Experimental Validation of Hybrid WDM/SDM Signal Delivery for Mobile Fronthaul over PONs using SDN-Enabled Sliceable Bitrate Variable Transceivers

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ABSTRACT

We demonstrate combined WDM/SDM delivery of mobile fronthaul in PONs, employing SDN-enabled S-BVTs based on adaptive multicarrier modulation. Experiments show successful BBU-RRU connectivity on several deploying strategies while coping with capacities beyond 50Gb/s per flow.

Keywords: Passive optical networks, space division multiplexing, wavelength division multiplexing, optical OFDM, optical fronthaul.

1. INTRODUCTION

5G demands a large increase in capacity while meeting a dynamic network management. Furthermore, a large number of antenna elements over small/femto cells are envisioned for 5G deployments. This will require a large transmission bandwidth in the fronthaul, allowing to increase data rate per end user and application demand [1]. Therefore, the current and future network paradigm is expected to be based on a hybrid configuration where the segment closest to the end user will be supported by 5G wireless communications, while optical fiber links will support radio access networks (RANs) demanding very high capacity.

In order to cope with that, wavelength division multiplexing (WDM) can be employed, reusing the already deployed fiber infrastructure in the residential access, while providing flexible connectivity and high capacity [2]. Nevertheless, this solution is bounded to certain spectral regions and is not able to scale when capacity requirements increase, as expected in highly dense urban areas [1]. To overcome this limitation, space division multiplexing (SDM) can be employed to provide spatial diversity, which, in combination with WDM, will enable a fronthaul infrastructure with unique 2-dimensional (2D) properties. A first approach for SDM can be based on bundles of standard single-mode fibers (SSMFs). A longer-term solution can rely on multicore fibers (MCFs) [3], providing a compact parallel transmission medium.

In this paper, we propose and experimentally demonstrate a hybrid WDM/SDM delivery of mobile fronthaul traffic in passive optical networks (PONs), following the software defined networking (SDN) paradigm. This combination enables setting up of specific spectral/spatial channels according to the requirements of the services to deliver, enabling the configuration of virtual RANs over a passive optical infrastructure, seeing them as private network slices where flows can be allocated in a 2D space (WDM+SDM). This is enabled in the data plane level mainly by the adoption of a hybrid WDM/SDM infrastructure and SDN-enabled programmable sliceable bitrate variable transceivers (S-BVTs). The S-BVTs are able to transmit data flows with variable rate according to the network and path conditions. Specifically, we propose to use cost-effective S-BVTs based on orthogonal frequency division multiplexing (OFDM) and direct detection (DD).

2. CONCEPT

The network and signal delivery scheme is depicted in Fig. 1a. There, programmable S-BVTs are present at the central office in order to concurrently serve different cell sites. At the other end of the network, each cell site has a programmable BVT. Therefore space and spectrum resources can be managed by a centralized SDN controller in order to provision the different services, possibly including residential access and/or some other that could require a direct interface with the metro/aggregation segment. All the devices/systems belonging to the central office and, especially, the (S-)BVTs can be programmed by means of the corresponding SDN agents, allowing an automated channel establishment between the central office and the cell sites in a 2D space (WDM+SDM). We propose to employ the same wavelength for upstream and downstream in order to maximize the utilization of the network resources and simplify the network management.

Several deployment strategies can be approached for the external plant in order to enable SDM. A first step can be using SSMF bundles, since cables deployed in the field typically have a loose-tube design containing several fibers [4]. This would enable to reuse legacy infrastructure. Nevertheless, approaching this brown field migration scenario would entail different challenges, such as the relative delay between signals propagating through different fibers and the impact of environmental conditions such as temperature variations and unequal mechanical stress. In fact, this delay is tied to the cable structure and its helix factor, leading to differences of up to 1 μs in 10 km of fiber. Therefore, it would be desirable to have an external plant entirely based on MCF. A first approach can be to deploy the MCF only in the feeder section of the network. This section can be easily installed/upgraded to increase capacity at a limited cost [4]. In this case, a core-routed PON architecture can be envisioned, where different cores provide different services and/or connectivity to different geographical areas. This would be enabled by a fan-in/out device integrated in the remote nodes of the network. In order to maximise the network capacity, an external plant entirely composed by MCF should be envisioned, entailing different challenges, such as the implementation of MCF power splitters.

