DSP enabled Fiber-Wireless IFoF/mmWave link for 5G Analog Mobile Fronthaul

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Abstract—An Analog RoF-based Mobile Fronthaul architecture compatible to 5G requirements is presented. Experimental demonstration of 24 Gb/s IFoF transmission based on Digital Subcarrier Multiplexing technique is reported using a centralized DSP unit. Combined with 60 GHz radio equipment, successful indoor uplink/downlink experiments are demonstrated using Single Carrier QPSK/16-QAM achieving up to 4 Gb/s total capacity over a fiber/wireless link.

Index Terms—Mobile Fronthaul, Analog RoF, Indoor measurements, Millimeter Wave Radio, Digital SCM, Digital Precompensation/Equalization, M-QAM

I. INTRODUCTION

We have reached a critical point where the first wave of 5G compliant technologies and architectures have moved beyond their research and development phase and are now on the verge of commercial exploitation [1]. However, there are still more than a few technology issues that remain open and their resolution will have a significant impact to future 5G topologies. One of these key issues, is the synergy between 5G wireless technologies and optical transport, a topic that has been recently receiving increased attention. Since optical fibers have been identified as the chosen medium for transporting mobile traffic towards and from centralized baseband controllers, Radio-over-Fiber (RoF) is gaining momentum as the appropriate solution to distribute radio signals at mmWave frequencies from the Baseband Units (BBUs) to a large number of Remote Radio Heads (RRHs) [2].

Several techniques have been proposed in literature for this data transport that exploit either Analog (A-RoF) or Digitized (D-RoF) radio signals over the fiber channel [3]. The latter, has been adopted as the current standard for Long Term Evolution-Advanced (LTE-A) mobile networks where the fronthaul interface is based on the Common Public Radio Interface (CPRI). However, even though the evolution of CPRI protocols currently appears as the preferred option from the 5G industry cooperation [4], the poor scalability of D-RoF in terms of bandwidth requirements makes the A-RoF concept as a highly appealing fronthaul approach for future Centralized/Cloud Radio Architectures (C-RAN). Although A-RoF is prone to distortions, transmission impairments and nonlinearities of both fiber and wireless parts [5], its inherent bandwidth efficiency advantage over the bandwidth-hungry CPRI techniques, as well as the less complex RRH design required, leads to increased cost-efficiency when 5G network specifications are considered [6].

In this frame, the research landscape of Analog Mobile Fronthaul (MFH) solutions has been recently revisited to address the challenges of the analog fronthaul protocol, considering the design goals and requirements of 5G topologies. Thorough simulation studies have been carried out to investigate the performance of A-RoF links operating at tens of Gb/s focusing on the fiber channel characteristics [7]. Experimental demonstrations have been conducted focusing on the performance evaluation of Analog MFH optical links using different modulation schemes and spectral allocation for radio signals consisting of LTE waveforms. In particular, effective transportation of single-carrier 48×20 MHz LTE [8] and 24×100 MHz OFDM-64-QAM (Quadrature Amplitude Modulation) [9] signals on IFoF at a few km-long Single Mode Fibers (SMF), while the use of multiple parallel modulators revealing record FH capacity of 1Tb/s CPRI equivalent data rate over 20km SMF [10] have been recently reported. NTT reported 256-QAM wireless transmission with DSP-assisted analog RoF for MFH on LTE-B [11]. Recently, channel aggregation based on advanced DSP techniques were presented for Optical Fronthaul [12]. Moreover, real-service distribution has been demonstrated in the 28 GHz band, with a 5G prototype video transmission at 1.5 Gb/s [13]. However, research efforts to jointly evaluate on the same Fiber-Wireless (Fi-Wi) experimental testbed the A-RoF concept for the optical part together with mmWave radio deployments for air transmission, are still below expectations.
This work addresses this research gap by presenting extensive experimental results for IFoF MFH links supporting V-band air transmission. We introduce a DSP-assisted A-RoF concept to efficiently accommodate multiple broadband radio signals using commercial off-the-shelf electronic/photonic components. Within this frame (Fig. 1), a centralized BBU which serves a number of RRHs, provides a complete set of digital functionalities allowing for the optical transport of the radio waveforms through the installed fiber infrastructure and their transmission through the air using mmWave carriers. In this centralized approach, the appropriate data signal waveforms are generated in the DSP-enhanced BBU and seamlessly transported through the fiber/wireless link. This centralized approach concentrates the entire digital processing of the link on the BBU side while the served RRHs are responsible only to handle the vast spectral slices with their mmWave radio hardware. These experimental studies have revealed the impact of optical transport channel impairments (fiber loss, chromatic dispersion, nonlinearities due to electro-optic conversion) on complex-modulated Intermediate Frequency (IF) carriers generated from the BBU. Different types of IQ signals in terms of symbol rate, number of radio bands, modulation type and radio carrier frequencies, have been employed to quantify the A-RoF performance using Error Vector Magnitude (EVM) measurements at the receiver side. The Fi-Wi transmission experiments were evaluated on both DownLink (DL) and UpLink (UL) operation and the additional distortion due to V-band RF electronics considering the effects of a realistic 60 GHz indoor wireless environment. The DL/UL operation was demonstrated for Single Carrier (SC) radio bands, carrying different M-ary Quadrature Amplitude Modulated (M-QAM) signals.

