

# Digitized Radio-over-Fiber Transceivers for SDM/WDM Back-/Front-haul

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## ABSTRACT

In this paper we analyze the perspective of digitized radio over fiber (DRoF) fronthaul, showing how to meet the requirements to cope with the future radio access networks (RANs). This entails the introduction of space division multiplexing (SDM) while increasing the flexibility and capacity of the DRoF transceivers.

Since the evolution of the DRoF fronthaul is being revised and re-defined, in the blueSPACE project we propose two different DRoF transceiver options. The first option consists on simple transceiver, based on the recent standard specifications and, therefore, expected to be deployed in the short-term. The second options is a more advanced transceiver that features high flexibility, relying on a strong DSP and targeting a long-term deployment. Besides a basic characterization of both solutions, we also analyze additional aspects related to the design and implementation of these two DRoF solutions and their integration into an SDM based RAN. This includes the programmability and interaction with the control plane.

**Keywords:** Optical fronthaul, digitized radio over fiber, PONs, space division multiplexing, WDM.

## 1. INTRODUCTION

Digitized radio over fiber (DRoF) is a popular fronthaul technology that is being worldwide deployed for giving service to radio access networks (RANs). In order to deal with the high capacity demand of 5G, new radio waveforms featuring increased bandwidth are expected in an environment where small cells are massively deployed [1]. For example, one single antenna element with 800 MHz bandwidth would require 50 Gb/s DRoF; so a 3-sector cell with single antenna elements and massive (16x16) MIMO would require 2.4 Tb/s data rate. This implies DRoF technology to be upgraded in order to guarantee its scalability while meeting its stringent capacity/latency requirements [1]. This may come with a simple adaptation of DRoF to space division multiplexing (SDM) by deploying multicore fibers (MCFs) [2]. This approach does not only deal with the network external plant, but also with the architectures for central office (CO) and cell sites (CSs).

In order to alleviate the capacity and latency requirements of DRoF, several standards are being defined. They propose to fragment the operations carried out at the baseband units (BBUs) so that different radio functions are implemented in three entities: the remote radio unit (RRU), the central unit (CU) and the distribution unit (DU) [3]. So, DRoF needs a high degree of flexibility while meeting a reasonably high capacity: DRoF is expected to evolve from simple and rather static systems to a more sophisticated and flexible ones. Hence, the proposal of the blueSPACE project is to adopt two different solutions: DRoF-A and DRoF-B. DRoF-A is a simple high-capacity solution, based on (pseudo) multi-level intensity modulation [4]. This solution is able to work at a fixed data rate and does not require a digital signal processing. So, DRoF-A targets short-term deployment while coping with the requirements for actual fronthaul standards [5][6]. DRoF-B, on the contrary, is a more sophisticated and flexible solution. It relies on digital signal processing (DSP) for generating an orthogonal frequency division multiplexing (OFDM) waveform adopting intensity modulation, and featuring bitrate flexibility. Thus, DRoF-B is proposed as a long term solution, when fully flexible connections are expected. These two solutions will be encompassed with the network evolution, which is expected to gradually acquire more functionalities as the blueSPACE network concept (including SDM) is adopted [2].

In this paper we analyze the perspective of DRoF back-/ front-haul within blueSPACE, showing how to fulfill the associated requirements in line with the evolution of RANs. We also review the programmability and interaction with the control plane. Also, we discuss a possible architecture to generate the different radio signals from the DRoF based on direct RF conversion in combination with optical beamforming using the blueSPACE analog radio over fiber (ARoF) transceivers [2] and a suitable optical beamforming network (OBFN).

## 2. CO AND CELL SITE DESIGN

Fig. 1 shows a generic scheme for the SDM based DRoF RAN. There, a CO is attached to an optical metro/core network in order to provide connectivity to the edge. A pool of BBUs and/or CUs is envisioned to be connected

