Fronthaul Performance Demonstration in a WDM-PON-Based Convergent Network

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***Abstract*— Cloud Radio Access Network (C-RAN) and Fixed Mobile Convergence (FMC) receive a lot of attention recently because of the cost decrease and the performance improvement that they represent for telecommunications' operators. In this paper, a fixed/mobile convergent architecture is introduced based on the integration of fronthaul links with fiber access infrastructure and central office assets. Tests have been performed on a wireline business service and an LTE fronthaul link measuring performances in terms of Ethernet frame loss, BER and jitter on the CPRI protocol data transport and finally EVM and frequency accuracy on the LTE signal.**

Keywords*— *C-RAN; FMC; Fronthaul; LTE; CPRI

I. INTRODUCTION

In the coming years, a significant growth of data traffic in fixed and mobile networks is expected due to the increasing number of User Equipment (UE) and bandwidth-hungry services. In order to deal with this, first studies have begun on the future 5G network. Among the identified key enablers, we focused in this paper on two main aspects. The Fixed Mobile Convergence (FMC) [1], consisting in the mutualization of fixed and mobile networks based on two main assets: i) the optical fiber infrastructures [2] which are more and more common in the access segment due to Fiber-To-The-Home (FTTH) deployment and the backhaul for last mobile generation (LTE) and ii) central office facilities which evolve to support high broadband services and become parts of the virtualization network trends by hosting data-center functions. Cloud Radio Access Network (C-RAN) and Virtual RAN (V-RAN) [1] concepts propose to centralize [3], virtualize (implementing base station functions in virtual machines on generic servers) and pool some previously distributed equipment. This mobile evolution has two main requirements: i) achieving fronthaul links between Base Band Units (BBU) and Remote Radio Head (RRH) over optical fiber in the access network segment and ii) hosting facilities compatible with an easy operation and management of pooling and virtualizing equipment. In this paper, we will focus our interest on the fiber infrastructure asset and the transport of the fronthaul interfaces which are based on the Common Public Radio Interface (CPRI) resulting from the digitalization of radio signals [4].

After presenting the evolution of optical fiber sharing in the access networks in Section II, we describe, in Section III, a novel WDM-PON system with tunable transceivers permitting the transport of fixed and mobile data traffic in the access. Different performance measurements are carried out on the experimental setup described in Section IV. Obtained results are discussed in Section V.

II. EVOLUTION OF FIBER SHARING

The simplest solution to achieve an optical access link for either fixed or mobile networks is Point-to-Point (PtP) fiber (dark fiber). It has been deployed for business access, copper wireline backhaul and mobile backhaul in the past.

A first level of fiber sharing was applied for residential optical access (FTTH), where a fiber is shared by up to 128 subscribers with the use of Time Division Multiplexing (TDM) in Gigabit capable Passive Optical Networks (G-PON) according to ITU-T G.984 [5].

Now, with the massive deployment of FTTH and LTE and the emergence of C-RAN, fiber becomes increasingly a scarce resource. A higher level of sharing is then needed.

Coarse Wavelength Division multiplexing (CWDM) is a robust solution for fronthaul deployment. It is highly reliable, cost effective, compatible with outdoor environments and it permits reusing the existing backhaul infrastructure. It offers up to 18 channels with 20 nm spacing according to ITU-T G.694.2 [6]. The classic CWDM architecture needs two fibers, one for the uplink and one for the downlink. Using one fiber for the transmission in both directions was the first proposed improvement. It is achieved by dividing the CWDM channel into two sub-channels of 6.5 nm width each [7]. The wavelength multiplexing and de-multiplexing of these two sub-channels is achieved inside the optical front head of the transceiver. The regular passive CWDM devices and single fiber infrastructure could be used. This allows the reuse of the same engineering process that is used for FTTH infrastructure and solves the issue of unbalanced downstream and upstream latency in fronthaul links.

