SDN-Controlled Energy-Efficient Mobile Fronthaul: An Experimental Evaluation in Federated Testbeds

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***Abstract*—When evolved NodeB (eNB) flexible functional split is implemented in Cloud-Radio Access Network (Cloud-RAN) 5G systems, fronthaul connectivity between the virtualized functions must be always guaranteed. This study proposes the utilization of Software Defined Networking (SDN) to control mobile fronthaul. In particular, this study investigates the ability of the SDN-based control of reconfiguring the fronthaul to maintain virtualized network function connectivity when cell and optical access turn into sleep mode (off mode) for energy efficiency purposes. The experiments in two federated testbeds show that, upon cell and optical access turning on and off, the fronthaul reconfiguration time is limited to few tens of milliseconds.**

***Index Terms*—SDN, fronthaul, 5G, Cloud-RAN, TWDM PONs, Energy Savings.**

I. Introduction

Software defined networking (SDN) [1] has emerged as a strong candidate to improve the control of telecommunication networks also in the context of mobile x-hauling (i.e.,front/backhauling). Solutions are not only proposed by academia but are also supported by the industry [2]–[4]. For example, in [4] an SDN-controlled optical topology-reconfigurable mobile fronthaul is proposed to carry bidirectional collaborative multipoint (CoMP) flows between mobile cell sites and baseband units (BBUs). The proposed solution, evaluated in a local testbed, achieves end-to-end packet delay in the order of few microseconds but the topology reconfiguration time is in the order of milliseconds. In [5], SDN and OpenFlow are extended to control an optical access/aggregation network and implement software-defined Optical Line Terminal (OLT) and software defined Optical Network Units (ONUs). In the considered solution, part of the optical spectrum unutilized by the PON is reutilized for providing Orthogonal Frequency Division Multiple Access (OFDMA) mobile backhaul (MBH). Other studies in the literature prove the feasibility of an SDN-based approach for provisioning multi-technology multi-tenant connections [6]. In parallel, a scheme for flexible networking is presented in [7] for the mobile front-and/or backhaul through reconfigurable nodes, where the capacity of the mobile x-haul can be distributed among data centers of cloud radio access network (C-RAN) to adapt to actual load conditions at BBUs. In addition, in [8], [9], a qualitative and quantitative analysis of fronthaul reconfiguration techniques along with a study of advantages/disadvantages of Ethernet-based fronthaul solutions is presented. Furthermore, the concept of flexible functional split is introduced, as in [10], to increase the applicability of the C-RAN paradigm while taking into account the trade-off between centralization and backhaul requirements (e.g., capacity and latency).

Some studies already proposed several architectures for the utilization of C-RAN together with SDN and Network Function Virtualization (NFV) for mobile x-haul [11]. However their initial evaluation focused mainly on the coordination between function migration and network reconfiguration.

This study proposes the utilization of Software Defined Networking (SDN) to control mobile fronthaul when energy efficient schemes are implemented not only at the eNB but also in part of the RAN. In particular, this study investigates the ability of the SDN-based control of coordinating cell and optical access device turn on/off with the reconfiguration of the aggregation segment of the fronthaul for providing seamless connectivity between User Equipments (UEs) and virtualized, but static, mobile network functions.

The experiments in two federated testbeds show that, upon cell and optical access on/off, the fronthaul reconfiguration time is limited to few tens of milliseconds.

II. SDN-controlled Energy Efficient Fronthaul Architecture

Fig. 1 depicts the considered SDN-controlled network architecture. It is assumed that the network carries both fronthaul traffic (e.g., 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. It consists of a Wavelength Division Multiplexed (WDM) Passive Optical Network (PON) access and an OpenFlow based layer 2/3 aggregation network. Each antenna A_i is connected to an ONU (i.e., ONU_i). Toward the aggregation network, each Optical Line Terminal (OLT) Line Card (LC_i) is connected to an interface of an Ethernet OpenFlow (OF) Layer 2 Switch

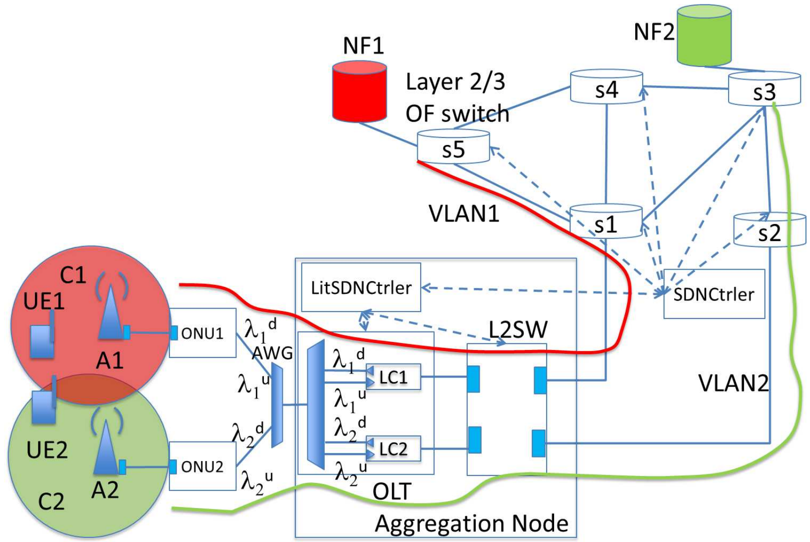

Figure 1. SDN-controlled x-haul architecture.