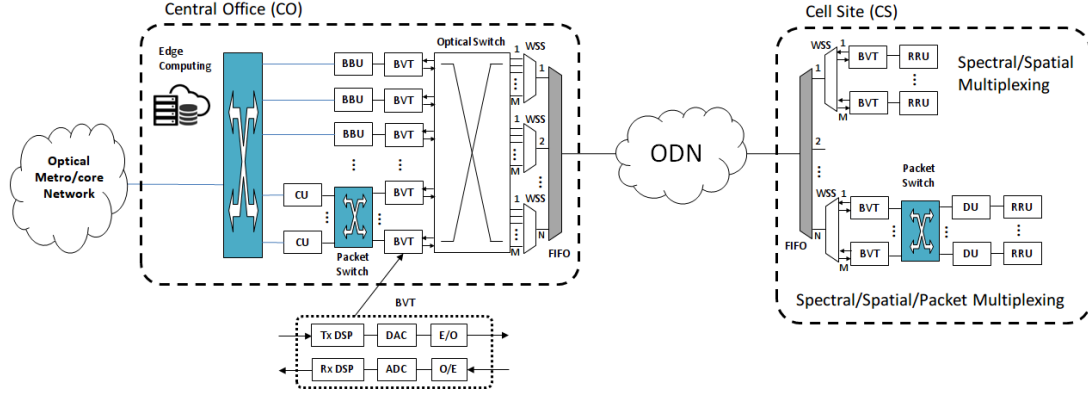


Figure 2: DRoF signal distribution scheme. BBU: Baseband unit; BVT: bandwidth/bitrates variable transceiver; CU: central unit; DU: distributed unit; FIFO: Fan in/out device; RRU: remote radio unit; WSS: wavelength selective switch. Insets show a simplified BVT scheme and the corresponding DSP blocks.

to the optical bandwidth/bitrates variable transceivers (BVTs). In case needed, a packet switch can be interposed between the CUs and BVTs to attain packet multiplexing. So, the traffic served over the network corresponds to either the fronthaul or midhaul segments as defined in [3], depending on the configuration of the CO and the CSs. The BVTs can be configured by the control plane for an optimal management of the network resources [7].

The parameters to be configured at each BVT include nominal central frequency and constellation/power depending on the implemented option. The inputs/outputs of each BVT are connected to an optical switch in order to perform the appropriate connections to each of the wavelength selective switches (WSSs), which are performing the wavelength division multiplexing/demultiplexing of  $M$  different signals into arbitrary portions of the spectrum according to the control plane indications. The main outputs of the WSSs are connected to the fan-in/out (FIFO) devices for spatial division multiplexing on  $N$  different fiber cores. The CO is delivering its data signals to the optical distribution network (ODN) in order to give connectivity to the different cell sites.

As for the cell sites, different options are envisioned in blueSPACE [2]. A generic cell site is depicted in Fig. 1. There spatial and/or wavelength multiplexing is used. It is also shown the eventual interconnection between BVTs and DU for midhaul traffic delivery. In this case, the packet switch after the CUs is feeding directly the BVTs at the CO. So, each BVT can serve different cell sites where DUs and RRUs are located, which are properly interfaced by the suitable packet switches after the BVTs. For the case of fronthaul traffic, the BBUs are also present at the CO. So, the cell sites only contain the RRUs together with the appropriate packet switches (in case needed) and the corresponding BVTs.

The main optical modules composing the CO and the different cell site options are: the optical switching matrix of the CO; the WSSs (either at the CO or the cell sites); and the different BVTs. A first description of their corresponding functions and programmability capabilities can be found in [9]. A bidirectional amplification stage [8] at the CO can be included to ensure a minimum power to be delivered to the ODN as well as to the different components of the CO. Different strategies can be approached for signal duplexing. Either SDM or WDM duplex can be implemented, depending on the network design. For example, in spatial multiplexing, each cell site has a specific assigned wavelength and, thus, an SDM-based duplex is recommended [9].

### 3. TRANSCIEVER DESIGN

The inset of Fig. 1 shows a generic scheme for the BVTs present at the CO and CSs. Each BVT is composed of 6 main blocks: DSP at transmitter (DSP Tx) and at receiver (DSP Rx) sides; electric/optic (E/O) and optic/electric (O/E) front-ends; digital to analog converter (DAC) and analog to digital converter (ADC).

The DSP blocks are in charge of converting the data delivered by the digital radio units (BBUs, DUs, RRUs,...) into digital signal waveforms and vice versa. This is performed according to the approached modulation format: PAM-4/duobinary for DRoF-A, and OFDM for DRoF-B. For PAM-4 and duobinary, simple processing is performed at the DSP, (i.e. constellation mapping, pulse encoding, digital filtering,...). These operations can be performed with no DSP when employing a specific hardware. For the OFDM, DSP is mandatory in order to create a suitable OFDM waveform. By including a set of training symbols the signal to noise ratio (SNR) of the optical channel can be monitored and communicated to the control plane, which decides the right profile of bit/power loading by using a suitable algorithm [10] and configures the BVT accordingly. Training symbols are extracted at the DSP Rx and used for the different possible equalization schemes: zero-forcing and minimum mean squared error equalization (MMSE).

