Performance evaluation of SDN-controlled green mobile fronthaul using a federation of experimental network testbeds

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Abstract
When evolved NodeB flexible functional split is implemented in virtualized radio access network 5G systems, fronthaul connectivity between the virtualized network functions (VNFs) must be seamlessly guaranteed. This study proposes the utilization of software defined networking (SDN) to control the mobile fronthaul. In particular, this study investigates the ability of the SDN-based control of reconfiguring the fronthaul to maintain VNF connectivity when cell and optical access turn into sleep mode (off mode) for energy efficiency purposes. The evaluation of the proposed scheme is performed by federating two remote experimental testbeds. Results show that, upon cell and optical access turning on and off, the fronthaul reconfiguration time is limited to few tens of milliseconds.

Keywords SDN · Fronthaul · 5G · Virtualized RAN · TWDM PONs · Energy savings

1 Introduction
Nowadays the use of Internet is exploding and the communication networks are massively adopted for the exchange of data. Other than maximizing the performance of the communication networks in terms of maximum throughput, one of the key research aspects is the efficient utilization of the energy consumption, with particular attention at both core (e.g., optical) and metro-access networks.

Software-defined networking (SDN) [1] is an emerging control plane architecture, able to increase the flexibility and the automation in the control of telecommunication networks. SDN has been applied to numerous network scenarios, including also the context of mobile access networks (i.e., both fronthaul and backhaul).

Considering the concept of energy consumption, several solutions have been proposed, able to reduce the consumption of energy in both macro-cells [2] and small cells [3]. Moreover, also the RAN segment has been under evaluation, considering energy efficiency. In fact, both international standardization bodies (i.e., ITU-T and IEEE) and research institutions [4] proposed energy saving solutions for passive optical networks (PONs). The focus of such solutions is to decrease the energy consumption of the PON customer premises equipment (CPE) (i.e., optical network units, ONUs) in a scenario with 10 Gbps PONs (e.g., XG-PON) [4].

Considering the case of time and wavelength division multiplexed (TWDM) PONs, also at the optical line terminal (OLT) side the energy can be saved, according to the traffic load. In fact, when the traffic load is low, some of the transceivers in use at the OLT can be turned off, while the other active transceivers are shared among the ONUs equipped with tunable transceivers [5–8]. However, in this case the reduction of energy consumption results in the increment of the latency experienced by the traffic.

Considering the SDN literature, a massive adoption of such an architecture is demonstrated by the large number of studies, designed not only by academia researchers but also in the industry panorama [9–11]. Considering, for example, the solution proposed by [11], an SDN-based fronthaul
scenario, based on optical topology-reconfigurable network, is shown. More specifically, bidirectional coordinated multi-point (CoMP) flows between mobile cell sites and baseband units (BBUs) are carried along the network. The proposed solution has been evaluated in a local testbed, achieving an end-to-end packet delay in the order of microseconds while the topology reconfiguration time is in the order of milliseconds. Thus, the proposed solution is compatible with a centralized coordinated radio resource control (RRC) implementation whose latency requirements are in the order of seconds [12]. More recently, in [13], 3GPP proposed possible functional split options with maximum one-way allowed latency requirements in the order of milliseconds for higher-layer functional split (i.e., RRC split and packet data convergence protocol—PDCP split). The lower-layer functional split options (i.e., option 5–option 8) latency requirements in the order of hundreds of microseconds. However, these fronthaul latency requirements have not yet been evaluated.

In [14], the SDN architecture and in particular the OpenFlow protocol are extended in order to control an optical access/aggregation network. In fact, the authors propose the implementation of software-defined OLT and software-defined ONUs, able to reuse the portion of the spectrum not used by the PON in order to provide an orthogonal frequency division multiple access (OFDMA) mobile backhaul.

The SDN-based approach applied to mobile access is widely adopted in the literature. In [15], an SDN-based provisioning for multi-technology multi-tenant connections is shown. The authors of [16] presented an SDN-based solution to increase the network flexibility for both the mobile fronthaul and backhaul. More specifically, relying on reconfigurable nodes the capacity of the mobile crosshaul is distributed among data centers of cloud radio access network (i.e., DC C-RAN) according to the load conditions at BBUs.

