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Real-Time Demonstration of ARoF Fronthaul for High-Bandwidth mm-Wave 5G NR Signal Transmission over Multi-Core Fiber

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***Abstract*—This paper presents an experimental demonstration of analog radio-over-fiber (ARoF) fronthaul for high-bandwidth, high-capacity millimeter wave (mm-wave) extended fifth generation mobile network (5G) new radio (NR) signals over an optical distribution network with optical space division multiplexing (SDM). ARoF is shown to alleviate fronthaul capacity bottlenecks, transporting an 800 MHz wide extended 5G NR signal and allowing to maintain full centralization in a centralized radio access network (C-RAN). The proposed ARoF fronthaul architecture features a transmitter that generates the ARoF signal and an optical signal carrying a reference local oscillator (LO) employed for downconversion at the remote unit (RU) from a single radio frequency (RF) reference at the central office (CO). An SDM based RAN with 7-core multi-core fiber (MCF) allows parallel transport of the uplink ARoF signal and reference LO at the same wavelength over separate cores. Transmission of an 800 MHz wide extended 5G NR fronthaul signal over 7-core MCF is shown with full real-time processing, achieving 1.4 Gbit/s with BER$<3.8 \times 10^{-3}$ and thus below the limit for hard-decision forward error correction (FEC) with 7 % overhead. Downconversion at the RU is performed electrically with the remote-fed LO provided by the CO.**

Keywords*—5G, millimeter wave, space division multiplexing, analog radio-over-fiber, fronthaul.

I. Introduction

As the demand for mobile data continues to increase and the range of applications expands, fifth generation mobile networks (5Gs) promise unprecedented data rates, low latency and support of extreme user densities [1], [2]. For the first time for mobile networks, 5G new radio (NR) includes the use of millimeter wave (mm-wave) carrier frequencies to allow the use of larger signal bandwidths and thus achieve the required Gbit/s end-user capacities [2]–[4]. Centralized radio access networks (C-RANs) have been shown to provide significant gains in terms of CAPEX and OPEX by centralizing network functionality and complexity at the central office (CO) and reducing footprint and energy consumption of the remote unit (RU) [5], [6]. The resulting introduction of the fronthaul segment, which transports the radio waveforms between CO and RU in digitized form over optical fiber, however poses stringent requirements on latency and, due to high-resolution digitization, requires large data-rates even for small radio frequency (RF) bandwidths [7], [8]. With signals above 100 MHz bandwidth to be used in 5G NR, traditional digitized radio-over-fiber (DRoF) fronthaul based on CPRI can not cope and analog radio-over-fiber (ARoF) fronthaul becomes the only option to maintain full centralization and avoid an – at least partial – return to a distributed RAN [9], while also minimizing the required optical bandwidth.

In addition to ARoF, space division multiplexing (SDM) in the optical domain can help alleviating the capacity concerns of 5G C-RANs, providing multiple independent parallel paths at a potentially lower cost point than wavelength division multiplexing (WDM) or in combination with the latter to further increase capacity [10]–[13]. SDM may further help in avoiding differential delays or different chromatic dispersion experienced by related signals, or by allowing simultaneous transport of signals at identical wavelength within the same fiber [9], [14], [15].

In this work, an ARoF over multi-core fiber (MCF) link is demonstrated with full real-time processing of the ARoF signal in a custom ARoF baseband unit (BBU) and intermediate frequency (IF) transport over 10 km of 7-core MCF. Optical and 9 m wireless transmission at 25.5 GHz of an 800 MHz wide extended 5G NR signal, compliant with 3GPP orthogonal frequency division multiplexing (OFDM) numerology [16], are shown, achieving a data rate of 1.4 Gbit/s and bit error rates (BERs) below 3.8×10^{-3}. Optical two-tone generation based on an Mach-Zehnder modulator (MZM) and optical heterodyning are employed for upconversion to mm-wave, while an unmodulated copy of the two tone signal, transported through the MCF, provides the LO for RF downconversion at the RU. The demonstrated ARoF fronthaul link thus achieves centralization of all frequency references, analog IFoF transport with optical heterodyning for mm-wave upconversion as well

