Flexible Optical Circuit Switched Network Architecture based on Tunable SFP+ Transceivers for Reconfigurable Low-Latency 5G/6G Networks

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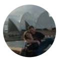

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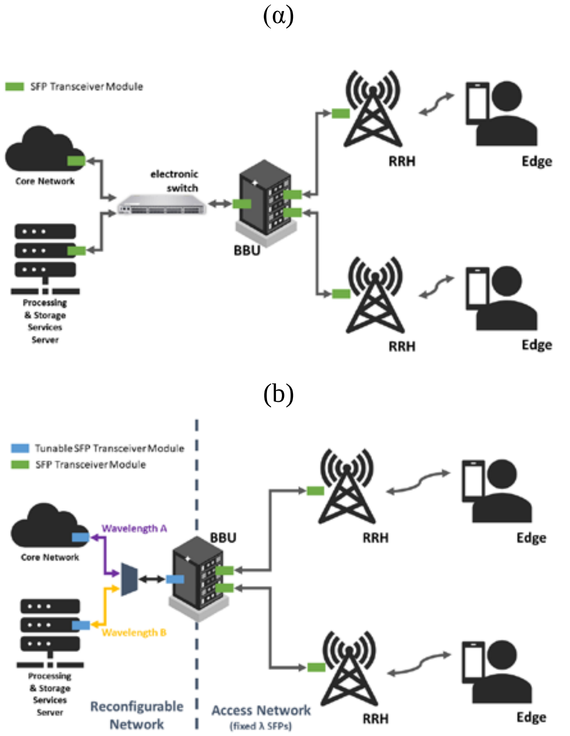
***Abstract*—A flexibly reconfigurable optical circuit switched edge network architecture relying on wavelength-tunable SFP+ transceivers is presented for the first time for reconfigurable, low-latency 5G/6G networks. The proposed solution employs traditional cost-effective, fixed-wavelength 10G SFP+ transceivers as grey optics towards the access side of the network and programmable tunable 10G SFP+ transceivers at edge part of the network at the Central Office premises, while allowing for flexible reconfiguration of the edge network all-passively via an additional AWG wavelength demultiplexer. The proposed solution allows to reconfigurably interconnect different access network end points to different processing and storage services or the core/metro network, with remote management and monitoring capabilities. The main component of the proposed network solution exploits a two-port Smart Network Interface Card (Smart NIC) X6 BlueFiled protoype by NVIDIA and a set of commercial 10G SFP transceivers. The operation of the network bridge is experimentally demonstrated for the first time, being fully characterized in terms of broadband wavelength support across the whole C-band and fast packet-slot operation within slots of 817 ms duration, validating its suitable for .**

Keywords*—*5G/6G, Tunable transceiver, base band unit, latency, Reconfigurable Optical Networks, Optical Switching

I. INTRODUCTION

On the verge of the 5G/6G era, there has been an insatiable global demand for both broadband fixed and mobile services, stimulating a drastic surge of the traffic being circulated in the access and mobile fronthaul network respectively [1]. Emerging demanding and bandwidth-hungry applications, including enhanced Mobile Broadband Connectivity (eMBB), Machine-to-Machine (MtM) communications, Internet of Things (IoT) etc [2], are rapidly progressing necessitating strict bandwidth requirements for the end-to-end communication. Moreover, the introduction of 5G/6G and the rise of industrial internet applications, are enforcing a strict latency-oriented framework, with services delivered by an edge-infrastructure, e.g. low-latency processing, video caching/video processings, etc. At the same time, the dynamic characteristics of the mobile traffic or Industry 4.0 necessitate an adaptable and reconfigurable network with a flexible bandwidth allocation that can better align with the dynamic variations of user requirements, ranging from more evenly distributed Fixed Wireless Access (FWA) and broadband Fiber To The Home (FTTH)/Passive Optical Network (PON) traffic to peak to more temporarily concentrated eMBB traffic at hotspots or trains.

