Experiments on Shared- and Dedicated- Power over Fiber Scenarios in Multi-core Fibers

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***Abstract*— We explore the potential of optical power delivery in multicores fibers, either using individual cores only for power or to share both data and power signals into the same core. A comparison between both scenarios in terms of power levels for different link lengths and number of elements required is provided. We measure the impact of high power-over-fiber signals at 1480nm on the data transmission quality in a 4-core multicore fiber. Both dedicated- and shared-core scenarios are evaluated showing both negligible data traffic quality performance changes.**

Keywords—multicore fiber, C-RAN, power over fiber, shared core, dedicated core

I. INTRODUCTION

Power-over-fiber (PoF) technique, i.e. the delivery of power through an optical fiber, is now seen as a realistic option not only to feed some reconfigurable elements in optical access network [1] but also to optically powering controlled beam steering in radio-over-fiber (RoF) networks [2] and remote antenna units (RAU) in picocellular access network architectures [3]. The reduction of the cell size of RAUs, boosted to support the higher data rate demands of radiofrequency signals targeted by the upcoming 5G technology, has opened up new application niches for this PoF technology [4-5]; where power consumption demands are foreseen to be dramatically reduced. This includes novel concepts as PoF pooling [6] which can make PoF scalable to outdoor small cell deployments. On the other hand, towards supporting the increasing capacity and flexibility required of future optical networks for wireless data convergence, space-division-multiplexing (SDM) is proposed to meet the data service requirements for future long-haul ultra-high capacity, radio access and short-reach or data-center networks. In this framework multi-core fiber (MCF) solutions offer a good migration path for adoption of high-capacity SDM technology [7-8]. Previous works have been reported for remotely feeding antenna units while analyzing the data transmission quality, as in a 300m-long multimode fiber link [9] or in a 100m-long double-clad fiber counterpart [10]. However, the mid-term natural evolution to a broadband networking architecture compliant with the capacity demands and with a cost-effectiveness operator desire envisions future deployments in SDM-MCF technology at any portion of the network with the added-value of PoF remote antenna feeding capabilities. The success of such optically powered solutions depends to some extent on the influence of the high-power PoF signals on the data traffic quality in the case of coexistence of both along the same fiber lead. A simple way to transmit simultaneously optical data and remote power feeding into a MCF could be done by using one individual core per signal, i.e. dedicated-core scenario, as reported in [11]. In that work, four individual cores from a 7-core fiber were employed for powering a 100-GHz photoreceiver obtaining an electric power supply of 21mW per core. However aiming to a more efficient PoF deployment both power and data signals can be injected into the same core, i.e. shared-core scenario. But to the best of our knowledge, there is a lack of work of the PoF impact on the data signal in this MCF-shared scenario.

Hence, in this work we address and compare theoretical studies for dimensioning power levels and experimental results of the data transmission quality with simultaneous power by light delivery. Both dedicated- and shared-core scenarios are addressed. PoF signals up to +26dBm are injected into an individual core. The influence of the PoF signal in coexistence with data traffic on the bit error rate (BER) performance is reported. Results boost the design of future SDM-MCF radio access systems, particularly in the indoor scenario, with remote optical powering capabilities.

II. SHARED AND DEDICATED PoF SCENARIOS

For remote PoF delivery via MCF there are two scenarios:

- "power dedicated cores", one or more of the multiple individual cores of a multicore fiber are exclusively used for optically remote feeding.
- "shared cores", some individual cores of the multicore fiber transmit simultaneously data/control and power over fiber signals.

The proposed powering architectures are shown in Fig. 1, as an extension to MCF from the fiber bundle approach [12].

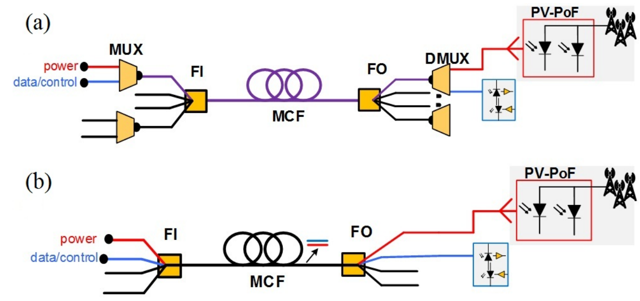

Fig.1. Proposed powering architectures on MCF. (a) shared core: power and data/control multiplexed on the same core. (b) power dedicated core: separate power cores from data traffic. Fan-in device (FI), Fan-out device (FO), Photovoltaic converter (PV).

