-up used in the experiments made up of the 5G NR data transmission block using ARoF and the power transmission block using PoF. The 5G NR block consisted of the 1550 nm Laser Diode (LD), connected to a Polarization Controller (PC), emitting a 16 dBm optical carrier. The optical carrier was modulated using a Mach-Zehnder Modulator (MZM) and an Arbitrary Waveform Generator (AWG). The 5G NR signals used in the experiments were Matlab-generated 5G NR Test Models (TM) specified in the 3GPP standard, with fixed bandwidth of 50 MHz, Sub-Carrier Spacing (SCS) of 15 kHz and Radio Frequency (RF) carrier of 3 GHz, and different modulation formats. The PoF generation block was made of a 1480 nm HPL with a maximum optical power of 1.5 W and an optical isolator (ISO). The signals generated by the LD and the HPL were then launched into and extracted out of the different optical fibers. For the SMFs and HCFs, a Multiplexer (MUX) and a Demultiplexer (DEMUX) were used to respectively launch and extract the signals. In the case of the MCF, two FIFOs were employed to inject and extract the signals, which were transmitted through different cores. At the output of the fibers, the LD signal was optically filtered with a Tunable Optical Filter (OTF), detected using a photodetector (PD) and amplified using a radio frequency Amplifier (AMP).

The 5G NR signal was captured by an oscilloscope (OSC) and analyzed using Matlab. An Erbium-Doped Fiber Amplifier (EDFA), with fixed output to 7 dBm, was placed at the output of the modulator only when the 11.1 km HCF was used. The PoF signal, after transmission, was injected into a 1480 nm PPC with a maximum optical input power of 600 mW. The electrical energy generated by the PPC was controlled by a DC/DC power converter with integrated Maximum Power Point Controller (MPPC) and fed to the electrical load, a Blue Tooth Low Energy (BLE) device. This full circuit was specifically designed for the experiments.

The PoF wavelength was chosen to be 1480 nm because, even though 1480 nm is not as efficient wavelength for PPCs as 860 nm [28], the power transmission efficiency improves due to the lower attenuation of silica optical fibers at 1480 nm, therefore is commonly used for PoF systems with lengths of several kilometers [29]; compared to 1550 nm it provides better PPC efficiency. Moreover, since 1480 nm is a typical pump wavelength for EDFAs and Raman amplifier in C-L band, there is a wide variety of HPLs with high efficiency, single mode lasers and a large number of devices that operate at that wavelength.

Successful experiments were performed showing HCF capability at long distance, avoiding the impact of nonlinear effects which would otherwise occur in SCF links. Special attention was paid to the impact of SRS in ARoF links transmitting 5G NR signals on a 3 GHz RF carrier using TM1.1, TM3.1 and TM3.1.a with QPSK, 64 QAM and 256 QAM modulations.

When a SMF replaced the HCF as the transmission medium, SRS provoked noise transfer from HPL to data channel as data and power feed propagated in the same glass core. Meanwhile, in MCF different cores were used for data and energy transmission and the same core was used in HCF with almost no penalty due to non-linearity effects even at 11.1 km. This allowed for the delivery of ARoF and PoF over those long distances without interference.

The results, see Fig. 3, showed that there was a degradation of the 5G NR signal only for both SMFs. For example, for the least demanding signal, TM1.1, the EVM limit imposed by the standard was exceeded for the 9.8 km SMF when PoF signal powers over 800 mW were launched, and for the 3.3 km SMF the same effect but to a lower extent was shown. For the rest of the optical fibers, no degradation was shown for any of the HPL

