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Bidirectional ARoF fronthaul over multicore fiber for beyond 5G mm-wave communications

Javier Pérez Santacruz, Gleb Nazarikov, Simon Rommel, Antonio Jurado-Navas, Idelfonso Tafur Monroy

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A B S T R A C T

Fifth-generation mobile networks (5G) is the established solution to satisfy the highly demanding key performance indicators such as traffic volumes, bit-rate, latency, and power consumption, among others of the future telecommunication infrastructure. The already saturated sub-6GHz spectral band does not accommodate such requirements and forces the move towards higher frequencies, with the millimeter-wave (mm-wave) domain being an adequate band to operate. However, the exploitation of mm-wave signals in the mobile cells implies the deployment of an enormous quantity of small cells with associated equipment, footprint, and control. Thus, analog radio-over-fiber (ARoF) emerges as a suitable technology because of their attractive benefits such as low latency, low hardware complexity, and reduced power consumption. However, through investigation of experimental ARoF systems adhering to the 5G standard is scarce. Therefore, in this work, a novel and efficient bidirectional ARoF scheme based on multicore fiber (MCF) and oriented to 5G mm-wave communications is proposed and experimentally validated. The setup configurations are according to the 5G standard, enabling a wireless link at 26GHz (n258, K-band) and time division duplex (TDD) communication. The proposed scheme is thoroughly evaluated under all the 5G numerologies and with different bandwidth settings. Moreover, key design considerations of the experimental testbed are explained and discussed to optimize the final yields of the system. The experimental results of both transmission directions are compared and analyzed, and prove the viability of the proposed bidirectional ARoF system as an excellent solution to be part of the future 5G mm-wave network.

1. Introduction

The surging of new applications and services, such as 4K video streaming, internet of things (IoT), augmented reality, and autonomous driving, demands a substantial enhancement in mobile networks [1]. In order to adapt to the upcoming data traffic demands, the current mobile networks must be upgraded and improved in terms of capacity, latency, number of connected devices, and data rate. For this reason, the fifth generation (5G) of mobile networks arises as solution to satisfy the exigent performance indicators. The ongoing deployment of 5G technology aims to fulfill most requisites of the arising services and applications by exploiting the sub-6GHz band [2]. However, looking at a further perspective, the already congested sub-6GHz band cannot provide sufficient bandwidth to satisfy the exponential growth of mobile data traffic [3,4].

Therefore, moving towards higher frequency bands is the straightforward manner to achieve a great improvement in terms of data rate, with the millimeter-wave (mm-wave) domain being the next band on the market to become operational. Nonetheless, the use of mm-wave signals implies a significant decrease of the cell coverage area due to the increase of the free-space path loss (FSPL) [5]. Thus, respecting the current mobile network, the number of mm-wave cells required to cover the same surface will be much larger. This enormous number of expected mm-wave cells implies a huge increment of the complexity in the radio access network (RAN). However, the arrival of mm-wave cells or remote access units (RAUs) will increase drastically the data traffic in the fronthaul. To solve this severe issue, analog radio-over-fiber (ARoF) emerges as an excellent solution by highly reducing the complexity in the RAUs, allowing a scalable deployment of the mm-wave cells for beyond 5G [6]. Moreover, other benefits such as high spectral efficiency, low latency, and large bandwidth are inherently related to ARoF [7].

Previous works reported in [8–11] present and validate bidirectional mm-wave ARoF systems by using simple modulation formats such as amplitude-shift keying (ASK) and quadrature phase-shift keying.
and multiple-output (MIMO) and beamforming solutions become estau [6]. In addition to this, the implementation of multiple-input (NGFI) an added alternative. However, the arrival of mm-wave RAUs adopted C-RAN solution, with next generation fronthaul interfaces technology in LTE-A. For 5G networks, enhanced-CPRI (eCPRI) is the

networks. Nonetheless, the implementation of C-RAN implies a new maintenance, and reduced energy consumption [18]. For these reasons, offers other benefits such as higher flexibility, lower latency, lower

In the C-RAN, several processes and operations are moved from the antenna site, where the baseband processing is performed, with the core of the network. In the other hand, centralized-RAN (C-RAN) includes the central office (CO) as an additional node in the mobile network. In the C-RAN, several processes and operations are moved from the RAUs to the CO, reducing the complexity of the RAUs and diminishing the operating expenses (OPEX). Furthermore, respecting D-RAN, C-RAN offers other benefits such as higher flexibility, lower latency, lower maintenance, and reduced energy consumption [18]. For these reasons, C-RAN is the operating architecture for LTE-Advanced (LTE-A) and 5G networks. Nonetheless, the implementation of C-RAN implies a new segment between the CO and RAU, called fronthaul [6].

