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Integrated Wireless-Optical Backhaul and Fronthaul Provision Through Multicore Fiber

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ABSTRACT In this paper we propose multicore fiber (MCF) as the medium to transport the different signals associated with various wireless applications (ranging from access to fronthauling and backhauling) from the baseband unit (BBU) to the cell-site. Using 1 km of a 7-core MCF, we simultaneously transmit fronthaul and backhaul signals from the BBU to the cell site, where they are converted to carrier frequencies in the mm-wave and sub-THz band, respectively. The backhaul is evaluated with a 12.5 GBd 16-quadrature amplitude modulation (QAM) signal, whereas the fronthaul is evaluated with a 7 Gbit/s on-off keying (OOK) signal carrying 14 LTE-compatible channels. The fronthaul signal is generated with a novel compression technique that achieves an efficiency 3-times higher than the one obtained with the common public radio interface (CPRI) protocol. Optical heterodyning is implemented at the cell site for optical-to-RF conversion. The local oscillator (LO) signal required for optical heterodyning is transmitted in a dedicated core, reducing the system complexity and enabling its straight-forward reuse for uplink (UL) transmission. The experimental demonstration includes the simultaneous full-duplex transmission of both the fronthaul and backhaul signals, using 6 cores of the MCF at the same time and achieving a gross data rate of 57 Gbit/s.

INDEX TERMS Backhaul, centralized-radio access network (C-RAN), fronthaul, mm-wave communications, multicore fiber (MCF), optical communications, photonics, radio-over-fiber (RoF), space division multiplexing, sub-THz communications.

I. INTRODUCTION

Centralized radio access networks (C-RANs) aim to enable the mass deployment of cell sites with optimized capital and operational expenses. This is of especial importance when targeting high-frequency bands, as the associated wireless range is limited due to radio propagation considerations and technological constraints [1]. In the C-RAN architecture, the classical base station (BS) is split into several remote radio heads (RRHs), which are served by a single unit called the

baseband unit (BBU) [2]. In addition to a reduced coverage cost per unit area, this arrangement has the advantage of advanced inter-cell coordination since the management of all the RRHs is done from the same centralized location (the BBU). The link between the BBU and a RRH goes by the name of fronthaul. As high data rates need to be supported in fronthaul links (currently up to around 24 Gbit/s [3] but expected to exceed Tbit/s bitrates in massive multiple-input and multiple-output (MIMO) 5G systems [4]), optical fiber is typically the solution of choice. However, considering the dramatic increase in complexity and cell density forecast for future mobile generations, optical fronthauling may become

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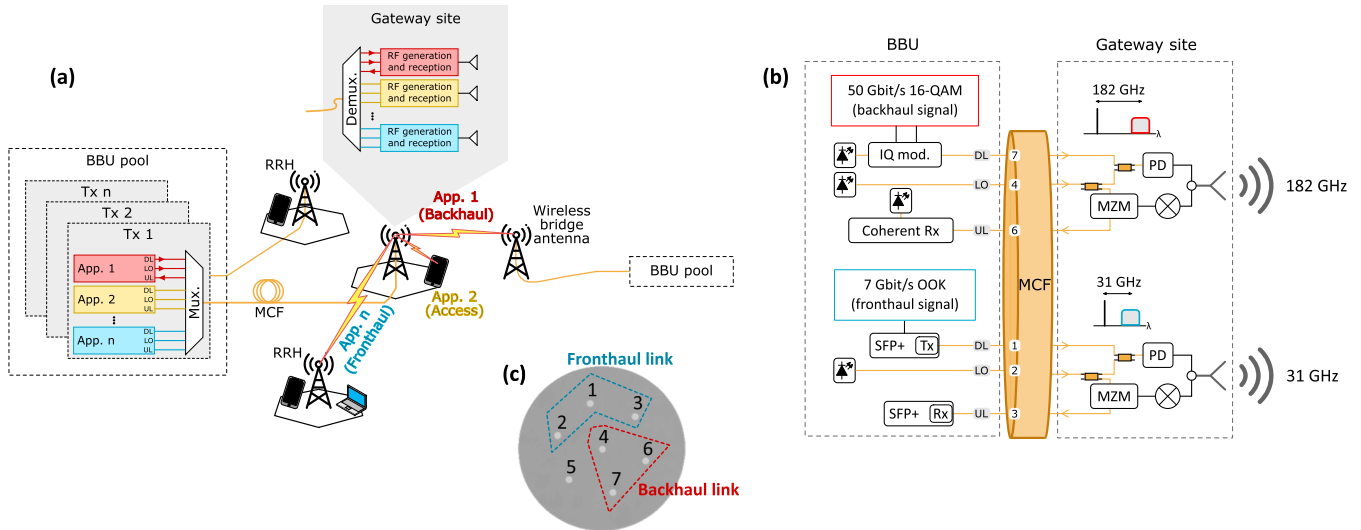