Highspeed DACs and ADCs are used to convert the corresponding digital signals to the analog electrical domain and vice versa. These blocks can be avoided for a simple implementation (DRoF-A).

As for E/O and O/E front-ends, the options are limited by the total cost of the solution. As shown in Fig. 1, a large number of BVTs is needed at the CO and at CSs. Therefore, the E/O and O/E modules are based on

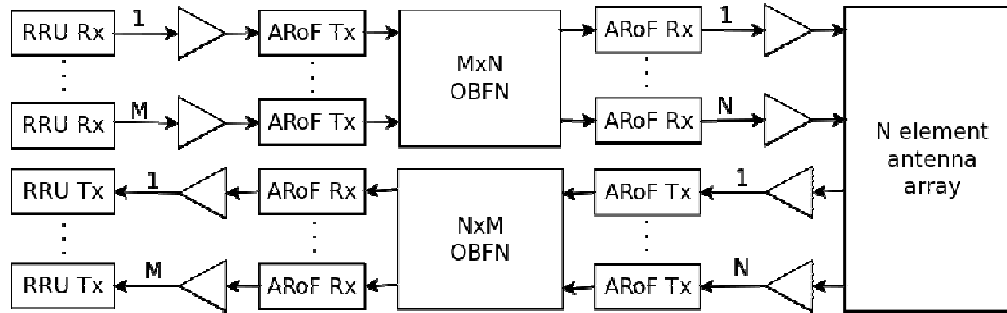


Figure 4 General scheme for including optical beamforming in the DRoF approach.

intensity modulation and direct detection (DD). So, a simple photodiode is used for optic-electric conversion. Nevertheless, sensitivity is an issue for large bandwidth photodiodes. In fact, high bandwidth APDs are the preferred option, although other options are not discarded, e.g. PIN diodes with semiconductor optical preamplifiers. Regarding E/O stage, we have two different possibilities: i) direct modulated laser (DML) and ii) external modulation of a continuous wave laser (CWL). Even a simple direct modulated laser is the preferred option in terms of cost, its performance is limited in terms of bandwidth, linearity and chirp. Therefore, in case performance might be a crucial issue, an external modulation scheme is the preferred option. Wavelength tunability is also an option that is envisioned for the E/O modules, with the corresponding cost increase of lasers.

The most interesting feature of the BVTs is their capability to be programmed and monitored by the control plane. The DRoF-B transceivers have a complete set of commands that allow to set the nominal central frequency, the bit and normalized power per symbol per OFDM subcarrier, the supported forward error correction (FEC) code (either HD-FEC or SD-FEC), and the equalization type (either zero forcing or MMSE). In turn, the monitored parameters are the SNR per OFDM subcarrier and the overall BER. Therefore, the control plane can set the parameters of the transceivers according to the network status and requirements. For example, it can configure a BVT with a uniform bit/power loading in order to retrieve the SNR profile of a given connection. Afterwards, the controller can calculate the right bit/power loading profile to attain the capacity required for that connection and configure the BVT accordingly. Also, the most suitable equalization type can be set according to the constellations used for bit loading along with the suitable FEC encoding/decoding.

#### 4. BEAMFORMING

The architecture depicted in Fig. 1 can also benefit from the inclusion of an optical beamforming stage at the cell sites, between the RRU analog input/output and the electrical signal conditioning stages for antennas. So, additional optoelectronic blocks can be included in the DRoF in case beamforming is needed. The scheme is shown in Fig. 2. For the sake of clarity, we have decoupled the RRUs into two different entities that account for the digital receiver (Rx) and transmitter (Tx), whose output/input delivers/receives an analog radio signal.

