Demonstration of FPGA-based A-IFoF/mmWave transceiver integration in mobile infrastructure for beyond 5G transport

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Abstract *We demonstrate the successful operation of an FPGA-based A-IFoF/mmWave transceiver into an existing MNO infrastructure, delivering 4K video streaming and IP-calls over mobile core network. Physical layer connectivity was successfully established, with EVM measurements of <10% for QPSK waveforms propagated through different optical-wireless network segments.*

Introduction

Whilst the first 5G wireless networks have already been deployed, a series of promising converged optical/wireless based topologies such as Indoor Distributed Antenna System (DAS) [1], Fixed Wireless Access (FWA)-based Mobile Fronthaul (MFH) [2] and backup links [3] have been explored as emerging network technologies in the transition phase towards the beyond 5G era (Fig. 1). Converged Analog Intermediate Frequency-over-Fiber (A-IFoF) / Over the Air (OTA) topologies have been widely discussed during the last years as bandwidth efficient, low-latency, low-cost solutions, benefiting from key enabling technologies of future 6G networks, such as millimeter Wave (mmWave) and THz radio units [3], optical switching [4] and advanced multi-format Subcarrier Multiplexing (SCM) schemes[1].

The integration of analog optical-wireless links along the mobile transport layer is a crucial link in the network's evolution chain, where both analog and digital optical transceivers will coexist in the same core infrastructure [2],[5]. To this end, real-time reconfigurable Field-Programmable Gate Arrays (FPGAs) have been studied as Ethernet-compatible baseband processor platforms for the generation and processing of Intermediate Frequency (IF) upconverted multicarrier signals, proper for native radio waveforms wireless transmission. Published work on the use of FPGAs in A-IFoF and converged Fiber-Wireless (FiWi) links have focused mainly on the 28GHz central frequency for the wireless propagation [1],[6]-[7]. These papers demonstrate the potential of real-time implementation of the analog transport layer approach, by delivering impressive proof-of-concept experiments in laboratories. However, the integration of these solutions in a mobile core network as well their seamless operation in true mobile services, has been reported much more scarcely. In the cases that the transmission of data traffic over converged A-IFoF/wireless setups has been achieved, either a commercial digital unit was employed [8], or it was limited to video streaming. In the latter case, media converters and different engines were combined for the accomplishment of multi-layer functions, PHY layer baseband processing and digital to analog conversions [3],[9].

In this paper, we attempt to take a significant step forward, by presenting for the first time to the best of our knowledge, the successful integration of a real-time analog transceiver over an existing mobile infrastructure. A single FPGA-based platform was used both as Ethernet bridge and