FIGURE 1. (a) Converged optical-wireless network with a multicore fiber (MCF) providing application-specific signals to a cell site. (b) Block diagram of the fronthaul and backhaul links using MCF. In this demonstration, a 50-Gbit/s backhaul system operating at a wireless carrier frequency of 182 GHz together with a 7 Gbit/s fronthaul system operating at 31 GHz are transmitted over 1 km of a 7-core MCF. And (c) transverse cut of the 7-core MCF with the core assignment used in the experimental evaluation. App.: application, BBU: baseband unit, DL: downlink, and UL: uplink.

prohibitive. Instead, one could deploy a multi-hop wireless network where only a few sites have a direct optical connection with the BBU (“gateway” sites) and the rest relay the fronthaul signals through wireless links [5], effectively sharing the expensive fronthaul equipment. To have the required bandwidth (BW) for such an application, one must turn to mm-waves (30-300 GHz) and sub-THz frequencies (0.1-1 THz), where transmission windows with BWs as wide as 94 GHz are available [6]. Mm-wave and sub-THz fronthaul links, thus, can be a cost-efficient complement to optical fiber in C-RAN networks.

The link between two different BBUs or a BBU and a more centralised network unit is referred to as backhaul. Optical fiber is likely to be the most common choice for future C-RAN backhaul links. However, there are certain situations where the deployment of optical fiber is not economical, such as in crowded urban areas (where the cost of digging trenches for the fiber deployment can be high), historical areas, or isolated areas with difficult accessibility [7]. In these scenarios, establishing a wireless link to bridge the “fiber-unfriendly” area can be advantageous. We envisage, hence, a scenario where future cell sites also support fronthaul or backhaul functionality depending on their cost/complexity. This implies that cell sites will need to be able to operate at different radio frequencies: at low radio frequencies (RFs) for small-BW applications (e.g. access), and at mm-wave and sub-THz frequencies for large-BW applications such as fronthaul or backhaul. With these wireless applications, we expect to see a very heterogeneous—yet highly integrated—network where optical and wireless technologies coexist as depicted in Fig. 1 (a).

In order to simultaneously transport the different signals associated with each application to the “gateway” site, we propose to use multicore fiber (MCF) optical medium.

Using this approach, the signals of different applications can be transmitted in different cores of the same MCF link. This approach, in contrast to conventional wavelength division multiplexing (WDM), avoids the need for optical filtering at the cell tower, thus reducing the system complexity. Furthermore, MCF spatial multiplexing removes any restrictions on the central transport wavelength allowing wavelength reuse, which is not possible with WDM [8]. An advantage of this is that a single laser can provide the optical carrier for all the applications.

The system configuration that we propose for the multi-application site provision via MCF is depicted in Fig. 1 (b). A photodiode (PD) is used for optical-to-RF (O/Rf) conversion. This allows direct mapping between the two domains and avoids the conversion to baseband required by electronic RF sources. The local oscillator (LO) for optical heterodyning is transmitted through an independent core of the same MCF. This enables a straight-forward reuse of this carrier for the uplink (UL) transmission and achieves a laser-free antenna unit without the need for a demultiplexing device. If there are not sufficient cores to convey one signal per core, the LO can be transmitted with the downlink (DL) signal and then use a coupler and an optical filter at the cell site to recover it. In that case only two cores, rather than three, would be required for each full-duplex application.

