Optical fiber solution for mobile fronthaul to achieve Cloud Radio Access Network

Philippe CHANCLOU[1], Anna PIZZINAT[1], Fabien LE CLECH[1], To-Linh REEDEKER[1], Yannick LAGADEC[1], Fabienne SALIOU[1], Bertrand LE GUYADER[1], Laurent GUILLO[1], Qian DENIEL[1,2], Stephane GOSSELIN[1], Sy Dat LE[1], Thierno DIALLO[1], Romain BRENOT[3], Francois LELARGE[3], Lucia MARAZZI[4], Paola PAROLARI[4], Mario MARTINELLI[4], Sean O'DULL[5], Simon Arega GEBREWOLD[5,*], David HILLERKUSS[5,*], Juerg LEUTHOLD[5,*], Giancarlo GAVIOLI[6], Paola GALLI[6]

[1]*Orange Labs, 2 Avenue Pierre Marzin, Lannion, 22307,France*
Email: philippe.chanclou@orange.com
[2]*Telecom ParisTech, 46 rue Barrault, Paris, 75634, France*
[3]*III-V Labs, Route de Nozay, Marcoussis, 91461, France*
[4]*Politecnico di Milano, Dept. Electronics and Information - PoliCom, via Ponzio 34/5, 20133 Milan, Italy*
[5]*Institute for Photonics and Quantum Electronics of the Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany, * now with the Institute of Photonic Systems (IPS), Swiss Federal Institute of Technology - ETH Zurich, Switzerland*
[6]*Alcatel-Lucent Italia, Via Trento, 30 20871 Vimercate, Milano, Italy*

Abstract: This paper describes the technical aspects of optical access solutions for mobile fronthaul application. The mobile context and main constraints of fronthaul signals are presented. The need for a demarcation point between the Mobile operator and the Fiber provider is introduced. The optical solution to achieve such a network is discussed. A WDM network with passive monitoring at the antenna site and automatic wavelength assignment is proposed based on self-seeded solution.

Keywords: Optical Fiber Network, Mobile Network, Wavelength-Division Multiplexing (WDM) Network, Digital Radio over Fiber

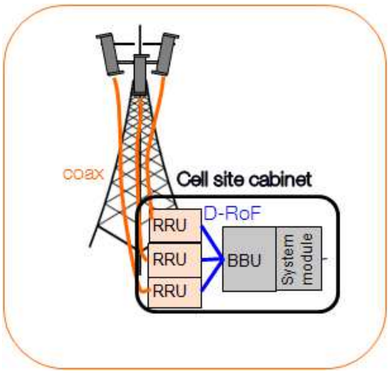
1. Introduction

Cloud radio access network (C-RAN) comes with an innovative architecture solution. This new architecture consists of centralizing the Base Band Unit (BBU) of several base stations. The BBU will not be placed on the cell site anymore; the BBU will be located in a Central Office (CO) or point of concentration.

C-RAN breaks down the traditional base station into a centralized BBU which will be shared between multiples Remote Radio Head (RRH) thanks to the implementation of resource pooling. As a consequence, a new connectivity segment is created between the multiple distributed RRHs and the centralized BBU called “fronthaul”. This new transport segment will be based on Digital Radio over Fiber (D-RoF) technology implemented over fiber resources.

We propose in this paper, after considering the C-RAN context, to high light the requirements of the fronthaul network segment. This section will be followed by a discussion on what we have in our basket to achieve this optical fiber network. We will finish this paper by a technical presentation of a Wavelength Division Multiplexing (WDM) solution which achieve a passive monitoring at the antenna site and assign automatically and passively the wavelength to the colorless transceiver.

2. Context of Cloud Radio Access Network



RRU: Remote Radio Unit
RRH: Remote Radio head
BBU: BaseBand Unit
CSG: Cell-Site Gateway
D-RoF: Digital Radio over fiber
(CPRI or OBSAI standard)

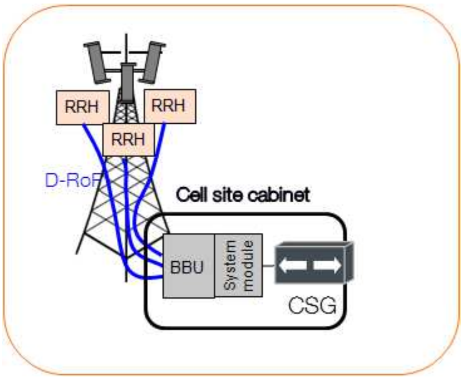


Figure 1: Step 1: Macro base station, all base station hardware is located in a radio cite cabinet, and the antennas are driven through coaxial cables.

