Available Resources for Reconfigurable Systems in 5G Networks

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***Abstract*—In this paper, the concept of a Radio-over-Fiber based Centralized Radio Access Network is explained and analyzed, in order to identify a set of resources within the network that can be used as a base in the design of reconfigurable systems. This analysis is then used to design a different reconfigurable systems to be implemented as part of the next generation Radio Access Unit. These systems are then implemented and experimentally tested, allowing to demonstrate their operation. The obtained results allow to show the feasibility of the systems and the implementation of a flexible architecture for the next generation of networks.**

Keywords–Mm-wave communications; Optical fiber networks; mobile communication.

I. Introduction

The next generation of networks comes from the ideas of achieving higher capacity, allowing more users in the network and integrating new technologies. These ideas come with different requirements for the networks, in terms of data rates, mobility, latency and spectrum allocation [1].

One step to solve some of these challenges is the use of carriers within the millimeter-wave (mm-wave) frequencies, with the Ka-band (26 GHz to 40 GHz) and the W-band (75 GHz to 110 GHz) being two interesting candidates for the implementation [2]. These higher carrier frequencies allow the use of wider bandwidths in the wireless channels, thus increasing the capacity of the link. The main disadvantage is the high atmospheric attenuation in these frequency ranges. This effect has been addressed by proposing a modification on the Radio Access Network (RAN), consisting of an increase in the number of wireless access points, allowing better coverage in the mm-wave link.

In addition to increasing the number of access points, another big change has also been proposed in the RAN. This change centralizes the processing and operation of the RAN in what is known as the cloud or Centralized RAN (C-RAN). The efforts here are set to simplify the wireless access points, easing their implementation and reducing the implementation (CAPEX) and operation (OPEX) costs of the network [3][4].

Lastly, Radio-over-Fiber (RoF) techniques have been proposed to be the backbone technology of the C-RAN to interconnect the different points of the network and distribute the signals [5][6][7][8]. In this technique, the radio signal is modulated and accommodated to be transmitted in the wireless channel in the source; this signal is then used to modulate a laser, so it can be transmitted directly to the antenna in the optical domain.

In this paper, the architecture of a RoF based C-RAN is analyzed, in order to show the available resources that can be used for the design of reconfigurable networks. Then, some solutions are presented and evaluated, showing the added capabilities of reconfigurable systems within the C-RAN. In Sections II, a general description of the concepts of C-RAN and photonic up-conversion is presented. In Section III, we discuss the available resources in the C-RAN that can be used on the design of flexible systems; Section IV presents some examples of reconfigurable systems in the network. We summarize the discussion and results on Section V.

II. Base technologies

This section explains the two main technologies used as a base for the proposed architectures: the architecture of the C-RAN and photonic up-conversion, used in RoF transmissions to generate the electrical signal in the mm-wave band.

A. The implementation of the C-RAN

The typical architecture of the C-RAN is composed of the Central Office (CO) and the Radio Access Units (RAUs). In this implementation of the RAN, the Base Band Units (BBUs) are taken away from the RAUs, and located in the CO as a virtual BBU (vBBU) pool. This change will simplify the design and implementation of the RAUs and allow the network to centralize the processing in the CO. A typical implementation of the C-RAN is presented in Fig. 1, alongside some examples for different types of access within the network.

The CO will have additional tasks and roles within the network, acting like the gateway between front- and backhaul, being in charge of collecting the signals, process them and redistribute them to each RAU as necessary. This centralization will ease the operation on each RAU and limit the processing points, which in turn will help to reduce the total latency of the system. Moreover, removing the BBU from the RAU will take away most of their complex operations. The signals will be modulated and processed in the CO; and the RAU will accommodate them to be wirelessly transmitted. Therefore, the RAUs will work as interfaces between the wireless and the optical networks.