In the proposed system, the received RF signal is first down-converted to an intermediate frequency (IF) and then mapped to the optical domain with a Mach-Zehnder modulator (MZM). Alternatively, for direct RF/O conversion, the signal can be sent directly to the modulator provided both the modulator and its driver amplifier have enough BW. If the wireless carrier frequency is low, standard lithium niobate or InP optical modulators could be used. At high frequencies, such as mm-wave or sub-THz, an ultra-broadband

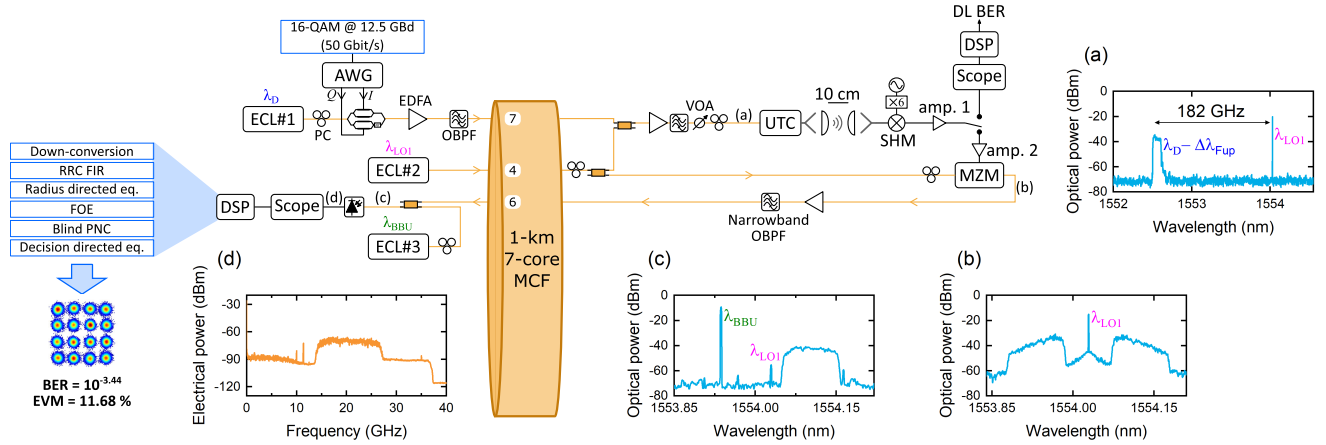


FIGURE 2. Block diagram showing the backhaul system operating at 182 GHz. Included as an inset is the spectrum measured at: (a) input of the UTC ($\Delta\lambda_{Fup}$ is the wavelength shift corresponding to the up-conversion frequency of the digital SSB signal); (b) output of the MZM; (c) input of the single-ended PD at the optical receiver; and (d) received electrical UL signal.

modulator would be required. Recently, several demonstrations of plasmonic modulators with BWs extending to the sub-THz region have been demonstrated [9]. Their main disadvantage is a high associated optical loss but progress is being made to reduce it [10] and they may be a good candidate for RF/O conversion in future cell sites.

In this work, backhaul and fronthaul signals are transmitted through 1 km of a 7-core MCF (shown in Fig. 1 (c)) to the cell site, where they are mapped to the sub-THz and K_a (26.5-40 GHz) bands, respectively. The backhaul system is evaluated with a 16-quadrature amplitude modulation (QAM) 12.5 Gb/s signal which is transmitted wirelessly at 182 GHz. The mobile fronthaul system is evaluated with a 7 Gbit/s on-off keying (OOK) signal which is transmitted at 31 GHz. For full-duplex transmission evaluation, the received DL signal of each system is reused as the electrical input signal for the UL transmission. To the best of the authors' knowledge, this is the first experimental demonstration of a MCF link supporting fronthauling and backhauling and including the RF conversion at the cell site.

This paper is structured as follows: in section II, the experimental arrangement for backhaul and fronthaul evaluation is described in detail. The full-duplex performance of each system is assessed in terms of bit error rate (BER) and error vector magnitude (EVM). Although each system and the associated results are presented in two different subsections, the laboratory demonstration includes the simultaneous full-duplex transmission of both systems, using a total of 6 cores at the same time and achieving an aggregated gross data rate in the DL and UL of 57 Gbit/s. Section III is devoted to the investigation of the potential impairments associated with a wavelength reuse scenario. This is done for one system at a time by matching the LO wavelength of the untested system to the wavelength of the signal under investigation. Finally, section IV summarizes the main conclusions of this work.