Then, the authors of [17, 18] focused on Ethernet-based fronthaul solutions, analyzing the performance of fronthaul reconfiguration techniques, with specific attention to their advantages and disadvantages. Other studies proposed several architectures in order to envisage the adoption of SDN, network function virtualization (NFV) and C-RAN in mobile crosshaul scenarios [19]. However, the proposed schemes are preliminary solutions that present partial functionalities and focus on the coordination between the network reconfiguration and the network function migration according to the network status.

This paper presents and validates a novel solution for mobile fronthaul reconfiguration based on cell on/off scheme. It extends the work proposed in [20] by adopting the SDN paradigm in order to control the mobile fronthaul. The novelty of this paper consists in the implementation of a scheme based on the interaction between a TDM-PON SDN controller and a metro network SDN controller when energy-efficient schemes are employed in both the mobile and fixed networks. The current trend is to equip PONs with SDN controllers, but few of them are commercially available [21]. Moreover, the paper is among the first ones proposing the interaction between mobile network and wired access/metro network [22]. The proposed solution improves the energy efficiency of the system including the eNB side and part of the RAN. In particular, this study analyzes the adoption of the SDN-based control plane to coordinate both mobile cell and optical access devices. The idea is to reconfigure the aggregation segment of the fronthaul (i.e., turning on/off its line cards) in order to provide seamless connectivity between user equipments (UEs) and virtualized mobile network functions.

The evaluation of the proposed solution has been performed using two experimental federated testbed facilities. During the carried-out experiments, we have found that the fronthaul reconfiguration time takes few tens of milliseconds when the cell and the optical access are activated or deactivated.

2 Federation of heterogeneous research network testbeds: ultraaccess and virtual wall

Novel networking concepts are being created in research laboratories all over the world and demonstrated in testbeds whose utilization is constrained to local researchers. Usually, these network testbeds involve unique prototype components and measurement equipment. A wider impact and analysis of the possibilities of the new technology could be achieved if these testbeds are open to other researchers through an advanced Internet service. Moreover, the federation of a large amount of disperse testbed facilities can make it possible for multiple researchers to experiment with future Internet protocols and applications on a big computational grid for a given period of time. This is one of the goals of Global Environment for Network Innovations (GENI) in USA and Future Internet Research and Experimentation (Fed4FIRE) [23] in Europe. Both initiatives aim to create a large-scale virtual laboratory for networking and distributed systems research and education.

2.1 The federation: Fed4FIRE

A number of projects aim to build a cross-national facility to enable experimentally driven research in different parts of the world. Most of them are focused on a single research community. Fed4FIRE (2012–2016), consolidated in Fed4FIRE+ (2017–2021) is an EU project that intends to build an open, accessible and reliable framework for the federation of Internet research infrastructure across community

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Sample community domains include optical networking, wireless networking, software-defined networking, cloud computing, grid computing and smart cities.

All these heterogeneous communities, including next-generation optical networking, were involved in the project to guarantee compatibility and support of heterogeneous infrastructure and experimentation requirements. The keys of this target framework are:

1. Open experiment life cycle management software;
2. Experimental measurement and monitoring tools;
3. Trust and security mechanisms and
4. Advanced inter-testbed connectivity services.

However, to achieve the federation of optical networking testbeds several issues must be solved. Most optical laboratory devices do not feature the programmability required to embed federation software, and lack the virtualization capabilities required to enable secure access to the infrastructure to external users. Consequently, those elements of a testbed that do not support this functionality need to be assisted by a computer. We have focused on this scenario and have integrated an optical access network testbed called UltraAccess as powerfully as possible: a wavelength division multiplexed passive optical network (WDM-PON) at Carlos III University (UC3M). This testbed is covered in the next section.

