Power-over-fiber in a 10 km long multicore fiber link within a 5G fronthaul scenario

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We evaluate the impact of Power-over-Fiber (PoF) technology on the fronthaul of a 5G-NR network with an Analog-Radio-over-Fiber at 25.5 GHz on a 10 km long multicore fiber. The study in this Letter analyzes the bit error rate (BER) performance for different levels of energy transmitted by the PoF system. 133 mW of maximum optical power at reception is demonstrated showing negligible BER impact or data transmission BER improvement in a dedicated and shared scenario. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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Power-over-Fiber (PoF) technology is a good strategy for providing energy to remote points free of electromagnetic interference, with low-weight, good galvanic isolation and with an easy integration within the telecommunication operators infrastructure. Optical fibers are also among the technologies supporting the increasing capacity of 5G radio access networks (RAN), as part of the back/fronthaul infrastructure for transmitting radio-over-fiber (RoF) signals.

The new 5G-NR technology paradigm with centralized architecture (CRAN) reduces resource requirements and simplifies network management and maintenance by reducing the complexity of the remote radio heads (RRHs). These new features mean a significant reduction in RRH power consumption. This optimization makes it possible to use PoF technology to feed some critical elements, with the corresponding advantage of a centralized remote control and power supply—all from the optical domain. Some studies show that it is possible to achieve a reduction in consumption of up to 40% [1]. In this sense, it is proposed to implement sleep modes in the RRH based on an intelligent control of the resources according to the traffic and the number of users [2]. Others proposed switching the energy between different RRHs, depending on traffic demand [3] through a software defined network. A summary about the main achievements in PoF applied to RoF for different types of fibers and commercial products is reported in [4]. This includes the use of multicore fibers (MCFs) as in [5–7] for driving an analog photoreceiver in the 90 to 110 GHz band at short distances in a dedicated scenario; that is, data are sent in a different core to the one used for energy delivery. On the other hand, a 20 m 4-MCF link is used for optically powering in [8], in both a dedicated and shared scenario with data and energy in the same core. The use of the MCF in optical fronthauling [9,10] is currently under development to increase the capacity of the infrastructure while providing compact deployments. On the other hand, PoF technology and 5G technology with different modulation schemes are reported in [11], and the need of new strategies for efficiently powering 6G networks, including PoF capability, is currently pointed out [12].

In this Letter, we evaluate the PoF technology in the fronthaul scenario of a 5G-NR network from a base band unit (BBU) providing data traffic with quadrature phase-shift keying (QPSK) modulation and 800 MHz of bandwidth, in a 10 km long MCF as part of an Analog-Radio-over-Fiber (ARoF) link. The evaluation is carried out by analyzing the bit error rate (BER) behavior for different power transmission levels. Additionally, some relevant BBU and MCF parameters for the study are characterized.

In the following, the experimental setup is described. The proposed system is developed in the framework of the blueSPACE project (EU H2020 5G-PPP) [10], and it is composed of two systems: the baseband unit (ARoF BBU) and the power transmitter (PoF system). For this experiment, the BBU is configured to generate a QPSK modulation with 800 MHz of bandwidth. Two configurations are used—with and without a radio link of 9 m in the 3GPP n258 band. The experiment uses a 10 km long link of a seven-core MCF fiber. A local oscillator (LO_F = 10.25 GHz) is injected into the first Mach–Zehnder (MZM_1), configured in an optical carrier suppression mode. The second Mach–Zehnder (MZM_2) is used to modulate the electrical signal at an intermediate frequency (IF_TX) of 5 GHz. Core number 7 is used to send the ARoF signal; meanwhile, the core number 4 sends a copy of the two-tone signal after MZM_1, which is used on the remote site to perform the downconversion. The millimeter-wave RF signal is generated by
estimating the BER behavior due to the combined impact of
than the average value.
signal decreases, with the standard deviation always being lower
expected, increase as the power of the intermediate frequency
levels replace the insertion losses introduced by the ARoF sys-
tem efficiency at 1480 nm.
scenario and for the two configurations is analyzed. The objec-
tives of this characterization are (1) to evaluate the BER stability
of 25.5 GHz, given by the expression $F_{RF} = IF_{TX} + 2 \cdot F_{LO}$. The remaining elements are used for amplification and condition-
ing of the ARoF signal. For more details; see [13]. The PoF system consists of a high-power laser (HPL) at a 1480 nm
wavelength, an optical splitter (SP1, 50:50), an optical switch
(4 × 4), and the photovoltaic cells (PVCs). This PVC has a
maximum optical power of 200 mW and operates in the range
between 1300 and 1600 nm. The control of the switching is
done externally via a USB interface, which allows us to select
the type of scenario: shared or dedicated. In the shared scenario,
data and power are multiplexed through core number 7 while, in
the dedicated scenario, power is sent only through core number
1; see Fig. 1.