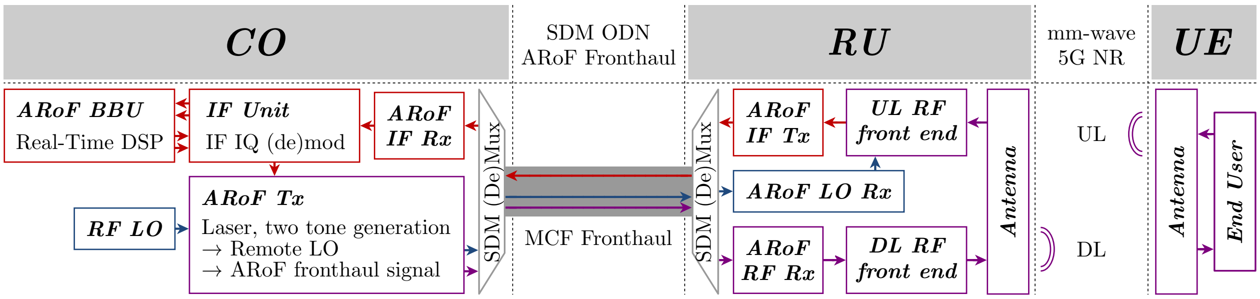

Fig. 1. Fronthaul architecture with CO, AROF fronthaul over SDM based ODN, RU and mm-wave 5G NR air interface to the end user.

as – to the best of the authors' knowledge for the first time – full real-time processing of an 800 MHz AROF extended 5G NR signal after wireless transmission at 25.5 GHz.

II. Fronthaul Architecture and Experimental Setup

The proposed fronthaul architecture is shown in Fig. 1, outlining the CO, the SDM ODN with MCF, the RU, as well as the mm-wave 5G NR air interface and end user (UE). At the CO, the processing is performed at the AROF BBU, including analog-to-digital conversion for the downlink as well as digital-to-analog conversion for the uplink. The analog baseband IQ signals are fed to the IF unit for modulation onto the IF carrier, which in turn drives the AROF transmitter. The latter further receives an RF LO, used for two tone generation both for remote-feeding the LO and for the downlink AROF fronthaul signal. The signals are multiplexed for transmission over the SDM-based ODN for transport to the RU, where they are received by corresponding AROF receivers, performing optical heterodyne upconversion to mm-wave. The signal is amplified by the downlink RF front end and radiated towards the UE over the mm-wave 5G NR air interface. In the uplink direction the signal received form the UE at the RU is amplified by the uplink RF front end and downconverted using the remote-fed LO. The IF signal is transported over an IF AROF link over the same SDM-based ODN to the CO, where it is received by an IF AROF receiver and fed to the IF unit for downconversion to baseband IQ signals.

The experimental setup employed to validate the AROF fronthaul link with real-time digital signal processing (DSP) is shown in detail in Fig. 2. The real-time AROF BBU generates a 5G NR signal with a total of 4096 subcarriers, spaced at 240 kHz, of which 3136 are active, resulting in an effective signal bandwidth of 760.32 MHz. The chosen modulation for the subcarriers is quadrature phase-shift keying (QPSK). The BBU further includes a digital to analog converter (DAC) and analog to digital converter (ADC) generating and receiving separate I and Q baseband signals respectively. Translation between baseband and IF is performed by the IF unit, employing a single IF LO at $f_{IF,LO} = 5\,\text{GHz}$ and a pair of IQ-modulator and -demodulator.

Optical two-tone generation is performed by an MZM biased at the null point driven with an RF/2 LO at $f_{RF/2,LO} = 10.25\,\text{GHz}$, resulting in a spacing of 20.5 GHz between the two optical tones [17]. The two-tone signal is amplified and split in two equal branches, one directly transmitted via the MCF to the RU, where, after amplification by 30 dB, it serves as RF LO at $f_{RF,LO} = 20.5\,\text{GHz}$ for electrical downconversion of the uplink signal. The other copy of the two-tone signal is modulated with the IF signal from the IF unit in a second MZM, before being transmitted to the RU via a separate core of the