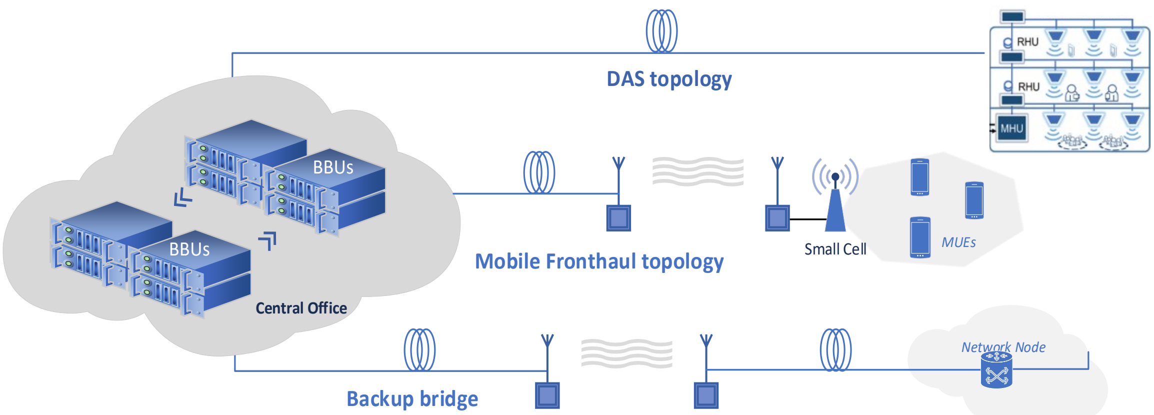

Fig. 1: A-IFoF- based topologies for beyond-5G usecases and network segments

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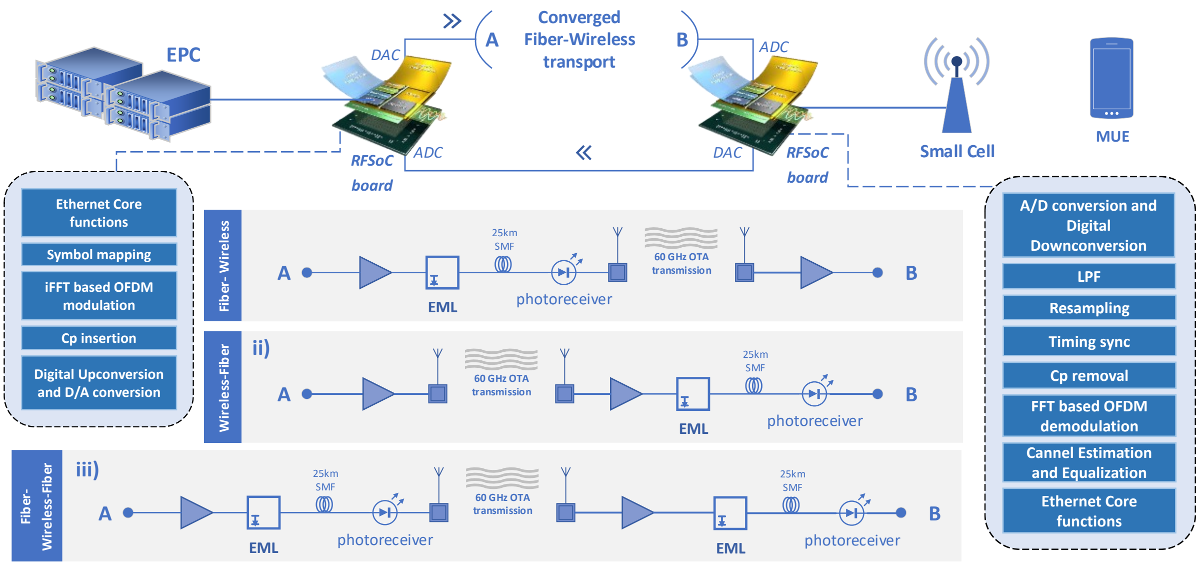

Fig. 2: Experimental setup of (i) FiWi, (ii) WiFi and (iii) FiWiFi downlink segments of the FPGA-enabled EPC-to-Small cell interconnection.

as Digital Signal Processing (DSP) engine. Three alternative optical/wireless converged network topologies were investigated and successfully demonstrated: (a) FiWi, (b) Wireless-Fiber (WiFi) and (c) Fiber-Wireless-Fiber (FiWiFi). Physical layer performance was evaluated through Error Vector Magnitude (EVM) measurements, which were found to be less than 10%, while network quality was validated by the successful delivery of real-world services such as a 4K online video streaming and a live Internet Protocol (IP) call.

Concept and experimental Setup

Fig. 2 shows the experimental set-up used for the the demonstration of the proposed FPGA-based A-IFoF/mmWave transceiver. The existing mobile infrastructure of Greece's largest Mobile Network Operator (COSMOTE) was exploited, which among others included an Evolved Packet Core (EPC) and a Small Cell. Between these two network units, a single integrated, power-efficient Radio Frequency System-on-Chip (RFSoC) platform, emulated both Ethernet and signal processing functions of a Baseband Unit (BBU). The Ethernet core performed data link layer functionalities to map the incoming Ethernet traffic to the DSP engine, as well as, to recover Ethernet frames from the demodulated waveforms. These functionalities include basic error handling, flow control for access to the physical layer, frames encapsulation and Virtual Local Area Network (Vlan) taging. The proposed A-IFoF/V-band transceiver implementation relied on a Xilinx Zynq Ultrascale+ RFSoC device on ZCU111 development board[10], which hosted a 10G/25G Ethernet core, an FPGA board and Digital-to-Analog/Analog-to-Digital Converters (DAC/ADC).

The RFSoC's FPGA engine generated OFDM signals using a fixed 256-tap inverse Frequency Fourier Transform (iFFT) algorithm. The FPGA clock was 256MHz, corresponding to the transmission of 204 MHz useful bandwidth, after zero-padding (52 out of 256 sub-carriers). A Cyclic Prefix (CP) of 64 samples length was inserted to the signal before the DACs. The complex OFDM signals were digitally up-converted through the DAC boards at 1.5 GHz IF. Moreover, the RFSoC implemented two independent and identical transmitter/receiver side DSP block chains and provided two pairs of DACs/ADCs, for the establishment of full-duplex connectivity. However, due to the lack of lab equipment, the investigated experimental layouts implemented only one signal direction (defined by A and B points in Fig. 2), while in the other direction the IF signals were propagated over an electrical SMA cable.

Furthermore, the signals genereted in the RFSoC platform propagated in the fiber by exploiting highly linear Intensity Modulation/Direct Detection (IM/DD) opto-electronic units in three different optical-wireless network layouts. The FiWi and its symmetrical WiFi layout intended to emulate a bidirectional FWA scenario, while the extended FiWiFi layout served as a wireless bridge, interconnecting terminals of two spatially separated fiber transport segments [3], [11]. In the FiWi layout (Fig. 2 - i), the DAC output was amplified via a controllable gain amplifier and then used to drive the Electro Absorption Modulator (EAM) segment of an EML. The optical signal was transmitted over a 25 km fiber spool of Standard Single Mode Fiber (SSMF) and detected by a 10G photoreceiver. The photoreceiver output was fed to an IF-to-V-band