In order to validate the integration of 5G-NR and PoF tech-
nology, the time-dependent behavior of the BER in the two PoF
scenarios and for the two configurations is analyzed. The objectives of this characterization are (1) to evaluate the BER stability
in a back-to-back configuration (B2B, IF$_{TX}$ connected to IF$_{RX}$),
(2) to measure the transfer function and estimate the fiber chro-
matic dispersion, and (3) to calculate the PoF transmission sys-
tem efficiency at 1480 nm.

The BBU stability analysis is performed at different attenu-
ation levels of the IF$_{TX}$ output signal: 0, 10, and 14 dB. These
levels replace the insertion losses introduced by the ARoF sys-
tem. Table 1 shows the average BER and standard deviation
(STD) for the different attenuation values. The BER values, as
expected, increase as the power of the intermediate frequency
signal decreases, with the standard deviation always being lower
than the average value.

The measurement of the transfer function of the MCF allows
estimating the BER behavior due to the combined impact of
cromatic dispersion and self- and cross-phase modulation
(SPM and XPM) nonlinear effects, both of significant relevance
in PoF and RoF systems, depending on power levels and link
lengths. The fiber-induced SPM improves the frequency-length
product by shifting the power fading to higher frequencies [14],
in comparison to power fading provoked only by chromatic dispersion [15]. In [11], a simulation performed using a Virtual
Photonics Instrumentation Tool, shows the impact of both
effects (SPM and XPM) on a 10 km SMF ARoF link at 17 GHz
with PoF in a shared scenario. It is observed that, at low HPL
power levels (<800 mW), the impact of both effects is negli-
gible. In our experiments, we are working with power levels
within the MCF below 500 mW, so these effects are not going
to be significant. The measurement of the transfer function of
the MCF helps us to confirm that the transmitted RF signal is far
away from the critical frequency affected by power fading. On
the other hand, both phenomena are sensitive to power instabil-
ities, and the HPL can induce noise in the data channel through
stimulated Raman scattering (SRS) [16]. The Brillouin effect
has not been considered, since the linewidth of the HPL laser
used is larger than 2 nm [4]. In the experiment, the transmis-
sion parameter S21 is determined using the spectrum analyzer
N9918A, which is configured as a network analyzer. Figure 2
shows a simplified schematic of the measurement setup in which
MZM$_1$, LO, EDFA, and SP2 have been omitted, and the LO
oscillator is disabled. This is done by injecting the excitation of
the analyzer through the MZM$_2$ driver (point I1; see Fig. 2)
and measuring the response at the PD output (point O1; see Fig.
2).

Initial calibration is performed by removing only the MCF
in order to eliminate the effect of the other elements of the
system on the measurement. Once the calibration procedure is
completed, the S21 parameter is measured. Figure 3 shows the
measurement and theoretical estimation of the fiber transfer
function. Additionally, it is observed that the critical fre-
quency value is approximately 18.20 GHz, and hence the
cromatic dispersion is 18.85 ps/nm/km [15], matching previous
measurements. The system energy efficiency (SEE) has been
calculated in both scenarios—shared (SEE$_{shared}$) and dedicated
(SEE$_{dedicated}$) [17].

This parameter is the ratio between the maximum electrical
power delivered by the PVC and the HPL optical emitted power.
The optical power received at the remote site is +18.96 (78.70
mW) and +21.23 dBm (132.74 mW) for the shared and dedi-
cated scenarios, respectively, when the HPL laser is configured
with emission power of +31 dBm (1.26 W). This maximum
power is intended to assure that no more than 500 mW are
injected into the MCF. Additionally, open circuit voltage ($V_C$)
and short circuit current ($I_C$) have been measured for different
HPL power levels ($P_{HPL}$) and PVC input powers ($P_{PVC}$); see
Table 2. Considering a 30% optical-to-electrical efficiency
of the PVCs, the SEE$_{shared}$ and SEE$_{dedicated}$ are approximately
1.80% and 3.10%, respectively.

