European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

End-to-End Demonstration of an SDN-reconfigurable, FPGA-based TxRx Interface for Analog-IFoF/mmWave X-haul

K. Kanta(1), P. Toumasis(1), G. Giannoulis(1), I. Stratakos(1), G. Lentaris(1), E. A. Papatheofanous(2), I. Mesogiti(3), E. Theodoropoulou(3), A. Margaris(4), D. Syrivelis(5), E. Kyriazi(1), G. Brestas(1) , K. Tokas(5), N. Argyris(5), C. Vagionas(6), R. Maximidis(6), P. Bakopoulos(5), A. Mesodiakaki(6), M. Gatzianas(6), G. Kalfas(6), K. Tsagkaris(4), N. Pleros(6), D. Reisis(2), G. Lyberopoulos(3), D. Apostolopoulos(1), D. Soudris(1), H. Avramopoulos(1)

(1) School of Electrical & Computer Engineering, National Technical University of Athens, Greece, kkanta@mail.ntua.gr, (2) Electronics Laboratory, Department of Physics, National and Kapodistrian University of Athens, (3) COSMOTE Mobile Telecommunications S.A., (4) Incelligent PC, (5) NVIDIA, (6) Aristotle University of Thessaloniki, Dep. of Informatics

Abstract *We present an E2E analog X-haul deployment demonstrator, based on successful integration of an SDN-reconfigurable, FPGA-based A-IFoF TxRx into MNO's infrastructure, relying on constant traffic monitoring and real-time adaptation of the TxRx capacity, showcasing concurrent services support (AR/VR, IoT,4K video streaming) over A-IFoF/mmWave transport implementation. ©2022 The Authors*

Introduction

Within the upcoming 6G era, the extreme bandwidth requirements of a series of high-throughput/low-latency demanding applications, (i.e. Augmented Reality/Virtual Reality (AR/VR) gaming), supported over the same transport infrastructure, drive the evolution of current X-haul deployments [1]. One step beyond the standard Common Public Radio Interface (CPRI)-based deployments, which are reaching their bandwidth exploitation capabilities' limits, currently evolving analog-based technologies, such as Analog-Intermediate Frequency over Fiber (A-IFoF), have already demonstrated in laboratory experiments, extremely high CPRI-equivalent rates (up to 1Tbps) [2], while being attractive for low-latency and easily scalable deployments, benefitting also from the large unlicenced spectrum availability at the mmWaves [3].

Actual deployment potential of such solutions remains the main challenge towards their adoption within future Radio Access Network (RAN) architectures. As such, the development of Field Programmable Gate Array (FPGA)-based analog interfaces that offer compatibility to standard protocol traffic has been recently discussed in the literature [4],[5]. Support of real traffic, through these interfaces, such as video streaming over Fiber-Wireless (FiWi) setups has been showcased, mostly in impressive laboratory-scale experiments, in which the analog Radio-over-Fiber (RoF) links served as static, pass-through transmission paths [6],[7].

Towards the full-scale integration of analog links in infrastructure deployments, the development of analog transceiver (TxRx) units exhibiting management and control functionalities alongside baseband processing, is crucial for the deployment of E2E RAN layouts, in which the physical deployment, control plane and service/applications layer operate in a seamless and interoperable manner. The concept of implementing Software Defined Network (SDN)-enabled RAN layouts has been discussed and experimentally presented, without involving though, physical layer testbeds [8],[9],[10]. An actual demonstrator involving SDN-based reconfiguration of A-IFoF transceivers has been only recently reported in [11], where steering of Ethernet traffic to different FiWi transmission paths through manual control of the employed SDN agent has been showcased.

In this paper, we aim to present a significant step forward by demonstrating the integration of a custom, SDN-reconfigurable, real-time A-IFoF TxRx interface, over a real Mobile Network Operator (MNO)'s infrastructure located in Athens, offering active adjustment of the capacity provided by the TxRx for converged A-IFoF/mmWave RAN transport, based on constant traffic monitoring by the SDN controller and automatic adaptation to the hosted applications' requirements. The demonstrated FPGA-based A-IFoF TxRx is an evolved version of the custom prototype reported in [11] and [4], enhanced with active SDN functionalities, enabling flexible traffic allocation and reconfiguration of the supported capacity. In the physical layer, Error Vector Magnitude (EVM) measurements of 7.3% for QPSK-Orthogonal Frequency Division Multiplexing (OFDM), converged FiWi transmission were achieved. The uninterrupted operation of the E2E deployment, was validated through the concurrent accommodation of real-world, services such as