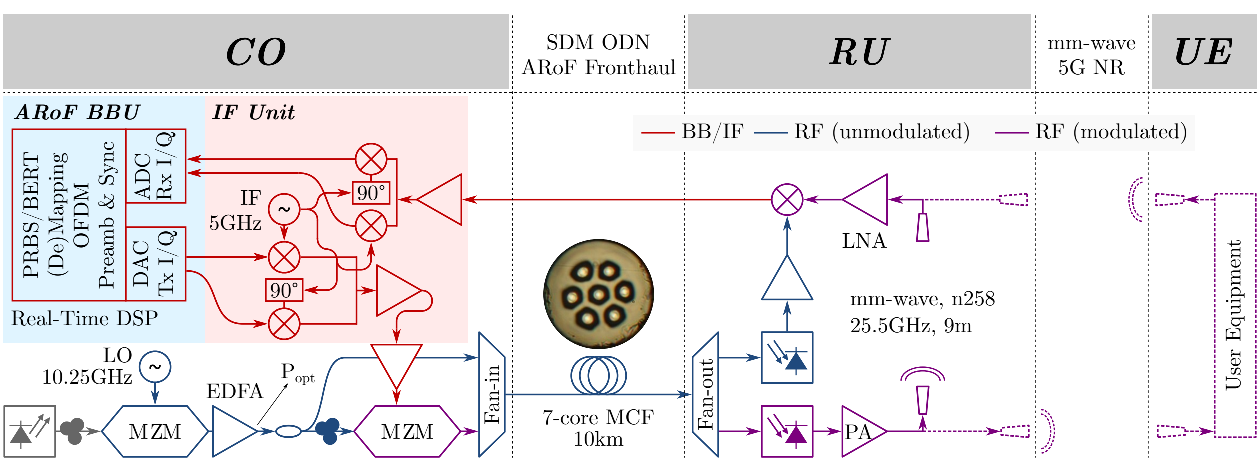

Fig. 2. Experimental setup for demonstration of AROF fronthaul with real-time processing of an 800 MHz wide 5G NR signal and a remote-fed LO. CO: central office, RU: remote unit, UE: user equipment, AROF: analog radio-over-fiber, SDM: space division multiplexing, ODN: optical distribution network, 5G NR: 5G new radio, RF: radio frequency, IF: intermediate frequency, BB: baseband, BBU: baseband unit, DSP: digital signal processing, PRBS: pseudo-random bit sequence, BERT: bit error rate tester, OFDM: orthogonal frequency division multiplexing, DAC: digita to analog converter, ADC: analog to digital converter, LO: local oscillator, MZM: Mach-Zehnder modulator, EDFA: erbium doped fiber amplifier, MCF: multi-core fiber, PA: power amplifier, LNA: low noise amplifier.

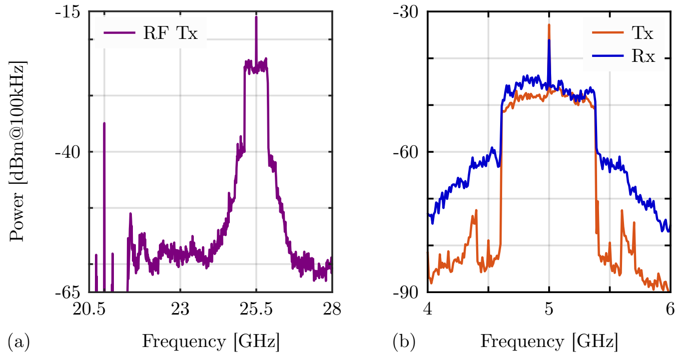

Fig. 3. Observed spectra at (a) RF transmission and (b) IF generation and reception.

10 km 7-core MCF; here the use of MCF allows the seamless transport of both signals, despite being at the same wavelength.

At the RU, the downlink RF signal is generated by optical heterodyning of the modulated two-tone signal on the photodiode (PD), resulting in a signal that includes modulated components at $f_{RF,low} = f_{RF,LO} - f_{IF}$ and at $f_{RF} = f_{RF,LO} + f_{IF} = 25.5$ GHz, as well as lower frequency components. The latter as well as the unwanted signal at $f_{RF,low}$ are removed by a high-pass filter, before the signal is amplified by 30 dB using a power amplifier (PA) and wirelessly transmitted at 25.5 GHz – i.e., in the 3GPP n258 band [16] – over 9 m. Wireless transmission is performed using a pair of horn antennas with a gain of 18.5 dBi each. The received signal is amplified by 40 dB with an low-noise amplifier (LNA) before being downconverted to IF and fed back to the IF unit. Finally, the baseband IQ signals are returned to the AROF BBU for OFDM decoding and demodulation, as well as real-time BER evaluation.

It should be noted that for experimental convenience and to emulate a realistic worst case scenario, no end user is included and the transmitted signal of the RU is also its received signal. As the end-user is expected to perform electrical up- and downconversion for both up- and downlink, the demonstrated link is assumed to constitute a worst case in terms of phase and amplitude noise, as both the RF signal and the LO for downconversion are generated by optical heterodyning after MCF transmission and thus required significant amplification.