These two scenarios are considered for feeding RAUs in a mobile fronthaul infrastructure. However in any case the first aspect to be considered is the limit in the amount of the delivered power in the fiber. It is clearly seen from Fig.1 that for the dedicated core scenario no optical demultiplexers (DEMUX) or filter devices are needed at the reception stage, whereas these elements are required for the shared core scenario in order to split the data traffic from the feeding power. This fact leads to an extra penalty in the power delivery as a result of their insertion losses. Thus the overall PoF system efficiency is reduced. Multiplexing devices should be also needed at the central office. Table 1 illustrates a performance comparison considering two types of MCFs, namely 4-core and 7-core, in terms of the power delivered to the RAU units for both scenarios as well as for different link lengths, respectively. The proposed configuration of SDM based optical fronthaul integrating different technologies, as described in [7,13], is shown in Fig. 2. In the dedicated core scenario, one individual core or two individual cores are considered for the PoF feeding in the case of a 4-core and a 7-core MCF, respectively. Rest of (free) MCF cores are used for up/down link purposes to provide small cell connectivity in both directions within the infrastructure and for a control channel. In the case of the 7-core MCF the two remaining cores may be employed to support up/down stream Passive Optical Network (PON) data traffic. The maximum power assumed to be injected on each individual MCF core is 500 mW. From our optical budget analysis the power reaching the RAU unit for the 5 km-long link results in 194.52mW and 389.04mW for the 4-core and 7-core, respectively. The power doubles in the 7-core MCF as the total input power is 1W for the two available cores, i.e. 500mW per individual core. The considered power losses are 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), all extracted from [14]. For the shared core scenario the same configuration is considered for the transmission channels where simultaneously all the cores are used for optical powering purposes. There is a maximum input power of 2W and 3.5W for 4-core and 7-core with reaching powers at the RAU site after 5km of distance of 618.04mW and 1081.5 mW respectively.

Despite the higher power levels available at the RAU site in this proposed scenario, more elements are needed for multiplexing before the FI device and demultiplexing after the FO device for each core. The additional losses ~ 1 dB due to the mux/demux devices for each core are also included in the calculations for this scenario.

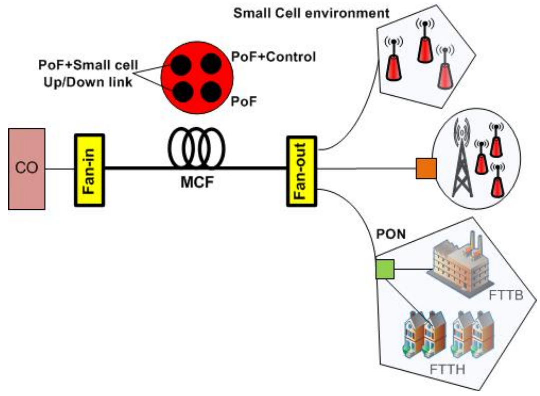

Fig. 2. MCF-based PoF configuration considered for future cellular networks.

FIFO devices have crosstalk levels of around 30dB, being more restricted than MCF crosstalk values that are negligible even at the highest length of 5 km considered in our analysis (< -50 dB). This FIFO crosstalk, that depends on the ratio between data traffic signal power and PoF levels, could affect the signal transmission quality not only in the shared but also in the dedicated core scenario. If this is the case, optical filters centered on the channel wavelength could be used for more isolation. In this case, the PoF wavelength should be easily demultiplexed from the data channel, as it can be the case if transmitting data traffic at 1550nm and the PoF signal at 1480nm. According to our analysis, the shared core scenario provides a better performance in terms of the total amount of delivered power and so the number of the devices that could be remotely powered by light, but at the cost of using more optical elements and more complex topologies. The proposed architecture utilizing the MCF can build flexible Radio Access Network (RAN) as in [13] that can address its future challenges through SDM with the additional advantages of the integration of PoF. In the following section, we experimentally demonstrate negligible degradation on the signal quality.