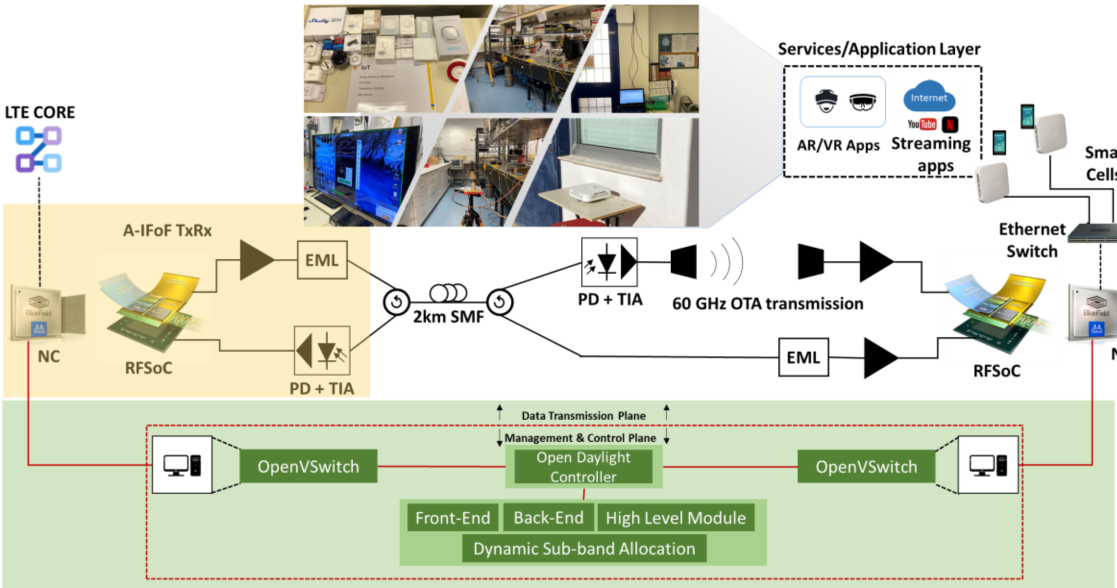

Fig. 1: Experimental Demonstrator layout, involving the Data, Control and Services layers.

AR/VR applications, as well as by obtaining live throughput measurements, using traffic monitoring tools, showcasing rates up to 474Mbps. The reactive SDN-enabled capacity reconfiguration capabilities of the presented solution were also successfully demonstrated.

Experimental Demonstration

The demonstrated E2E deployment is depicted in Fig.1. The implemented SDN-reconfigurable, FPGA-based A-IFoF TxRx was integrated with a commercial vendor Long-Term Evolution (LTE) network deployed across the interconnected COSMOTE-National Technical University of Athens (NTUA) testbed facilities.

The key component of the presented demonstrator was a custom real-time A-IFoF TxRx, hosting network management, baseband processing and electro-optic (e/o) PHY layer functionalities. This transceiver layout consisted of a Mellanox Bluefield Network Controller (NC), an integrated Xilinx Zynq UltraScale+ RFSoC platform, as well as small-form factor, low-cost e/o units. The NC handled the incoming Ethernet packets, by altering their VLAN tags to properly route the incoming traffic through the RFSoC's Digital-to-Analog/Analog-to-Digital Converter (DAC/ADC) ports and determine the number of the supported data streams, thus increasing the transceiver's throughput. Dynamic capacity allocation was achieved through the developed Network Performance Optimization (NPO) tool, which monitored the incoming traffic and deployed the second channel, when traffic exceeded a certain bitrate threshold that was set at the NPO. For this purpose, the Open-Daylight Controller, was responsible for Layer 2 routing rules, utilizing Open vSwitch Database Management Protocol (OVSDB) and OpenFlow.

The RFSoC platform [12], which was connected to the NC through its 10G SFP ports, included a 10G/25G Ethernet core, an FPGA board, and DAC/ADCs and served as a bidirectional Ethernet to IF-upconverted OFDM bridge. For full-duplex communication, the RFSoC board implemented two separate and identical Tx/Rx DSP block chains corresponding to two pairs of DACs/ADCs. The generated signals, occupying 204 MHz usable bandwidth, were digitally upconverted to 1,5 GHz IF.