This sub-channel CWDM version was recently updated with the possibility to have six sub-channels [8] based on 300 GHz spacing over the CWDM grid. Six sub-channels allow performing three bidirectional channels. We obtain a single fiber CWDM architecture offering up to 54 bidirectional channels. In the case that each sub-channel support the maximum CPRI rate (option 10, working at 24330.24 Mbit/s), this passive sub-channels CWDM infrastructure will be able to support symmetrical 1,3Tbit/s between antenna sites and the BBU hotel.

With such infrastructure, colored transceivers are needed in the BBUs and RRHs, which makes wavelength management difficult for mobile operators. Colorless transceivers are thus welcome.

In fact, the second Next Generation of Passive Optical Networks (NG-PON2) expects colorless transceivers with Dense WDM (DWDM) wavelengths [9]. It actually has two flavors which can be integrated in the same fiber infrastructure: Time and Wavelength Division Multiplexing (TWDM) PON for residential access and PtP WDM-PON for mobile backhauling, fronthauling and business services. Thereby NG-PON2 can offer a convergent access network.

The management of the wavelength tunability expected in PtP WDM-PON can be enabled by a signaling channel over a pilot tone as indicated in ITU-T G.989.2 [9]. This communication channel is named AMCC (Auxiliary Management and Control Channel) in the standard. In the specifications, it must be a RF carrier of 500 kHz and supports 128 kbit/s based on a NRZ (Non Return to Zero) signal with a modulation index of 10%. The pilot tone used in this paper has different specifications as described in section III, but the principal remains the same. The impact of the implementation of a signaling channel on the data plane performance is tested is Section V.

III. DESCRIPTION OF THE WDM-PON SYSTEM

The WDM-PON system under test is a prototype having three upstream channels in the C-band and three downstream channels in the L-band. The multiplexing of these channels is achieved with a cyclic Arrayed Waveguide Grating (AWG) offering 40 channels with a channel spacing of 100 GHz in L-band and ~97 GHz in C-band as standardized in ITU-T G.698.3. They are located in the Central Office (CO) and at the Remote Node (RN) as shown in Figure 1. One colored OLT is operating up to 10 Gbit/s and the two others at 1Gbit/s. The ONUs are colorless, they are tuned to the wavelength corresponding to the AWG port they are attached to, using a feedback-based wavelength locking process.

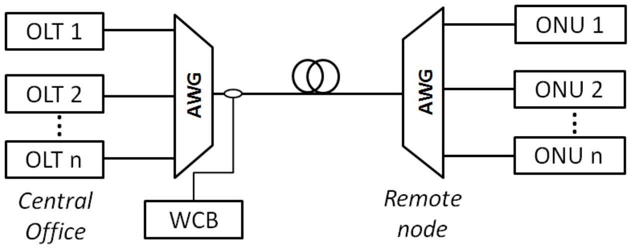

Figure 1: WDM-PON system architecture

In order to distinguish upstream signals and their deviation with respect to the ITU grid, a unique pilot tone in the frequency range [100 kHz – 1 MHz] is added to each ONU's upstream signal. The Wavelength Control Board (WCB) located at the OLT site measures the received power from different ONUs thanks to a Fast Fourier Transform (FFT) before and after a common centralized Fabry-Perot (FP) wave-locker. This wave-locker uses an etalon as a centralized discriminator which has a sinusoidal response over the (C-Band) spectrum with a 100 GHz free spectral range. It is operated so that ITU frequencies are located halfway up on the rising edge of its response curve. The ONU wavelength deviation can be calculated from the ratio of the signals' FFTs before and after passing through the FP etalon. By comparing this ratio with the ITU frequencies, the system can determine any deviation less than +/-25 GHz [10].

In the downstream, the feedback of the information on wavelength deviation and power levels is also implemented by using pilot tones with an additional Embedded Communication Channel (ECC) at the rate of 1 kbit/s. This pilot tone is added to the downstream WDM spectrum via an over-modulation performed by a variable optical attenuator [10].

IV. EXPERIMENTAL SETUP

Figure 2 shows the used experimental setup to measure performances of a business service and a fronthaul link using the proposed system.

An Ethernet tester is used to emulate the transmission of a 1 Gbit/s Ethernet business service. The performance is evaluated in terms of frame loss.