Figure 2: Step 2: Distributed base station with « traditional » backhaul, remote radio heads at the antennas are connected to the radio site cabinet through an optical fiber.

C-RAN is a new RAN architecture concept that may change the existing paradigm and the way the RAN evolves in future. In the first traditional generations of macro base stations (cf. figure 1), the radio-frequency transmitter and receiver electronics are located at the base of a tower, or in a building, and large diameter coaxial feeder cables are used to connect the electronics and the antennas. In a second step, see Figure 2, distributed RRH appears. The RRHs contain the RF transmit & receive components (including power amplifier, duplexer, low noise amplifier etc) and they can be mounted directly on the antenna mast thus only short coaxial jumpers are used for the connection to the antennas. Due to their lower capital and operating expenditures, these RRH are currently being deployed not just for new technologies (e.g. LTE and LTE-Advanced) but also in new and replacement infrastructure for older technologies (2G, 2.5G, 3G). The RRH can be linked to the Base Band Unit (BBU) by an optical singlemode fiber using a standard interface with a digital radio signal [1-4] (D-RoF, digital radio over fiber) such as CPRI (Common Public Radio Interface) [5] or OBSAI (Open Base station Architecture Initiative) [6] for the baseband transmit and receive signals. Moreover, the RRHs require power supply that can be quite compact and reduced in order to feed only the RRH.

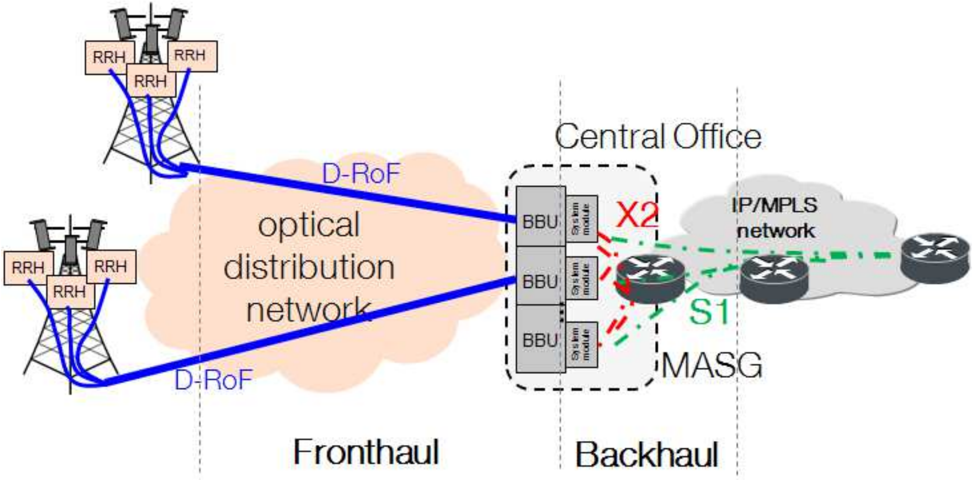


Figure 3: Step 3 BBU hostelling with stacking (or BBU centralization) based digital-radio over fiber link over optical distribution network, the baseband units are collocated in a central office and are connected to the radio towers through an optical distribution network

The next logical step (cf. figure 3), is to move the BBU to a central office. This logical step is possible due to the fact that optical fibers are available between antenna site and central

office. This fiber availability is in relation with the fact that traditional backhaul architecture (cf. step 2) will need also fiber to achieve 100 Mbit/s and up to 1 Gbit/s links. So in any case of evolution, the most part of antenna site will be connected by fiber.
This evolution step is call BBU centralization or BBU hostelling with stacking: BBUs of different base-stations are co-located in the same CO. Generally with BBU stacking there is one BBU that handles all the RRH located at the cell site and the BBU can communicate with each others within the BBU hostel via standardized X2 interface.