The simplification of the RAU comes with an additional advantage under the context of the implementation of mm-wave band links. Since the RAUs are the wireless access points of the network, their simplification will ease and reduce costs for their implementation and the desification process that was proposed to increase the total coverage of the network. In addition, the simplified design of the RAUs, will also allow

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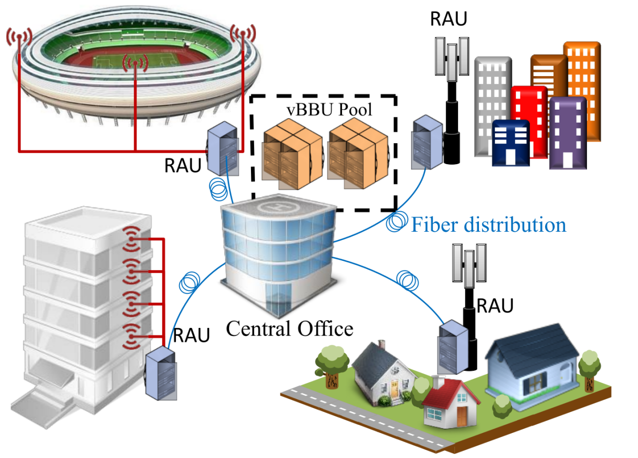

Figure 1. Typical implementation of the C-RAN. The heavy processing is performed in the vBBU pool located in the Central Office. The signals are centralized in the Central Office and then distributed to the RAUs. RAU: Radio Access Unit; vBBU: virtual Base Band Unit.

the implementation of new architectures within the RAN, as is the case of distributed antennas, to improve the connection in indoor and wide outdoor areas.

B. Photonic Up-conversion

The photonic up-conversion is a method to generate the mm-wave signals using the characteristics of optical devices as an advantage. In this process, the signal is generated through direct heterodyning in a wideband Photodiode (PD) [9]. This method takes use of two optical signals: one that contains the information ($s(t)$) modulated in a RoF signal that comes from the central office ($E_s(t)$), with an angular frequency ω_s; and one that is going to be used as an optical Local Oscillator (LO, $E_{LO}(t)$) at angular frequency ω_{LO}. The two signals are then expressed as:

$$E_s(t) = \sqrt{P_s} s(t) \cdot e_s \exp[-j(\omega_s t + \phi_s)] \quad (1)$$

$$E_{LO}(t) = \sqrt{P_{LO}} e_{LO} \exp[-j(\omega_{LO} t + \phi_{LO})] \quad (2)$$

where P_s, ϕ_s e_s represent respectively the power, phase and polarization unit vectors for the modulated signal; and P_{LO}, ϕ_{LO} and e_{LO} are the values for the LO. The electrical signal given at the PD will be composed of two components, one baseband component and one RF signal with a carrier of $\omega_{RF} = |\omega_s - \omega_{LO}|$. The baseband component is filtered by the limited bandpass bandwidth of the antenna. The final transmitted RF signal can be described as

$$E_{RF}(t) = 2\sqrt{P_s \cdot P_{LO}} \cdot s(t) \cdot e_s e_{LO} \cdot \cos[\omega_{RF} t + \phi_{RF}(t)]. \quad (3)$$

III. Available resources in the 5G generation access network

In the CO, the data will be processed in a BBU and it will be electrically modulated on an Intermediate Frequency (IF). The signal is then transformed into the optical domain and transported through the optical channel to the RAU using RoF techniques. In the RAU, the photonic up-conversion process (explained in Section II) takes place, transforming the signal back to the electrical domain for transmission through the wireless channel. The connection between the CO and the different RAUs is summarized in Fig. 2. Generally, in these applications, the PD (Optical/Electrical interface) and the Power Amplifier (PA) are integrated with the antenna. Therefore, the RAU will transport the signal to the antenna directly in the optical domain.

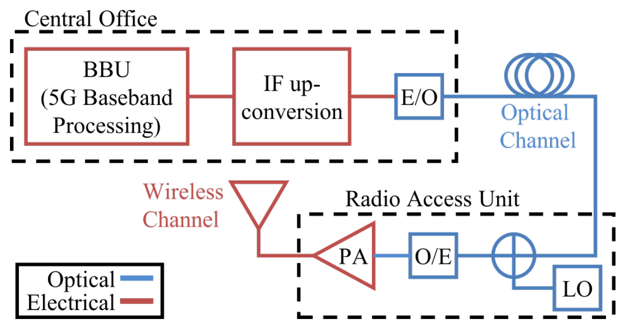

Figure 2. Simplified scheme of the signal path of the C-RAN. Composed by the Central Office, the optical channel, the Radio Access Unit and the wireless channel. BBU: Base Band Unit; IF: Intermediate frequency; E/O: Electrical to optical conversion; LO: Local Oscillator; O/E: Optical to electrical conversion; PA: Power amplifier.

In both the optical and wireless channels, there are different kinds of resources and applications that the network can use to achieve a better and more efficient transmission of the information. The following subsections provide a short review of some techniques previously proposed.