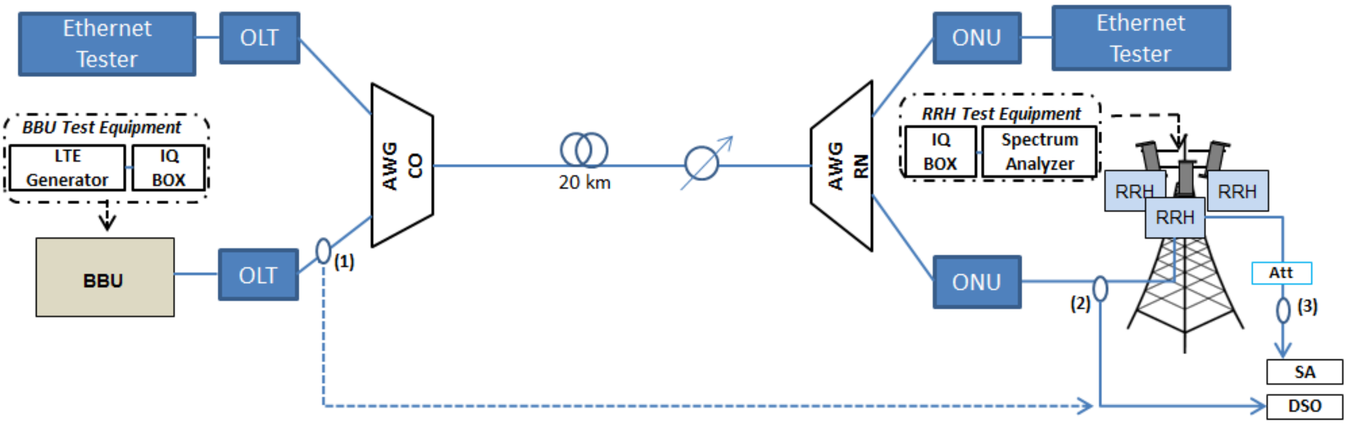

Figure 2: Experimental setup

In the adjacent channel, a mobile fronthauling service is transmitted using a signal generator for LTE generation and an IQ box for LTE to CPRI conversion.

The standardized E-TM3.3 LTE test model is used with 20 MHz carrier bandwidth. CPRI performance measurements are carried out in the downlink direction at three CPRI line rates: 2.45 Gbit/s, 4.91 Gbit/s and 9.83 Gbit/s.

At the reception after 20 km transmission over single mode optical fiber, an IQ box is used to convert the CPRI signal to LTE before analysis with an electrical Spectrum Analyzer (SA). This measurement equipment emulates the BBU and RRH as a first set-up before using a commercial BBU and RRH to confirm the measured values. The optical transmission is achieved at the BBU side with colored OLTs offering 22 dB of Optical Budget (OB) for a Bit Error Rate (BER) of 10^{-12}. At the RRH side, colorless ONUs (OB= 24 dB) with a pilot tone based tuning process are used. In order to evaluate the impact of this wavelength locking process and of the transmission on an adjacent channel, Error Vector Magnitude (EVM) measurements are done at the output of the RRH using an SA. Jitter on the electric signal is measured at the transmitter (1) and at the receiver (2) with a Digital Storage Oscilloscope (DSO) as shown in Figure 2 and a frequency accuracy evaluation of the LTE signal is carried out with an SA, this time at the output of a commercial RRH operating at 2.645 GHz. A latency measurement is done as well using CPRI measurement equipment to assess the delay introduced by the WDM-PON system.

V. RESULTS

When building a fronthaul transport solution, it is mandatory to take into account some technical requirements defined by the CPRI specifications and the 3GPP standard for respectively the CPRI and LTE performances.

The operation in adjacent channels could affect the transmission due to crosstalk. Also, using pilot tones for the wavelength tuning could generate noise as it is shown on the eye diagrams depicted in Figure 3. To address these points, we investigated the transmission performance in terms of Ethernet frame loss, EVM and frequency accuracy of the LTE signal, and jitter on CPRI signal.