Common public radio interface (CPRI) is the used C-RAN technology in LTE-A. For 5G networks, enhanced-CPRI (eCPRI) is the adopted C-RAN solution, with next generation fronthaul interfaces (NGFI) an added alternative. However, the arrival of mm-wave RAUs will drastically increase the data transmission in the mobile fronthaul [6]. In addition to this, the implementation of multiple-input and multiple-output (MIMO) and beamforming solutions become essential to overcome the high FSPL in the mm-wave domain, further increasing the data rate requirements of the future 5G fronthaul [6].

Thus, bottlenecks can appear in the fronthaul due to these demanding transport requirements [6]. Therefore, as mentioned in Section 1, ARoF surges as an excellent solution for the 5G mm-wave network since it implies low complexity RAUs, enabling a scalable deployment, and it relaxes the data requirements in the fronthaul, avoiding possible bottlenecks. Moreover, the combination of ARoF with multiplexing technologies, such as dense wavelength-division multiplexing (DWDM) and SDM, increases the scalability of ARoF systems and optimizes the cointegration with beamforming technologies [6,14].

Optical beamforming (OBF) has emerged as an efficient alternative of the conventional electrical beamforming because of its high dynamic beam steering properties, footprint capacity for scalable and low power solutions, and multi-beam transmission based on beamforming matrices [19]. MCF technology has a great potential to support optical MIMO or beamforming implementations since it enables an efficient manner to manage and control the spatial resources and the beamformed signals [20]. In addition, centralized OBF is an attractive implementation because the beamforming resources can be optimally assigned and the RAU dispenses with the optical beamformer, simplifying the complexity of the RAU. However, locating the optical beamformer in the CO results highly challenging in order to maintain the phase synchronicity of the beamformed signals [19]. A solution of this phase synchronicity problem consists of locating the optical beamformer in the RAU and thus lose the centralized beamforming feature. In conclusion, OBF is a promising and in-process technology that needs to be taken into account for the future 5G network.

Bidirectional communication must be considered for the validation of commercially viable solutions. The scheme of Fig. 1 shows a C-RAN architecture of an ARoF system combined with SDM and WDM to achieve a highly scalable 5G fronthaul. This architecture supports bidirectional communication with centralized beamforming to provide mm-wave wireless connectivity to end-users grouped into clusters. In the downlink direction, the CO realizes all the signal processing, management, and monitoring, simplifying the complexity of the mm-wave RAUs. The CO generates signals that are multiplexed with respect to the end-users and the RAU where the corresponding end-user is located. Then, these signals are transported through the optical fiber ring. DWDM channels are assigned to each RAU as illustrated in the spectrum signals of Fig. 1. By performing a demultiplexing process, the desired signal for each RAU is extracted and directly upconverted through optical heterodyning. Next, the resulting electrical signal is sent to the end-user through a mm-wave wireless link. For the uplink direction, an equivalent process is carried out. Respecting Fig. 1, it is important to mention that the two optical links of both directions use different spatial channels. In this manner, as mentioned above, the crosstalk between both direction is low because an SDM system is utilized [14–16]. Therefore, in this work, a MCF is employed to transport the optical signals of both directions.
3. Experimental demonstration

3.1. Experimental setup

This subsection describes the experimental setup employed to achieve bidirectional ARoF fronthaul for mm-wave 5G communications. Fig. 2 shows the experimental schematic [21]. First, in the downlink part of the CO, an external cavity laser (ECL) generates an optical carrier at 1550 nm with 16.8 dBm of power. Next, the generated optical carrier is modulated using a Mach–Zehnder modulator (MZM), biased in the null point, with an RF sinusoid of 11.5 GHz. In this way, the MZM produces two optical tones with a separation twice larger than the frequency of the RF input sinusoid [22,23]. In this case, the separation is 23 GHz (spectrum of point A in Fig. 2). For this implementation, the optical carrier is suppressed, avoiding the RF power fading induced by the optical fiber transmission dispersion [24]. Next, the two-tone signal is boosted by an erbium-doped fiber amplifier (EDFA). Later, the boosted optical signal is modulated by a second MZM, biased in the quadrature point, with the OFDM signal. An arbitrary waveform generator (AWG) with 12 GSa/s of sampling rate generates the downlink OFDM signal with an intermediate frequency (IF) of 3 GHz. In such a manner, the optical spectrum at the output of the second MZM is as shown in the frequency domain representation of point B in Fig. 2. Since the MZMs are sensitive to input polarization, a polarization-maintaining fiber (PMF) and a polarization controller (PC) are located before the first and second MZM, respectively. This second MZM corresponds to the last element of the downlink for the CO.