### 2.2 The federated testbed: UltraAccess at UC3M

UltraAccess testbed consists of a fully configurable WDM-PON network, including a WDM-PON OLT, a multipoint fiber infrastructure equipped with an arrayed waveguide grating (AWG), a set of optical network terminals (ONTs) and high-end Fed4Fire stations, providing end users with a dedicated capacity of 100–1000 Mb/s. The systems allows the configuration of advanced QoS features, traffic engineering and virtual LANs. The testbed features a seeded WDM-PON as standardized by ITU-T G.698.3. In the seeded WDM-PON approach, a broadband light is sliced by an AWG and injected into an anti-reflection-coated Fabry-Perot laser to create “seed” signals that transmitters can lock onto. This technique is very attractive due to its simplicity and cost-effectiveness, since the ONTs are colorless (i.e., they can transmit/receive on any wavelength) (Fig. 1).

### 2.3 The federated testbed: virtual wall at iMinds

At the time of experimentation, iMinds virtual wall has two kinds of setups: virtual wall 1 with 200 physical servers (e.g., 100 × quadcore, 100 × eight cores) and virtual wall 2 with 100 physical servers (e.g., 100 × 12 cores). All servers were equipped with a management Ethernet interface, and multiple (4–6 for the quad cores, up to 11 for the 12 cores) Ethernet interfaces that can be used for experimentation purposes. Both the virtual walls are controlled by testbed management software jFed based on Emulab. Multiple operating systems are supported (e.g., Linux (Ubuntu, Centos, Fedora), FreeBSD, Windows 7) on each node, and some of the nodes are connected to an OpenFlow switch to do OpenFlow experiments that supports software OpenFlow switches (OVS) and real OpenFlow switches.

### 3 SDN-controlled energy-efficient mobile fronthaul experiment

This section presents SDN-controlled energy-efficient mobile fronthaul architecture and setup of federated testbeds.

#### 3.1 SDN-controlled mobile fronthaul architecture

Figure 2 depicts the considered SDN-controlled crosshaul architecture. The architecture consists of a WDM-PON access and an OpenFlow-based layer 2/3 aggregation network. Antenna A1 and A2 are connected to ONU1 and ONU2, respectively. In the aggregation node, the OLT line card (LC1) and LC2 are connected to two interfaces of an Ethernet OpenFlow (OF) layer 2 switch (L2SW). On the other end, the L2SW two interfaces are connected to the aggregation network. Moreover, the aggregation node controller is used to control the OF L2SW, and this controller is implemented as a simple, light version of an SDN controller (i.e., LitSDNCtrler) as proposed in [24]. As shown in Fig. 2, the SDN controller (i.e., SDNCtrler) is used to control all the Ethernet OF Layer 2/3 switches in the aggregation network.
It is assumed that the chosen crosshaul functional split allows to carry both fronthaul traffic (digital radio signals transmitted from the remote radio head (RRH) to the base band units (BBU) in the C-RAN) and backhaul traffic (regular data packets) over a packet-switched network with QoS support. Mobile RAN network functions are generally indicated as NF1, NF2 and the evolved NodeB (eNB) is assumed to support cell on/off for energy efficiency purposes.

This paper presents a solution to improve the energy efficiency of the crosshaul by applying the contemporary sleep mode (i.e., on/off) of the WDM-PON devices that are connected to the cell implementing on/off. Thus, the contemporary reconfiguration is performed not only at the crosshaul optical access network but also at the crosshaul aggregation network. In particular, when the cell changes its status (i.e., on/off) the OLT is notified to turning on/off the ONU and the LC to which the cell is connected. Contemporarily, both the LitSDNCtrler and the SDNCtrler are notified of the changes and perform the necessary reconfigurations to allow the UE bearers to reach their original destinations (i.e., NF1 and NF2).