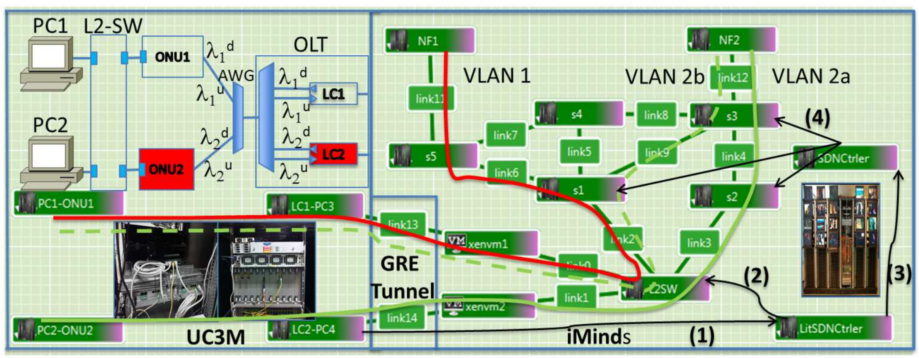

Figure 2. Federated testbed setup.

(L2SW), included within the aggregation node, that is, in turn, connected to the aggregation network. The OF L2SW is controlled by the aggregation node controller, implemented as a light version of an SDN controller (i.e., LitSDNCtrler) as proposed in [12]. The aggregation network consists of Ethernet OF Layer 2/3 switches and it is controlled by another SDN controller (i.e., SDNCtrler). Mobile radio access network (RAN) functions are generally indicated as NF_i and the Evolved Node B (eNB) is assumed to support cell turn on/off for energy saving purposes.

To improve the energy efficiency of the fronthaul this paper proposes the simultaneous sleep mode (i.e., complete turning off) of the WDM PON devices connected to the cell implementing on/off. This implies the reconfiguration of not only the fronthaul optical access network but also of the fronthaul aggregation network. In particular, every time the cell changes its status the OLT is notified and it initiates the procedure for turning on/off the ONU and the LC to which the cell is connected. At the same time, 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 $NF2$).

III. SDN-controlled Energy Efficient Fronthaul Implementation in Federated Testbeds

In this study the architecture depicted in Fig. 1 is implemented in two federated testbeds, depicted in Fig. 2, provided by the Fed4Fire project. The tesbeds are a WDM PON testbed located at UC3M, representing the fronthaul optical access segment, and an OpenFlow Ofelia island at iMinds, representing the fronthaul aggregation network. The WDM PON, features two pair of wavelengths with a capacity of 1 Gb/s each. The OpenFlow Ofelia island consists of Ethernet Open vSwitches (OVS) s_i interconnected by 1-5 Gb/s links. Two PCs on the ONUs side of the WDM PON emulate the UEs while the layer 2 switch (i.e., L2-SW) interconnecting the two PCs with the two ONUs emulate the possibility for the UE to be connected to either antenna. The layer 2 switch (i.e., L2SW) of the aggregation node is an OVS as well. The LitSDNCtrler, SDNCtrler, and all the OVS are implemented in the OpenFlow Ofelia island at iMinds. The two testbeds

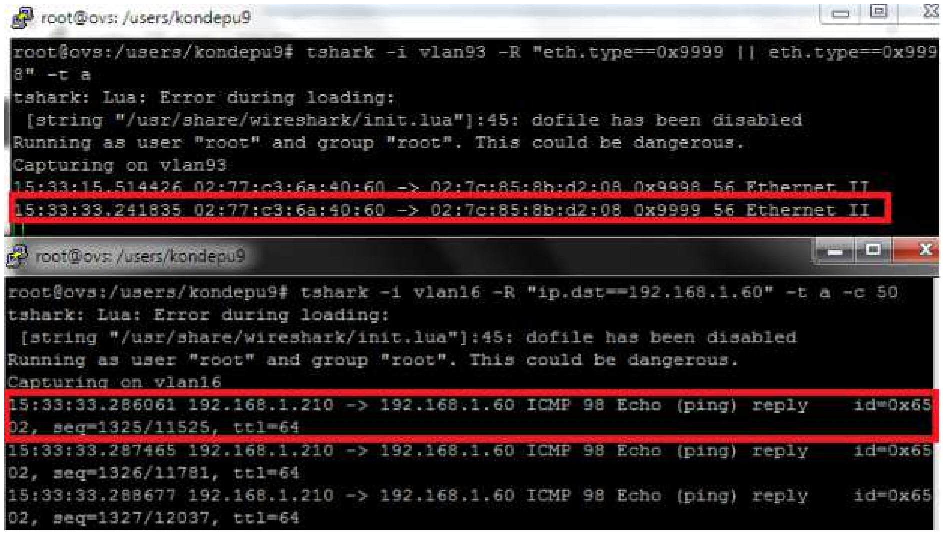

Figure 3. Reconfiguration timestamp capture.

are connected by means of Generic Routing Encapsulation (GRE) tunnels through the public Internet between two PCs connected to the OLT LCs and two Xen virtual machines (xenvm$i$) at iMinds. The tunnels carry both data and control communications at a rate of 100Mb/s. The signaling between the OLT and the LitSDNCtrler is performed in-band while the signaling between the LitSDNCtrler and the SDNCtrler is performed out-of-band through a direct connection.