III. Experimental Results

The evaluation of the presented AROF fronthaul system is based on observation of the spectra of the transmitted RF signal and the transmitted and received IF signals (Fig. 3(a) and (b), respectively), as well as on the real-time BER calculated by the AROF BBU and corresponding signal constellations (Fig. 4(a) and (b), respectively). Figure 3(a) shows the transmitted RF spectrum, clearly showing the targeted 25.5 GHz signal, as well as a tone at $f_{RF,LO}$ resulting from the beating of the two optical tones. The latter is suppressed by around 20 dB compared to the target carrier by the high-pass filter and as it is outside the antenna band it is not transmitted. Figure 3(b) shows a comparison of the transmitted and received IF signals centered at 5 GHz. While both signals have approximately equal power, the received IF signal has a severely degraded signal-to-noise ratio (SNR) of around 12 dB, compared to

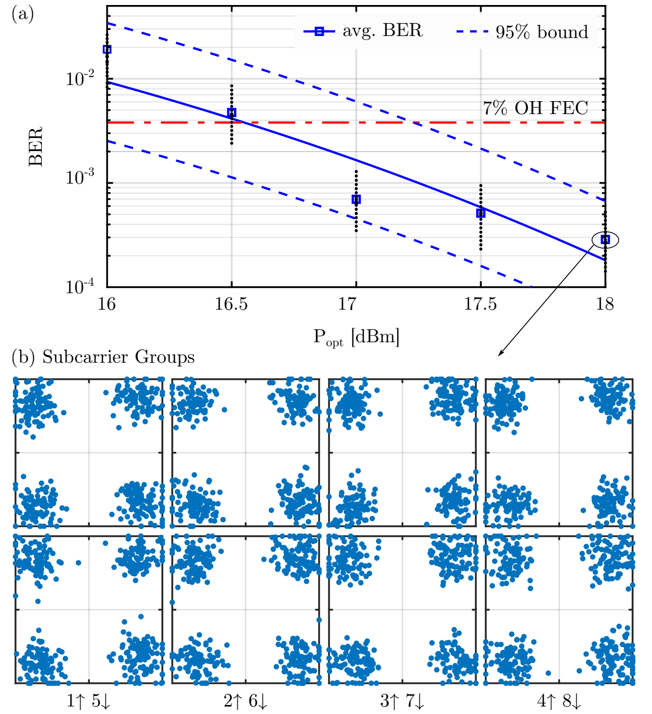

Fig. 4. Experimental results showing (a) the observed real-time BER over optical power and (b) the observed constellations.

>30 dB for the transmitted IF signal. The received IF spectrum further has a slightly lower carrier-to-signal ratio as well as a tilt towards the higher frequencies, suggesting a non-flat system response across the IF spectrum.

System BER performance was evaluated for different optical powers after two-tone generation and hence for the case where both RF signal and LO vary in power as optical power varies. Thus, every 1 dB of optical power reduction translates directly into 2 dB of RF and LO power reduction and thus an estimated 5 dB in received IF power degradation – where the additional 1 dB is due to lower mixer efficiency at lower LO levels. BER is measured repeatedly over short time intervals of a few seconds at each power level, to not only capture average BER, but also its variation over time. The resulting BER measurements as well as their averages are shown in Fig. 4(a), alongside the BER limit for a standard forward error correction (FEC) with 7 % overhead. The figure further shows the 95 % confidence bounds for the BER for any such short time interval, derived from the measured BER statistics.

Finally, Fig. 4(b) shows the received constellations, splitting the 800 MHz wide signals into eight subcarrier groups of equal width, i.e., roughly 100 MHz wide. As can be seen, the constellations are similar for all groups, with mainly the first and the two last groups exhibiting some degradation. This can be attributed to a reduced low-frequency performance of the modulator in the IF unit as well as bandwidth limitations of the latter and the slight power reduction at higher frequencies previously observed on the received IF signal.

The observed BER performance and constellations shows that the presented AROF fronthaul and mm-wave transmission link can easily reach the BER limit for a simple hard-decision FEC with some power margin. This suggests operation at lower powers or with higher order constellations – and thus increased capacity – to be viable when including more complex coding schemes such as the ones usually employed in mobile and radio communications.

IV. Conclusions

An ARoF fronthaul link with full real-time signal processing of an 800 MHz wide extended 5G NR OFDM signal and IFoF transmission over 10 km 7-core MCF was shown, achieving data rates of 1.4 Gbit/s after 9 m mm-wave wireless transmission at 25.5 GHz with BER below the 7 % overhead FEC limit. The proposed ARoF fronthaul link further employs a remote-fed LO for electrical downconversion, thus achieving not only minimum optical bandwidth requirements through the use of IFoF, but also maximum centralization of network functionality and complexity.

The demonstrated fronthaul link validates the ARoF fronthaul concept and shows a possible use and advantage of SDM in the RAN. In addition, through the use of fully real-time signal processing, the potential for timely deployment of such links for mm-wave and high-capacity 5G is shown.

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