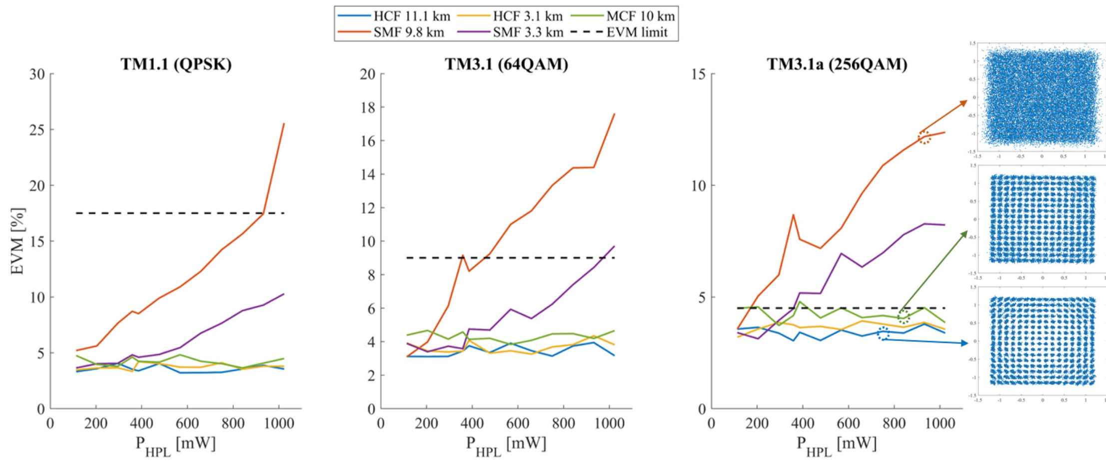

Fig. 3. EVM versus HPL power for ARoF link with different lengths and types of optical fibers. Tests Models (TM) 1.1 (QPSK), 3.1 (64 QAM), 3.1 a (256 QAM) and (—) EVM limit all defined by 3GPP. (Right) Constellations for HPL of around 1 W.

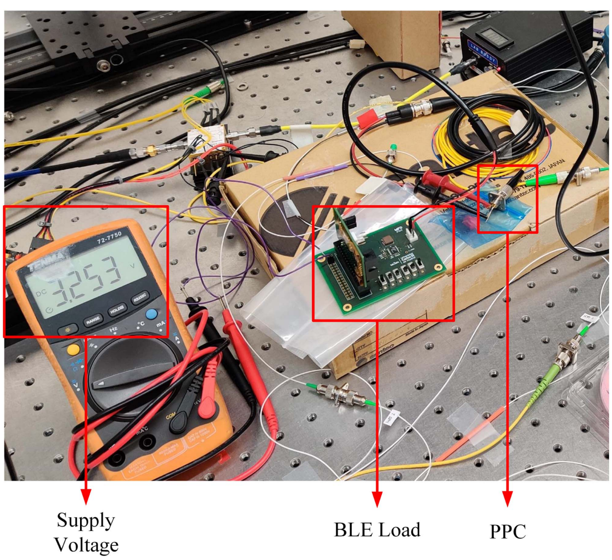

Fig. 4. BLE load optically powered with PPC and DC/DC converter.

powers. In the case of the MCF, this was because both signals were transmitted through different cores. In the case of the HCF, no noise coupling occurred because the propagation happened in air, meaning that SRS was much smaller than in silica fibers. To test this, the Raman On/Off gain was measured for all the fibers. The obtained results [23] showed that Raman On/Off gain was only present in SMFs, which agreed with the EVM degradation measurement. These experimental results showed that, to fulfill the EVM requirements of the 5G NR protocol with PoF signals, HCF or MCF must be used.

Finally, a photograph of the designed BLE load optically powered via 3.1 km of HCF is shown in Fig. 4. It is shown the measured voltage provided to the circuit.

Regarding the PoF signal at 1480 nm, the optical transmission efficiency (OPTE) was 50 %, 6.3 % and 3.6 % for longest length at SMF (9.8 km), MCF (10 km) and HCF (11.1 km) respectively. Meanwhile, at 3.3 km, there was an efficiency of 33.7 %. The same PPC having a conversion efficiency of 26 % was used in all cases. The BLE load required a maximum electrical power consumption of ≈ 20 mW when it was scanning for available Bluetooth devices and it was successfully powered with the 3.1 km HCF. Being the highest link length reported to date with PoF and ARoF with the best OPTE using HCF fibers. For both SMFs, the BLE load could be supplied. For the 10 km MCF, the BLE load could also be powered. However, with the 11.1 km HCF, the BLE load could not be supplied. It is expected to achieve lower HCF's attenuation at the HPL wavelength in the future.