IV. Evaluation Scenario and Results

The performed experiment is run by means of the jFed experiment toolkit, depicted in Fig. 2, provided by iMinds which is used to access the federated testbeds. Initially, two VLANs (i.e., VLAN1 and VLAN2a) are established to carry the traffic between the antenna which the UEs are connected to and the respective network function locations (e.g., $UE1$ is connected to antenna $A1$ of cell $C1$ that, in turn, is connected to the network function $NF1$ server). Then, a command is issued, through the OLT management interface, to turn off one ONU and the respective LC with the aim of emulating the turning off of the ONU and OLT LC upon cell turning off. Specifically $ONU2$ and $LC2$ (i.e., $PC2-ONU2$ and $LC2-PC4$ in Fig. 2) 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. 2, the VLAN path (labelled VLAN2b in Fig. 2) is ONU1-LC1-L2SW-s1-s3-NF2.

The considered performance parameter is the *VLAN reconfiguration time*, here 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: i) *ping* is continuously run between xenvm1 and NF2 server with packet interval of 1ms; ii) 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); iii) similarly, *ping* replies from the NF2 server are monitored at the L2SW. The monitoring is performed through the *tshark* tool installed in the L2SW.

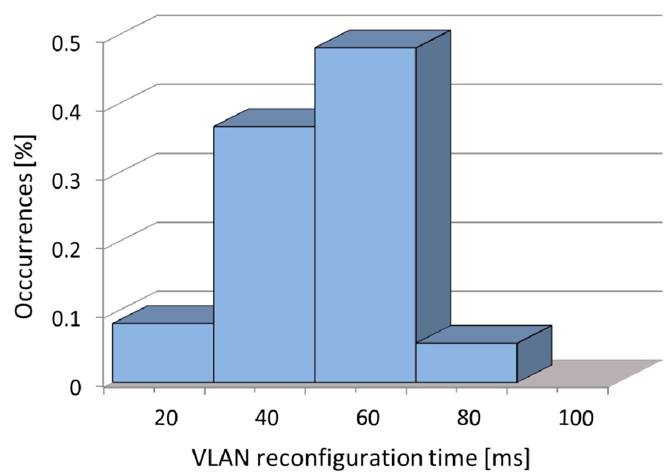

Figure 4. VLAN reconfiguration time sampled pmf.

Figure 3 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 $45ms$. 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 [13].

Figure 4 shows the sampled probability mass function of the VLAN reconfiguration time during a single experiment with duration of 3600s (60 reconfigurations). In particular, around 50% of network reconfigurations take between $40ms$ and $60ms$. Thus, it is experimentally proven that a VLAN reconfiguration time of few tens of milliseconds is achieved by the proposed SDN-controlled mobile fronthaul. Furthermore, fronthaul 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.

In the current experiment energy efficiency was not evaluated but an estimate can be provided by considering how often the cell is turned ON/OFF. The average energy savings for the considered scenario can be computed as follows.

The power consumed when both LCs of OLT and both ONUs are always ON is:

$$P_{ON} = 2(P_{ON}^{OLT} + P_{ON}^{ONU}), \tag{1}$$

where P_{ON}^{OLT} is the power consumed by an OLT LC when it is working and P_{ON}^{ONU} is the power consumption of the ONU when it is ON.

The power consumed when one LC-ONU pair is ON, and the other LC-ONU pair is OFF (as depicted in Fig. 2) is:

$$P_{OFF} = P_{ON}^{OLT} + P_{ON}^{ONU} + P_{OFF}^{OLT} + P_{OFF}^{ONU}, \tag{2}$$

where P_{OFF}^{OLT} is the power consumed by an OLT LC when it is OFF and P_{OFF}^{ONU} is the power consumed by an ONU when it is OFF.

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

$$\eta = 1 - \frac{T_{ON}P_{ON} + T_{OFF}P_{OFF}}{P_{ON}(T_{ON} + T_{OFF})} \tag{3}$$

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), $P_{ON}^{OLT} = 6W$, $P_{OFF}^{OLT} = 4.2W$ (our assumption), $P_{ON}^{ONU} = 3.2W$, and $P_{OFF}^{ONU} = 2.3W$ [14], the energy savings that can be potentially achieved are about 4%.

V. Conclusions

This study proposed the utilization of SDN to coordinate mobile fronthaul reconfiguration with cell ON/OFF and (part of) the mobile fronthaul ON/OFF for improving fronthaul energy efficiency. Results show that, once part of the fronthaul is turned OFF, communication between the user equipment and the server hosting a specific network function is recovered after few tens 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.

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