<table>
<thead>
<tr>
<th>Attenuation (dB)</th>
<th>Average</th>
<th>STD</th>
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<td>&lt;1 E-9</td>
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<tr>
<td>10</td>
<td>8.97 E-8</td>
<td>1.41 E-8</td>
</tr>
<tr>
<td>14</td>
<td>1.87 E-5</td>
<td>1.96 E-6</td>
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</table>

Table 1. Analysis of BER Stability at BBU

![Fig. 1. Integration of a PoF and ARoF in a 5G-NR scenario, with and without the radio links included.](image)

![Fig. 2. Measurement of the transfer function of the MCF.](image)
Table 2. PVC Short-Circuit Current and Open Circuit Voltage for Different HPL Power Levels

<table>
<thead>
<tr>
<th>$P_{HPL}$ [dBm]</th>
<th>$P_{PVC}$ [dBm]</th>
<th>$I_{sc}$ [mA]</th>
<th>$V_{oc}$ [V]</th>
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<tr>
<td>29</td>
<td>19.19</td>
<td>10.14</td>
<td>3.95</td>
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<tr>
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DEDICATED SCENARIO

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<th>P_{PVC}</th>
<th>I_{sc}</th>
<th>V_{oc}</th>
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<tr>
<td>29</td>
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SHARED SCENARIO

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<th>P_{PVC}</th>
<th>I_{sc}</th>
<th>V_{oc}</th>
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<tbody>
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<td>29</td>
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<td>18.96</td>
<td>9.87</td>
<td>3.96</td>
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On the other hand, the impact of power transmission in the shared (core 7) and dedicated (core 1) scenarios has been evaluated with and without a radio link. The analysis is carried out for 72 s with a sampling rate of 3 s, thus guaranteeing a reliable BER measurement. The HPL laser is set to: OFF and from +27 to +31 dBm in 1 dB steps. Figure 5 shows the main results of the experiment without a radio link included. The BER value obtained at OFF state is 1.89 E-4, which is used as a reference to compare with the rest of the HPL optical powers.

In all cases, the BER performance is slightly higher as the laser power increases, reaching a maximum average value of 2.00 E-3. In the dedicated scenario, the BER value remains invariant with respect to the HPL power emission condition at OFF state. The intercore MCF crosstalk (IC-XT) measured is lower than −50 dB, and there is a narrow-band demultiplexer at the reception stage with −24 dB crosstalk. In terms of IC-XT fluctuations, they are minimized as the HPL is a broadband source with 2 nm linewidth [18]. In the shared scenario, power fluctuations can affect the transmission quality, along with the BBU instabilities. We measure the temporal response of the HPL in the electrical domain and observe the maximum noise value to be around 30 dBm. The HPL noise is transferred to a data channel through SRS after a 10 km link length provoking small BER variations for different power levels, as shown in Fig. 5, being greater for 30 and 31 dBm.

Increasing the MCF core density will straightforward increase the overall delivered PoF power at the remote site. However, IC-XT decreases exponentially with core-to-core separation [19], and its impact on the data traffic quality and resulting BER performance should be carefully analyzed.

The study with a radio link is performed by including in the previous system two horn antennas separated by 9 m. The BER performance is evaluated for the same power levels as the
previous experiment. Figure 6 shows the results obtained for the shared scenario and, in all cases, the performance is worse, except for the HPL levels with higher noise.

In this Letter, we have demonstrated the feasibility of integrating PoF technology in the fronthaul of a 5G network with and without a wireless radio link. The experimental results have shown that the impact of power transmission in some cases improves the BER value, a result of interest for data transmission. The maximum transmitted optical power (133 mW) can be increased by optimizing the insertion loss of the system elements or using MCF designs that allow higher injected powers. To the best of our knowledge, there are no previous results of delivering PoF in a 10 km 7-MCF in coexistence with an ARoF transmission as a fronthaul of a high-bandwidth wireless link in the 3GPP n258 band.

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**Disclosures.** The authors declare no conflicts of interest.

**Data Availability.** Data underlying the results presented in this Letter are not publicly available at this time but may be obtained from the authors upon reasonable request.

**REFERENCES**