The rest of the paper is organized as follows: section II introduces the DSP-enabled A-RoF detailing the advantages offered allowing the operation of DSP-free RRHs. Section III presents the experimental setup and a set of results for the IFoF MFH scenarios obtained for various link configurations. Section IV comprises of the results of both fiber and air transmission of wideband radio signals. Section V discusses key-results and addresses open issues for the near-future experiments while the section VI concludes the presented work.

II. DSP-ENABLED A-RoF ARCHITECTURE FOR MOBILE FRONTHAUL

Unlike the conventional approach in Analog and Digital MFH implementations where a DSP processing unit lies on each RRH, we present an alternative A-RoF/mmWave topology with a centralized DSP-engine located only on the BBU. Such a topology removes baseband/digital operations from the antenna hardware, assigning the enhanced BBU a complete platform of baseband processing, applied on digitized signals of the physical layer. This platform is responsible for:

- **Modulation and Channel Mapping:** the appropriate data signals that will be transmitted over the Fiber/Wireless link are generated in the centralized BBU. Digital modulation techniques allow for generating any arbitrary Single-Carrier or Multi-Carrier scheme. Moreover, the use of Digital Sub-Carrier Multiplexing (SCM) techniques can also be supported to mitigate the effect of nonlinear distortion stemming from both fiber/RF parts [14]. For the SCM case, digital upconversion schemes are employed to generate the appropriate IF frequencies for A-RoF transmission, eliminating the need of external analog mixers and local oscillators. In this work, we focus on Single-Carrier M-ary Phase Shift Keying (M-PSK) and M-ary Quadrature Amplitude Modulated (M-QAM) formats (Single-band operation) along with sub-carrier multiplexed combinations of them (Multi-band operation).

- **Digital pre-Distortion and Channel Equalization:** As the “DSP-free” RRH units are not capable of baseband signal processing, the centralized enhanced BBU DSP engine serves on a two-fold dimension. Digital pre-distortion of the downlink based on the fiber/wireless channel response is performed, also accounting for the hardware components of the optical and the RF-antenna subsystems. In the uplink, channel estimation and equalization stages are enhancing the demodulation and detection of the received radio signals after Wireless/Fiber transmission. The above DSP functionalities are further supported by the BBU capability of generating the broadband baseband and IF-modulated signals. High-performing Digital-to-Analog Converters (DACs) and Analog-to-Digital Converters (ADCs) operating at increased sampling frequencies (compared to the symbol rate of each subcarrier) and supporting larger bandwidths compared to the current LTE/LTE-A systems support the increased data rates of the converged fiber/wireless transmission system.

Any cost increase induced by digital/analog interfaces is compensated by the exploitation of legacy Intensity Modulation/Direct Detection (IM/DD) optical transceivers and frontends. Conventional techniques

![Figure 2: Experimental Setup of the Analog RoF link.](image-url)
employing external modulators (Mach Zehnder Modulators (MZMs), Electron Absorption Modulators (EAMs)) and lasers (Distributed Feedback (DFB)) at the optical transmitter. Since IF frequencies are employed as a means to balance the bandwidth gap between the electronic and photonic devices, for the RoF transmission, the need for high speed optical frontends is eliminated. At the receiver, single photodiodes relax the optoelectronic conversion complexity, allowing simple interconnection with the RF frontends of the RRHs operating at low (IF) frequencies.

On the DSP-free RRH the downlink operation is achieved through, IF-to-mmWave upconversion and wireless transmission over the unlicensed frequency band (57-64 GHz). The UL direction requires the reverse operation since the RRH generates an IF-modulated signal that is transmitted back to the centralized BBU.