After the downlink process in the CO, the modulated two-tone signal is launched and multiplexed into one core of a MCF with 10 km of length. This length emulates the distance between the CO and the RAU as illustrated in the scheme of Fig. 1. The employed MCF contains 7 cores, provides an attenuation of 0.21 dB/km, and its chromatic dispersion is equal to 18 ps/(nm.km). Then, in the RAU part of the downlink, the transmitted optical signal through the MCF is received, demultiplexed, and sent to a photodiode (PD). By beating the two optical tones in the PD, an electrical signal is produced with an RF carrier at 23 GHz and two OFDM sidebands located at 20 GHz and 26 GHz, respectively (spectrum of point C in Fig. 2). The OFDM sideband at 26 GHz is the desired signal for the wireless link, located in the 5G n258 band. Later, the resulting electrical signal is boosted by a 30 dB medium power amplifier (MPA). Next, the boosted signal goes through an RF power divider and consequently is launched into the wireless link by a 24 dBi horn antenna. The distance of the wireless link is 9 m. The transmitter downlink antenna is the last device of the RAU in the downlink.

In the experimental results, the power of the EDFA is gradually changed to evaluate the performance of the proposed system by realizing a sweep in power, with 18.5 dBm being the maximum output power of the EDFA. Then, the RF sideband powers at 26 GHz are measured before the transmitter downlink antenna (point I of Fig. 2) in order to appraise the yields of the downlink communication. In the end-user side, the transmitted signal is captured by a 20 dBi horn antenna and amplified by a 40 dB low-noise amplifier (LNA). Next, the amplified electrical signal is mixed with a sinusoid of 25 GHz, shifting the desired OFDM sideband to 1 GHz of center frequency (spectrum of point D in Fig. 2). Finally, the resulting signal is sampled by a digital phosphor oscilloscope (DPO) with 12.5 GSa/s of sampling rate. In addition, as shown in the photographs of Fig. 2, the pair of antennas used in the RAU and in the end-user are the same, respectively. Furthermore, the pair of antennas for each direction are aligned in terms of height, altitude, and azimuth. Moreover, the separation between the RAU antennas is 8 cm meanwhile the end-user antennas are separated with a distance of 5.5 cm.

In the uplink direction, a second AWG, with the same features as the first one, creates an OFDM signal at 1 GHz of IF. This OFDM signal is mixed with a 25 GHz sinusoid which comes from the same RF synthesizer employed in the downlink downconversion. Hence, the OFDM signal is upconverted, resulting an RF carrier at 25 GHz and two OFDM sidebands at 24 GHz and 26 GHz, respectively (spectrum of point E in Fig. 2). The OFDM 26 GHz sideband is again the desired signal for the wireless uplink communication. To distribute both 25 GHz sinusoid signals in the end-user, an RF splitter, whose nominal insertion loss is 7 dB, is employed. After the uplink upconversion, a second 30 dB MPA is used to boost the electrical signal. Then, the boosted electrical signal is launched into the air by using a second 20 dBi horn antenna. This antenna forms the last element of the uplink direction in the end-user side. It is relevant to mention that the RF sideband power at 26 GHz is also measured for the uplink direction (point J of Fig. 2). In this case, the power is swept by modifying the output power of the RF synthesizer located in the end-user.