II. EXPERIMENTAL ARRANGEMENT AND FULL-DUPLEX TRANSMISSION RESULTS

A. BACKHAUL SYSTEM DESCRIPTION

The complete experimental arrangement used for the backhaul signal transmission is shown in Fig. 2. The in-phase and quadrature (I/Q) components of the 16-QAM signal are generated with an arbitrary waveform generator (AWG) operating at 50 GSa/s and with an analog BW of 12 GHz. Before digital-to-analog conversion in the AWG, the digital I/Q signals are built with Matlab as follows: first, four 2^{11} de Bruijn bit sequences are mapped into the 12.5 Gb/s 16-QAM symbols. A pair of root raised cosine (RRC) filters with $\alpha = 0.1$ (total signal passband bandwidth of 13.75 GHz) are then applied. Finally, the resultant complex signal is upconverted and subsequently filtered to achieve a single sideband (SSB) signal. After analog signal generation in the AWG, the two electrical signals are time-aligned with two phase shifters and electronically amplified before they are fed to an optical IQ modulator.

At the BBU, an external cavity laser (ECL#1 in Fig. 2) emitting at a wavelength of 1552.62 nm (λ_D) is used for data modulation. The tone for heterodyne beating is provided by another ECL (ECL#2) emitting at a wavelength of 1554.03 nm (λ_{LO1}), giving a frequency separation between the two lasers of around 175 GHz. Note that, since the optical signal is the upper sideband of the SSB signal, the actual frequency difference between ECL#2 and the signal is a bit higher, i.e., around 182 GHz. The MCF employed in this experiment is a 1-km-long single mode (SM) MCF with 7 cores (SM-7C1500(6.1/125)). The data signal is sent to the cell site through core number 7 (see Fig. 1 (c)), whereas the tone at λ_{LO1} is sent through core 4. At the Tx antenna unit, the signal and the LO tone are combined, amplified, filtered and fed into an unpackaged uni-travelling carrier (UTC) PD by means of a lensed fibre. The maximum optical power available at the input of the lensed fiber was measured to

be 16.5 dBm. Horn antennas with a gain of 20 dBi are used for both transmission and reception and placed at approximately 0.25 m from each other. A pair of Teflon lenses with a diameter of 5 cm and a back focal length of 75 mm are inserted between the two antennas to increase the collimation of the sub-THz beam. The experimental evaluation is done with a short distance between lenses (around 10 cm) due to the limited output power from the UTC, which was estimated to be few μW for an input optical power of 16.5 dBm.

On the Rx antenna unit, the signal is down-converted to an IF with a second-harmonic mixer, SHM (WR5.1SHM from Virginia Diodes). The local oscillator feeding the SHM is generated with an RF synthesizer followed by a $\times 6$ multiplier. After down-conversion, the signal is amplified by 40 dB and then digitized with an oscilloscope (80 GSa/s and 36 GHz BW) for DL evaluation. As only one UTC and SHM were available, the DL signal is reused for the UL by sending the received IF signal to a MZM biased at the minimum transmission point. After optical amplification, the UL signal generated with the MZM (see Fig. 2 (b)) is filtered with a narrowband optical band pass filter (OBPF) to suppress the upper frequency sideband. The resultant UL signal is then sent back to the BBU via core number 6. In the BBU, the received signal is combined with the optical carrier generated by ECL#3 at 1553.94 nm (λ_{BBU}). The separation between the UL signal and ECL#3 is around 20 GHz as shown in Fig. 2 (d). As a single-ended PD is used in the UL optical receiver, this frequency separation is used to avoid the signal-signal beating interference (SSBI). In a practical system, either a balanced PD or a suitable digital signal processing (DSP) algorithm [11] could be used to mitigate the SSBI and reduce the down-conversion frequency (and, thus, the required sampling rate of the oscilloscope).

As shown in Fig. 2, to demodulate both the DL and UL backhaul signals, a typical coherent DSP routine is used. This routine consists of: down-conversion, matched filtering, radius directed equalization (RDE), power-of-4 frequency offset estimation (FOE), blind phase noise compensation (PNC) and decision directed equalization (DDE). Differential coding and decoding is applied to only the first two bits to remove the quadrant ambiguity associated with square QAM constellations.