III. 2024 Power Over Fiber and B5G ARoF Links

A. B5G Radio and Power Over Hollow Core Fiber in 2024

The advantages of using HCF as part of B5G optical technologies was also pointed out in [24] where experiments on low latency capabilities in a Local 5G (L5G) wireless access network were reported. They installed a combination of SMF and HCF (of the photonic bandgap type PBGF), 500 m long, into a university campus. A mobile mid-haul (MHH) was implemented between CU and DU and accommodated into a commercial 10G-EPON where the L5G system was connected to the HCF cable with a total loss of 3.5 dB for data at 1577 nm. The experiments of L5G MHH over a Passive Optical Network (PON) reported had an improvement in latency of around 0.4 μs in 77.64 μs by using HCF in combination with SMF, but not PoF delivery was reported.

An optical fronthaul with four-channel A-RoF transmission with high data signal power using a 1-km PBGF-based HCF was reported in [30], but no PoF delivery was considered. The first channel was located at 1558.98 nm, and the others were separated by either 50 GHz or 100 GHz. The electrical data signal was based on the IEEE 802.11a standard using 64 QAM OFDM signal with a carrier-frequency at 5.2 GHz. The transmission loss of the fiber at 1550 nm was approximately 3.11 dB/km. An EVM below 2 % was achieved for the 4 channels

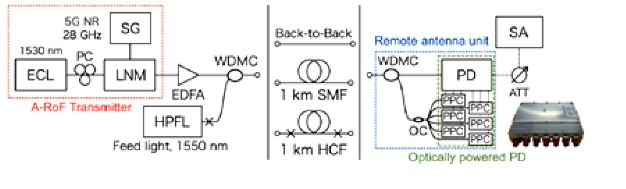

Fig. 5. Set-up for PoF and 5G NR ARoF simultaneous transmission through 1 km HCF. ECL: External cavity laser diode, PC: Polarization Controller, LNM: LiNbO3 modulator, EDFA: Erbium Doped Fiber Amplifier, HPFL: High Power Fiber Laser, WDMC: Wavelength Division Multiplexer Coupler, SMF: Single Mode Fiber, HCF: Hollow Core Fiber, PD: Photodiode, PPC: Photovoltaic Power Converter, ATT: Electrical Attenuator, SA: Signal Analyzer. (Right) photo of optically powered PD module, from [31].

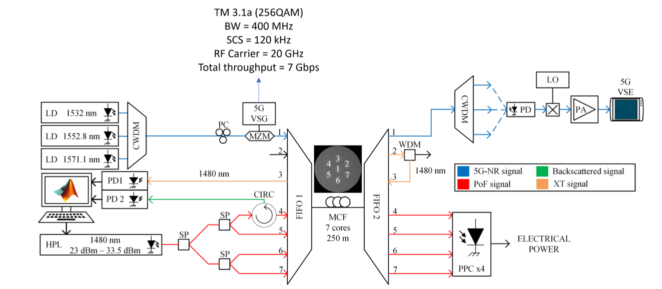

Fig. 6. Set-up for PoF and 5G NR ARoF simultaneous transmission with 7 Gbps throughput and integrating monitoring techniques and control signals [34].

during transmission with input power from 20 dBm to 26 dBm, where SMF provided a degraded signal.

There is only one work in 2024 apart from [23], integrating PoF and ARoF with 5G-NR communications using HCF [31]. It showed an ARoF transmission of 1 channel with a high-power feed light power over fiber using a 1 km PBGF-based HCF to drive a downlink photodiode module. The HPL worked at 1550 nm, meanwhile data transmission was based on a laser at 1530 nm externally modulated with a 64 QAM OFDM signal and a carrier-frequency at 28 GHz, see Fig. 5.

The HCF has the same characteristics as the one used in the previously discussed experiments [30]. Optimum ARoF transmission with 26.3 dBm optical data signal providing EVM below 3 % required 400 mW optical power reaching the PPCs that was achieved by launching 1538 mW into the link. The OPTE for this 1 km HCF link is 26 % while we were able to provide 33.7 % at 3.3 km HCF link, due to the better performance of NANFs in terms of attenuation and coupling losses. Finally, an experiment considering PoF over HCF at a distance of 1.21 km has been reported in [32], providing power delivery at 800 nm and data at 1550 nm but without ARoF transmission.