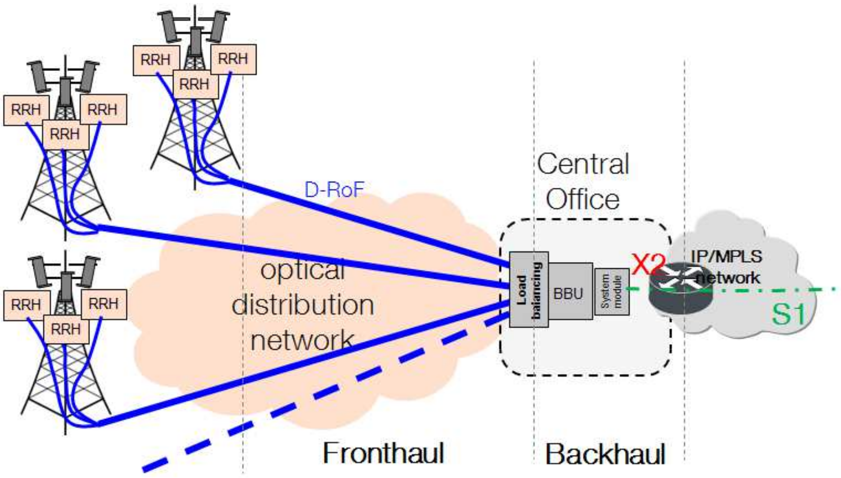


Figure 4: Step 4 BBU hostelling with resource pooling (C-RAN), a single baseband unit is connected to a high number of RRH located at different cell sites

Finally, step 4 (cf. figure 4) is C-RAN or BBU hostelling with resource pooling between all the BBU in the BBU hostel [7]. Now a centralized set of BBUs with resource pooling is capable of handling a large number of RRHs located at different antenna sites. The BBU pooling enables to allocate dynamically the BBU resources to the RRH, to load balance the mobile traffic between the BBU pools, and then to reduce CAPEX since the BBU usage is optimized. Moreover, at mid term the BBU pooling could be supported on general purpose IT platform that could be cheaper than specific telco hardware.

It can be noticed that the BBU Hostelling (step3 and step4) is an enabler for the CoMP feature that rely on very fast communication between BBUs by increasing drastically the uplink and downlink bitrates.

In steps 3 and 4, thanks to the baseband breakdown, a new connectivity segment called fronthaul appears between the RRHs on the cell site and the BBUs in the central office (cf. figures 3 and 4).

3. Which are the main constraints of fronthaul?

On the fronthaul, the dimensioning requirements take into account the state of the art. Earlier CRAN, RRH and BBU were connected locally inside the cell site with direct fiber to fiber connection. Depending on the cell site technologies, bandwidth requirements between the cell site and the central office where the BBU is localized will differ. Two standards (CPRI and OBSAI) exist for transport’s interfaces in both of them the radio signal is digitised (D-RoF, digital radio over fiber). CPRI and OBSAI share a number of similarities. Here, we focus on four important parameters of CPRI: bit rate, latency, jitter & synchronization, and fiber availability.

3.1 – High bit rate capacities needs on fronthaul

Different radio access standards have different CPRI data throughputs, so different transmission solutions need to be considered. CPRI link rates go from 614.4 Mbit/s up to

9.8Gbit/s. Table 1 gives the typical CPRI data rates corresponding to 1 carrier and 1 sector of different radio technologies.

RAN	GSM 1T1R	GSM 1T2R	WCDMA 1T1R	WCDMA 1T2R	LTE 10MHz 2x2	LTE 10MHz 4x2	LTE 20MHz 2x2	LTE 20MHz 4x2
CPRI Data rate	12.304 Mbit/s	24.608 Mbit/s	307.2 Mbit/s	614.4 Mbit/s	1228.8 Mbit/s	2457.6 Mbit/s	2457.6 Mbit/s	4915.2 Mbit/s

Table1: typical data rates of CPRI in function of radio technologies

Calculation of data rate R_D per CPRI link is based on the following expression:

$$R_D = M \; R_S \; N \; 2 \frac{10}{8}$$

with M = number of antennas per sector (cf. MIMO), R_S = sampling rate (sample/s), N = sample width (bit/sample), a multiplication factor of two to account for in-phase (I) and quadrature-phase (Q) data, and a factor of 10/8 for 8B/10B coding.

The requirements for the new connectivity segment between RRH and BBU, called fronthaul is strongly joined to CPRI data requirements related. The logical link between antenna site and BBUs has to consider several CPRI links at different bit rates in relation with symbol rate, sampling rate, sampling time, carrier number and antenna number, whereas it is independent of the modulation scheme.

3.2 - Latency constraints on the fronthaul

Since the link between RRH and BBU is at the level of the physical radio signal, the total latency that the radio signal can tolerate, includes the latency of the fronthaul. The most critical parameter comes from the up-link synchronization method Hybrid Automatic Repeat Request (HARQ). In case of retransmission, this parameter has a direct impact in case of retransmission, on peak data per user. After subtracting the mobile equipment processing time, considering maximum timing advance (667 µs, for LTE) and the assumption of a 10 km cell radius, the remaining time for round trip time propagation between RRH and BBU is only 700 µs for LTE and 400 µs for LTE-Advanced (including Coordinated MultiPoint (CoMP)). This includes both time delays for the fibers and equipments that could be placed on the link. So typically, BBU and RRH are connected without active equipments, thus meaning that LTE-Advanced time delay authorizes 40 km (80 km round trip time) reach between BBU and RRH (20 km ≈ 100 µs).