At the downstream side, an array of M RRU receivers delivers a convenient set of electrical analog IQ modulated IF radio signals in order to generate M different independent beams. These analog IF signals are amplified by an array of M electrical drivers and converted to the optical domain by a set of M ARoF transmission stages. These ARoF transmission stages feed an MxN OBFN. The ARoF transmission stages can be implemented in a single transceiver chip which can be directly coupled to the OBFN. The OBFN maps M incoming ARoF IF signals onto its N outputs, introducing relative delays between the different signal copies. It also couples each lane with an unmodulated optical tone conveniently spaced at the target RF frequency with respect to the ARoF output signal. Therefore, at the N ARoF Rx stages (typically composed by PIN+TIAs) an RF mm-wave signal is present after photodetection of the corresponding beating between the optical tone and the actual ARoF signals. After this photoelectric conversion, the resulting N different RF signals are boosted by an array of N power amplifiers and radiated by an N element antenna array.

In the upstream direction, the N RF signals, delivered by the N antenna elements, are amplified by the array of N low noise amplifiers and electrically downconverted to IF in the same manner as for ARoF (discussed in D3.1, omitted in Figure 2). These IF signals are injected to the ARoF transmitter. In turn, the OBFN processes the N incoming signals and delivers M different optical signals by applying the inverse operations as for downstream. The M signals are detected by a bank of ARoF receivers, whose outputs feed the RRU transmitters.

#### 5. DISCUSSION AND CONCLUSIONS

In this paper we have reviewed the DRoF fronthaul and seen how to fulfil the associated requirements in order to cope with the future RANs to be deployed under the blueSPACE vision. This entails the introduction of the SDM paradigm while increasing the flexibility and capacity of the DRoF transceivers.

Since the evolution of the DRoF fronthaul is still under definition, two different DRoF transceiver options have been analyzed. In DRoF-A, a transceiver is proposed to cope with the more recent specifications of the

Table 2 Summary of the main characteristics of DRoF transceivers

| Parameter                | Specifications DRoF-A       | Specifications DRoF-B  |
|--------------------------|-----------------------------|--|
| Optoelectronic front-end | DML+DD / CWL+EAM+DD         | DML+DD / CWL+MZM+DD  |
| Configuration parameters | Nominal central frequency   | Nominal central frequency<br>Bit per symbol per subcarrier<br>Power per symbol per subcarrier<br>Supported FEC (For BER analysis)<br>Equalization type |
| Monitoring parameters    | BER                         | SNR per subcarrier<br>BER  |
| DSP                      | None // simple data mapping | OFDM with 512 carriers and digital up/downconversion   |
| Capacity                 | Fixed at 25 Gb/s            | Variable, from 5 Gb/s up to 50 Gb/s*   |
| Sensitivity (B2B)        | -4 dBm (PAM-4)              | -15 dBm (50 Gb/s)  |
| Optical Bandwidth        | <20 GHz                     | 25 GHz (min.)  |

\* Depending on the bit/power per symbol per subcarrier assigned by the control plane.

standards and, therefore, expected to be deployed in short-term. DRoF-A is an extremely simple and reliable architecture that features limited flexibility. On the contrary, DRoF-B is a more advanced transceiver that features high flexibility, relying on advanced DSP. Thus, DRoF-B is targeting a mid- to long-term deployment. A summary of the specifications for both transceiver options is detailed in Table 1. It should be noted that DRoF-A and DRoF-B employ very similar opto-electronic front-ends, either at the transmitter or the receiver side. So, DRoF-A can be regarded as a predecessor of DRoF-B.

DRoF-A employs simple modulation formats and 10G-ready devices, which are widely used in network segments as the optical access. DRoF-B is tackling with increased data rates and flexibility at the expense of using a more complex architecture. So, DRoF-A is attractive in terms of cost, since it features a simple implementation and does not require the use of DSP. DRoF-B is the preferred option in terms of flexibility, because it has an increased number of parameters to configure. One of the most important features is the ability to vary the capacity, which can be programmed by the control plane according to the network requirements.

Also, we analyze a possible architecture for generating the different radio signals from the DRoF based on direct RF conversion. In the case of millimetric wave radio signals, this scheme is able to generate the IF radio signal, ready to be upconverted to the desired radio frequency. This is interesting for combining DRoF with optical beamforming, as the IF radio signals can feed the blueSPACE ARoF transceivers and pass through the suitable optical beamforming network before delivering the radio signals to the different antennas.

Therefore, the envisioned DRoF-based RAN constitutes a significant step forward towards flexibly providing high data rates in very dense areas in a limited reach, e.g. for the provision of high data rate services to a large number of concentrated mobile users at large events.

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