III. EXPERIMENTAL DEMONSTRATION – IFoF ENABLING BACKHAULING

A. Analog RoF link parameters investigation

Figure 2 depicts the experimental setup employed for the evaluation of the IFoF scenarios. An Arbitrary Waveform Generator (AWG) was used to provide the data signals for both single- (Ch1) and multi- (Ch1 to Ch6) band scenarios at modulation rates up to 1.25 Gbd. The programmable data source allowed the necessary Tx-side DSP operations described in the previous section. Pulse shaping (using Root Raised Cosine (RRC) shaping filters with roll-off factor $\alpha = 0.2$) and digital pre-distortion of the optoelectronic components were performed to the following experiments. To this end, channel estimation (using pilot tones) has been performed, prior the actual data transmission, where an amplitude and phase channel response was estimated on the frequency domain. Through the AWG, the pre-distorted data signals were digitally upconverted to the selected IF. A single-drive MZM was used to generate the IFoF signal carrying the radio bands with the intensity modulator biased at the quadrature point ($V_{e}/2$). A Continuous Wave (CW) DFB-laser emitting at 1543.73 nm of +10 dBm provided the optical carrier to the IFoF transmitter.

Two fiber links of Standard SMF (SSMF) (7 km & 25 km) were used to investigate the role of fiber length on the optical transmission. The optical power of the IFoF signal was measured by means of an optical power meter set prior to an off-the-shelf 10 GHz linear photo-receiver comprised of a photodiode (0.7 A/W responsivity) and a low-noise amplifier with 20 dB gain.

The Single-Band experiments were carried out by using an IF frequency of 5 GHz. The IFoF transmission at 5 GHz was selected in order to meet the specifications of the mmWave Upconverter at the radio part. Such selection easily accommodates the entire bandwidth (~7GHz) within the targeted unlicensed radio band and provides resilience against the power fading due to Chromatic Dispersion (CD) for fiber lengths up to 25 km [5].

Experimental studies on A-RoF MFH link were performed focusing on the symbol rate and the modulation order of the IF signal. The goal of this study was to fully characterize the effect of fiber channel for various radio signal characteristics. Besides, leveraging from the DSP capabilities for generating any complex modulation scheme at the transmitter side, the feasibility of increased spectrum utilization was also demonstrated. Generating different types of complex

<table>
<thead>
<tr>
<th>IF: 5 GHz</th>
<th>EVM rms (%)</th>
<th>EVM Req. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation format</td>
<td>btb</td>
<td>25 km</td>
</tr>
<tr>
<td>QPSK</td>
<td>1.68</td>
<td>4.37</td>
</tr>
<tr>
<td>8-PSK</td>
<td>1.78</td>
<td>4.52</td>
</tr>
<tr>
<td>16-QAM</td>
<td>2.16</td>
<td>4.62</td>
</tr>
<tr>
<td>64-QAM</td>
<td>2.19</td>
<td>4.84</td>
</tr>
<tr>
<td>128-QAM</td>
<td>2.29</td>
<td>4.90</td>
</tr>
</tbody>
</table>

**Figure 3:** Constellation diagrams of the received signals at different modulation schemes after transmission over 25 km SMF.

**Table 1. EVM measurements for different modulation formats @ 1 Gbd**

<table>
<thead>
<tr>
<th>Symbol Rate</th>
<th>EVM rms (%)</th>
<th>EVM Req. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF: 5 GHz / QPSK</td>
<td>btb</td>
<td>25 km</td>
</tr>
<tr>
<td>500 Mbd</td>
<td>1.45</td>
<td>2.66</td>
</tr>
<tr>
<td>750 Mbd</td>
<td>1.64</td>
<td>3.24</td>
</tr>
<tr>
<td>1 Gbd</td>
<td>1.70</td>
<td>4.37</td>
</tr>
<tr>
<td>1.25 Gbd</td>
<td>1.74</td>
<td>5.50</td>
</tr>
</tbody>
</table>

**Figure 4:** Constellation diagrams of the received signals for different baud rates after transmission over 25 km SMF.
waveforms carrying symbols rates of 1 Gbd, EVM values below the limits set by 3GPP specification were achieved [15] (with a minimum EVM margin of 5% for 64-QAM signals) for each format investigated, without any additional equalization stage at the receiver side. The successful IFoF transmission of a 128-QAM modulated IF carrier over a 25-km optical link corresponds to a spectral efficiency 5.83 b/s/Hz for the A-RoF link. EVM measurements for set of M-QAM and M-PSK schemes are presented in Table 1 and the respective constellation diagrams after detection and demodulation are also shown in Figure 3. Moreover, the reported results indicate that an identical EVM penalty of less than 2.7% was introduced by the fiber part for all the modulation types. This result implies that the IFoF transmission can be resilient to fiber channel impairments supporting more complex modulation types without any significant quality distortion.