A. Optical channel

The following techniques make use of optical technologies or devices to add extra functionality to the network. We will focus on three main techniques:

1) Wavelength: Within the optical channel, one of the most used resources is the wavelength of the optical carrier. In Wavelength Division Multiplexing (WDM), different signals are modulated in different carrier wavelengths, with a wavelenght separation predefined by the ITU standard [7][8][10]. All the RAUs will receive all the WDM signals and dynamically select one according a control signal from the CO.

2) Optical switches: Some optical channel use optical switches to redirect the signal to different points of the network [10][11][12]. In these implementations, the data is distributed in packets and signaling information is sent along with it, either in form of a label on the packet or a synchronization order from the CO. The RAU will then redirect the signal to different fibers that lead to different antennas, either in the same location or in distributed arrays of antennas.

3) Multicore Fibers: The last technique that has been proposed in these area, corresponds to the use of Multicore Fibers (MCF) in the implementation of the access networks [6]. In this technique, the different cores of the MCF are used to transmit different signals through the network. Each core is used as a different channel, which can be either reserved for up-link or down-link. Therefore, both the RAU and the CO can select in which core to transmit and in which to receive an optical signal.

B. Electrical channel

The techniques implemented in the electrical domain focus on the use of the RF spectrum or in modifications within the antenna to give extra tunability to the network. There are mainly three techniques to explore:

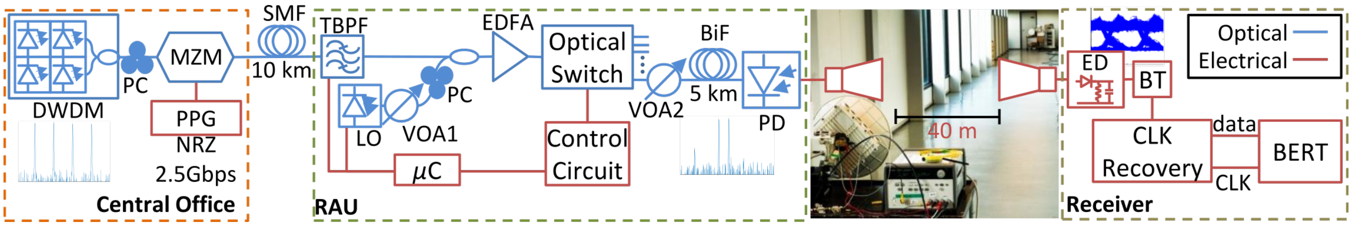

Figure 3. Implemented experimental setup to test the reconfigurable systems. DWDM: Dense wavelength multiplexion; PPG: Pulse pattern generator; NRZ: Non-return-to-zero; PC: Polarization controller; MZM: Mach-Zehnder modulator; SMF: Single mode fiber; RAU: Radio access network; TBPF: Tunable band pass filter; LO: Local Oscillator; μC: Micro-controller; VOA: Variable optical attenuator; EDFA: Erbium-doped fiber amplifier; BiF: Bend-insensitive fiber; PD: Photodiode; ED: Envelope detector; BT: Bias tee; CLK: Clock; BERT: Bit-error-rate tester..

1) Carrier frequency: Similar to the optical domain, the first technique consist of the use of multiple carrier frequencies during the transmission of the signal. In this case, the LO used within the system can be tuned, allowing to the RAU to change the carrier frequency as necessary [7][13].

2) Beam steering: In order to compensate for the atmospheric attenuation, it is desired to use antennas with high gain. However, with a higher gain, the antenna becomes more directive, which results in a low coverage area. The beam steering techniques aim to modify the direction pattern of these antennas, allowing them to change the direction of the main transmission lobe so they can achieve better coverage [14]. In this technique, the network will get feedback on the status of the communication link from the user terminal and adjust the radiation pattern of the transmitting antenna in order to enhance the power on each wireless link connected to the network.

3) Reconfigurable antennas: This technique modifies the antenna's pattern or operation to give additional functions to the system, that not necessaryly focus on the direction of the main lobe.This can be as is in the case of the Optically Controlled Reconfigurable and Multiband Slotted waveguide Antenna Array (OCRAA) [15] or the T-shaped antenna [16]. The former is an antenna which implements a silicon piece that acts as a switch in the antenna, modifying the radiation pattern by turning the antenna "on" and "off". The latter refers is an antenna that uses variable resistors to modify the resonant frequency of the antenna.