Nevertheless, this is putting significant load on the shoulders of the network operators, as they urgently need to come-up with drastic transformation of the network with architectural changes and energy-efficient, broadband communication systems. So far, edge networks, including optical access and fronthaul systems, are relying on Point-to-Point (PtP) optical communication links both towards the access part of the network, e.g. between the Baseband Unit (BBU) and the Remote Radio Head (RRH) Antenna, as well as towards the backbone of the network, e.g. the PtP optical links between the Core Network and the Processing and Storage Services Servers, as shown in Fig. 1(a), while


(α)

(b)

Fig. 1. (a) Conceptual representation of existing network architectures based on fixed point-to-point links and network switches and b) Proposed 5G/6G environment with the wavelength reconfigurable optical connections between the Core Network, the Processing and Storage Services Server at the edge, and fixed wavelenght tranciever modules at the access between the Base Band Unit, the radio components.

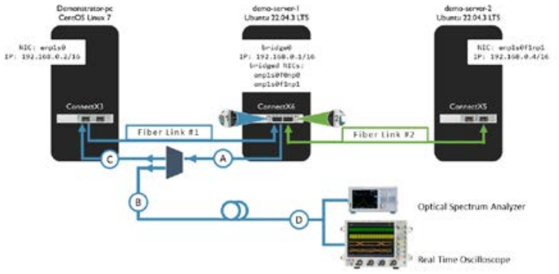


Fig. 2. The experimental implementation of the network. Powered measurements at point: A 1.5dBm, B 1.1dBm, C -10.3dBm, D -2dBm..

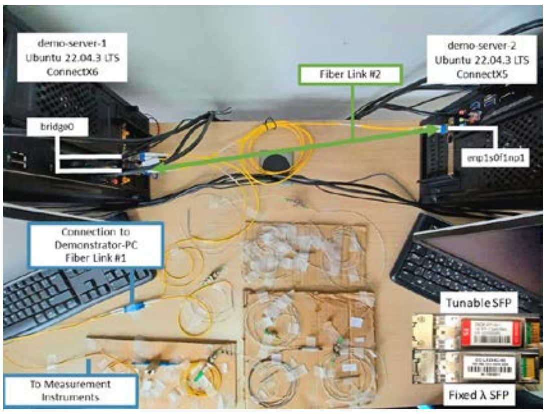


Fig. 3. Part of the experimental setup, including demo-server-1, demo-server-2, the Fiber Link #2 between them with fixed λ SFPs, the connections to Demonstrator-Pc via the Fiber Link #1 (tunable components) and the interception of it for analyzing purposes.

reconfigurable interconnectivity and access to processing/storage servers is provided via standard Ethernet switches [3]-[5]. However, at the edge part of the network, and particularly at the crucial aggregation infrastructure situated in close proximity to subscribers—the Central Offices (COs), more efficient optical solutions are required, with the telecom industry envisioning to soon restructure the traditional CO architecture to resemble more like a highly automated mini data center, accommodating more subscribers and locally hosting flexible data services at reduced costs and power consumption, as well as significantly lower latency values.[6] Our proposed solution is depicted in Fig. 1(b), including a set of fixed point-to-point links towards the antennas or network subscribers , offering cost-effective access, and programmable, wavelength tunable SFP+ transceiver modules at the edge part of the network, as marked with green color.

This paper describes the setup and measurements, with the target of creating an agile, programmable and wavelength reconfigurable network based on all passive optical components. The network will make use of tunable wavelength transceivers. In the first part, the tunability of the SFP+ transceivers is characterized, indicating support across the whole C-band, while later on a dynamic charactetrization of the data traffic is presented, containing speed, latency, power budget, and eye diagram transmission measurements. The second part embarks on the wavelength tuning process and contains measurements useful in understanding the accuracy and usability of the capability. Supplementary to this, experiments on the temporal aspect of are described in the third part, both for the network/application and the physical layer, presented a time-slotted operation where traffic is programmed at two different wavelengths, λ1 and λ2, at slots of 817 ms, while capturing only one of the two wavelengths, i.e. λ1. The presented slotted operation confirms a clear separation between the On and Off slotted operation, with fast reconfiguration. Finally, a review of how the equipment can handle and make use of the aspects is done.