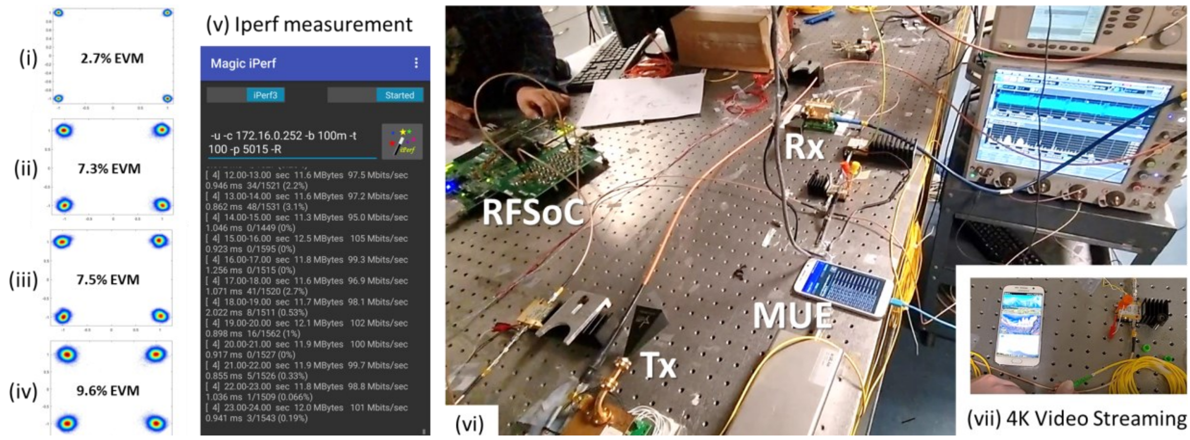

Fig. 3: EVM measurements and constellation diagrams after (i) electrical back-to-back (ii) FiWi, (iii) WiFi and (iv) FiWiFi real-time transmission, (v) *Iperf* measurements of the FiWi segment, (vi) photo of the implemented testbed and (vii) screenshot of 4K video streaming

radio board. An identical Receiver-side antenna module located at 1 m horizontal distance was used to receive the mmWave radio waveforms and direct them to the ADC of the RFSoC after RF-to-IF downconversion. Both commercial V-band radio boards operated at 60GHz. At the receiver side, real-time DSP was applied to the signal, including demodulation of the received OFDM symbols, as well as a Zero-Forcing (ZF) equalization algorithm. For the channel estimation, 21 pilot sub-carriers multiplexed with the data subcarriers were also transmitted.

Regarding the WiFi layout, an inverted but symmetrical link to the FiWi layout was implemented, as depicted in Fig. 2 (ii). Finally, as shown in Fig. 2 (iii), the FiWi layout was extended with an extra EML and a photoreceiver leading to the targeted FiWiFi layout. It should be also mentioned that the voltage input levels of all e/o and active RF components were carefully selected to ensure their linear operation.

Results and discussion

Fig. 3 (i) - (iv) show the EVM results of the received IF signal after converged FiWi, WiFi and FiWiFi transmission, and the corresponding constellation diagrams after real-time processing. A photo of the actual demonstration setup is depicted in Fig. 3 (vi). The initial signal generated by the RFSoC exhibited an EVM of 2.7% (Fig. 3 - i), while the use of the optical and RF modules through the FiWi setup introduced an EVM increase by 4.6%. As it was originally expected, the FiWi (Fig. 3 - ii) and WiFi (Fig. 3 - iii) transmission performance was similar, with an EVM offset of 0.2%. The identical EVM measurements in both links, is a strong indication that the active RF/optoelectronic units of the FiWi and WiFi testbeds were operating at their linear region. The extension of the FiWi link with an additional optoelectronic conversion stage, was responsible for an increase of the EVM value by 2.3% (Fig. 3 - iv) compared to the FiWi case. Nevertheless, in all cases the transmission was well-bellow the 3GPP threshold of 17.5% EVM for successful demodulation of the QPSK modulation[12], indicating the robustness of the proposed analog IFoF/V-band/IFoF transport solution, thus its scale-up capabilities.

Aside from the physical layer performance metrics, the capability of the proposed solution to support real-world services over the MNO's infrastructure was assesed. To this end, for all previously described network layouts, a Mobile User Equipment (MUE) was used to perform *Iperf* measurements, using Transmission Control Protocol (TCP) traffic, exhibiting 100Mbps stable connectivity (Fig. 3 - v). Finally, 4K online video streaming (Fig. 3 - vii), uninterrupted live IP-video teleconferences and web browsing were successfully demonstrated over the presented A-IFoF/mmWave network configurations.

Conclusions

We presented the first demonstration of an FPGA-based A-IFoF / mmWave transceiver integration in a deployed mobile core network infrastructure, performing real-world services. Successful physical layer connectivity was validated for OFDM waveforms propagating over different network segments, with <10% EVM values. The reliable operation of analog transport layer was also verified in service layer through *iperf* measurements, 4K online video streaming and live IP-video calls. The reported results open the door to the integration of FPGA-based analog IFoF/V-band engines in deployed mobile core infrastructures in the beyond-5G era.

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