Table 2 summarizes the measured EVM values for different symbol rates. It can be observed that for symbol rate variations between 500 Mbd to 1.25 Gbd, the EVM is slightly increasing from 2.66% to 5.50%, after 25 km transmission. Through this result a good agreement between the theory and experiment is appeared since the fiber CD introduces severe distortion for wideband signals [5]. Nevertheless, the measured EVM values are well below the EVM threshold for a QPSK modulated signal as specified by 3GPP. The respective constellation diagrams of the received signals at 25 km length are also depicted in Figure 4. This result reveals a strong scalability potential of further increase the transmission rate of a single IF-modulated band.

B. Increase Spectral Efficiency for MFH with SCM-RoF

The next evaluation step involves the increase of the overall bandwidth utilization for the proposed A-RoF concept by introducing a digitally generated SCM signal to extend the operating bandwidth of the single carrier approach which was discussed in the previous section.

Exploiting once more the DSP capabilities on generation of complex waveforms, four different subcarriers have been digitally synthesized, before feeding a single DAC channel in order to generate the desired multiband radio signal. The 4 sub-bands were assigned at 0.625 GHz, 1.875 GHz, 3.125 GHz and 4.375 GHz center frequencies (around 2.5 GHz) and each of them was modulated at 1 Gbd symbol rate, pulse-shaped with a root raised cosine filter (α = 0.2), utilizing thereby a total 5 GHz bandwidth. Figure 5(a) shows that in the case of back-to-back measurement, all sub-bands have almost the same performance and the modulation type does not affect the measured EVM values. After transmission over the 25-km fiber link, the effect of dispersion-induced power fading is evident, since the higher frequency components suffer from severe distortion compared to lower ones. The use of a higher order modulation format slightly increases the EVM value. With EVM values below 9%, all QPSK, 16-QAM and 64-QAM schemes achieve accepted performance in all the allocated spectrum bands [15]. With a 64-QAM scheme an overall capacity of 24 Gb/s is achieved.

To further extend the above SCM approach, a 6-band SCM signal was generated by exploiting the high bandwidth DAC provided by the AWG. A total bandwidth of 7.2 GHz with a center IF carrier at 3.6 GHz was achieved. In this case, the sub-carriers’ center frequencies were selected to be 0.6 GHz, 1.8 GHz, 3 GHz, 4.2 GHz, 5.4 GHz and 6.6 GHz while each of them was modulated with a QPSK at 1 Gbd. The performance was evaluated after 7 km and 25 km of fiber transmission and this set of measurements is depicted in the plots of Figure 5(b). As in the case of 4 bands, the first 3 subcarriers exhibit similar performance, while the bands located at higher frequencies result in higher EVM values. Such performance degradation for the 2 higher frequency bands can be explained, considering the RF plan for Subcarrier Multiplexing scheme as described in [17] and taking into account the severe distortion due to nonlinear Intermodulation effects [18]. The impact of dispersion is evident after 25 km transmission but not in the case of 7 km as it was originally expected. Higher frequency carriers would be needed to observe the effect of dispersion in a shorter fiber link, like this.

Figure 5: EVM measurements for each sub-band of the SCM A-RoF link (a) 4-bands, Constellation diagrams for 64-QAM after 25km, (b) 6-bands, Constellation diagrams for QPSK after 25km.
Comparing the EVM performance between the single band and multiple band IFoF transmission, it is evident that the signal distortion is increased for increased number of radio bands as it is expected. Moving towards wide-band, multi-carrier approaches, the analog photonic links suffer from cross modulation distortion (XMD) which introduces severe distortion in the modulated in-band of each signal [18].

C. A-RoF/mmWave Uplink and Downlink transmission using Single-Carrier M-QAM schemes

Combining the proposed A-RoF IM/DD optical fronthaul topology with commercial V-band radio hardware (operated at 57-64 GHz unlicensed band), indoor wireless measurements using directional antenna elements were performed.