II. PROPSED NETWORK ARCHITECTURE AND EXPERIMENTAL IMPLEMENTATION

The concept of a 5G environment with tunable wavelength capabilities is described in this section and presented in Fig. 1(b). The improvement from the currently implemented network is that the base station includes and can offer the users processing and storage services without necessitating to forward the traffic and service requests back to the core network or to pass through a standard electronic switch. As a result, various services that have a high demand can be brought closer to the edge, thus significantly lessening the ever-increasing traffic in the core network and the latency to deliver services to the end-user. In the proposed solution, five components are taken into consideration; the Base Band Unit (BBU), the Processing and Storage Services Server (PSSS), the Core Network, the Remote Radio Units (RRU) or Remote Radio Heads (RRH) connected to the Base Station, and the edge devices, operated by the end users. The users have access to the services and core network regardless of their relative location since they can connect to any access point serviced by the BBU. The radio access components are connected to the BBU using conventional fixed wavelength SFP+ transceiver modules. Thus, additional RRHs can be connected to the established BBU with relative low-cost optical components.

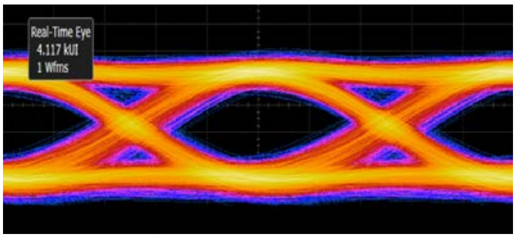


Fig. 4. Eye diagram of the signal produced by the 10G tunable SFP transceiver.

The BBU processes the downlink and uplink data traffic between the wireless network users and the core network. The Unit is connected to the access network via fixed wavelength SFPs. Additionally, BBU is connected to the core network and a server that offers the services from one port using a tunable wavelength SFP+ transceiver eiver module. Based on the demand, the unit activates one of the two links without the need for manual operation. A different colored link is used for each purpose, meaning that wavelength A is used in communicating with the core network and wavelength B is used to communicate with the PSSS.

In this case study, three optically connected computers are used. The central computer named demo-server-1, is running the Ubuntu 22.04.2 LTS Linux distribution. The second computer, demo-server-2 runs the same distribution, and the 3rd one, demonstrator-pc, has CentOS 7. In the first configuration, the demonstrator-pc, equipped with Mellanox ConnectX®-3 adapter card is connected to demo-server-1, equipped with NVIDIA® Mellanox® ConnectX®-6, using 10GBase SFPs and a single mode fiber optic patch cable. The connection referred to as Fiber Link #1 uses the following configuration: demo-server-1 has the 192.168.0.1/16 IP address, and demonstrator-pc has the 192.168.0.2/16. For the Fiber Link #2: demo-server-2 has the 192.168.0.4/16. The Reconfigurable Network includes access to the core network and the PSSS. The BBU is the link between the two networks. The RN is controlled by a Software Defined Network that analyses the AN and based on the demand it reconfigures where the BBU is connected.

To demonstrate the functionality of the proposed network described in section II, three optically connected computers are used. The first computer named demo-server-1 assumes the role of the BBU, and two SFP transceiver modules are connected to it, one with wavelength tuning capabilities and one with fixed wavelength. The second computer, named demo-server-2, assumes the role of the access network. Finally, the third computer, named Demonstrator-Pc assumes the role of the PSSS and the Core Network. Utilizing demo-server-1 as a central node, a network is created using demonstrator-pc and demo-server-2. A network bridge is configured in demo-server-1 to allow communication between the two further computers and simultaneous activation of the two links. The interfaces connected to the two other PCs are added and the IP address of the Fiber Link #1 for the demo-server-1 is assigned to the bridge. The setup is connected using 10G tunable SFPs and standard single mode fiber optical patch cables.