3.3 Jitter and synchronization

Concerning synchronization on the fronthaul segment, the CPRI frame is divided in three parts, the first part is the I/Q data, the second contains the control and management information, and the third is required for synchronization. The CPRI specification defines the maximum jitter transfer bandwidth of the Phase-Locked Loop (PLL).

For the frequency synchronization of LTE, frequency accuracy requirement to be met on the air interface of a base station is ±50 ppb (parts per billion). The requirement in the CPRI specification is expressed as a contribution of the fronthaul link for the overall requirement (e.g. a suitable portion of 50 ppb). A budget of 2 ppb is defined between the BBU and RRH.

For some option of LTE-Advanced, time and phase synchronization is required. This also include requirement on the delay calibration mechanism. A phase accuracy requirement budget is allocated to the CPRI link and the contribution of the link itself shall be taken into account. It is appropriate that both phase noise and asymmetries are considered (in fact the error in the delay measurement is also impacted by asymmetry in the CPRI link).

It has to be noticed that the budget allocated to the CPRI link is defined for a point to point connection and over a fiber link. Other transport solutions are not covered by the CPRI specification and need to be handled carefully especially when deploying services that required phase and time synchronization.

3.4 Fiber resources availability for fronthaul

Optical fiber or wireless transmission technologies are needed at the cell site to connect BBU and RRH. For some simple radio configurations microwave links could be an option. In any case, due to its large bandwidth fiber is the preferred option for LTE traditional backhaul and it is the standard solution to connect the fronthaul.

The most important assumptions to achieve the fronthaul are: i) the availability of optical fiber, ii) the legal and regulation aspects, iii) the operations, administration and management, iv) the cost efficiency of the CPRI transport. In order to clarify the business case, we propose (Figure 5), the definition of network demarcation points between what belongs to the mobile operators and to the fixed line operators (fiber providers). The main topologies of the optical distribution network between RRH and BBU are:

- Point to point (illustrated in Figure 5): each RRH (for example corresponding to a sector) is connected directly to the BBU. This solution could be expensive as the in number of fibers per antenna site grows quickly. Therefore, wavelength multiplexing of CPRI channels could be useful to achieve point to point.

- Daisy chain: several RRHs could be cascaded (with time division multiplexing of each RRH data rate) towards the BBU. This topology allows for a reduction of the number of fibers but at the same time introduces a single point of failure. Given the CPRI bitrates, it is feasible to chain 2G or 3G RRH while LTE requires CPRI link very high bitrate to support 3 LTE sectors.

- Multi-path : ring and mesh topologies have the advantage of addressing the issue of network availability by closing the chain and providing an alternative path to maintain connectivity between the BBU and the RRHs in the presence of a link failure on any of the segments in the ring.