IV. Reconfigurable Systems in the Access Network

In this section, we collect some proposed solutions and their results, to design reconfigurable RAUs. All of them are based on the same principle and same base architecture, as presented in Section III. A more detailed configuration is presented in Fig. 3, based on the proposed system presented in [7]. This architecture gives a general overview of the general components for the implementation of wireless links enhanced with the implementation of RoF.

In the Central office, the DWDM signal is generated with a set of equally distanced lasers. Then, a Mach-Zehnder Modulator (MZM) is used to modulate these lasers with a Non-Return to Zero (NRZ) Pseudo-Random Bit Sequence (PRBS) of $2^{15}-1$ bits at a rate of 2.5 Gbps coming from a Pulse Pattern Generator (PPG).

The signal propagates through a Standard Single Mode Fiber (SSMF) to reach the RAU. In the RAU, the reconfigurable systems will be installed and a LO will be added to the signal, before reaching the wideband PD (in this case with a bandwidth of 90 GHz), which will convert the signal to the electrical domain. The electrical signal will then be wirelessly transmitted by a high gain antenna.

The receiver will collect the signal using a second high gain antenna and demodulate it. In this scenario, high order modulations of are not explored, meaning that this process can be performed using an Envelope Detector (ED). The signal is then recorded with a Digital Storage Oscilloscope (DSO) or analyzed in real time with a Bit Error Rate Tester (BERT).

The following subsections, will discuss the design of the different reconfigurable subsystems and show some of the obtained results of their operation.

A. Wavelength selection

The wavelength selection system, was designed using a tunable bandpass optical system. The central frequency of the system is controlled by a micro-controller (μC) connected to the network. Once the μC receives the order to change the value of the filter, it uses a Digital-to-Analog Converter (DAC) connected to the filter to move the passband.

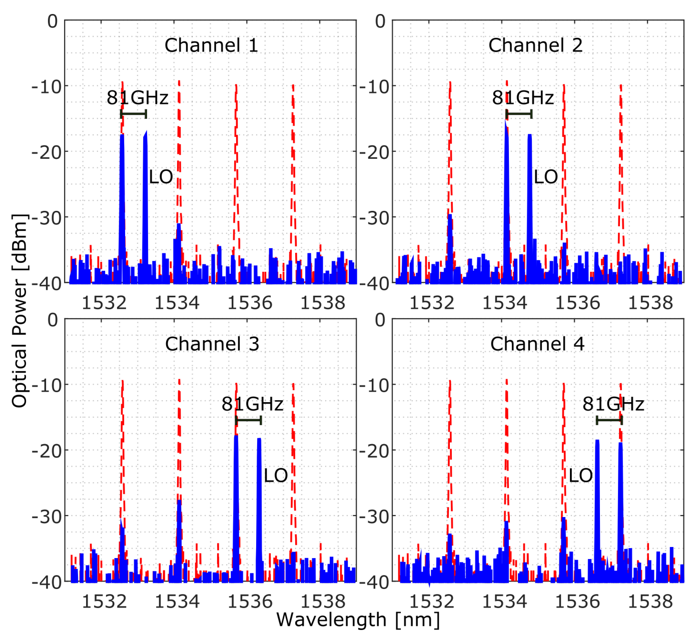

Figure 4. Reference DWDM signal (red) with the selected channel and corresponding optical local oscillator.

Four modulated optical channels with a spacing of 100 GHz between carrier wavelengths were used to test the system. Fig. 4 shows the spectra of each channel after being selected with the filter and the added local oscillator. The

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original DWDM is shown as reference in red in the background of the spectra. From the results, we can see that each signal was correctly extracted but that there are still some residues of the other channels, due to the slope and maximum attenuation of the frequency response of the filter. Two types of channels can be identified: the corner channels, corresponding to channels 1 and 4; and the center channels, channels 2 and 3. The main difference between these channels is that the center channels will have interference coming from the two adjacent channels, making their performance different than the one for the corner channels.

The measured BER traces can be found in Fig. 5(a). It can be noted that all channels present error-free results. As expected the slope of the traces for the corner channels follows the same performance, but the center channels are affected by the interchannel interference and present a different performance. The sensitivity is around $-4.4\,\mathrm{dBm}$ for channels 1, 2 and 3, and $-5.6\,\mathrm{dBm}$ for channel 4, after comparing to the Forward Error Correction (FEC) limit, corresponding to an overhead of 7%,.