B. BACKHAUL PERFORMANCE RESULTS

The BER results for the DL and UL 50 Gbit/s backhaul signal are plotted in Fig. 3 against the UTC photocurrent squared (proportional to the emitted RF power). For each BER point, 2.5×10^5 bits were analysed, making the lowest reliable measured BER to be around 10^{-5} . The constellation diagrams included in Fig. 3 correspond to: (b) and (e) lowest photocurrent levels, (c) and (f) lowest BER values, and (d) and (g) highest photocurrent levels for the DL and UL transmission, respectively. As can be observed from Fig. 3 (a), (d) and (g), saturation effects occurred for squared photocurrent values higher than approximately 10 mA^2 (corresponding to an optical input power to the UTC of around 14.5 dBm).

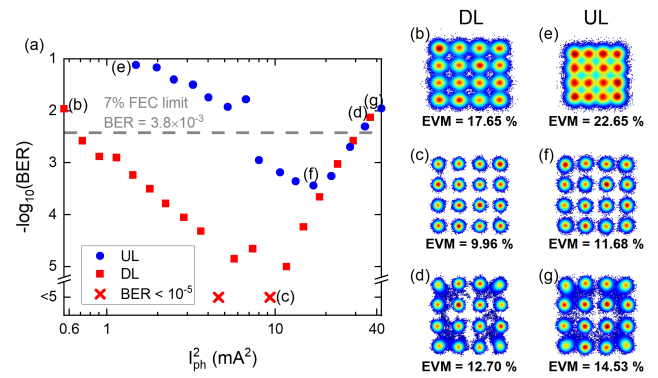


FIGURE 3. (a) BER performance of the backhaul DL and UL signals vs. the square of the measured photocurrent at the UTC. Examples of received 16-QAM constellations and measured EVM for: (b) and (e) lowest photocurrent, (c) and (f) lowest BER, and (d) and (g) highest photocurrent levels for the DL and UL transmission, respectively.

These saturation effects originated in the UTC and are likely to be due to either thermal or space-charge effects [12]. The UTC was biased with a voltage of -2 V as lower voltages did not improve the transmission performance.

One of the factors contributing to the penalty between the UL and DL ($\sim 10 \text{ dB}$) is the strong frequency roll-off of the combined response from: (i) the electronic amplifier after the SHM (amp. 1 in Fig. 2), (ii) the MZM driver amplifier (amp. 2 in Fig. 2), and (iii) the MZM. This roll-off can be seen in the spectrum of Fig. 2 (b). A less strong roll-off was observed when using only amp. 1 in the DL transmission. In order to mitigate this negative feature of the UL, the OBPF after the MZM was used for both filtering and power equalization purposes. For this reason, the signal in Fig. 2 (c) is flat along the spectrum.

C. FRONTHAUL SYSTEM DESCRIPTION

The schematic of the experimental arrangement used for fronthaul evaluation is shown in Fig. 4. At the BBU, we use a novel digital radio-over-fiber (DRoF) fronthaul compression technique that achieves a transmission efficiency 3-times higher than that obtained with the popular common public radio interface (CPRI) protocol [13]. While CPRI needs around 1.23 Gbit/s to transport a single 20-MHz-bandwidth long term evolution (LTE) channel, the proposed technique only requires 400 Mbit/s to convey the same LTE signal.

The DRoF Tx unit comprises two main parts: an analog front-end and a field programmable gate array (FPGA). The analog front-end converts the input RF to an IF and then digitizes the IF signal with a 14-bit analog-to-digital converter (ADC) operating at 150 MSa/s. After digitization, the FPGA applies a digital automatic gain controller (DAGC) to maintain the signal power level and ensure the dynamic range of the signal is not affected after compression. The FPGA then compresses the signal in order to reduce the quantisation bit width. After this first compression stage, the signal is down-converted to baseband, where an RRC filter is applied to remove spectrum redundancy. The second compression stage decimates the signal sampling rate in the