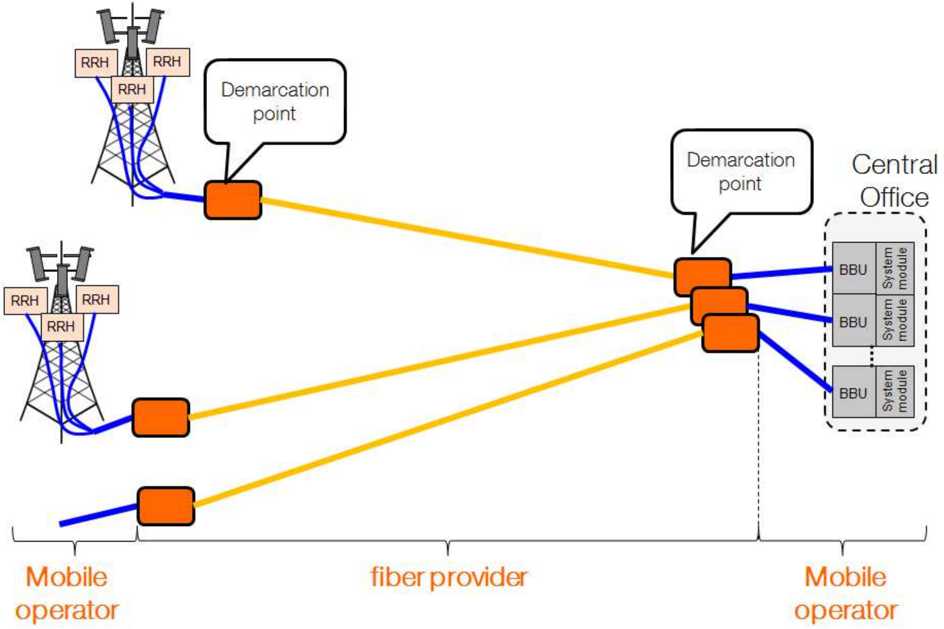


Figure 5: Network demarcation between Mobile operator and fiber provider

Considering the antenna site, due to the small volume and weight of the RRH, small and discrete radio towers can be realized with a small installation time and low maintenance cost. In order to follow this policy of a “light network”, the optical solution at the antenna site will be preferred as passive (no power consumption) and compact.

To summarize the fronthaul’s constraints, this network segment will need an optical fiber infrastructure and equipments with versatile bit rate, a reach of up to 40km, without significant impact on jitter and synchronization, CPRI multiplexing with passive & compact form at the antenna site offering demarcation points between mobile and fixed networks.

4. Discussion on optical network for the fronthaul

Here, we discuss several existing optical solutions to achieve transport the CPRI data: i) Optical Transport Network (OTN), ii) Passive Optical Network (PON), iii) PtP with CWDM.

i) The OTN is a solution based on ITU-T G.709 which allows for time multiplexing of several tributaries on a single wavelength or Dense WDM network (typically 4 times 2457.6 Mbit/s CPRI inside a line rate around 10 Gbit/s). Protection and service level agreement at the demarcation points can be provided. The OTN equipment needs to be supplied with power (separate power units are required for mobile and fixed line operators).

ii) PON is the common and low cost solution to implement Fiber to the Home networks. Nevertheless, gigabit capable PON (G-PON) is unattractive for the fronthaul due to the high bandwidth required per sector. XG-PON1 (XG for 10 Gbit/s) will also suffice as the upstream bandwidth is limited to 2.5 Gbit/s. Newer standardizations might offer an option such as ITU-T G.987 that allows for XG-PON2 with 10Gbit/s symmetrical traffic. Otherwise, one needs to wait for the finalization of Next Generation-PON2 (ITU-T G.989), which is based on 4 to 8 wavelengths stacking of a “XG-PON1” system. Similar to OTN, the PON equipments need to be supplied with power at the antenna and the central office site. An other drawback for PON interfaces is the fact that the time division multiple access solution requires a ranging time window when a new optical network unit is connected and issues with jitter induced for other traffic.

For these two previous solutions, a compression of CPRI could be proposed to reduce the line rate. Active devices have to be introduced into the antenna and central office sites to achieve compression and decompression in a way that latency and jitter constraint are respected.

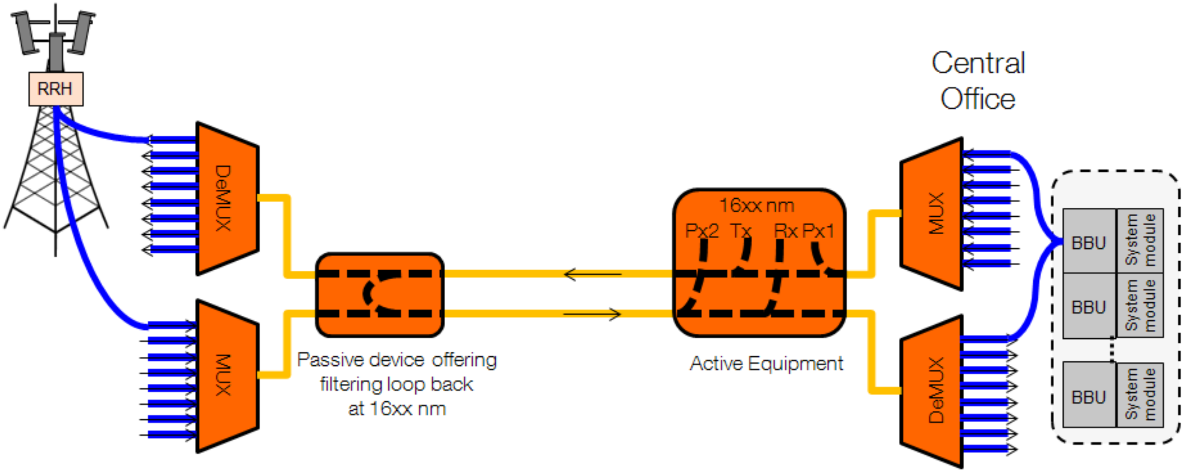


Figure 6: WDM network configuration to achieve passive monitoring at the antenna site

iii) The last solution that we consider in this manuscript is point to point fibers with wavelength multiplexer (MUX) (cf. Figure 6). In order to obtain a mostly passive network, we consider, at the antenna site, a passive loop back device for a monitoring wavelength (typically a wavelength in band U between 1625 nm and 1675 nm) and a passive pass through for fronthaul signals based on WDM. The service level agreement will be based on the analysis of fiber infrastructure performance (based on an optical budget survey and an optical power monitor, illustrated as Px1 and Px2 in Figure 6).