Regarding the dimension of traffic to support, it should be noted that the most bandwidth hungry service is the mobile fronthaul based on the common public radio interface (CPRI), which on the other hand, does not allow any dynamic management of the capacity in the transport network, since this kind of traffic requires high constant bit rate independently of the cell loads. In order to relax these requirements, several radio functions can be decentralized and adopted by the remote radio units (RRUs), trading latency and data-rate against flexibility. This is envisioned in the recent recommendations from the 3GPP [5], where different functional splits have been reported. For example, split options 1-2 can tolerate up to 10 ms of one-way latency, while option 8 tolerates only up to 250 μs [5]. In this sense, it can be assumed that latency is mainly due to propagation over fiber and, thus, transmission distance is the main constraint. Since we are envisioning a deployment for a high dense urban scenario featuring small distances (<6 km), the propagation delay is expected to be less than 30 μs. Regarding capacity, the requirements are of up to 4 Gb/s for split options 1-2 and beyond 150 Gb/s for option 8 [5]. Consequently, this should be taken into account when allocating the network resources in order to provide fronthaul services. So, it is desirable to have mechanisms for the dynamic management of bandwidth/capacity of the network, being the (S-)BVT one of the suitable technologies for that [2].

A SDN controller is proposed for efficiently managing the devices and provisioning the services. In fact, the (S-)BVTs can be configured by a suitable SDN controller for an optimal management of the network resources [6][7]. The parameters to be configured at each (S-)BVT can include wavelength, spatial channel (i.e. core), capacity and power per flow. In this sense, (S-)BVTs based on DD-OFDM provide advanced spectrum manipulation capabilities, including arbitrary sub-carrier suppression and bit/power loading. Thus, DD-OFDM transceivers can be configured for achieving a targeted reach and/or data rate adopting simple devices [7].

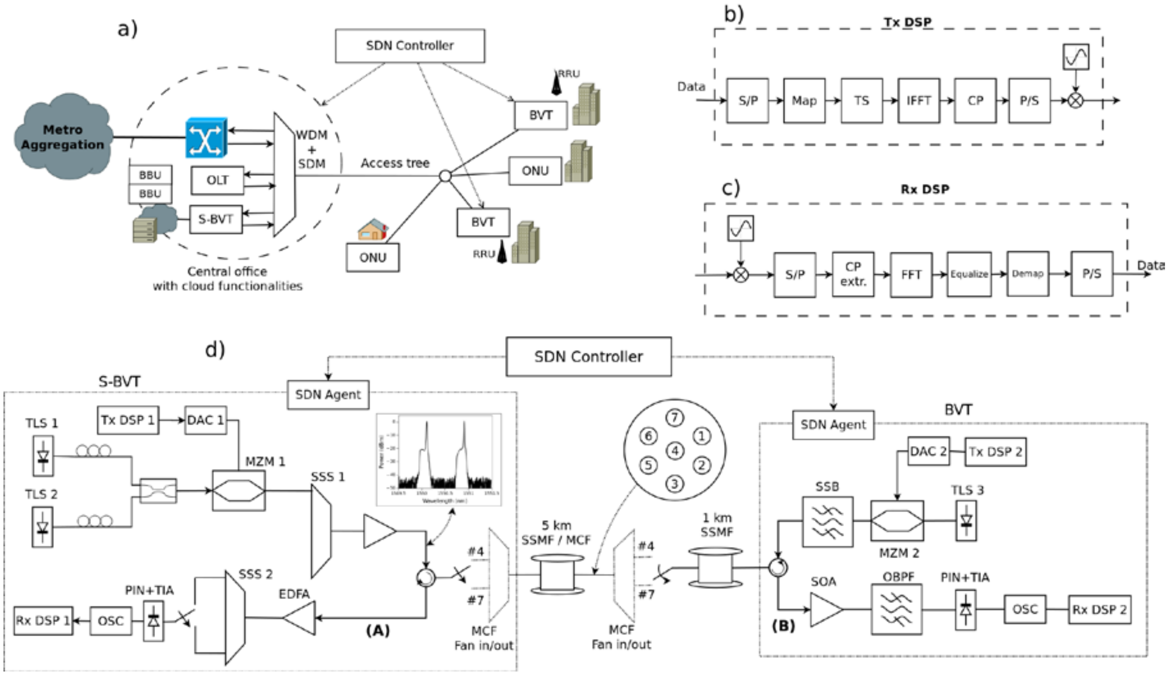

Figure 1. (a) Network concept. (b-c) DSP details for generating the OFDM signals in the experiments. (d) Experimental setup.