B. B5G Radio and Power Over a Single Fiber in 2024

The interest of increasing optical power delivery at long distances, along with data transmission in MFH using a single fiber has driven attention not only by using HCF, but also MCF as a potential solution to increase the delivered power by using multiple cores. The overall efficiency of the PoF system, from optical power feed to optical fiber to electrical power delivered to the load, should be as high as possible, as B5G/6G networks take into account the reduction in power consumption as a main Key Performance Indicator (KPI). It is also relevant to take into account the HPL wavelength, which is related to losses in optical fibres, being this the dominant factor when compare to PPC efficiency at long distances [29]. Next, we discuss some of the different works that have been reported in RoF and PoF considering a single fiber combining both capabilities.

There are different proposals for delivering PoF and data using MCF, including mostly 7-core MCF and 4-core MCF. There is a proposal in [15] using a 4-core MCF for delivering data (10.4 Gbps) and PoF (using a 1550 nm HPL) in all 4 cores in a bidirectional 14 km link providing up to 1 W to the load; but without ARoF signals. In [33], they proposed using 7-core MCF, with 4 cores for delivering power at 1549.66 nm, 1 core for data transmission and 1 core for an additional functionality, in this case pumping (at 976 nm) a remote EDFA. Around 500 mW electrical power were delivered at 0.5 km while transmitting an electrical data signal based on the IEEE 802.11 (maximum throughput of 54 Mbps) using 64QAM with a carrier-frequency at 5.2 GHz with good EVM values. Another proposal using a 7-core MCF was shown in [34], with 4 cores for delivering PoF, 2 for monitoring purposes and one core for data transmission of 5G NR signals on 3 optical carriers multiplexed using a CWDM Multiplexer and modulated with a MZM and a SMW200 A 5G NR signal generator, see Fig. 6. The 5G NR signal was a 256 QAM Test Model (TM) 3.1a, with a bandwidth of 400 MHz and a SCS of 120 kHz modulating a 20 GHz electrical carrier. Providing a 7 Gbps throughput ARoF signals with EVMs between 3 % and 4 % for all the channels and 226 mW electrical power at 0.25 km.

Aligned with the KPI of 6G in terms of improving energy efficiency, a PoF pooling was proposed in [35], to provide energy-aware device control and resource allocation capabilities. The implementation allowed working with multiple optical fibers, sharing HPL between RUs and integrated battery charging. Experiments on PoF systems based on SMF links with different lengths connecting RUs at 10 km (RU1) and 15 km (RU2) while sharing the same HPL were reported. The optically powered RU selection was made with an optical switch controlled through a PoF agent that took into account whether the cell was occupied, the throughput demand and the cell battery status. Electrical powers of around 190 mW and 125 mW were supplied to RU1 and RU2 respectively. The PoF pooling concept was also tested for 4-core MCF and 7-core MCF set ups and included sleep mode operation with power consumptions of 5.8 mW at the RUs.

IV. PoF and 5G ARoF Transmission

Different analyses about experimental demonstration of PoF and RoF are reported by different authors. A table summarizing the situation up to 2019 was reported in [36]. An analysis considering delivered electrical power versus transmission distance with and without simultaneous data and power transmissions using a single optical fiber were reported in [14]. Those data were updated and discussed considering the metric defined as the product of power and link length (Wxkm) in [15], but without emphasis on radio signals. Studies providing relevance