To fully evaluate the performance of the optical transceivers and network architecture, so as to gain a comprehensive understanding of the properties and behavior of the equipment used to create the network, two different sets of experimental tests are performed, including characterization of the tunable SFP+, as well as a dynamic network slotted operation. The configuration depicted in Fig. 2, and a photo of the experimental setup is shown in Fig. 3 Specifically, the outgoing signal of the 10G DWDM C-band Tunable SFP, operated from the ConnectX6 adapter, is split into two channels using a 90/10% optical splitter. The 10% powered channel is connected to Demonstrator-Pc, making Fiber Link #1 operational. The second channel (90% of the total power) is connected to the measurement instruments. Random data in 10 Gbits/sec rate are exchanged during the duration of the tests.

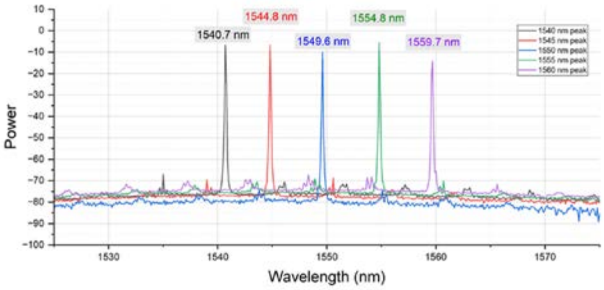


Fig. 5. Wavelength spectrum graph of 5 different channels produced by the 10G tunable SFP transceiver module.

III. STATIC CHARACTERIZATION OF THE SFPS

Firstly, in order to check the signal integrity and quality of the optical transmissions, an eye diagram was recorded using a real time oscilloscope. The captured diagram is depicted in Fig. 4, revealing a wide open eye diagram with clear separation of the logical ‘1’ and ‘0’ at 10 G operation, revealing its suitability for being deployed in the network.

Secondly, the optical signal is rerouted towards an optical spectrum analyzer, targeting to assess the supported spectrum range of the tunable SFP+ transceiver and its wavelength tuning capabilities. The lower wavelength supported is 1530.7nm and the higher is 1563.5nm, while the optical emissions spectrum can be divided into 82 channels. Figure 5 depicts five indicative different channels with peaks at 1540.7nm, 1544.8 nm, 1549.6 nm, 1554.8 nm and at 1559.7nm. The peaks exhibit more than 60dBm higher than the noise level are consistent and narrow shaped. The measurements clearly indicate the laser emission of a CW optical signal across the whole C-band, allowing for broad tunability and network reconfigurability.

IV. DYNAMIC TIME SLOTTED NETWORK OPERATION

Following the static characterization of the SFPs, the performance operation of the SPs in a dynamic optical network and time-slotted operation was evaluated.

The target of the following experiment is to perform dynamic time-slotted operation with wavelength reconfiguration and to determine the time needed for the emission wavelength of the transmitted signal to change. After observing the signal at an Optical Spectrum Analyzer and the power meter, it was clear that the signal never stopped to transmit data-traffic (in our case it was standard TCP traffic) when the wavelength change is performed and instructed by the network administrator computer. In order to measure the time to set-up a new wavelength, the wavelength

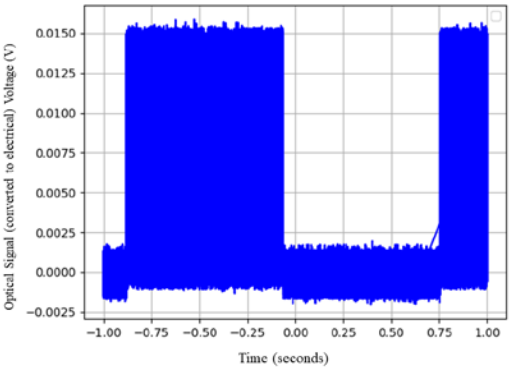


Fig. 6. Slots of 2s Recording of the signal of Wavelength A, when data is transmitted in 0,817s slots alternating between wavelength A and B.