In the Downlink (DL) direction, the DAC output was amplified and fed to an Electro-absorption Modulated Laser (EML) emitting at 1560.42nm. The optical signal was transmitted over a 2 km fiber spool of Single Mode Fiber (SMF) and was detected by an 10G linear photoreceiver. The photoreceiver output was connected to the IF-to-V-band upconverter board equipped with a 60 GHz directional antenna. An identical Rx-side radio unit located at 1 m horizontal distance received the mmWave radio waveforms and directed them to the ADC unit of the RFSoC board. At the receiver side, real-time DSP was applied to the signal, including a Zero-Forcing (ZF) equalization algorithm. A symmetrical optical link was used for the implementation of the Uplink (UL) segment of this setup.

The described setup was integrated with a commercial vendor LTE network deployment, in the transport segment between the Evolved Packet Core (EPC) and two Small Cells. The Small Cells provided full duplex E2E connectivity, offering access to mobile services (VoLTE, HD/4K video streaming, AR/VR/ IoT services).

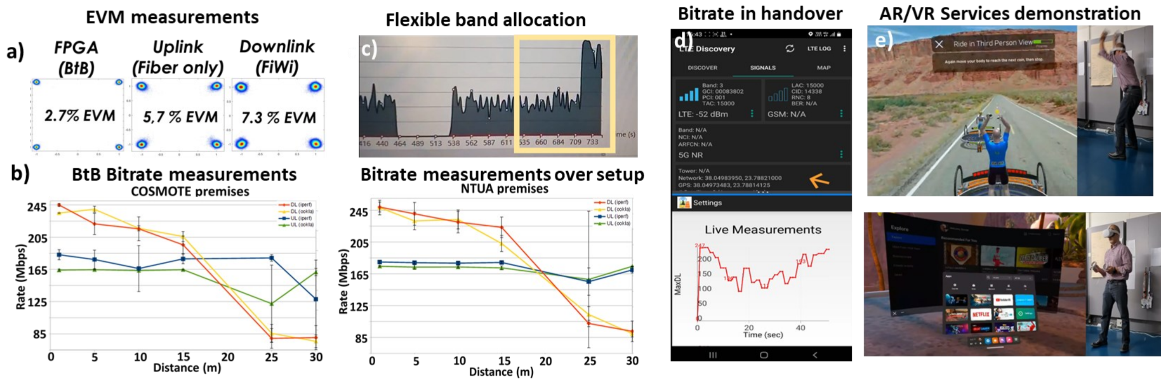

Fig. 2 a) Constellation diagrams and EVM measurements in Back-to-back (BtB), Uplink (Fiber), Downlink (Fi Wi), b) Bit rate measurements of the transmitted data in both COSMOTE premises (back-to-back) and NTUA (over the deployed infrastructure), c) Demonstration of the dynamic activation of second channel, d) Bitrate measurements captured in the process of handover, e) Demonstrations of AR/VR and streaming services.

Results

The physical layer evaluation results are presented in Fig.2(a). The depicted EVM measurements and constellation diagrams were derived after real-time processing of the signals detected at the DACs' outputs, after fiber (UL) and FiWi (DL) transmission and indicate successful signals' retrieval (EVMs of 2.7%, 5.7% and 7.3% respectively). The measured EVM values are in all cases well below the requirement of 17.5% set by 3GPP for QPSK signals [13], validating the preservation of signal's integrity over the FiWi analog transport segment.

The next step was to assess the analog transport segment's impact, on the seamless operation of the E2E service deployment. For this purpose, the concurrent accommodation of applications with high throughput/low-latency requirements, including AR/VR gaming, 4K video streaming and Internet-of-Things (IoT) applications (Fig.2(e)) was performed, displaying zero deterioration of the services' Quality of Experience (QoE). Fig.2(b) depicts the relation of distance between a UE and the closer Small Cell on the achievable data rate, before and after integrating the FiWi transport link into the EPC-to-Small Cell interconnection. In both cases, the maximum achievable throughput (measured through Iperf and Ookla traffic monitoring tools) is limited by the Small Cell's capacity reaching 245Mbps DL and 190Mbps UL, while throughput reduction due to distance is similar in both cases. These measurements were also performed during UE handover between two Small Cells (Fig.2(d)), indicating the unimpacted operation of the E2E deployment, as well the correct operation of RAN's critical Control-Plane.