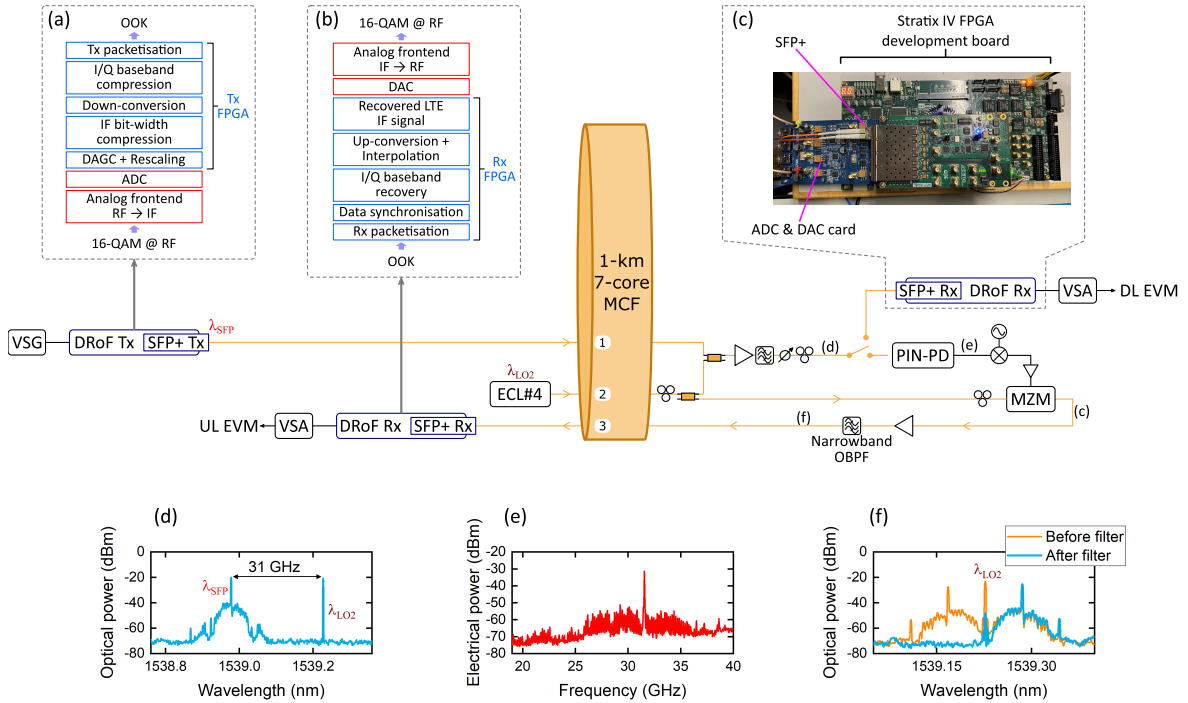


FIGURE 4. Block diagram of the fronthaul system operating at 31 GHz. Included as insets are: the processing steps performed at the (a) DRoF Tx and (b) DRoF Rx units, (c) the DRoF unit and SFP+ transceiver, and the spectra of (d) PIN-PD input signal, (e) generated electrical signal at 31 GHz, and (f) UL signal before (blue trace) and after (orange trace) optical filtering.

frequency domain to minimise the bit rate. Finally, the resulting data stream is packetized using the 8b/10b coding scheme with a k28.5 synchronisation code to allow for word alignment restoration at the receiver. In the DRoF Rx, the received digital bits are de-packetised, decompressed and upconverted back to an IF before digital-to-analogue and RF conversion as depicted in Fig. 4.

The DRoF Tx is fed by a vector signal generator (VSG), which is used to generate a 20-MHz LTE-compatible 16-QAM channel with a carrier frequency of 37.5 MHz, a symbol rate of 15.36 MBd, and a RRC α factor of 0.1. Upon digitization on the 14-bit ADC of the DRoF Rx front-end, a 2.1 Gbit/s (14-bit $\times$ 150 MSa/s—where 150 MSa/s is the sampling rate of the ADC) data stream is generated. After applying the DSP steps described previously, this bit rate is compressed to 400 Mbit/s. Before packetization, the 400 Mbit/s signal is replicated several times to simulate a multi-channel scenario. In this experiment, the capacities corresponding to sending simultaneously 4 and 14 channels—resulting in line bit rates of 2 and 7 Gbit/s, respectively—were evaluated. The packetized signal from the DRoF Tx is then modulated onto a distributed feedback (DFB) laser operating at a wavelength of 1538.98 nm (λ_{SFP}) through an enhanced small form-factor pluggable (SFP+) transceiver.