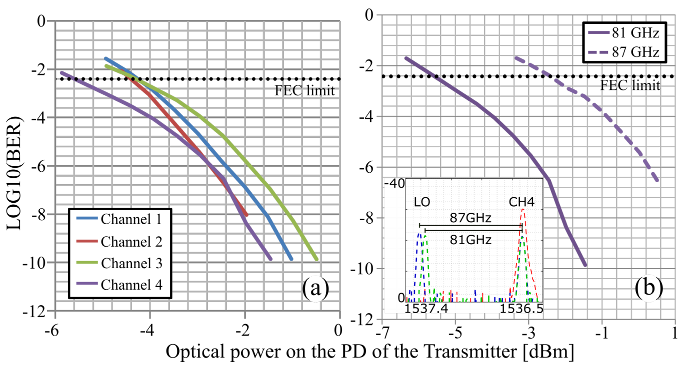

Figure 5. Measured BER vs optical power at the PD located in the RAU: (a) For the different wavelength channels; (b) for the different mm-wave Carrier frequencies.

B. Carrier Frequency selection

This system was designed by employing a tunable laser as LO. The tunable laser is controlled by the same μC as before. Once the wavelength of the LO laser changes, the output carrier frequency of the system changes in a similar way, as explained in Section II.

Fig. 5(b) shows both the optical spectra for the two different LOs and the measured BER of the two systems. In the demonstration the two resulting electrical carrier frequencies were 81 and $87\,\mathrm{GHz}$ as shown in the optical spectrum. The BER traces show that at $87\,\mathrm{GHz}$ the performance of the systems deteriorates significantly. The sensitivity of the system, compared to the FEC limit, moves from $-5.6\,\mathrm{dBm}$ to $-2.6\,\mathrm{dBm}$ for the higher frequency. This $3\,\mathrm{dB}$ difference corresponds not only to added attenuation on the channel, but the change of the slope shows that there is an additional effect. The performance is also affected by the cut-off frequency of $90\,\mathrm{GHz}$ of the PD.

C. Optical Switches

For this application, the solution is based on the design presented in [11]. In this case, a similar topology as in Fig. 3 was used to generate wireless packets in the Ka-band. This implementation consisted on the use of an optical switch to transfer the signal to different antennas in the RAU. The optical switch is controlled by a synchronization signal given by the CO; in the experiment, this signal is generated directly in the PPG.

Fig. 6 shows the operation of the system, in terms of the measured BER and the recorded times slots of the packets. The BER traces were captured for the Back to Back (B2B) case and after the wireless transmission. In both cases, the performance presents similar slope, the main difference between the two being the added attenuation due to the wireless channel. Additionally, Fig. 6 also shows the switching process of the received packets divided in time slots. In this figure, a packet can be observed in a time slot with a blank space used as safeguard for the transition. The different lines show the process of switching between a different number of outputs, demonstrate the correct transmission of the packets.

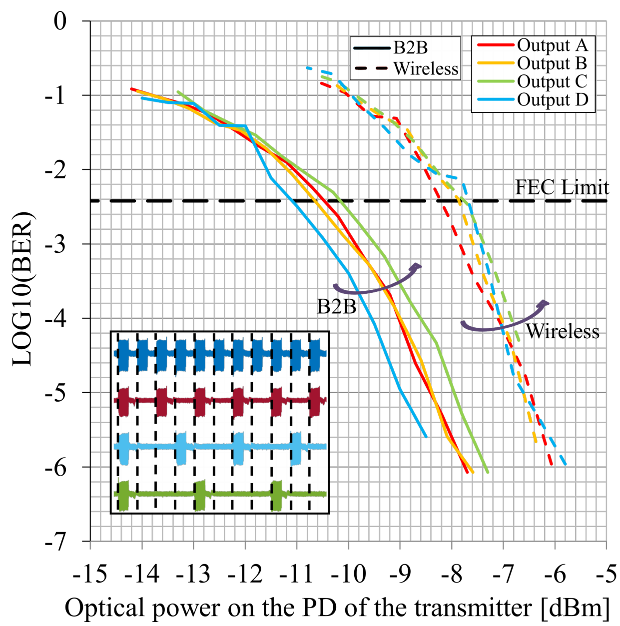

Figure 6. Measured BER vs optical power at the PD located in the RAU for the implementation using optical switches. In the side, the generated packet in time slots, with each line showing the effect of transmitting the packet to one, two three and four active outputs.