A. EVM values and Ethernet frame loss:

First, we started by investigating EVM values of the LTE signal and Ethernet frame loss while attenuating the Received Optical Power (ROP) in the ONUs with a Variable Optical Attenuator (VOA). For QPSK, we measured 0.07% of EVM for ROP greater than -25.5 dBm when using the test instrumentation. The Ethernet transmission in the adjacent channel was frame loss free at this ROP. We start losing Ethernet frames at ROP = -28 dBm. A degradation of the EVM value (1%) is noticed when we use a commercial RRH due to the amplifier noise. The same EVM value is obtained when using a dark fiber fronthaul. Therefore no EVM degradation is introduced by pilot tone use.

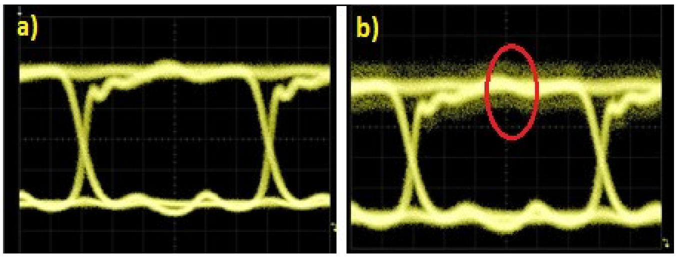

Figure 3: 2,45 Gbit/s Eye Diagram before (a) and after (b) adding a pilot tone

The same test was done for a 64QAM transmission using the test model E-TM3.1 at the three tested line rates (2.45 Gbit/s, 4.91 Gbit/s and 9.83 Gbit/s), leading to the same EVM value (0.07%).

No EVM variation is observed when we remove the Ethernet signal. Thus, there is no inter-channel crosstalk impact on EVM.

These results are compliant with 3GPP maximum EVM value of 17.5% for QPSK and 9% for 64QAM [11].

B. Jitter introduced by the system:

Secondly, we evaluated the jitter introduced by the system on the CPRI signal. The measured values in Unit Intervals (UI) are displayed in Table 1. We notice that there is more jitter at the receiver compared to the measured values at the transmitter, which we believe can be attributed in part to the active components used for the wavelength locking operation in the ONU. We also observe that the measured values comply with the CPRI specification for line rates 2.45 Gbit/s and 4.91 Gbit/s. However, the maximum value is slightly exceeded at 9.83 Gbit/s. It is important to note here that the design of the WDM-PON prototype was not optimized for best timing performance. Resynchronization with an appropriate Clock Data Recovery (CDR), absent in this prototype, would substantially improve the jitter results and should provide specification compliance also at 9.83 Gb/s.

C. Fronthaul BER and synchronization:

Jitter is a phase variation whose frequency components are above 10 Hz. Therefore, this phenomenon could introduce errors in the transmission, if the decision regarding the signal's amplitude is not made at the correct interval in time due to the introduced phase shift [12]. Moreover, the synchronization of the User Equipment (UE) with the network can also be affected. In fact, the central clock generating the LTE frequency in the RRH should be synchronized to the bit clock of the received CPRI signal [4]. Thereby, imprecisions in the transmitted clock could influence the accuracy of the generated

TABLE 1: JITTER MEASUREMENTS AT DIFFERENT CPRI LINE RATES

	2.45 Gbit/s	4.91 Gbit/s	9.83 Gbit/s	Maximum values according to CPRI specification
Deterministic jitter at Transmitter (1)	58.2 mUI	139.9 mUI	192.3 mUI	170 mUI
Total jitter at Transmitter (1)	71.7 mUI	139.9 mUI	192.3 mUI	350 mUI
Deterministic jitter at Receiver (2)	103.5 mUI	199.8 mUI	383.2 mUI	370 mUI
Combined Deterministic and Random jitter at Receiver (2)	135.9 mUI	271.7 mUI	536.8 mUI	550 mUI
Total jitter at Receiver (2)	136.mUI	271.5 mUI	537.8 mUI	650 mUI

LTE frequency and the synchronization of the UE consequently. According to 3GPP, the most stringent requirement on LTE frequency accuracy on the air interface is ±50 ppb (Parts per Billion) for wide area base stations [11].