### 3.2 SDN-controlled energy-efficient mobile fronthaul implementation in federated testbeds

Figure 3 shows the implemented of two federated testbeds provided by the Fed4Fire project, corresponding to the

![SDN-controlled cross-haul architecture](image)

**Fig. 2** SDN-controlled cross-haul architecture

![Federated testbed setup](image)

**Fig. 3** Federated testbed setup
architecture depicted in Fig. 2. Here, the considered testbeds are a WDM-PON testbed and an OpenFlow Ofelia island located at UC3M and iMinds, respectively. The UC3M testbed represents the crosshaul optical access segment, and the iMinds testbed represents the crosshaul aggregation network. As shown in inset of Fig. 3, the WDM-PON supports two pair (i.e., $\lambda_1^u$ and $\lambda_1^d$, and $\lambda_2^u$) of wavelengths with a capacity of 1 Gb/s each. The OpenFlow Ofelia island consists of five OVSs (i.e., s1, s2, s3, s4, and s5) interconnected by Gb/s links. Two PCs (i.e., PC1 and PC2) of the WDM-PON emulate the end users (i.e., UE1 and UE2), and the two PCs are connected with two ONUs by utilizing the L2SW. Here, the L2SW emulates the possibility, for the UE to be connected to either antenna (i.e., A1 or A2). Note that the L2SW at the aggregation node is also an OVS. All the OVS, the LitSDNController and SDNCtrler are implemented in the OpenFlow Ofelia island at iMinds. The two testbeds are integrated using Generic Routing Encapsulation (GRE) tunnels through the public Internet between two PCs connected to the OLT LCs and two Xen virtual machines (i.e., xenvm1, xenvm2) at iMinds. The tunnels carry both data and control communications at a rate of 100 Mb/s. The signaling between the OLT and the LitSDNController is performed in-band, while the signaling between the LitSDNController and the SDNCtrler is performed out-of-band through a direct connection.

4 Utilized tools

4.1 Experiment management and control

Figure 4 shows the testbeds and the basic Fed4FIRE tools used to perform the experiment. The experiment uses several resource reservation, experiment control and measurement and monitoring tools including common interfaces protocols. Here, the F4F portal offers access to the required Fed4FIRE tools and testbeds (e.g., jFed). The jFed tool was used to reserve the resource from both the testbeds (i.e., UltraAccess and iMinds Ofelia island) by using slice-based federation architecture (SFA) interface. During the experiment, the resources of the testbeds (i.e., wavelengths, VLANs, ONUs, LCs, and L2SWs) were controlled by experiment control (EC) with the help of SSH protocol. The resource controller (RC) (i.e., SSH) is capable enough to interact with all the resources in the testbeds.

The Orbit Management Library (OML) framework is used for measurement and monitoring the testbeds. OML uses databases running on the aggregate manager (AM). OMF is a framework that provides a set of tools to describe, instrument and execute experiments and collect their results and a set of services to manage and operate testbed resources. This framework basically requires an experiment controller (EC) that processes an OMF Experiment Description Language (OEDL) description of the experiment scenario and controls the required nodes and a resource controller (RC) daemon at every resource, which receives messages from the EC and executes the commands.

4.2 Measurement collection: the orbit management library (OML)

Another important aspect that is tightly related to experiment and resource control is measurement collection. Our testbed provides this feature through OML. OML is a generic software framework for measurement collection. It allows the experimenter to define the so-called measurement points (MPs) inside new or preexisting applications so that these MPs generate measurement streams (MSs) that can be directed to a central collection point and stored in measurement databases. It is composed of two entities. The first one is an OML server responsible for collecting and storing measurements inside an SQLite3 or PostgreSQL database. The UltraFlow access testbed offers a local SQLite3 database so that experimenters can direct their measures there. The second one is an OML client library that essentially provides a C API to be used inside applications. There are also native implementations in Python (OML4Py) and Ruby (OML4R) as well as third-party libraries for Java (OML4J) and Javascript/WebSocket (OML4JS). The OML group offers both OML-enabled applications and good tutorials for OML client application programming.

The other tools were used to measure bandwidth and latency such as: thrulay traffic generator [25] tool was used to measure the bandwidth between the source and destination node. In addition, it also provides latency with different quantiles. tshark is a network protocol analyzer tool was used to measure the network reconfiguration time by

![Fig. 4](Image)
capturing packets as described in Sect. 5. Ping tool was used to measure the round trip time between the source node and destination node. It was also used to test the tunnel delay between UC3M and iMinds testbeds.