was dynamically changed between two different wavelength values, e.g. between the 1540.7 nm marked with black color in Fig. 5 and the 1544.8 nm marked with red color in Fig. 5. The output of the transmitted signal was then filtered at the black colour of 1540.7 nm and captured at a real time scope or power monitor and optical spectrum analyzer, effectively operating in a dynamic time-slotted manner. To determine the time that this change requires, a script that performs the wavelength change between two channels every given number of seconds is written. Using the configuration depicted in Fig. 2 with an optical filter that allows only one of the two wavelengths through before the RTO, the signal is captured in a period of 2s. In the capture depicted in Fig. 6 two iterations of the wavelength change performed by the script are recorded. In the first complete recorded time slot the data is transmitted in the wavelength allowed by the optical filter as a result 0.815s of data transmission is visible. Afterwards, data is transmitted in a different wavelength that is filtered and as a result nothing is recorded for 0.815s until the next iteration. The data transmission voltage difference from the noise levels is adequate with consistent high (1) state levels at 150mV. Regarding wavelength tuning capabilities, the signal wavelength change occurs in a brief amount of time and occurs in the expected time determined by the controller.

V. TIME-DELAY, LATENCY PERFORMANCE OF THE NETWORK BRIDGE

To determine whether the data rate between the computers that communicate through the central computer where the network bridge of the Smart NIC and the tunable SFP+ are installed and if any significant additional latency is induced by this network bridge, time-delay and latency measurements were performed. Specifically, two iperf3 tests were performed in two different setups, including the Smart NIC bridge or completely bypassing the Smart NIC bridge, while maintaining the same fiber lengths. Firstly, the cables are connected directly with an LC/LC adaptor, bypassing the Smart NIC, hence maintain the same propagation time delay between the two outer demo PCs. The data transfer rate is 9.35Gbits/s. Afterwards, the two computers are linked to the central node with the Smart NIC, where exactly the same transfer rate was measured, revealing was no additional speed limitation, imposed by the Smart NIC bridge.

Another important aspect of edge networks is the end-to-end latency and hence it was critical to determine whether the addition of the bridge increases the time required to for data to route from one point to another. In order, to perform latency tests, between the two nodes, the ping process is used. Firstly, a bash script is created that performs ping tests for a predefined number of packets and intervals between the dispatch of each packet. The process is done for packets with data sizes: 64, 128, 256, 512, 1024, 2048, 4096, and 8192 bytes. Four tests are conducted for 2000 packets per size category. The first two tests are conducted with an interval of 1s, when the connection is direct (LC/LC coupler) and routed through the bridge. The same cables and transmitters are used for both connections to ensure that no latency is added due to extended cable length. The process is repeated for an interval of 2ms (rapid). The results are depicted in Fig. 7 comparing the two different experimental setups at all various packet level sized. As it can be seen, there was only a minimal delay of 0.15 ms added on average, when the central node is used to connect the two devices, in comparison with the direct fiber connectivity with LC connector that bypasses the Smart NIC. Still the short Round Trip Time is measured when the two nodes are directly connected without the interval of packet dispatch notably affecting the RTT. The delay was also depending on the packet size, slightly increasing for larger packet sizes, owing to the longer store and forward time of the packet. Furthermore it should be highlighted that the additional 0.15 ms has been taken into account twice in the current measurements, as the test was measuring the RTT between the two outer pcs, implying that the overall Smart NIC bridge with the tunable SFP adds only 750 μsec delay-latency in a single pass, i.e. less than 0.1 ms, which does not compromise the low latency requirements of 5G/6G applications, and where adheres even to the strictest 1ms latency requirement of the most stringent URLLC applications [6], while on the other hand introduces significant flexibility in the network reconfiguration.

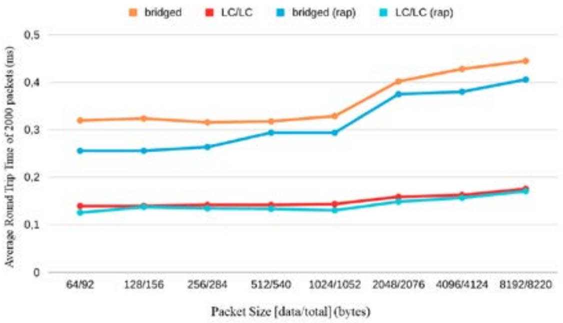


Fig. 7. Average Round Trip Time in ms for two thousand packets of size x.

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