TABLE I
SUMMARY OF CO-TRANSMISSION EXPERIMENTS OF POWER-OVER-FIBER (POF) AND DATA

Ref. year	Fiber Type	Single Fiber PoF+Data	λ_{PoF} (nm)	λ_{data} (nm)	Distance (km)	HPL Power (W)	Delivered Electrical Power [W]	Throughput	RoF Configuration
[38] 2005	SMF	Yes	1480	1560	2	0.3	0.0265	NA	2.45 GHz W-CDMA
[39] 2008	MMF	No	834	850	0.3	0.25	0.112	54 Mbps	IEEE802.11g 2.5 GHz, 64-QAM OFDM
[40] 2012	MMF	Yes	980	850	0.1	1	0.06	54 Mbps	IEEE802.11g 2.4 GHz, 64-QAM OFDM
[41] 2019	DCF	Yes	808	1550	1	150	7	54 Mbps	IEEE802.11g 5.4 GHz, 64-QAM OFDM
[42] 2021	SMF	No	1480	1310	14.4	2.24	0.226	6.6 kbps	No
[43] 2021	DCF	Yes	808	1550	0.3	150	43.7	54 Mbps	IEEE802.11g 2.4 GHz, 64-QAM OFDM
[26] 2021	MMF	No	808	1532	0.1 (PoF)-10 (data)	5.407	2.34	10 Mbps	5G-NR 20 GHz, TM1.1 QPSK
[44] 2021	SMF	Yes	1480	1532	10	2	0.226	1.2 Gbps	5G-NR 13-17 GHz, 254 64 16 QAM
[45] 2021	POF	Yes	405	605	0.01	0.02	0.0015	1 Gbps	No
[46] 2021	MCF	Yes	1480	1550	10	1.26	0.133	1.6 Gbps	5G-NR 25.5 GHz, QPSK BW=800 MHz
[47] 2022	MCF	Yes	1550	1310	5.8	12	0.64	1.5 Gbps	No
[48] 2022	MMF	No	975	1551	0.1-12.5	2.2	0.516	600 Mbps	3.5 GHz, 64-QAM BW=100 MHz
[6] 2022	MCF	Yes	1064.8	1546-1550*	1	60	11.9	9 Gbps	5G-NR 3.5 GHz, 64-QAM OFDM
[49] 2023	MCF	Yes	1480	1532,1552.8,1571.1	0.25	2	0.131	1.8 Gbps	5G-NR 20 GHz, 256-QAM OFDM
[15] 2024	MCF	Yes	1550	1310	14.1	18	1	10.3 Gbps	No
[50] 2024	MMF	No	808	1550	0.5-10	8.1	0.71	360 Mbps	5G-NR 3.5 GHz, 64-QAM OFDM
[33] 2024	MCF	Yes	1549.6	1550	0.5	2	0.58	54 Mbps	IEEE802.11g 5.4 GHz, 64-QAM OFDM
[23] This breakthrough	HCF	Yes	1480	1550	11.1	1.02	0.01	300 Mbps	5G-NR 3 GHz, 256-QAM OFDM
[23] This breakthrough	HCF	Yes	1480	1550	3.1	1.02	0.11	300 Mbps	5G-NR 3 GHz, 256-QAM OFDM
[31] 2024	HCF	Yes	1550	1530	1	1.591	0.1**	NA	5G-NR 28 GHz, 64-QAM OFDM
[32] 2024	HCF	Yes	801	1550	1.21	NA	0.05	9.95 Gbps	No
[51] 2025	DCF	Yes	976	1550	0.25	22.3	1.5	2.4 Gbps	5G-NR 26 GHz, TM3.1 64-QAM BW=600MHz
[16] 2025	MCF	Yes	1480	150,1550,1560,1310	0.25	3.46	0.689	35 Gbps	5G-NR 14.7 GHz, 256-QAM
[52] 2025	SMF	Yes	1064	1310.1	1	14	0.9	3.5 Gbps	5G-NR 6 GHz, 256-QAM BW=500 MHz

*NA=No data available. POF=Plastic Optical Fiber. *6 channels, ** estimated from data and commercial PPCs*

to throughput were reported in [6], [37] and more recently in [16] and [27], meanwhile an analysis based on PoF wavelength as a differential parameter was provided in [29].

In this section, we include a table showing the evolution of experiments of co-transmission of PoF and data including electrical power delivered, distance and throughput with different types of optical fibers, HPL and data wavelengths. Only experiments including power and data transmission with electrical energy delivered to the load (so integrating a PPC) are considered. The main focus is on experiments showing co-transmission of ARoF and PoF as part of MFH in a single fiber, but some tests with other type of data signals and considering different fibers for data and PoF transmission are also reported to provide a general view of the topic context. For optically powering at distances greater than 1 km the most relevant parameter is optical fiber losses and long wavelengths are more adequate. More specifically, the extrapolations reported in [29] showed that the combination of MCFs with HPLs at 1064 nm provided good efficiencies with high power levels in dedicated configurations up to 4 km; for longer distances HPLs at 1480 nm or 1550 nm reached better values. As shown in Table I, when considering co-transmission of ARoF and PoF with HPL at 1064 nm the maximum reach distance was 1 km, with a ratio between electrical power in the load to optical power from HPL of 19,8 %. Meanwhile co-transmission of ARoF and PoF at a longer distance of 14 km was achieved with HPLs at 1480 nm with SMF in [26] but with the limited scalability to maximum power and throughput of SCF. Meanwhile we reported in [23] the co-transmission of ARoF and PoF with HPL at 1480 nm at 11.1 km and 3.3 km meanwhile only 1 km is reached in [31] with equivalent electrical power levels, and with the great scalability to maximum power and throughput of NANF.