Concerning the WDM part, several technical solutions exist to achieve such networks. We propose here to highlight some requirements dedicated to fronthaul:

- In order to obtain a passive solution at the antenna site for the fiber provider, the WDM transceiver must be inside the RRH and BBU and must be compatible with standard Small Form-factor Pluggable (SFP). These transceivers will be managed by the mobile operator and the WDM infrastructure by the fiber provider.
- To minimize wavelength monitoring and stabilization and avoid inventory problem, the following approaches could be considered:
    - Coarse WDM transceivers could be a first approach with large operating temperature range (typically Antenna site could be located in severe environmental condition) and an adequate wavelength grid. Presently, this solution is the most pragmatic approach to achieve fronthaul trial. But in case of massive deployment, inventory problems could burden the Mobile network administration.
    - Colorless transceivers could be used to suppress inventory issue. Based on the first assumption that we have only “SFP” to achieve the active part of the WDM network, solutions based on external seeding source for re-modulation are excluded. To realize the colorless transceivers several approaches can be considered :
        - Employing a wavelength tunable optical source: due to technological feasibility (optical gain bandwidth) this solution will be only available for dense WDM grid. The main drawback of this solution is the wavelength assignment policy. Due to the fact that BBU and RRH will not perform the wavelength management, SFPs have to host all the functions to discover, assign, and maintain the adequate wavelength on their boards.
        - Employing a wavelength selectable optical source. Compared to the previous solution, this one needs a technical intervention to pick out the appropriate wavelength. One solution is to connect a special jumper cord in front of the transceiver, which contains a wavelength selective reflection filter. By this way, an external cavity laser at the appropriate wavelength [8] is achieved between a reflective laser diode inside the transceiver and the reflection filter. The issue is the inventory of wavelength selective cord and temperature drifts of the cord versus optical multiplexer.
        - Employing a broadband optical source [9-10]. The optical signal generated by the transceiver is spectrally sliced and multiplexed by the DWDM infrastructure. This solution has a limited bit rate times reach (vs. optical budget) factor in function of optical spectral slice width, due to inherent excess intensity noise and chromatic dispersion.
        - Employing a combination of modulator and broadband optical sources. In this case, the transceiver emission has to host a reflective modulator (typically a Reflective Semiconductor Optical Amplifier (RSOA)) to send back with modulation the optical carrier coming from opposite SFP and a broadband source to light the opposite SFP modulator. This combination could be problematic without photonic integrated circuit, to achieve compact and low cost transceivers. Rayleigh backscattering limits also the performance.
        - Employing a self-seeded optical source. This solution assigns automatically and passively the wavelength source. We propose to develop this solution in the next section.

5. Self-seeded WDM solution

In self-seeded solutions, each transceiver creates its own wavelength carrier to form the transmitter source [11]. This scenario seems highly favourable as there is no longer any requirement to provide wavelength specific sources. Each transceiver automatically creates a laser field that tunes to the connection port of the optical multiplexer (MUX). An optical cavity is established between an optical reflector (Faraday Rotator Mirror (FRM)) and the RSOA (with single polarisation emission). The modelling [12] of the RSOA operating in a self-seeded cavity is represented in the schematic of figure 7 a). The RSOA provides four functions: the injected optical signal is amplified, gain saturation suppresses the modulated component of the injected signal, the high reflective facet reverses the propagation direction, and the RSOA provide the directly modulation capability via the injection of current, so that fresh data is imprinted. A 45 ° Faraday Rotator (FR) is used at the RSOA output to preserve polarization operation of the source cavity [13]. The distribution fiber, which connects the transceiver with the RSOA and the MUX, can present lengths from several meters to hundreds of meters. The simulated eye diagram after 100 round trips is displayed in Figure 7b) after low pass filtering and compared with measurements (Figure 7c): optical eye diagram after the FR), showing good agreement and clear eye opening due to cancellation of the recirculating signal.