The rest of the arrangement is similar to the one used for the backhaul evaluation in subsection II-A. In the fronthaul link, the DL, optical LO and UL signals are transported through core number 1, 2 and 3, respectively, of the same 7-core MCF. The optical LO is generated by another ECL (ECL#4)

emitting at a wavelength of 1539.1 nm (λ_{LO2}), giving a frequency difference between signal and LO of 31 GHz. The carrier at this frequency is generated in a PIN-PD. In this case, no wireless transmission is performed due to the lack of suitable antennas. The down-conversion at the Rx antenna unit is performed by a mixer (instead of a SHM as in the backhaul system) and only one electrical amplifier is employed before re-modulation to the optical domain. The error vector magnitude (EVM), measured with a vector signal analyser (VSA), is used as the performance metric. It is important to say that, if the DRoF Rx is implemented after a wireless link (i.e., there is no need for optical re-modulation), the MZM and SFP+ transceiver can be replaced by an IF envelope detector.

D. FRONTHAUL PERFORMANCE RESULTS

In Fig. 5, the EVM results for the DL (Fig. 5 (a)) and UL (Fig. 5 (b)) are shown for both 2 and 7 Gbit/s data rates. The EVM is plotted against the optical power at the input of the SFP+ transceiver for the DL, and against the estimated power of the 31-GHz tone generated in the PIN-PD for the UL. The latter is calculated according to:

$$P_{31\text{GHz}} = (\Re^2 P_{\text{opt}}^2 / 2) R_L, \quad (1)$$

where $\Re$ is the PD responsivity, P_{opt} is the optical power at the PIN-PD input (it is assumed that the power from the signal and LO are the same), and R_L is the load resistance. The beat-note power values in the bottom axis of Fig. 5 (b) are obtained for $\Re = 0.6$ [14], $R_L = 50 \Omega$, and the values of

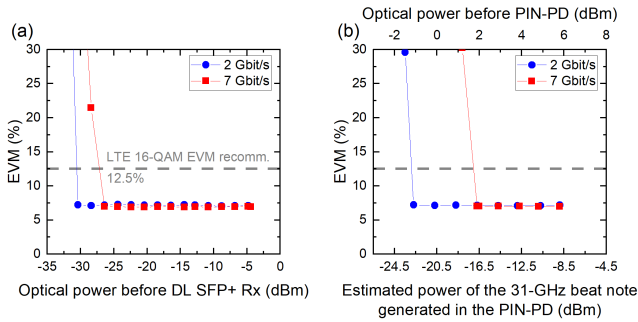


FIGURE 5. Measured EVM for 4 LTE channels (2 Gbit/s) and 14 LTE channels (7 Gbit/s) in the (a) DL and (b) UL fronthaul transmission.

P_{opt} shown in the top axis of this figure. The required optical power to achieve an EVM below the LTE recommendation (12.5 %) for the 7-Gbit/s line rate was 4- and 3-dB higher than that required for the 2-Gbit/s rate in the DL and UL, respectively. For the UL, this corresponds to an electrical power penalty of 6 dB.

From the results in Fig. 5 (b), the achievable wireless transmission distance for a certain transmitted power and Tx and Rx antenna gains can be estimated. Assuming 1 dB loss from the cable connecting the PIN-PD and the mixer, the minimum electrical power required at the mixer input to produce an EVM below 12.5 % is -25.5 and -17.5 dBm for 4 and 14 channels, respectively. Using off-the-shelf components for the K_a band, it is easy to achieve a transmitter output power of 25 dBm [15], and antenna gains of 40 dB [16]. If we allow a 5 dB reserve for implementation issues (such as antenna misalignment), the back-to-back system margins are 123.5 and 117.5 dB. The achievable transmission distance can be then calculated from the free-space path loss formula (FSPL) as:

$$d = \sqrt{\text{FSPL}} \frac{c}{4\pi f}, \quad (2)$$

where f is the carrier frequency. Substituting FSPL by the system margins calculated previously and f by 31×10^9 in (2), distances of 1151 and 577 m are obtained for 4 and 14 channels, respectively. Even in the latter case, the obtained value is higher than LTE urban micro (200 m) and macro (500 m) inter-site distances [17]. Hence, using off-the-shelf components, the proposed system could successfully support the simultaneous transmission of 14 LTE channels in urban fronthaul links. Higher channel aggregation will also be possible when FPGA transceivers supporting higher data rates are deployed.