V. DISCUSSIONS AND PERSPECTIVES

A. Impact

Experiments on MFH based on HCF with successful co-transmission of 5G-NR signals at different modulation formats such as QPSK, 64 QAM and 256 QAM with an optical carrier in the C-band, delivering more than 1 W at 1480 nm with low losses, open the path to co-transmission of high PoF signals and 5G-NR high throughput and low latency signals in a single fiber. Self-powered MFH in remote locations or scenarios such as stadiums, disaster environments, data centers requiring high capacity and low latency will be deployed. New flexible MFH based on centralization of data and power distribution with high coverage and optimized energy efficiency by providing power on demand only in those areas where it is required would be a reality. The capacity of new HCF to provide low attenuation at different wavelength bands can also be a great advantage for matching high PPC efficiency and high OPTE of PoF transmission. Its integration with other energy sources (to complement solar panels at night or batteries in tunnels) is also attractive, depending on the geographic characteristics, surpassing distance limitations and space constrains.

B. Limitation

Overall energy efficiency needs to be improved to make Radio-Power over Fiber a more attractive approach. In terms of PoF system efficiency, it depends on the electrical to optical conversion in HPL, interconnection of HPL to optical fiber, optical fiber losses and optical to electrical conversion in the PPC. The updated PPC state-of-the-art reviewed in [53] highlights the efficiency improvements achieved in recent years. The maximum reported efficiency at high power levels (30 W output power) is 61 % at 808 nm, going up to 69 % at 860 nm but with low output voltages of 1.2V [54] and up to 75 % at low temperatures of 150 K. At 960 nm there are efficiencies of 48 % and 22 W output power and 42 % at 1064 nm. Most high output powers and high conversion efficiencies used vertical multi-junction designs [28]. At long wavelengths, there are efficiencies of 48 % at 1470 nm and 7 W output power that increases up 77.5 % at 1480 nm and 77 K. A path towards better efficiencies should continue to reach Electronic Power efficiencies at least at around 80 %. Output voltages of around 5-6 V can be available at commercial PPCs but current RUs require voltages of 48 V, and consequently the need of power electronics to convert/adapt supply voltages. Future minimalist cells to be deployed with low power consumption based on photonically driven antennas with uni-travelling carrier photodiodes will relax those requirements, albeit requiring high-power RoF links [55] that can be achieved with HCF MFHs.

In terms of transmission media, HCF transparency in different wavelength ranges, standing high power levels, low latency and high linearity are attractive features, but those fibers are not yet deployed and are expensive. Nevertheless, HCFs being able to meet global standards, including those of size, could be used without any changes to existing infrastructure [56]. They can provide enhanced capacity and flexibility to allocate high power and high data rates without requiring new ducts/infrastructure. Special attention should also be given to HPL interconnection with HCF, as single mode lasers, which are currently challenging to obtain in some wavelength regions, due to the relative lack of suitable fiber dopants [32] and when available, exhibiting poor wall-plug efficiency and high cost in comparison with semiconductors laser. There are great advancements pushed by 4.0 additive manufacturing making more efficient fiber lasers at 1060 nm commercially available with up to 50 % wall-plug efficiency that can push the final decision about the selection of energy delivery wavelength in a specific direction. The input coupling losses to interconnect a HCF of arbitrary core size with standard SMF with minimum losses of 0.08 dB in first and second window was reported in [57], accompanied by reduced undesired coupling into higher-order modes. Those results are expected to be extrapolated to other communication windows.

On the other hand, current regulations of electrical systems in communications environments are very restrictive. These systems require schemes that ensure safety in the event of fiber damage and the integration of PoF signal monitoring techniques for safety and control purposes, helping to prevent power-related malfunctions. Most monitoring techniques currently proposed are based on Rayleigh scattering or crosstalk [49] [34] present on SCFs, being scattering effects in HCF, 3-4 orders of magnitude smaller. Nevertheless, several techniques for monitoring HCF transmission systems have recently been demonstrated based on coherence reflectometry techniques, but requiring stabilized lasers and coherent [58] or polarization diversity [59] detection, adaptation should be required in the context of PoF signal monitoring.