3. EXPERIMENTAL SETUP

Figures 1b-d show the experimental setup for two spectral flows and a MCF with up to 7 cores. The digital signal processing (DSP) and signal up/downconversion at the transmitter/receiver are performed off-line, following the steps detailed in Figs. 1b-c [7]. At the transmitter side, randomly generated data are mapped into the corresponding constellation (up to 256-QAM). The rate-adaptive Levin-Campello algorithm is used for adaptive bit/power loading [7]. Then, four training symbols (TS) are included every 100 OFDM frames. The resulting symbols feed an inverse fast Fourier transform (IFFT) of 512 subcarriers. Next, a 2% cyclic prefix (CP) is added and the obtained OFDM symbols are serialized. The digital OFDM signal, running at 20 Gbaud, is clipped and upconverted to an intermediate frequency of 10 GHz. The resulting signal is converted to the analog domain by a digital-to-analog converter (DAC) at 64 GSa/s. This analog signal is conditioned and injected to the corresponding Mach-Zehnder modulator (MZM 1, MZM 2) biased at the quadrature point and excited by the corresponding tunable laser sources (TLSs). The flows resulting after the MZMs are filtered using a liquid crystal on silicon reconfigurable optical spectrum selective switch (SSS) for downstream, and a tunable bandwidth variable optical filter for upstream, both configured to have 25 GHz bandwidth per channel and slightly detuned in order to obtain an optical single sideband (SSB) signal. Two flows are generated at downstream, centered at 1550.12 nm and 1550.92 nm; they are depicted in the inset of Fig. 1d. A single flow is generated for upstream, able to be tuned to each of these wavelengths.

The optical signal resulting from the downstream transmitter is injected into the feeder section of the access tree. Since we are targeting a highly dense urban scenario, this feeder section is composed of a 5-km fiber spool (either SSMF or MCF), followed by a drop section composed of a 1-km SSMF spool. The power delivered is set to +5 dBm per flow in the downstream, while the upstream flows feature -1.9 dBm.

The incoming signal is preamplified in the downstream receiver by a semiconductor optical amplifier (SOA), filtered out by an optical band pass filter (OBPF) and photodetected. Similarly, the received signal in the upstream receiver is preamplified by an EDFA, filtered by an SSS and photodetected. A real-time oscilloscope (OSC) operating at 100 GSa/s digitizes the detected currents.. The corresponding baseband OFDM signals are recovered after down-conversion, off-line demodulated, equalized and de-mapped. Bit error ratio (BER) is then measured by error counting.

The SDN controller configures the (S-)BVTs by activating the slices, forward error correction (FEC), wavelength, core and bit/power loading algorithm. Also, it is able to switch between signal-to-noise ratio (SNR) estimation and data transmission modes. When operating in SNR estimation, all the OFDM subcarriers are loaded with dummy data using a 4QAM constellation at the transmitter, while noise and power of each symbol are estimated at the receiver. This information is collected by the corresponding agent and passed to the SDN controller. In turn, the SDN controller uses this information to configure the (S-)BVTs when operating in transmission mode, so the optimum constellation is employed at each OFDM subcarrier. A sample configuration is shown in Fig. 2a.