In the RAU side, a second 24 dBi horn antenna is employed to receive the transmitted uplink signal. Then, the captured uplink signal is amplified by a second 40 dB LNA and mixed with the 23 GHz tone of the downlink by using the second output of the power divider located in
the RAU. Subsequent to the downconversion of the uplink, the desired OFDM sideband is transferred to a center frequency of 3 GHz (spectrum of point F in Fig. 2). Next, the undesired higher frequency components are suppressed by using a low-pass filter (LPF) with a cutoff frequency of 5.5 GHz. Later, the filtered signal is amplified and modulated into the optical domain by a third MZM, biased in the quadrature point (spectrum of point G in Fig. 2) and using an optical carrier at 1548 nm, generated by a second ECL with 16 dBm of optical power. The resulting optical signal is launched into a different core of the MCF than the one used in the downlink and, in this manner, the last process of the uplink RAU block is completed. The usage of independent optical channels for both directions instead of one single optical fiber results more efficient in terms of yields due to the crosstalk reduction [14–16].

Regarding the processes realized in the CO for the uplink, the transmitted optical signal into the MCF is demultiplexed respecting the employed uplink core. Consequently, the demultiplexed signal beats at a second PD, converting the optical signal into the electrical domain (spectrum of point H in Fig. 2). Later, the resulting electrical signal is amplified and, finally, sampled by a second 12.5 GSa/s DPO. For both transmission directions, different OFDM signal traces are sent to the experimental testbed by using the two aforementioned AWGs. According to the DSP in the receiver part, an offline process is carried out in the sampled signals caught by the pair of used DPOs. Therefore, the performance of both directions can be studied, analyzed, and evaluated. More details about the DSP process is found in the next subsection.

TDD communication is performed in the experimental setup of Fig. 2, as the 5G standard determines for mm-wave communications. Therefore, the downlink optical signal is unmodulated in the uplink time slot and vice versa. This fact allows the resulting 23 GHz tone from the downlink to be employed as local oscillator (LO) in the uplink downconversion process performed at the RAU, realizing effective reuse without causing signal interference. In such a manner, an extra RF synthesizer at the RAU can be avoided, reducing the volume, complexity, and power consumption. Furthermore, an RF synthesizer with an output power of 16 dBm is shared at the end-user for both directions, reducing hardware complexity. This type of reuse to simplify the system is highly desirable in mm-wave 5G communications since the number of expected RAUs is enormous. With the reusability of the RF carrier in two parts of the system and thus the avoidance of additional RF synthesizers, the proposed mm-wave ARoF bidirectional scheme is highlighted as an efficient and low complexity solution.

3.2. DSP process

This subsection aims to explain the main key aspects of the used DSP to get the experimental results. Fig. 3 illustrates the utilized DSP process. The transmitter DSP block process is performed offline and the resulting signals are transmitted by the AWGs of both directions. This DSP process can be observed in the orange block of Fig. 3. First, the classical OFDM transmitter is realized consisting of the following blocks: M-QAM modulator where M specifies the modulation order; insertion process of reference symbols such as demodulation reference signal (DM-RS) and phase-tracking reference signal (PT-RS) for posterior channel and phase noise compensation [17]; injection of null symbols in the OFDM band edges to reduce the out-of-band (OOB) emissions and enable more guard band between technologies in the used mm-wave band; inverse discrete Fourier transform (IDFT) to move from frequency-domain to time-domain; and an adding cyclic prefix (CP) process [26]. After the OFDM transmitter blocks, an IF modulation is carried out. For that, the real and imaginary parts of the generated time-domain OFDM signal are separated in two branches. Subsequently, the signals of both branches are upsampled and multiplied by a sine and cosine, respectively for upconversion to the desired IF (3 GHz for downlink, 1 GHz for uplink).

The receiver DSP process is depicted in the green block diagram of Fig. 3 and is the same process for both directions. First, the captured IF signal by the DPO is filtered by a band-pass filter (BPF), eliminating the non-desired frequency components. Consequently, an IF demodulation process is executed to convert the received signal into the baseband domain. However, since the frequency downconversion is not performed in the experimental setup with the same frequency used in the upconversion process, the frequency values of the IF demodulation are different from the ones utilized in the IF modulation. In particular, the uplink and downlink signals must be demodulated with frequency values of 3 GHz and 1 GHz, respectively (spectrums of points H and D in Fig. 2). After the IF demodulation, the resulting baseband signal is downsampled and synchronized by using a preinserted preamble. Afterwords, a coarse carrier frequency offset (CFO) compensation is carried out. Then, the CP is removed in every OFDM symbol and a discrete Fourier transform (DFT) is realized to move into the frequency-domain. Later, a linear interpolation based intercarrier interference (ICI) estimation technique is executed by employing the PT-RS signals inserted in every OFDM symbol [27]. This method is also denominated LI-CPE and its function consists of compensating the common phase error (CPE) and ICI produced by phase noise and CFO [28].
4. Transmission results