TABLE I. MCF designs with different cores usage and configurations

Fiber Type	Cores Configuration							
	Small cell	Control	PON	Power	Link Length	P(mW) at RAU	No. of elements	
4-Core Fiber	1 upstream 1 downstream	1	0	1	20m	244.66	3	PoF Dedicated Scenario
					1km	233.82		
					5km	194.52		
7-Core Fiber	1 upstream 1 downstream	1	1 upstream 1dowmstream	2	20m	489.32	3	
					1km	467.65		
					5km	389.04		
	Cores Configuration							
	Small cell	Control	PON	Power	Link Length	P (mW) at RAU	No. of elements	
4-Core Fiber	1 upstream 1 downstream	1	0	4	20m	777.24	11	PoF Shared Scenario
					1km	742.92		
					5km	618.04		
7-Core Fiber	1 upstream 1 downstream	1	1 upstream 1 downstream	7	20m	1360	17	
					1km	1300		
					5km	1081.5		

III. EXPERIMENTAL SETUP

A BER tester using a Coarse Wavelength Division Multiplexing (CWDM) SFP transceiver operating at 1550nm of wavelength is used to generate and evaluate the BER performance of a 2.6Gbps bit-rate data traffic signal (NZR, PRBS=2^{31}-1). The optical circulator is employed to provide additional isolation at 1480nm to the SFP optical source. Then, a variable optical attenuator (α_2) is used to adjust the signal power injected from the optical data source to allow BER measurements. A continuous-wave high-power laser (HPL) with a main lobe at 1480nm and output optical power up to 2W is employed as a PoF source. However maximum power handlings of the MCF fiber fan-in/fan-out devices are restricted to 350mW so PoF optical powers injected into each core of the MCF are limited to +26dBm in the experiments. Both signals are connected to and transmitted through a 20m-long 4-core singlemode MCF fiber by means of a fan-in (FI) device. Whereas for the dedicated-core scenario the data traffic signal and the PoF signal are injected into separate individual cores in the shared-core scenario both signals are previously combined by means of a WDM mux (~1dB insertion loss). At the MCF fiber end a fan-out (FO) device splits the 4 individual cores into 4 singlemode fiber patchcords with FC/APC connectors. At reception a high-power WDM demux device is employed to separate the data and PoF signals with a proper λ-channel selection after a 100m-long SMF fiber lead. The data traffic signal is then passed through an optical filter to provide additional 40dB of optical isolation with respect to the PoF signal and through a 99/1 optical coupler for power monitoring purposes before being connected to the receiver of the SFP CWDM transceiver. Fig. 3 depicts the experimental setup to evaluate the data traffic impact when injecting the PoF signals in both dedicated- and shared-core scenarios. In a previous work [15] we reported for short-reach fiber lengths the benefits of operating the PoF technique at around 800nm with multimode fibers. But the higher attenuation of the MCF at 800nm and the high coupling losses from HPL to single mode fibers result in a better overall efficiency if the PoF signal operates at 1480nm.

IV. EXPERIMENTAL RESULTS

BER experimental results for the dedicated- and shared-core scenarios are shown in Fig. 4(a) and Fig. 4(b), respectively.

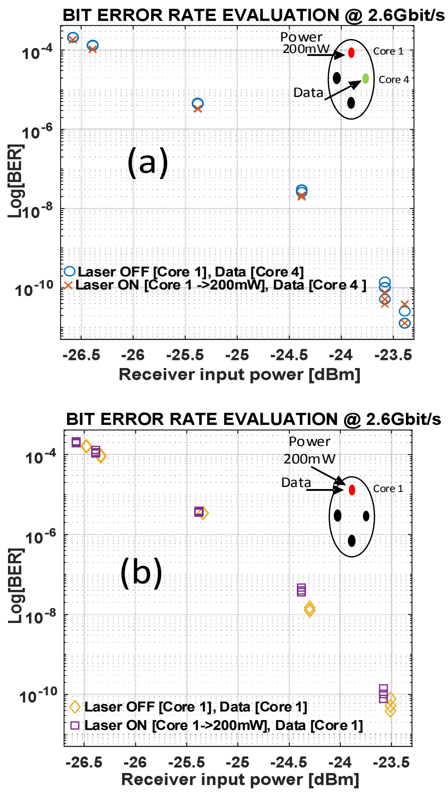

Fig. 4. BER impact results in the (a) dedicated- and (b) shared-core scenarios. A 200mW optical power PoF signal per core is injected.

In both cases, the real PoF signal optical power injected into the MCF fan-in device is fixed to 200mW. This is achieved by employing a variable optical attenuator (α_1) on the HPL branch and taking into account the different insertion losses of the two experiments, as the shared core scenario needs additional WDM mux devices.