There is also a need of additional studies to check power supply stability over several years in HCF.

C. Future Vision

The initial stage of Radio-Power over Fiber development as B5G MFH based on HCF goes together with the deployment of new optical fibers, providing low latency, high throughput, high power RoF and PoF transmission in different wavelength bands with low losses and high PPCs and HPL efficiencies. Nevertheless, the costs associated with the installation of new fibers raise the problem of the economic viability of this solution, depending on the scenarios [60]. Once this analysis is completed, some applications will appear initially to power some parts of the system, considering simultaneous power and data transmission as a means of enhancing the resilience of the network. Meanwhile the integration of a centralized control that allows reducing consumption during periods of inactivity will come in parallel. This would happen either in a brownfield (reusing existing pipes and other infrastructure) or most likely in a greenfield deployment. On the other hand, fully powered RUs would come next, either in the context of point to point or PON deployments in remote locations, to which it would be difficult to provide electrical power over copper links, requiring galvanic isolation and practical immunity to electromagnetic interference or an independent redundant power supply. Another scenario includes the flexible supply of high-density minimalist cells with self-powered RU deployments using PoF in combination with solar power supply, depending on meteorological conditions and geographical factors.

In this scenario, it is envisaged that the development of new RU hardware equipped with the characteristics of centralized management that can make PoF cost effective by sharing the energy resources and delivering the energy only when required [8]. All this combined with Software-Defined Networking benefiting from its versatility and programmability. New Distributing Fiber Sensing (DFS) capabilities were recently reported in HCF [58] making it feasible to combine DSF, PoF, RoF and energy harvesting from PoF and DFS as already proposed in submarine cables with MCFs integrating communications, sensing and PoF [61], [62]. Radio-Power over fiber will be present in temporal settlements requiring B5G connectivity with a massive number of users (concerts, stadiums...) or difficult to access areas using tethered drones to provide connectivity. The new ecosystem considering fiber as the transmission media instead of light in free space when combining wireless data and power transfer as proposed in [63] for 6G networks. A general view of some of these applications appears in the concept figure of this paper.

VI. Conclusion

Future B5G/6G mobile networks face challenges in terms of providing high throughputs, ultra-low latency and extensive coverage while reducing power consumption to permit large scale deployments with small cells. We discussed the potential of considering MFH based on HCF for co-transmission of ARoF to maximize the spectral and power efficiency in combination with PoF to supply the small cells and provide resilience to the network. Our experiments with successful co-transmission of 5G-NR signals at different modulation formats including 256 QAM with an optical carrier in the C-band, delivering more than 1 W at 1480 nm with low losses at several kilometers and supplying a Bluetooth Low-Energy load with NANF, open the path to co-transmission of high PoF signals and 5G-NR high throughput and low latency signals in a single fiber. We also analyzed the performance of MFH with different optical fibers reported in literature with special attention to ARoF and PoF co-transmission in a single fiber, supplying electrical power to the load and covering long distances. Self-powered MFH in remote locations or scenarios such as stadiums, disaster environments, data centers requiring high capacity and low latency will be deployed. New flexible MFH based on centralization of data and power distribution with high coverage and optimized energy efficiency by providing power on demand only in those areas where it is required would be a reality. The capacity of NANF to provide low attenuation at different wavelength bands is a great advantage for optimizing high PPC efficiency and high OPTE of PoF transmission, in addition to increasing throughput. It must be acknowledge that, to make the above scenarios realistic, substantial challenges need to be addressed, not just related to NANF performance. Among them, improving the PPC and HPL conversion and wall plug efficiencies respectively, increasing PPC output voltages and handing powers, new single mode lasers at shorter wavelengths, reducing the cost of NANF, PPC and HPL, simplifying RUs and reducing its power consumption, new regulations for RU power supplies, new monitoring techniques to provide security and resilience, long term tests to warranty stable power supply, optimization of ARoF transmitters and receivers and the minimization of all types of excess loss. The adoption of NANF based systems in other optical communications field could help to reduce costs and make the technology available helping the expansion of green field deployments of resilience MFH covering distances of tenths of km with high throughput requirements.

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