Finally, SDN-controlled dynamic, capacity allocation was demonstrated. More specifically, through constant monitoring of the traffic profile via the NPO tool, the developed SDN controller, activated a second transmission channel, supported by the implemented A-IFoF TxRx to duplicate the available bandwidth, when requested. For demonstration purposes, the second deployed channel relied on a bidirectional RF link, interconnecting an independent pair of DACs and ADCs. The aggregated throughput supported by this solution reached 474Mbps, fully exploiting the capacity of two Small Cells, operating concurrently. Fig.2(c) represents the instant duplication of the transport layer's capacity after maximization of the throughput request of both Small Cells, monitored by the NPO tool.

Conclusions

We presented the first demonstration of an SDN-enabled A-IFoF/mmWave integration into MNO's deployed core infrastructure, relying on the active SDN-based, capacity reconfiguration of the employed prototype FPGA-based A-IFoF transceiver. Successful physical layer connectivity was validated for QPSK-OFDM waveforms, with <7.3% EVM values. The reliable operation of the E2E deployment was also verified in service layer through traffic monitoring measurements, as well through the concurrent accommodation of AR/VR, IoT and 4K video streaming applications, reaching up to 474Mbps throughput, after SDN-enabled automatic activation of a second, parallel transmission lane, also supported by the developed TxRx. The reported E2E demonstrator showcases the suitability of SDN-controllable A-IFoF interfaces for deployment into MNO infrastructures and paves the path towards analog-based RAN transport solutions in the beyond-5G era.

Acknowledgements

This work was funded by the European Commission H2020 5GPPP Projects 5G-PHOS, under grant agreement 761989.

References

[1] W. Saad, M. Bennis, M. Chen, A vision of 6G wireless systems: applications, trends, technologies, and open research problems. IEEE Netw. 34(3), 134–142 (2020). https:// doi. org/ 10. 1109/ MNET. 001. 19002 87

[2] S. Ishimura, A. Bekkali, K. Tanaka, K. Nishimura and M. Suzuki, "1.032-Tb/s CPRI-Equivalent Rate IF-Over-Fiber Transmission Using a Parallel IM/PM Transmitter for High-Capacity Mobile Fronthaul Links," in Journal of Lightwave Technology, vol. 36, no. 8, pp. 1478-1484, 15 April15, 2018, doi: 10.1109/JLT.2017.2787151

[3] G. Kalfas, "Next generation fiber-wireless fronthaul for 5G mmWave networks," IEEE Com. Mag. 57 (3), 2019

[4] Kanta, et.al, H. Demonstration of a Hybrid Analog–Digital Transport System Architecture for 5G and Beyond Networks. Appl. Sci. 2022, 12, 2122. https://doi.org/10.3390/app12042122

[5] "Space Division Multiplexing 5G Fronthaul with Analog and Digital Radio-over-Fiber and Optical Beamforming – the blueSPACE Concept", doi:10.5281/zenodo.1402052, August 2018

[6] S. Rommel et al., "Real-Time Demonstration of ARoF Fronthaul for High-Bandwidth mm-Wave 5G NR Signal Transmission over Multi-Core Fiber," 2020 European Conference on Networks and Communications (EuCNC), 2020, pp. 205-208, doi: 10.1109/EuCNC48522.2020.9200921

[7] P. Toumasis, "Demonstration of FPGA-based A-IFoF/mmWave transceiver integration in mobile infrastructure for beyond 5G transport," ECOC, Bordeaux, France, Sep. 2021

[8] Muñoz, R., et.al, “Experimental demonstration of advanced service management in SDN/NFV Fronthaul Networks deploying ARoF and PoF.” ECOC 2019. https://doi.org/10.1049/cp.2019.1191

[9] E. Datsika et al., "SDN-Enabled Resource Management for Converged Fi-Wi 5G Fronthaul," in IEEE Journal on Selected Areas in Communications, vol. 39, no. 9, pp. 2772-2788, Sept. 2021, doi: 10.1109/JSAC.2021.3064651

[10] A. Rostami, Kun Wang, Z. Ghebretensaé, P. öhlén and B. Skubic, "First experimental demonstration of orchestration of optical transport, RAN and cloud based on SDN," 2015 OFC, pp. 1-3, doi: 10.1364/OFC.2015.Th5A.7

[11] Ronis Maximidis et al., “A Centralized and Reconfigurable 4x2.5Gb/s Fiber-Wireless mmWave Fronthaul for Network Sharing Applications”, ECOC 2021, Bordeaux, France (2021)

[12] Zynq UltraScale+ RFSoC, breaf overview, accessed May 2022

[13] 3GPP specification TS 38.201, NR; Physical layer; General description, April 2017