The Role of Power-over-Fiber in C-RAN Fronthauling Towards 5G

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ABSTRACT
We explore the potential integration of power-over-fiber (PoF) systems for the next generation 5G cloud radio access network (C-RAN) front-haul solutions based on spatial division multiplexing with multicore fibers. Different architectures, including spatial division multiplexing with multicore fibers for both shared- and dedicated-core scenarios, are discussed. The PoF energy delivery to the remote site depending on the efficiencies of the different components and on fiber limitations is addressed as well as impairments related to non-linear effects mainly. The impact of high power-over-fiber signals on the data traffic signal quality is analysed. This study may help in the design of future remote power by light delivery added-value solutions for 5G Radio over Fiber systems and radio access networks with optical fronthauling.

Keywords: power-over-fiber, 5G mobile communication, remote antenna unit, multicore fiber, C-RAN fronthaul.

1. INTRODUCTION
The mobile traffic explosion fosters 5G (5th Generation) cellular network evolution to increase the system rate around 1000 times higher than the current systems and to manage the expected monthly global mobile data traffic that was expected to surpass 30.6 exabytes this year [1]. The reduction of the cell sizes for providing this high bandwidth requirement foresees a huge increment in the power consumption demand by the massive installation of remote antenna units (RAUs). Thus centralized/cloud radio access network (C-RAN) approaches are being considered as a 5G fronthauling solution to minimize this impact, to allow a sustainable scalability and to reduce the geographic distribution of maintenance sites [2,3]. Moreover, power consumption demands of future 5G-based RAUs can be dramatically reduced, especially if Analog Radio over Fiber (ARoF) mobile fronthaul is considered [4,5], where processing is done at the Central Office (CO). This upcoming 5G technology opens up new application niches for the power-over-fiber (PoF) technology [6], where low power simplified antenna units (around 80 mW) are required as part of future 5G-based RAUs [7] together with some strategy for energy saving to reduce the impact of the power consumption of the remote antenna units, including the capability of turning into sleep mode some RAUs [8] with total energy savings estimations of more than 30% [9]. Additionally, remote local battery charging with energy harvesting devices can also be used to backup operations and to provide feedback to the central office (CO) in case of failure.

The use of multicore fibers (MCF) in the C-RAN scenario provides compact designs to develop optical front-haul technologies targeting spatial division multiplexing (SDM) with increased aggregated capacity [10]. MCF can also contribute to downsizing the footprint by using optical fiber composite low-voltage cables. Radio-over-Fiber (RoF) mixed with PoF through MCF can be suitable for small cell operations in advanced radio access networks (RAN) [11]. The PoF pooling concept in 5G front-haul architectures with Software Defined Network (SDN) capabilities also uses MCF [12], demonstrating that PoF capabilities can be enabled by a Software Defined Network (SDN) controller to increase the user’s service throughput.

Hence, in this work we address the integration of PoF in next generation centralized/cloud radio access network front-haul architectures with MCF-based deployments. Different remote feeding scenarios are proposed and analysed. Energy efficiency delivery is studied and some experimental results on the data transmission quality impact with simultaneous optical power delivery signals of hundreds of mW are also presented. Theoretical maximum PoF power levels are also analysed for different types of fibers.

2. PoF INTEGRATION AND POWERING ARCHITECTURES
Novel front-haul technologies in support of the RAN growing traffic demand based on the introduction of SDM to increase the aggregated capacity of the infrastructure have been proposed, as in the H2020 BlueSPACE project concept paper [13], where SDM is achieved using compact designs based on MCFs compared to fiber bundling and where the concept of PoF pooling is also introduced. Other MCF-based in-field test-beds are currently under development [14]. Important challenges face the MCF-based C-RAN architecture such as the proper address of the bit rate fronthauling requirements, the scalability issues to guarantee fiber availability while increasing the number of sector-cells, and compatibility in supporting other features, such as capacity increase by carrier aggregation, dynamic capacity allocation or current/evolved versions of passive optical access networks (PONs). Final challenges reside as well in the integration of centralized control, powering, supervision and management...
characteristics. The proposed configuration of SDM based optical fronthaul integrating different technologies is shown in Fig. 1a.