4.1. Experimental measures

The objective of this subsection consists of investigating and analyzing the main limiting factors of the proposed bidirectional transmission setup that is illustrated in Fig. 2. Phase noise is considered one of these main limiting factors in mm-wave ARoF systems, being more degrading in OFDM signals especially using the standardized 5G numerologies [28,30,31]. For this reason, the phase noise is measured in the experimental setup before the DPO of each direction. The resulting phase noise measures are shown in Fig. 4a. Since the carrier signals are shared and reused in both directions, the phase noise power spectral density (PSD) of the uplink and downlink are similar. Thus, the phase noise does not imply performance differences between both directions. In addition, the phase noise levels of Fig. 4a is relatively low and it cannot be critical for high subcarrier spacing values such as 120 kHz or 240 kHz [28]. Hence, additional and complex phase noise compensation methods are not necessary to be employed for these subcarrier spacing configurations (Fig. 3).

Moreover, power shortage is another of the limiting factors in mm-wave wireless scenarios due to the high FSPL [5]. Then, power sweeps are realized in both direction to evaluate the performance of the proposed system in terms of SNR. As mentioned above, the power sweeps of the uplink and downlink are executed by modifying the power of the RF synthesizer located in the end-user and the EDFA, respectively. In order to properly compare the results of both directions, the experimental results must be represented on the same axis. Thus, the power sweeps of the uplink and downlink must be referred to the same parameter. The selected common parameter is the RF sideband power that is launched into the wireless link. This RF sideband power attributes to the power of the OFDM single-band signal located at 26 GHz in the spectrum, excluding the rest of transmitted signals such as the RF carrier. As mentioned above, the RF sideband powers are measured before the transmitter antennas of its respective direction (see points I and J of Fig. 2).

Fig. 4b represents the power map to get the desired RF sideband power of the two directions. Discrete points of the power sweeps are illustrated too with orange circles in these figures. These points are employed for the horizontal axis representation in the experimental results of the next subsection. The bottom x-axis of Fig. 4b concerns to the LO input power of the mixer located at the uplink path of the end-user. Meanwhile the top x-axis refers to the received optical power at the input of the PD located in downlink path. Furthermore, the powers related to the left OFDM side bands at 24 GHz and 20 GHz for the uplink and downlink, respectively, are also represented. The power of the left and right OFDM bands are very similar for the uplink direction (see Fig. 4b). However, examining the downlink measures of Fig. 4b, the power of the two OFDM sidebands are not symmetric in the downlink because several devices involved in the downlink path of the setup, such as the MPA, are less optimized at 20 GHz than at 26 GHz. Another important consideration regarding Fig. 4b is the linearity between the experimental power sweep values and the RF sideband power. By observing Fig. 4b, the uplink power map shows a saturation point at approximately 10 dBm of LO power due to the 1 dB compression loss of the end-user MPA. In addition, the uplink curves of Fig. 4b present two different slopes from −10 dBm to 10 dBm due to the non-linear transfer function of the RF mixer. For the downlink power map, the slope keeps constant with a value of −2 dB/dB.

As mentioned before, different OFDM bandwidth configurations are evaluated in the experimental setup. The SNR is measured in the received signals for both directions and the different bandwidth configurations. These SNR measures are illustrated in Fig. 4c as a function of the RF sideband power at 26 GHz. The RF sideband power values are obtained from the power mapping exhibited in Fig. 4b.

Table 1

| OFDM configuration parameters. | Sweep in subcarrier spacing | | | | | |
|---|---|---|---|---|---|
| Config. | 1 | 2 | 3 | 4 | 5 | 6 |
| Δf [kHz] | 15 | 30 | 60 | 120 | 240 | 480 |
| N | 2^14 | 2^13 | 2^12 | 2^11 | 2^10 | 2^9 |
| T_{cp} [μs] | 4.8 | 2.4 | 1.2 | 0.6 | 0.3 | 0.15 |

the channel is equalized based on the DM-RS signals. Lastly, the QAM demodulator decodes the processed data symbols into bits.