4.3 Accessing Fed4FIRE resources: jFed

Fed4FIRE federated resources and in particular UltraAccess testbed accept users from Fed4FIRE-trusted identity providers. They can configure experiments interconnecting resources from multiple testbeds at the same time, reserve and access them via Fed4FIRE tools such as jFed [26]. In order to use this tool, users need to provide a user certificate and a password to log in. They can get an account and download their certificates from iMinds authority provider [27]. Once logged in, users can set up their experiments by choosing which types of resources and from which testbeds, configure those resources (operative system, software to be installed, network configurations, measurement options, etc.), launch the experiments and access the resources, just by double clicking on their icons. UltraAccess testbed offers a detailed tutorial on how to perform all the process right from the first step, the user getting an account, up to performing some simple experiments including measurements [28]. The other important feature of jFed is jFed timeline; it is used for executing commands instantaneously on multiple nodes or to execute commands based on a timeline.

5 Evaluation scenario and results

5.1 Day/night cell on/off

Figure 3 shows the considered experiment setup performed using the jFed experiment toolkit. The jFed tool is provided by iMinds, which is used to access the federated testbeds. Initially, two end-to-end VLANs (i.e., VLAN1 and VLAN2a) are set up between two servers of the network functions (i.e., NF1, and NF2) and two end users (i.e., UE1 and UE2). For example, UE1 is connected to antenna A1 of cell C1 that, in turn, is connected to the network function NF1 server.

As shown in the inset of Fig. 3, to emulate the tuning off the ONU and OLT LC upon cell turning off, a command is issued through the OLT management interface to turn off one ONU and the respective LC. Specifically ONU2 and LC2 (i.e., PC2–ONU2 and LC2–PC4 in Fig. 3) are turned off. Upon issuing the ONU and LC turn off command, the OLT notifies the LitSDNCtrler (1) that, in turn, reconfigures the aggregation node L2SW (2) and it triggers the SDNCtrler (3) to initiate the reconfiguration of the aggregation network switches (4). In such a way, the VLAN between UE2, now connected to A1 and C1, and the NF2 server is maintained. Specifically, as shown in Fig. 3, the VLAN reconfiguration time, defined as the time elapsing between the transit of the reconfiguration triggering message sent by the OLT to the LitSDNCtrler through the L2SW (in-band signaling) and the detection of the first successive ping reply from the NF2 server at the L2SW. Note that the additional constant delay due to the GRE tunnel is not taken into account. In addition, the contribution of the ping round trip time can be considered negligible because all the involved devices (i.e., OVS, controllers, and servers) are located in the same local network. The VLAN reconfiguration time measurement is performed as follows: (1) ping is continuously run between xenvm1 and NF2 server with packet interval of 1 ms; (2) reconfiguration request commands sent by the OLT to the LitSDNCtrler are monitored at the OVS implementing the L2SW at iMinds (in this way the L2SW becomes a synchronization point for the measurement); (3) similarly, ping replies from the NF2 server are monitored at the L2SW. The monitoring is performed through the ts hark tool installed in the L2SW.

Figure 5 shows the timestamp of the arrival, to the L2SW, of the reconfiguration triggering message sent by the OLT to the LitSDNCtrler and the timestamp of the arrival of the first successive ping reply from NF2 server to the L2SW (red colored rectangles), after about 45 ms. The control plane message exchange for network reconfiguration is the major contributor to the VLAN reconfiguration time, while the L2SW reconfiguration time contributes only for few tens of microseconds, as reported in [29].

Figure 6 shows the sampled probability mass function (PMF) as a function of the VLAN reconfiguration time. The experiment duration is set to 3600 s (60 reconfigurations). As shown in the figure, around 50% of network reconfigurations take between 40 and 60 ms. Thus, it is experimentally proven that a VLAN reconfiguration time of few tens of milliseconds is achieved by the proposed SDN-controlled mobile crosshaul. In addition, crosshaul energy savings proportional to the cell off time and the difference between the energy consumed by the ONU and the OLT during on and off periods are possible.

