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Bidirectional K-Band Photonic/Wireless Link for 5G Communications

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Abstract—A bidirectional analogue radio-over-fiber link relying on photonic heterodyning and time-division duplex is experimentally demonstrated, successfully transmitting 5G OFDM signals with data rates of 2.4 Gbit/s and 1.2 Gbit/s in down- and uplink directions over 4 m of wireless distance. An optical frequency comb laser is used together with a demultiplexing module based on injection locking to generate stable K-band (18 – 27 GHz) signals, which eliminates the need for complex high-speed electronics for mm-wave generation.

I. INTRODUCTION

THE strong growth in mobile data traffic oblige to embrace new spectral assignments in the lower millimeter wave (mm-wave) range which, alongside the adapted flexible numerology for orthogonal frequency division multiplexing (OFDM) in 5G new radio (NR), will lead to data rates up to 10 Gb/s [1,2]. Analogue radio-over-fiber (A-RoF) with mm-wave generation by optical heterodyning has been suggested as an efficient method for mobile fronthaul, providing seamless integration with existing optical distribution networks [3, 4]. However, the duplexing in the radio link, enabling bidirectional transport, is one of the key challenges to be addressed in mm-wave 5G NR, as it must afford sufficient flexibility to allow asymmetric resource allocation and to cope with varying channel conditions and signal quality between up- and downlink. Time division duplex (TDD), as defined for mm-wave 5G NR [2], is a simple duplex scheme which provides temporal separation of the uplink and downlink signal transmission as well as the capability of spectral reuse of the same frequency channels.

We experimentally demonstrate a bidirectional hybrid optical and wireless link based on A-RoF and TDD for 5G communications. This link can be directly integrated into optical distribution networks according to ultra-dense wavelength division multiplexing (UDWDM) standard. This is achieved by using photonic heterodyning based on an optical comb for both up- and downconversion to/from mm-wave.

II. EXPERIMENTAL SETUP

The experimental setup is depicted in Fig. 1. A frequency comb laser serves as light source for the entire system (optical spectrum in Fig. 1(a)). Four 12.5 GHz spaced lines are demultiplexed by injection locking, matching the UDWDM grid. Two of them (λ_1 and λ_3) are used in the downlink, while the other two (λ_2 and λ_4) are employed in the uplink.

In the downlink, an OFDM signal, generated within and arbitrary waveform generator (AWG), is modulated onto λ_1 by using a Mach-Zehnder modulator (MZM). This signal is combined with λ_3 , located 25 GHz away, as well as λ_4 which will be used for the uplink with remote modulation. Two optical circulators connected to 15 m of standard single-mode

Fig. 1. Schematic of experimental setup and signal spectra: (a) comb spectrum, (b) optical spectrum before WSS, (c) optical spectrum incident on PD at remote station, (d) optical spectrum of tone for uplink transmission.

fiber (SMF) are used to allow bidirectional A-RoF transmission in a single fiber, as shown in Fig. 1.

At the access point, an erbium doped fiber amplifier (EDFA) and a variable optical attenuator (VOA) control the optical power available for wireless and uplink transmissions. The optical spectrum at this point is depicted in Fig. 1(b). In a further step, a wavelength selective switch (WSS) separates the signals for the downlink (modulated λ_1 and unmodulated λ_3 , Fig. 1(c)) and the optical carrier for the uplink (λ_4 , Fig. 1(d)). The 25 GHz signal is generated by photonic heterodyning on a high bandwidth photodiode (PD) [4]. This signal is first amplified by a 30 dB gain medium power amplifier (MPA), and then an electrical circulator isolates up- and downlink directions. Finally, an 18 dBi standard gain horn antenna radiates the downlink wave.