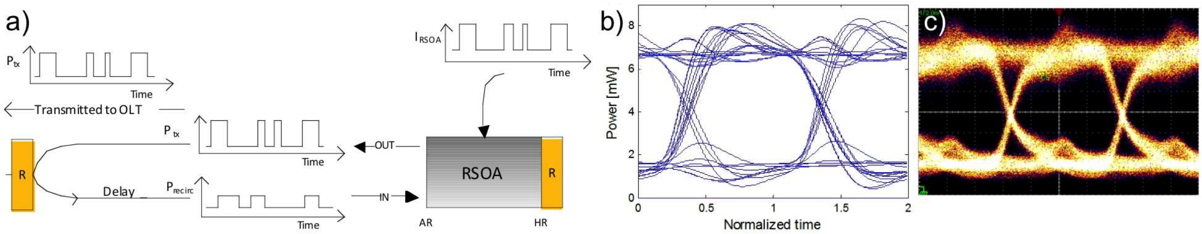
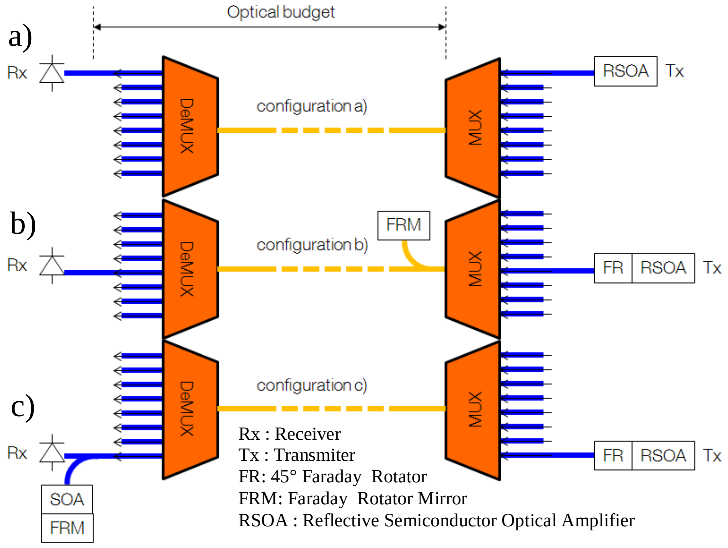


Figure 7: a) Schematic of self-seeded cavity, b) 2.5 Gbit/s simulated eyediagram (Ibias 130 mA Imod ± 50 mA). c) Self-seeded transmitter 2.5-Gbit/s measured output eyediagram.

We propose here to compare three different configurations (cf. Figure 8): a) the spectrum sliced solution based on the RSOA as a reference configuration, b) the standard self-seeded solution, and c) the amplified self-seeded solution to achieve an extra-long cavity source between the two end-to-end transceivers (between RSOA and FRM with a second SOA to overcome the cavity losses). In these configurations, the wavelength is assigned automatically and passively by the optical infrastructure with a RSOA colorless emitter.



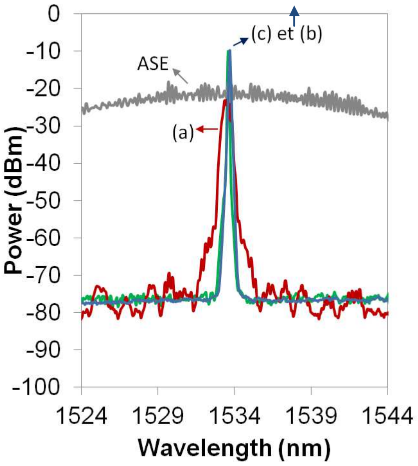


Figure 8: Three experimental configurations (a) spectrum-sliced (b) self-seeded and (c) amplified self-seeded

Figure 9: Optical spectrum for the three configurations

The three concepts have been experimentally tested. For the experiment we exploit a quantum-well RSOA with a high signal TE mode reflection gain, above 30 dB at 1540 nm (@ bias current of 100 mA) and for configuration c) a SOA with small signal gain (> 20 dB) and a low polarization dependent gain (< 1 dB) at 1550 nm (@ bias current of 130 mA) is used. We use a single cyclic 16-channel Gaussian Arrayed Waveguide Grating MUX with a channel bandwidth of 100 GHz and an Insertion Loss (IL) of 2 dB. In order to investigate the optical budget, which is defined between the MUX and the receiver (Rx), we emulate transmission losses using a variable optical attenuator and single-mode fiber reach. At reception, an avalanche photo diode is used with a clock and data recovery circuit and a bit error rate tester. The RSOA is directly modulated with 2 Vpp at 2.5 Gbit/s by a 2^{31}-1 pseudo random bit sequence with a non-return to zero pulse shape. The RSOA is biased at 70mA for scheme a) and 90mA for scheme (b) and (c). An improvement of 12 dB in optical power is obtained for self-seeded and amplified self-seeded source (c) compared to spectrum sliced source (a) as shown in figure 9.