The focus of this study is more on the fronthaul reconfiguration time. However an estimate of the energy efficiency can be provided by considering how often the cell is turned on/off. Without considering the cell energy consumption, and by assuming that a cell is OFF for one fourth of a day (e.g., during the night), if the power consumed by an OLT LC when it is working is 6 W and when it is off is 4.2 W (our assumption) and the power consumption of the ONU when it is on is 3.2 W and when it is off is 2.3 W [30], the energy savings that can be potentially achieved are about 4%. In general, they can be as computed as follows:
The power consumed when both LCs of OLT and both ONU are always on is:

\[ P_{\text{on}} = 2(P_{\text{OLT, on}} + P_{\text{ONU, on}}) \]  

The power consumed when one LC-ONU pair is on and the other LC-ONU pair is off (as depicted in Fig. 3) is:

\[ P_{\text{off}} = P_{\text{OLT, on}} + P_{\text{ONU, on}} + P_{\text{OLT, off}} + P_{\text{ONU, off}} \]  

From Eqs. (1) and (2), the average energy savings for the considered scenario can be computed as:

\[ \eta = 1 - \frac{T_{\text{on}} P_{\text{on}} + T_{\text{off}} P_{\text{off}}}{P_{\text{on}} (T_{\text{on}} + T_{\text{off}})} \]  

The analytical formulation of average energy efficiency as a function reconfiguration time has been presented in [31]. Here, we showed that when the reconfiguration time increases, less reconfigurations are performed. As a results, the turn ON time of the LCs of OLT increases; hence, the OLT energy efficiency decreases. The interested reader can refer to [31] for a detailed explanation and to explore more results.

### 5.2 Fast cell on/off

In this section, the performance when a fast cell on/off scheme is implemented is reported in Fig. 7. Thrulay traffic generator [25] tool is used to measure the end-to-end average frame delay (i.e., UC3M PC2 to iMinds server2) while periodically turning on/off LC2. When LC2 is turned off, the traffic is aggregated to LC1, as shown in Fig. 3. Thrulay server modules are running at both the servers of iMinds, and Thrulay client modules are running at PCs that are attached to both the ONU. UDP traffic is generated from the clients with different traffic loads, packet size is set to 1400B and UDP buffer size is set to 262142B. The experiment duration is 2400 s for all the considered scenarios. The automated reconfiguration request commands are periodically sent from the PC4 attached to LC2 (i.e., LC2–PC4 as shown in Fig. 3) to the LitSDNCtrlr, and they are monitored at the OVS implementing the L2SW at iMinds.

The considered performance parameter are One-way Delay and One-way Packet Loss Ratio. The One-way Delay is defined as the time it takes for a packet to reach its destination. The One-way Packet Loss Ratio is defined as ratio between the number of received packets at the destination (e.g., NF2) and the number of packets sent at the source (e.g., PC2).

Figure 7 shows the one-way delay as a function of reconfiguration period \( T_{\text{rec}} \). As expected, the one-way delay increases as \( T_{\text{rec}} \) increases, because the number of packets buffered during the reconfiguration period increases. The one-way delay is around 700 ms when the cell is always ON, and there is an increase of 100 ms when reconfiguration period \( T_{\text{rec}} \) is set to 30 s by the cell turning on/off periodically. The one-way delay increase due to buffering, GRE Tunnel and reconfiguration time described in Sect. 5.1. Table 1 shows the one-way packet loss ratio as a function of reconfiguration period \( T_{\text{rec}} \).

### 6 Conclusions

This study proposed an SDN-based solution to coordinate cell on/off with part of the mobile crosshaul on/off (and subsequent reconfiguration) for improving crosshaul energy efficiency. Results show that, once part of the crosshaul is turned off, communication between the user equipment and the server hosting a specific network function is recovered after few tens of milliseconds.

The experiments carried out to assess the approach relied on third-party-provided network equipment over a testbed federation platform. This shows that complex setups for 5G crosshaul experimentation can be realized and used for valid experimentation, thanks to the advances in virtualization.
and tested federation currently available to the research community.

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