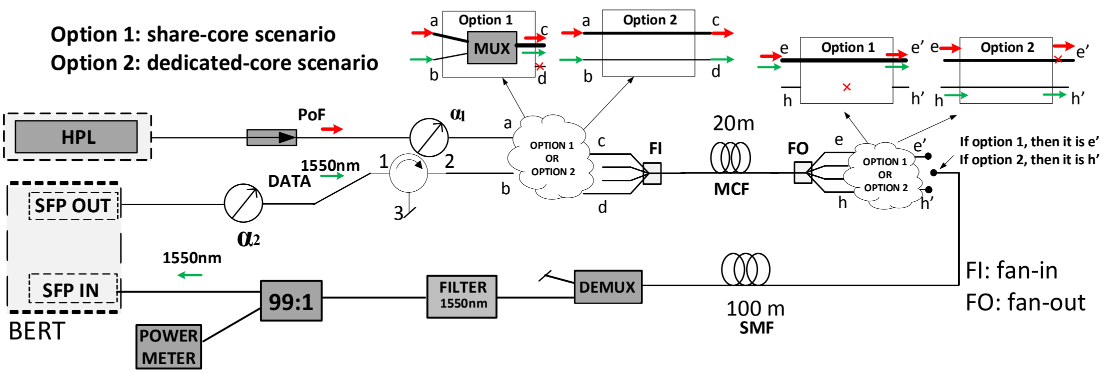

Fig.3 Experimental setup for the PoF dedicated- and shared-core scenarios to evaluate the data traffic impact.

As expected, the BER impact in the dedicated-core scenario, see Fig. 4(a), where data traffic is sent through core-1 shows almost no difference between adding a PoF channel in core-4. We took core-4 of the MCF as our worst case; it is an adjacent channel with respect to the data traffic launched from the fiber geometry. Moreover, we measured a worse crosstalk performance between core-4 and core-1 compared to core-2 and core-1. However, interesting results from Fig. 4(b) also reveal no significant impact of the shared-core scenario on the BER performance at the injected PoF power levels considered.

In the shared-core scenario we also analyzed the BER impact on other MCF individual cores and for PoF signals beyond 200mW. Results are shown in Fig. 5 where we selected as starting points for the analysis different arbitrary BER values of individual cores obtained from the link. MCF core-3 was not tested due to its high insertion loss that resulted in a BER value $<10^{-2}$. In the shared-core scenario negligible impact on the BER value is noticed for all individual cores tested while injecting PoF signals up to around 320mW, i.e. setting the HPL output power to +26dBm.

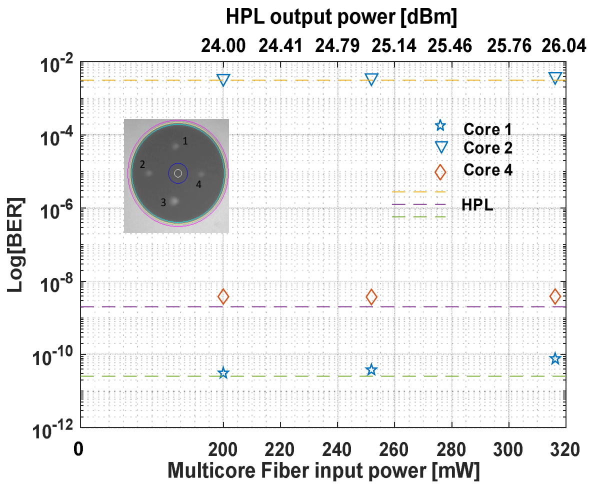

Fig. 5. Shared-core scenario BER impact results for different optical powers injected from the PoF signal into different MCF cores.

V. CONCLUSION

Shared and dedicated PoF scenarios have been proposed as part of the infrastructure to be used for future 5G cellular networks. These approaches can support RAN and PON with the integration of PoF. A comparison between both scenarios in terms of power levels for different link lengths and number of elements required is provided. Crosstalk of FIFO and MUX/DEMUX devices are also discussed. As expected, higher power levels can be delivered in the shared core scenario but more elements are required. On the other hand, the impact of introducing a PoF signal for remote optically powering purposes on the data traffic signal quality is evaluated for a MCF fiber in both dedicated- and shared-core scenarios. Experimental results show negligible penalty on the BER performance in both cases. Particularly, in the shared-core scenario where both PoF and data signal coexist over the same MCF individual core, no BER significant differences are measured when injecting up to 320mW of PoF optical power. A filter centered on the data channel wavelength is used in the experiments to improve the isolation.

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