![Figure 1](image_url)

**Figure 1**: (a) Proposed configuration of SDM-based optical fronthauling integrating different technologies; (b) Use-case: available PoF channels on a 7-core MCF depending on the scenario considered.

For remote PoF delivery via MCF there are two scenarios: “power dedicated cores” where one or more of the multiple individual cores of a multicore fiber are exclusively used for optically remote feeding, and “shared cores” where some individual cores of the multicore fiber transmit simultaneously data/control and power over fiber signals [6]. Figure 1b depicts a different core usage and configuration design for a 7-core MCF, as an illustrative example, with PON integration and PoF capabilities. In the dedicated-core scenario, two individual cores are considered for the PoF feeding where rest of (free) MCF cores are used for up/down link purposes to provide small cell connectivity and PON data traffic integration in both directions within the infrastructure and for a control channel. For the shared-core scenario same configuration can be considered for the transmission channels where simultaneously all MCF cores may be devoted for optical powering purposes. These proposed powering architectures on MCF are shown in Fig. 2. Fan-in (FI) devices feed power to each core whereas Fan-out (FO) devices spatially separate the signals coming from each core. CO and RAU include additional MUX/DMUX devices in the shared-core architecture. All these passive devices should at the same time handle high optical powers, have small insertion losses and provide high crosstalk. Adding a bandpass filter at the data/control central channel wavelength increases the isolation.

![Figure 2](image_url)

**Figure 2.** Proposed powering architectures on MCF. (a) Shared core: power and data/control multiplexed on the same core. (b) Power dedicated core: separate power cores from data traffic. Fan-in device (FI), Fan-out device (FO), Photovoltaic converter (PV).

### 3. PoF SYSTEM DESIGN

Any PoF system requires wavelength matching between HPLD, PV efficiency and optical fiber attenuation. The overall PoF figure of merit in terms of energy efficiency is a critical design factor in any PoF system. It directly depends on: the electrical-to-optical conversion efficiency at the transmitter site, the transmission efficiency of the optical distribution network, and the optical-to-electrical conversion efficiency of the PV cell at the remote site. The optical fiber selection for the power distribution network determines the efficiency of the system versus distance and the power that can be delivered to the remote site. This power depends on the transmission loss, the optical fiber damage threshold and the non-linear effects. From Fig. 3a it is shown that for link lengths less than around 1.3 km, PV efficiency is the dominant effect and 808 nm would be a good choice for PoF deployments such as future 5G scenarios in autonomous driving and home networks. Meanwhile for longer distances, convergent to that of for C-RAN fronthaul fiber deployments, optical fiber attenuation starts to be dominant and 1480 nm provides better efficiency. For MCFs however a different SEE performance for each core suffices because of the asymmetry between the different cores in a MCF. The different attenuation coefficient between the central and external cores implies reducing the distances, although limited to around 100 m from our previous experiments to achieve the same performance [6].
The PoF input power limit is bounded due to its maximum power density for light injection as well as its non-linear effects. The ultimate fiber damage power density threshold in silica fibers is upper bounded to around 5 MW/cm² in CW operation. PoF systems based on MMFs can support higher powers than those based on SMFs; as MMFs have higher effective areas although the mode field diameter (MFD) determines the fiber effective mode area ($A_{\text{eff}}$) should be considered, especially in Graded-Index fibers [15]. Considering a single individual MCF core with 8μm of MFD at 1480 nm this leads to a maximum optical PoF power injection of around 2.5 W per MCF core. A simple power budget analysis leads to a power delivery at RAU of 780 mW and 2.1 W for the dedicated- and shared-core scenarios, respectively, see Fig. 2, if 1 W per individual core is injected into the system and if we consider both core assignments proposed in Fig. 1b for a 7-core MCF. For this calculations a 5 km-long MCF link is considered with insertion losses due to the fan-in device (FI) (~1.9 dB), the fan-out device (FO) (~1.2 dB) and transmission loss (0.2 dB/km) for an operating PoF laser wavelength of 1480 nm. These optical power delivery values should be then scaled by around a 0.40 factor due the PV cell efficiency (i.e. 40%) to estimate the remote electrical power delivered at the remote site.