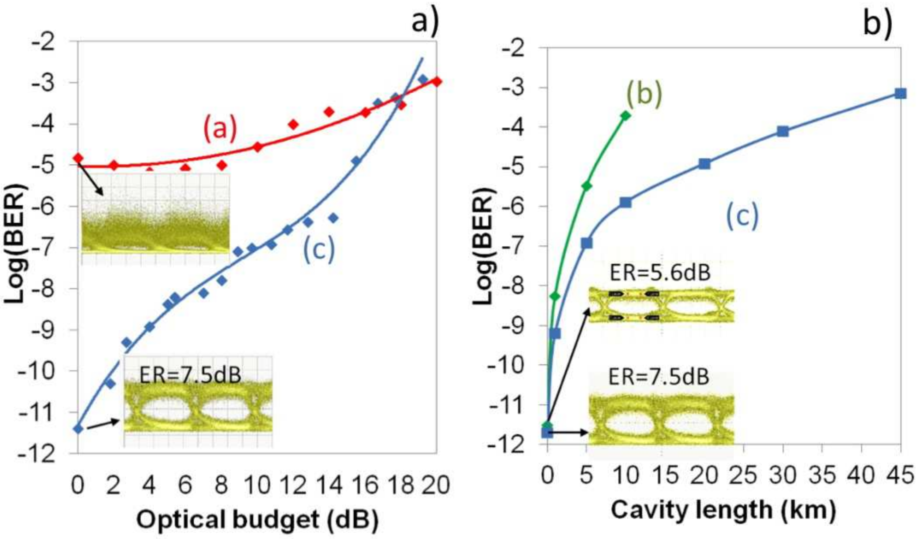


Figure 10:1 a) BER performances at 2.5Gbit/s for configuration (a) and (c). b) BER performance at 2.5Gbit/s for configuration (b) and (c) as a function of cavity length.

Figure 10 (a) presents the bit error rate (BER) measurement versus the optical budget in the case of back-to-back (BTB) configuration (no fiber reach) at 2.5 Gbit/s. For the amplified self-seeded configuration, an optical budget of 19 dB can be tolerated in order to achieve a BER of $1\text{x}10^{-3}$, which is the limit for an error free transmission when using forward error correction (FEC). Also, we observed a better extinction ratio (ER) and a better BER performance for amplified self-seeded configuration when the optical budget is lower than 18 dB. Figure 10 (b) depicts the impact on the cavity length (fiber length between the RSOA and the MUX in case b) or in any network part for case (c)) at 2.5 Gbit/s for these two extra-long cavity sources. Varying from 10m to 10 km of fiber length, the BER performance of the self-seeded transmitter degrades from 10^{-11} to $4\text{x}10^{-4}$. By using the amplified self-seeded scheme, we observed a better ER and that the BER performances are improved for cavity lengths from 10 m to 10 km. Besides, for the first time, we can successfully reach up to 45 km of source cavity length at a bit rate of 2.5 Gbit/s and a BER smaller than 10^{-3}.

6. Conclusions

New fronthaul segment appears between RRH and BBU to acheive C-RAN architecture. This is the key differentiating element with respect to traditional RAN. High capacity, low latency, and specific values for jitter and synchronisation are required for fronthaul based on optical fiber distribution network to connect the antenna site to the BBU hotel. This optical network has to be optimized in order to make an efficient usage of fibers and minimize deployment cost. We highlight a solution to realize a monitoring of this optical network with passive device at the antenna site. To deal with the high number of digital radio over fiber links per antenna site (one potential link per carrier, per radio sector, per mobile generation), this optical network requires WDM. Coarse WDM could be the first approach. But in case of massive deployment, the main technical issue is to realize colorless transceiver to decrease inventory problems and operation, administration, and maintenance cost.

Self-seeded RSOA based technology for WDM network is an attractive solution to provide an automatic and passive wavelength assignment of the transceiver. In this paper we compare the technical results at 2.5 Gbit/s of three solutions based on RSOA: the spectrum sliced, self seeded and amplified self seeded. The optical network and colorless transceivers shown in this paper are attractive candidates [14-15] for advancing RAN.

Acknowledgements

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