At the end user, after propagating over a wireless distance of 4 m, the signal is received by an identical horn antenna attached to another electrical circulator. Later, it is boosted by a 40 dB gain low noise amplifier (LNA) and downconverted to an intermediate frequency (IF) by a mixer. A vector signal generator (VSG) at 27 GHz serves as local oscillator (LO), resulting in an IF of 2 GHz. The IF wave is recorded by a digital phosphor oscilloscope (DPO) for off-line processing. In the uplink, a second OFDM signal is electrically upconverted to K-band reusing the same LO. The output wave at 27 GHz is amplified by a 30 dB gain MPA and directed to the circulator for radiation via the antenna.

Again, at the access point, the received radio frequency (RF) signal from the end user is amplified by a 40 dB LNA

Fig. 2. Photographs of laboratory setup: (a) optical setup at central location, (b) setup at remote station, (c) antenna unit at remote station with circulator and LNA, (d) end user antenna unit with circulator, mixers and amplifiers.

before being used to modulate the uplink tone (λ_4 , Fig. 1(d)) in a MZM for optical transmission to the central unit, generating two side bands 27 GHz away. At the central unit, the wave coming back through the uplink is isolated by a circulator and coupled with the fourth optical tone (λ_2) extracted from the comb source. The relative frequency difference to the lower side band is 2 GHz, correspondingly heterodyne photonic downconversion produces an IF signal centered at 2 GHz. This technique considerably simplifies the receiver electronics. However, it should be mentioned that due to the path length difference between λ_4 and the upstream modulation, the phase noise of the mixing product may be high and may negatively affect the received signal. This issue implies a limitation in the maximum fiber length between the central unit and the access point, depending on laser and comb purity and stability and locking performance of the demultiplexer. Finally, the signal is amplified by a 19 dB gain amplifier and filtered by a 5.5 GHz low pass filter to remove the unwanted frequency products. Again, a DPO is used to record the data for off-line processing. Figs. 2(a)-(d) show the described experimental setup in the laboratory.

III. RESULTS

The link is evaluated by measuring bit error rate (BER) after the wireless transmission of 4 band OFDM signals based on 5G NR numerology. These signals are generated by mapping QAM symbols originating from a random bit stream onto 4096 OFDM subcarriers spaced at 60 kHz. The signals for the two directions are chosen to have asymmetric properties in terms of data rate. In the downlink, where signal to noise ratio (SNR) is good, the transmitted OFDM subcarriers are modulated with 16-quadrature amplitude modulation (QAM) symbol, whereas in the uplink, where SNR is worse, quadrature phase-shift keying (QPSK) is used. The obtained data rates are 2.4 Gbit/s and 1.2 Gbit/s respectively, showing an asymmetric link determined by signal quality.

The BER results are shown in Fig. 2. In the downlink, BER is measured with respect to the optical power at the photodiode, while in the uplink is measured with respect to LO power supplied to the RF mixer. Downlink transmission is achieved with BER below the limit for a hard-decision forward error correction (FEC) with 7 % overhead (OH) and little variation is found with the optical power. The later can most likely be attributed to saturation of the receiver LNA.

Fig. 3. BER performance of 4 band OFDM signals transmissions using 16QAM (downlink) and QPSK (uplink) symbols within 980 MHz bandwidth.

In the uplink direction, the relation between electrical LO power and generated RF signal is less straight forward. Nevertheless, a similar behavior is seen, where for low powers BERs around the 7 % OH FEC limit are obtained, while for higher powers again saturation of the receiver LNA causes the signal to degrade. In the saturated regime, BER is increased to the point that a FEC with 25 % OH would be required. Receiver LNA saturation appears to be the dominant limiting factor in the two cases; thus, a longer wireless transmission distance can be achieved.

IV. CONCLUSION

A successful bidirectional multi-Gbit/s transmission of 5G NR OFDM signals through a K-band A-RoF link based on TDD was experimentally demonstrated. Data rates of 2.4 Gbit/s for down- and 1.2 Gbit/s for upstream were achieved over 4 m wireless distance within a bandwidth of 980 MHz and with BERs below the limits for 7% and 25 % OH FEC respectively. The presented work showcases comb-based A-RoF as a key enabler for bidirectional handling of 5G mm-wave signals, allowing fiber-wireless convergence and ultra-large capacities.

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