On other hand, non-linear effects such as Stimulating Brillouin Scattering (SBS) and Stimulating Raman Scattering (SRS) should be paid attention to maximize the PoF efficiency. Figure 3b shows the simulation results run in Virtual Photonics Instrumentation software where the output power vs input power of a PoF system is shown for 7-core MCF different link lengths in a dedicated-core scenario. A 1480 nm HPL 100 GHz linewidth was considered. Power delivery penalties due to SBS and SRS are considered as well as simultaneous data traffic in the C-band. PoF delivery is not penalized by non-linear effects up to 1 km for 2 W input power in each core. However, injecting the same input power per MCF core while increasing the link distance results in a dramatic decrease of the PoF performance. A deeper insight of the influence of the non-linear effects on the PoF efficiency can be seen in [6].

4. PoF EXPERIMENTS

Different tests on 20 m-long and 200 m-long 4-core MCFs are performed to explore the influence of PoF signal from a HPL at 1480 nm with 2 nm of bandwidth. This HPL linewidth selection assures minimum impact of non-linear effects on the PoF efficiency. 2.6 Gbps bit-rate data traffic signals from a SFP transceiver operating at 1550 nm are employed. The setup is described in detail in [16].

Figure 3: (a) PoF system efficiency vs link length for different HPL wavelengths. No penalty due to HPL-fiber coupling is considered; (b) Output power vs input power. 1480 nm HPL, 100 GHz linewidth. 7-core MCF dedicated-core scenario. Note: SEE is the ratio between the energy provided to the load and the energy provided by the HPL.

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Figure 4: (a) Shared-core scenario BER impact for different PoF optical powers injected into different individual MCF cores; (b) Data traffic BER vs received power: dedicated- (HPL on core 2) and shared- (HPL and data on core 1).
For both shared- and dedicated-scenarios negligible BER penalty is measured between switching the HPL OFF and ON for any MCF core combination. Figure 4a shows the negligible impact on (arbitrary) BER values in the shared-core scenario tested while injecting PoF signals up to around 320 mW (HPL output of +26 dBm), measured at the FI device and limited its power-handling requirements. Figure 4b shows the 2.6 Gbps BER data traffic at 1500 nm versus received optical power for both scenarios with PoF signal of 300 mW at the input of the FI device. Negligible PoF impact is noticed in the data traffic.

5. CONCLUSIONS

The PoF technique may provide remote energy controlled from the CO via optical fiber to: a) allow the RAUs to enter into a sleep mode operation independently of the main power network, b) to recharge a local battery during idle periods of cell transmission and/or during the night. An operation maintenance cost reduction and power consumption savings are envisaged as main network performance key aspects that can benefit by the introduction of PoF.

Shared- and dedicated- power-over-fiber (PoF) scenarios are proposed as part of the infrastructure to be integrated for future C-RAN 5G cellular networks with foreseen low-power consumption RAUs. Greater power levels can be delivered in the shared-core scenario however more elements are required as MUX/DEMUX devices thus penalizing the PoF system efficiency due to the additional insertion losses in the link. Nevertheless the greater net effective area using all cores in MCF in the shared-core improves the power delivery efficiency in comparison to the dedicated-core counterpart. With a proper selection of the PoF HPL optical source non-linear effects such as SBS and SRS can be avoid thus obtaining optimum PoF transmission efficiencies for a specific link length. Some 4-core MCF experiments show that the impact on the data traffic quality signal in any of the proposed scenarios is negligible for injected PoF optical power levels up to around 300 mW limited by the FI device power handling.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the H2020 EU-funded project BlueSPACE (grant no. 762055), the Spanish Ministerio de Economía, Industria y Competitividad and Comunidad de Madrid under grants P2018/NMT-4326, Y2018/EMT-4892, TEFLON-CM, and in part by FSE, respectively.

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