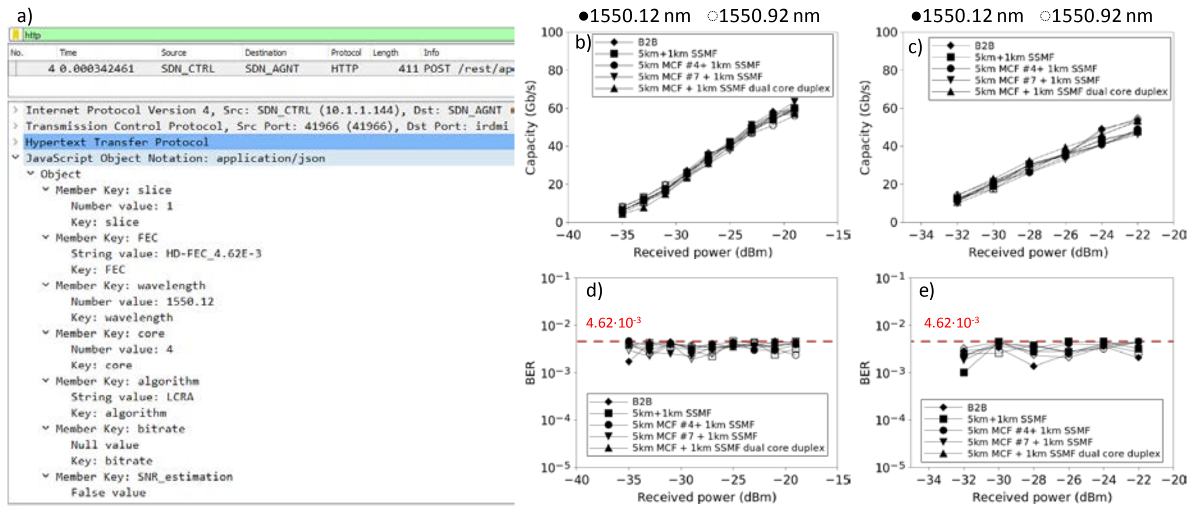

Figure 2. (a) Sample JSON object corresponding to the configuration of the S-BVTs at maximum capacity. (b-e) Experimental results in terms of maximum capacity (b, c) and the corresponding BER (d, e) versus received power for the cases of: (b,d) downstream and (c,e) upstream.

4. RESULTS

Results are shown in Figs. 2b-c. A BER threshold is set to $4.62\cdot10^{-3}$ for a 7% FEC overhead [8], being ensured for all the cases (Figs. 2d-e). The received power is measured after attenuation at points (A) and (B) of Fig. 1d for upstream and downstream, respectively. The network is envisioned to cover a power budget of 25 dB. So, the received power threshold is set to -20 dBm for downstream and to -26.9 dBm for upstream. Please note that filled markers of Figs. 2b-e correspond to measurements at 1550.12 nm while the empty markers relate to 1550.92 nm, being both wavelengths highly overlapped one to each other.

First, a back-to-back (B2B) configuration is tested featuring a maximum gross capacity around 54 Gb/s per flow at -22 dBm for either upstream or downstream. At the received power threshold, the maximum capacity is above 53 Gb/s for downstream while for upstream is about 34 Gb/s at both wavelengths.

Next, the impact of bidirectional transmission after 6 km (5 km feeder + 1 km drop) of SSMF is assessed. We observe that these configurations are aligned with the B2B case, achieving capacities around 51 Gb/s per flow at the received power threshold for downstream. For upstream transmission, the capacity is about 34 Gb/s for both flows at the same threshold, as in the B2B case. However, the upstream maximum capacity at -22 dBm is limited to 47 Gb/s mainly due to the Rayleigh backscattering and eventual reflections of the downstream signal caused by bidirectional transmission over a single fiber [9]. The optical signal to Rayleigh ratio (OSRR) measured is of 41.9 dB for downstream and 25.3 dB for upstream.

Afterwards, we substitute the SSMF feeder by a 5 km MCF feeder and the corresponding fan in/out devices, featuring single-core bidirectional transmission over the central core (#4) and a core near the cladding (#7). In these cases, the results obtained are similar to the SSMF ones. In fact, for the downstream we obtain ~52 Gb/s, while achieving around 33 Gb/s in upstream for both flows at the proposed power threshold. In this case, the OSRR measured is about 35.8 dB (downstream) and 21.6 dB (upstream) for both cores, being lower than the values corresponding to the SSMF feeder.

Finally, we assess the case when bidirectional operation is achieved by transmitting the downstream over the central core (#4) and the upstream over the external one (#7). There, we obtain results similar to the previous cases at the proposed power threshold. Nevertheless, the maximum capacity measured is now increased, mainly in the upstream sense, featuring values above 50 Gb/s, like in the B2B case. This is due to the fact that now there is no bidirectional transmission over the same core and, consequently, no penalty related to Rayleigh backscattering.

The capacity results obtained can be compared with the requirements reported in [5]. Therefore the achievable functional split is limited to split option 7a, due to the system capacity reported. Nevertheless, it should be noted that this capacity is reported per flow. Therefore, in case of being able to concurrent transmit/receive more than one flow per RRU (i.e. employing also S-BVTs at the RRU side), the split option supported can be increased. For example, split option 7b can be supported with 2 flows in downstream and 3 flows in upstream.

5. CONCLUSIONS

A hybrid WDM/SDM networking scheme for mobile fronthaul has been experimentally demonstrated with SDN-enabled DD-OFDM S-BVTs. Different deployment strategies (SSMF bundles and multicore fibers) have been analyzed for a highly dense urban area scenario; achieving capacities above 50 Gb/s per wavelength and fiber/core.

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