D. Reconfigurable Antennas

Fig. 7 shows the device presented and tested in [15]. This device consist of a slotted waveguide antenna that has a silicon switch in its slots. Once the silicon pieces are illuminated (”on” state), the radiation pattern of the antenna changes, creating two states of operation for the device. When the device is in the ”on” configuration, the gain will increase approximate of $9\,\mathrm{dB}$. This functionality allows the use of an extra boost of power to have higher coverage in indoor applications.

E. Beam steering

The advantage of beam steering is the capacity to redirect the main lobe of an antenna array. This can be used to enhance the coverage of a RAU or to use it as a switch between different receivers, thereby creating a dynamic wireless bridge. One example is shown in Fig. 8, based on the implementation proposed in [17]. Here two similar transmitters where placed side by side and a receiver antenna with a mechanical beam

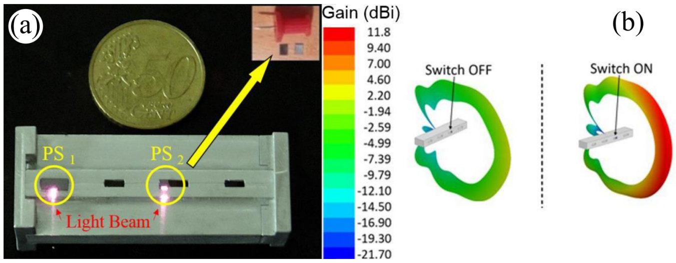

Figure 7. Optically reconfigurable antenna: (a) fabricated device and (b) Operation

steering platform was used to switch between them, as shown in 8(b) and (c).

The BER traces in Fig. 8(a) are the measurements of the received signal for each transmitter in two cases: first in the case that only one of the transmitters is active at the time of measurement used as reference to see the channel interference; and the other case to analyze the system with the two transmitters active.

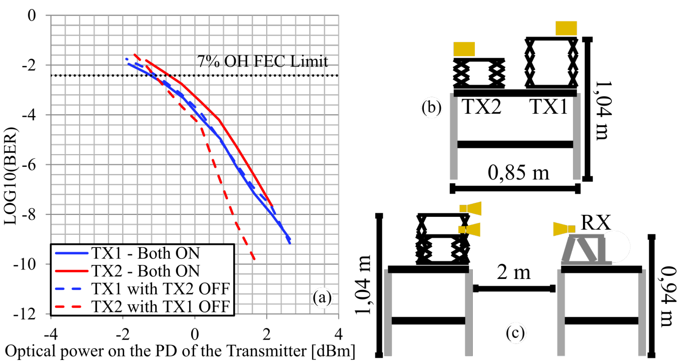

Figure 8. Example with mechanical beam steering: (a) Measured BER traces vs power on the PDs, (b) Front view of implementation (c) Side view of implementation

To generate the two signals, the RoF signal was divided in two paths; each path was used to feed a different PD and then go through the amplifiers and the antennas. In one of the paths, an extra waveguide section was used to generate diversity between the signals. From the curves it be observed the effects of the interference in TX2 being higher than in TX1. This is due imbalances in the power of both transmitters due to the different components in the paths. Nevertheless, all the traces seem to join for a sensitivity around $-1.2\,\mathrm{dBm}$ and present error-free transmissions.

V. Conclusion

In this paper, an overview on the architecture of the RoF based C-RAN and the basic elements that compose it was presented. The architecture was simplified and analyzed in order to provide a insights on reconfigurability within the access network. This analysis was expanded with a set of experimental results for different reconfigurable systems in the network. The presented systems serve as proof of concept for techniques as dynamic wavelength and electrical frequency carrier selection, optical switches, beam steering and reconfigurable antennas. In each test, the results presented values below the FEC limit for a 7% of overhead, showing the feasibility of the solutions. Nevertheless, since the C-RAN requires that the RAUs to be cost-efficient and easy to deploy, there is still work to consider in the integration of the diferent components and the design of the control information within the newtork, ir order to implement the RAU as part of a software defined network.

In overall, the presented solutions allow to show the capability of a C-RAN architecture, completely controlled by the central office, providing some insights on a reconfigurable optical and electrical system for the next generation of networks and leaving the discussion open for the introduction of new designs and new components for the network.

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