Different OFDM configurations are generated and transmitted for both directions. In particular, two sweeps of one of the OFDM parameters are evaluated and compared. The first sweep is regarding the subcarrier spacing and the second one refers to the total bandwidth. The common OFDM parameters of these two sweeps are the following: 80% of the subcarriers are active, DM-RS signals on every 14th OFDM subcarrier and the second one refers to the total bandwidth.

The OFDM configuration parameters are illustrated in Table 1 where sweep in subcarrier spacing (BW = 245.76 MHz) [29]. Every RB is composed of 14 subcarriers [17]. The remaining parameters are detailed in Table 1 where Δf is the subcarrier spacing, N is the total number of subcarriers, T_{cp} is the CP duration, and BW is the transmitted bandwidth. Considering all the mentioned parameters, the transmitted spectral efficiency in term of baud rate is 0.683 Baud/Hz. Therefore, since the highest modulation order employed in the experimental testbed is 64-QAM and the largest used bandwidth is 983.04 MHz, the maximum achieved throughput is 4030 Mbps.
By observing the SNR measures of Fig. 4c, it can be noticed that the downlink power sweep presents shorter range than in the uplink part. Moreover, SNR measures are quite similar for both directions in each bandwidth configuration. Hence, it can be determined that the SNR level is roughly the same for two directions at the same RF sideband power. This statement is relevant since the BER results of both directions will be compared by using the RF sideband power as the same x-axis parameter.

4.2. Experimental results

The experimental results of this work are shown, analyzed and discussed in this subsection. As commented in Section 3, the subcarrier spacing and bandwidth of the OFDM signal, and the wireless launched power are swept. Figs. 5a and 5b are obtained by processing the received signal of these sweeps for the uplink and downlink. Moreover, two different modulation orders are employed: 16-QAM (upper graphs) and 64-QAM (bottom graphs). Fig. 5a represents the BER results as a function of the subcarrier spacing for the different bandwidth configurations. The used OFDM parameters of these BER results are depicted in the sweep of subcarrier spacing section of Table 1. Examining the graphs of Fig. 5a, the BER presents an exponential decay as the subcarrier spacing increases for all the bandwidth configurations. This behavior is due to the fact that phase noise and the CFO introduce more distortion into the OFDM signal for lower subcarrier spacing values [28]. However, starting approximately at 120 kHz of subcarrier spacing, the BER shows a slight worsening for higher subcarrier spacing values. The reason of this BER behavior is because the subcarrier density is lower for higher subcarrier spacing values and, thus, the channel equalizer performs worse due to the shortage of DM-RS symbols (this behavior is easier perceived in the 64-QAM graph of Fig. 5a).

The results of Fig. 5a are obtained by setting the maximum power of the launched power sweep. Hence, by observing the BER results of Fig. 5a, the best subcarrier spacing configuration can be selected. 120 kHz or 240 kHz of subcarrier spacing present the lowest BER for both directions, the evaluated modulation orders, and all the bandwidth configurations. It is relevant to highlight that the final phase noise of the experimental setup is not excessively high (Fig. 4a). Otherwise, the BER curves of Fig. 5a would tend to a continuous exponential decay [30]. Comparing the uplink and downlink BER results of Fig. 5a, it can noticed that the uplink results show lower BER for all the cases. This BER difference between both directions appears more clearly in Fig. 5b. The BER results of Fig. 5b are plotted against the RF sideband power and for the three bandwidth configurations and a subcarrier spacing value of 240 kHz (see parameters of sweep in bandwidth of Table 1). The RF sideband power measurements of Section 4.1 are employed to plot these results. In addition, the 25% and 7% overhead (OH) FEC limits are illustrated in the graphs of Fig. 5b.