In order to verify these two potential jitter impacts, we started by measuring the BER with the CPRI test equipment. We obtained a BER < 10^{-12} for the three CPRI line rates as required in the CPRI specification [4]. Afterwards, we measured LTE frequency deviation at the output of a commercial RRH during 24 hours using 2.45 Gbit/s CPRI line rate since it is the only available line rate in commercial systems for now. The used time interval between the measurements is one second. The results with respect to 2.645 GHz, the nominal LTE frequency, are depicted in Figure 4.

We measured ±1.4 ppb when using fronthaul over dark fiber while 99.99% of the measured points using the WDM-PON system had ±2 ppb frequency deviation.

The few remaining points were up to 20 ppb certainly due to electric jitter or brief fluctuations of the optical power or wavelength. Nonetheless, these values remain below the maximal value defined by the 3GPP standard (±50 ppb). Yet again, implementing CDRs for resynchronization should improve these results.

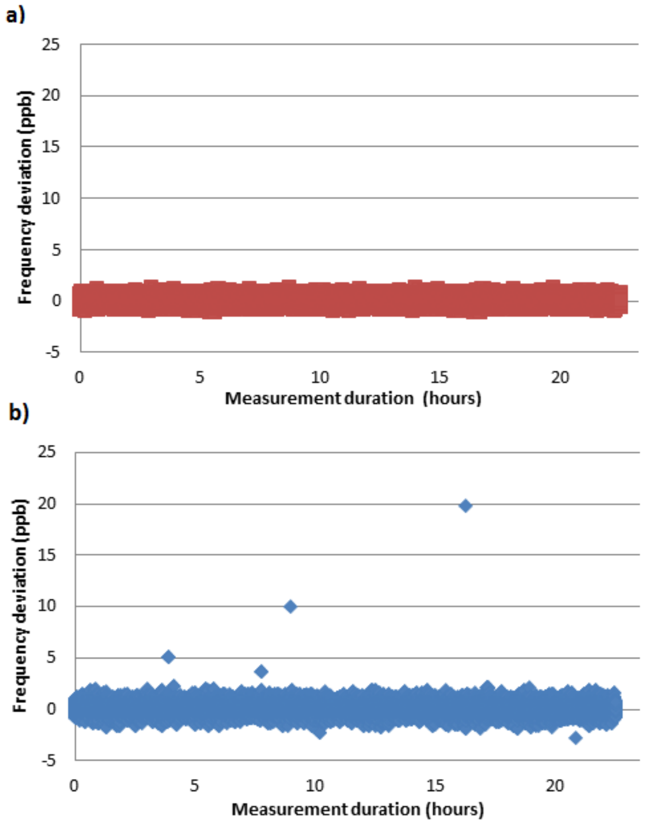

Figure 4: a) Frequency deviation measured at the RRH output using fronthaul over dark fiber
b) Frequency deviation measured at the RRH output using fronthaul over WDM-PON

D. Latency:

Latency is among the dimensioning parameters that we also need to consider. RAN vendors recommend a maximum round trip delay of 150 µs, i.e. 15 km [13] optical fiber to allow CoMP implementation. Only 26 m are lost for the maximal fronthaul distance due to the latency introduced by the system (130 ns).

VI. CONCLUSION

The tremendous increase of data traffic requires fixed and mobile network densification leading to colossal investment in network infrastructures. FMC with the fronthaul integration in the access network is the solution for cost effective deployments with efficient fiber sharing and improved performances. In this paper, a WDM-PON based system is proposed for the transport of mobile fronthaul and wireline business services. End to end performances in terms of frame loss, EVM, jitter and frequency accuracy have been demonstrated in the lab and on LTE commercial fronthaul. Compliance with 3GPP standard has been demonstrated and we have shown that the introduction of pilot tones and the co-existence of fixed and mobile services have no impact on fronthaul performance.

ACKNOWLEDGMENT

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