Figure 6 illustrates the experimental setups employed for both UL/DL scenarios. For the DL operation (Figure 6a) the signal after the transmission through the A-RoF link was received by a photoreceiver (Avalanche Photodiode (APD) Transimpedance Amplifier (TIA)). This IF modulated output is fed into a mmWave upconverter connected to a V-band directional antenna (Tx-antenna). The V-band converter had a nominal noise figure of 8 dB at maximum gain. Standard pyramidal gain horn V-band antennas of 23 dBi gain and 10° beamwidth were employed. The signal received by an identical antenna located in a 5 m horizontal distance from the Tx-antenna. The antennas, together with the up- and downconversion units, were mounted on wooden tripods and kept fixed at a height of 1.4 m above the floor. We evaluated the Fiber-Wireless (Fi-Wi) link on the receiver side by capturing the modulated data on a real time oscilloscope. Since none of the antennas perform equalization or any baseband processing, the response of the mmWave components (e.g. local oscillators, mixers, filters, waveguides) was evaluated using the DSP platform at the Rx antenna.

For the UL operation (Figure 6b), the IF modulated signal feeds directly the Tx-antenna frontend, while the Rx-antenna is used as the driving signal for the MZM of the A-RoF link. The now reversed Wireless/Fiber link (along with the passive and active electronic components) is evaluated at the output of the A-RoF link where the photoreceiver provides the input to the Digital Oscilloscope for offline processing.

In both cases, after the digitization of the received signals, digital downconversion from the IF frequency to baseband was performed. There, matched filtering, resampling and proper timing synchronization was applied in order to extract a single-sample per symbol sequence. For the equalization stage, a static 5-tap Radius Directed Constant Modulus Algorithm (CMA) algorithm was employed for off-line equalization of both fading effects stemming from both fiber-air transmission and to remove the frequency response from mmWave components. Finally, a Carrier Phase Recovery stage compensated for the phase noise due to local oscillators’ mismatches. Statistical constellation analysis and error

![Figure 7: Experimental Setup of the Analog RoF/mmWave link. (a) Downlink direction, (b) Uplink direction.](image)

![Figure 6: (a) EVM bar-diagram measurements for A-RoF/mmWave transmission in uplink and downlink directions (b) Constellation diagrams for QPSK and 16-QAM after Rx-side DSP.](image)
counting was employed for estimating and measuring the transmission quality.

In this experiment Single-Carrier QPSK and 16-QAM at 1 Gbd symbol rate were employed as modulated radio signals. A root-raised-cosine pulse shaping filter with 20% excess bandwidth resulted a total 1.2 GHz to be transmitted through the fiber/wireless link. In Figure 7 we present an EVM bar diagram for both uplink and downlink operation using the above modulation types. Two different test cases were investigated by introducing the long fiber part of 25 km. The reported results reveal that the combined fiber/wireless link (25 km fiber and 5 m air-transmission) achieve accepted performance in terms of EVM as specified by the 3GPP specification. A fair direct comparison between the UL/DL cases should not, however, be considered from the above results since both cases were investigated by keeping constant the setup parameters (Electro-optic modulator, RF amplifiers, optical and RF power levels). Under realistic conditions, both cases would be implemented by using dedicated opto-electronic parts for each case (UL/DL) being properly configured at optimum points.

IV. CONCLUSION

An experimental demonstration of a Mobile Fronthaul architecture has been presented. A DSP-assisted A-RoF topology was demonstrated offering the generation and transmission of broadband radio signals capable of supporting the targeted specifications for 5G-era. Single Carrier and Digital Subcarrier multiplexed signals with high order modulation formats (M-PSK and M-QAM) have been examined for increasing the overall capacity of the fronthaul link, exhibiting robust performance for fiber distances up to 25 km. The optical transport of multiband radio signal carrying up to 24 Gb/s (using 64-QAM signals) was experimentally demonstrated showing EVM values below 9%.

Radio devices operating at V-band connected to the A-RoF link and an evaluation of the complete fiber/wireless channel has been performed for both UL/DL cases. Demodulation and detection of the radio signals has been achieved utilizing standard DSP only after the fiber/wireless transmission without any processing units at the antenna subsystems. Single carrier schemes at 1 Gbd using QPSK and 16-QAM formats were detected and demodulating utilizing receiver-side DSP. The fiber-wireless transmission of 4 Gb/s was successfully demonstrated for both UL/DL cases using 16-QAM schemes exhibiting EVM below the 14% requirements for systems operating at the region of the mmWave regime.

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