Inspecting the graphs of Fig. 5b, it can be observed that the BER decreases as the RF sideband power increments and the bandwidth decrements [21]. This BER dependence of the RF sideband power and the bandwidth are because these two parameters are directly related to the final SNR. Moreover, it is noticed a BER gap between the uplink and downlink results at the same RF sideband power. The reason of this gap is because the degradation of the signal in the downlink is higher than in the uplink. Another consideration to take into account is that the uplink achieves slightly higher RF sideband powers than in the opposite direction, accomplishing lower BER results. In the graphs of Fig. 5b, the BER value of all the cases is under the 25% OH FEC threshold at the maximum RF sideband power, except for the 64-QAM downlink case with 983.04 MHz of bandwidth. For the 16-QAM BER curves, all the cases are under the 7% OH FEC threshold at the maximum power. These BER yields under the OH FEC limits prove the validity of the proposed bidirectional ARoF system as a strong candidate to be part of the future 5G mm-wave network.
In order to thoroughly analyze and understand the aforementioned experimental results, simulations are realized considering additive white Gaussian noise (AWGN), phase noise, and CFO. The AWGN is measured for the different configurations and all the RF sideband power points and, thus, the final SNR is obtained (see Fig. 4c). The phase noise is artificially simulated respecting the PSD curves of Fig. 4a. The achieved simulations and the experimental results are shown in Fig. 5c in terms of BER as a functions of the measured SNR. The points of these BER results coincides sequentially with the RF sideband power points of Fig. 4c. In Fig. 5c, the 64-QAM modulation order is only considered and the uplink and downlink results are depicted in the upper and bottom graphs, respectively. Furthermore, it can be noticed in these two graphs that the different bandwidth configurations are overlapping because the selected x-axis parameter is the SNR instead of a power magnitude. The experimental and simulated BER curves of Fig. 5c exhibit a mismatch that increases as the SNR values increase. This fact provides a hint that the experimental results include non-linearity effects that are not considered in the simulations. For lower SNR values, the experimental and simulated BER curves are very similar because the AWGN is the dominant impairment. As the SNR increases, the non-linearity degradation becomes more degrading than the AWGN impairment.

Signal compression is one of the mentioned non-linearities in the experimental testbed of Fig. 2 and mainly comes from RF amplifiers and the signal modulation process in the MZM. In addition, the mismatch between the simulations and the experimental results is larger in the downlink than in the uplink and is numerically represented in Fig. 5c at 24 dB of SNR: 13.5 dB of SNR mismatch for the uplink and 2.5 dB for the downlink. The summary of conclusions regarding the results of Fig. 5c implies that the proposed bidirectional mm-wave AROF system presents more non-linearities in the downlink than in the uplink. The compression of the signal is measured for both directions at the different points of the power sweep. These compression results indicate that the downlink signals are more compressed than the uplink signals. The compression of the signal can be the main non-linearity factor of the received signal in the experimental setup and thus it determines the difference of non-linearity effects between both directions.

5. Conclusions

This article highlighted the importance of AROF to deploy, in a scalable way, future 5G mm-wave networks. To accomplish it, SDM and WDM were emphasized as suitable multiplexing techniques to enable a bidirectional ARoF fronthaul with centralized beamforming. Consequently, an efficient and novel bidirectional AROF scheme based on the usage of MCF was experimentally demonstrated. The novelty of the proposed schematic resides in the utilization of MCF to enable an efficient ARoF bidirectional link and the reuse of the carriers for the up and down-conversion processes of both transmission direction links. In this manner, the complexity, energy consumption, and cost are reduced. Moreover, the proposed schematic allows to transmit OFDM signals at the central frequency of n×258 Band (26 GHz, K-band) by employing the TDD multiplexing technique as the 5G standard determines.

To prove the validity of the proposed scheme for mm-wave 5G communications, a thorough measurement campaign was carried out by sweeping four different experimental parameters: the subcarrier spacing (covering all the 5G numerologies [15 kHz to 480 kHz]), the transmitted bandwidth, the modulation order (16-QAM and 64-QAM), and the launched wireless power. The transmitted OFDM signals in the experimental setup were in accordance with the 5G standard. Furthermore, experimental measurements such as phase noise and wireless power conversion were shown and discussed to evaluate the performance of the experimental setup. For reproducibility matters, the details of the employed DSP block of both transmitter and receiver parts were also explained. Moreover, to optimize the overall performance, design considerations of the experimental testbed were described in detail.

The experimental results of both transmission directions were analyzed and compared in detail. The discussions of the results led to the conclusion that 120 kHz and 240 kHz of subcarrier spacing are the best configurations for the system under test. Another conclusion, achieved by comparing the experimental results and simulations, was that the downlink path performs worse in terms of non-linearity effect than the uplink. In addition, the experimental results exhibit acceptable pre-FEC BER values, proving the validity and efficiency of the proposed bidirectional ARoF system as an excellent solution to play a significant role in beyond 5G mm-wave radio systems.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This work was partially financed by the 5G STEP FWD and blueSPACE projects (GA nos. 722429 and 762055).

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