III. INTER-CORE CROSSTALK EVALUATION FOR CO-DIRECTIONAL WAVELENGTH REUSE

In section II, all signals propagating in the same direction are allocated to different wavelengths to avoid any cross-talk interference. Although this configuration may be optimum in terms of interference it does not exploit an important feature of MCFs: wavelength reuse for co-directional signals. One advantage associated with this is that a single optical source can be used in the BBU for the generation of multiple data

signals. To determine the viability of wavelength reuse on the proposed system, crosstalk interference analysis was carried out in the DL of the backhaul and fronthaul arrangements shown in Fig. 2 and 4, respectively. Each system was measured separately by matching the wavelength of the laser acting as LO in the untested system to that of the signal under investigation (i.e., for the backhaul analysis λ_{LO2} was tuned to match λ_{D} , and for the fronthaul analysis λ_{LO1} was tuned to match λ_{SFP}). The power of this laser was also increased to its maximum level of +9.5 dBm (from 5.5 dBm used in section II).

With +9.5 dBm being injected first into core 2 (for backhaul analysis) and then into core 4 (for fronthaul analysis), and with the rest of the signals turned off, the level of power measured at the outputs of cores 7 and 1 was -44.6 dBm and -36.8 dBm, respectively (the difference being due to the core arrangement, which is shown in Fig. 1 (c)). This level of crosstalk did not seem to cause any penalty on the DL transmission of either the backhaul or fronthaul system as shown in Fig. 6 (a) and (b). Note that, although this evaluation was limited to an input power of +9.5 dBm, it has been demonstrated that power levels of up to +18 dBm can be used without significant distortion if a bidirectional signal assignment (in which signals transmitted in adjacent cores are in opposite directions to each other) is used [18].

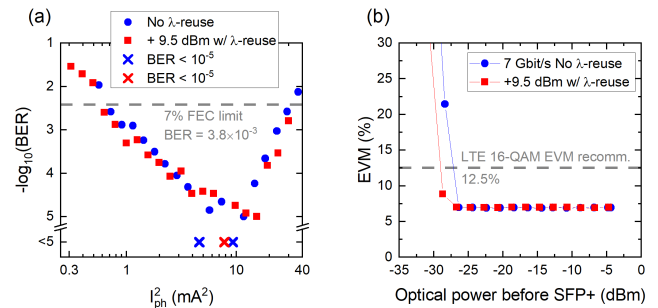


FIGURE 6. DL performance with and without co-directional wavelength reuse in: (a) the backhaul system and (b) fronthaul system.

IV. CONCLUSION

In this paper we evaluate the viability of using MCF to convey different application-specific signals from the BBU to the cell site. A system simultaneously transmitting bi-directional backhaul and fronthaul signals over 1 km of a 7-core MCF (with 6 active cores during the evaluation) is demonstrated, achieving a gross data rate in the DL and UL transmissions of 57 Gbit/s.

The backhaul is evaluated with a 12.5 GBd 16-QAM signal and includes a short wireless link at a carrier frequency of 182 GHz. The optical-to-RF conversion is achieved through optical heterodyning in a UTC. The LO signal required for optical heterodyning is transmitted in a dedicated core, enabling its reuse for UL communication and achieving a laser-free antenna unit. A BER below the 7% FEC limit is achieved with squared UTC photocurrent levels

of 0.7 and 8 mA² for the DL and UL (which reuses the received DL signal for re-transmission), respectively.

The fronthaul is evaluated with a 7-Gbit/s OOK signal carrying 14 LTE channels. This signal is generated with a novel compression technique that achieves an efficiency 3-times higher than that of obtained with the CPRI protocol. In this case, the signal is converted (also through optical heterodyning) to a carrier frequency of 31 GHz. When only optical transmission through the MCF is evaluated, the SFP+ transceiver requires an input optical power of −30 dBm to produce an EVM below the 12.5% LTE recommendation. When conversion to 31 GHz and re-modulation to the optical domain are included, an optical power of 2 dBm is required at the input of the PIN-PD generating the 31-GHz signal to produce an EVM below 12.5%. Link budget analysis confirms that the proposed fronthaul system could support both LTE urban micro (200 m) and macro (500 m) inter-site distances.

We further investigate the potential impairments associated with a wavelength reuse scenario. No interference effects are observed for an injected optical power of up to +9.5 dBm, confirming that multiple data signals could share the same wavelength and, thus, be generated in the BBU with a single optical source. Future work will focus on developing a simulation model to estimate the capacity limit of the system.

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