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Wavelength Reconfigurable Point-to-Multipoint Fiber-Wireless Fronthaul with 10 Gb/s traffic for Network Sharing Applications

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***Abstract*—A reconfigurable Fiber-Wireless fronthaul that can steer 4λ-WDM IFoF channels with 4x 2.5 Gb/s data traffic of 16-QAM signals to V-band Phased Antennas Array using an AWGR as an all-passive any-to-any wavelength router is experimentally evaluatedpresented towards promoting the co-existence of multiple fronthaul streams of Mobile Network Operators/Tenants operating over a single, shared 5G C-RAN architecture, while simultaneously satisfying for the first time, the 5G Key Performance Indicator (KPI) requirement for a 10 Gb/s aggregate peak-data traffic capacity through FiWi mmWave/IFoF links based on Phased Array Antenna with RF beamsteering.**

***Index Terms*—5G, Optical Fronthaul, analog Radio over Fiber, C-RAN, millimeter-Wave**

I. Introduction

The emergence of 5G communications is stimulating new services that demand extreme peak data rates of 10-20 Gb/s per cell, as envisioned by telecommunication experts [1][2], with an area traffic capacity of up to 10 Mb/s/m^2[1], putting enormous pressure on the mobile optical transport network as it will require aggregate traffic capacities of hundreds of Gb/s. Moreover, to support such high performance, the 5G NR standard has adopted ultra-wideband mmWave frequency ranges, making Radio Access Network (RAN) densification a necessity and, thus, leading to an extremely large number of Base Stations (BSs), overburdening the X-haul (backhaul, midhaul, fronthaul) segment [3][4], while the promise of the 6G vision is only expected to further increase the load of the RAN [5]. To increase the efficiency of the RAN, a low-layer split between the Remote Radio Unit (RRU) and the Base Band Unit (BBU) has been proposed [5]-[8], forming the notion of the Centralized-RAN (C-RAN) architecture. C-RAN promises to satisfy the long-term needs of mobile networks by dynamically connecting multiple RRUs to a centralized pool of Based Band Units, forming Point-to-Multipoint (PtMP) architectures with statistical multiplexing of hardware towards favoring higher energy-efficiencies and lower equipment cost-expenses. In this topology, the BBUs are pooled in a centralized location that can host multiple processing functions, while multiple optical fronthaul streams will be linking the BBU pool to the RRUs, necessitating extensive fiber-installation to inter-connect all antenna-sites. Alternatively, Fiber-Wireless (FiWi) connectivity to various RRUs can be deployed [8]; however, such FiWi links need to exhibit traffic capacities equal to fiber links, enabling the replacement of the last-mile optical fronthaul link by a mmWave segment with beamsteering capabilities. Furthermore, the dynamic nature of mobile traffic and emerging 5G use cases, such as ultra-high mobility broadband and hotspots, require constant reconfiguration and steering of the available optical network throughput to congested cell sites [8][9].

To support such densely deployed FiWi links in a cost-efficient way, spectrally efficient Analog Radio over Fiber (ARoF) schemes supporting high capacity, increased energy efficiency, and low cost were developed [6], [8], [9]. By interfacing ARoF schemes [6]-[9] with mmWave Phased Array Antennas (PAAs) [10]-[11], a demonstration of up to 4 Gb/s Wavelength Division Multiplexing (WDM) delivered at a 4λ-FiWi V-band Small Cell with 360^o coverage was shown in [12], [13], while up to 6 Gb/s over a single PAA beam has been demonstrated in [14]. On the other hand, the use of an integrated photonic Si_3N_4 Reconfigurable Optical Add/Drop Multiplexer (ROADM) allowed achieving up to 4×10 Gb/s FiWi steerable capacity in [12], necessitating, however, an active WDM device.

To this end, centralized and reconfigurable FiWi fronthaul architectures are promising solutions to interconnect multiple BBUs to several mmWave RRUs. Nevertheless, maintaining a dense RAN network consisting of FiWi fronthaul links and mmWave RRUs may still become prohibitively expensive for a single traditional wide-area Mobile Network Operator (MNO); therefore, new business models based on infrastructure sharing between multiple MNOs have been also proposed, where multiple network operators/tenants may co-exist and share a field-deployed fiber infrastructure [16], and in-turn sharing of the equipment cost-expenses between various MNOs, Such X-haul infrastructure sharing concepts requires developing Point to MultiPoint reconfigurable high-capacity FiWi links that may penetrate the mobile X-haul network domain, that is currently being mostly limited to legacy point-to-point BBU-RRU connectivity.

Here, we experimentally present the concept and results of a centralized and wavelength reconfigurable any-to-any FiWi fronthaul-interconnected architecture, capable of routing 4λ-WDM channels, each of them being a 2.5 Gb/s IFoF channel carrying 16-QAM waveforms to V-band PAA with 90^o degrees steering capability. Using an all-passive AWGR, the presented work efficiently interconnects any optical fronthaul interface of an edge box unit to any of the four mmWave PAAs, delivering an aggregate peak traffic-capacity of 10 Gb/s through mmWave PAA beamsteering, so as to meet the respective 5G Key Performance Indicator (KPI) of peak data traffic set by expert alliances NGMN [1] and ITU [2].

II. Concept And Network Architecture

An example of the proposed centralized and reconfigurable FiWi architecture is shown in Fig. 1.

It consists of an Edge-Box that hosts N = 4 line-cards, each of them dedicated to a specific MNO. Specifically, each edge-box line-card requires a 4λ multi-wavelength optical Tx array to generate four WDM streams. The 4λ WDM output streams are fiber-connected to the four input-ports of a low-loss, polarization-independent AWGR, whose outputs are fiber-connected at various master RRUs which in turn are wirelessly connected to slave RRUs. In this way, the AWGR is utilized as an all-passive wavelength router supporting any-to-any interconnectivity. As can be seen in Fig. 1, the AWGR circularly routes the input wavelength enabling collision-free any-to-any interconnection.

The proposed RAN supports reconfigurable allocation of a 4λ WDM FiWi IFoF mmWave downlink traffic to four different AWGR output-ports and, respectively, to a large number of different RRUs deployed in the network. At the same time, the AWGR concentrates four individual downlink-wavelengths from the four different AWGR input-ports, streamed from four different MNOs, routing them to a single WDM optical stream at the first AWGR output port.. This connection is taking place over a common and shared FiWi link to a certain cell-site location, e.g., a hotspot with a temporarily high traffic load peak. Although 60 GHz mmWave PAAs are used in this work, the concept can be extended to multi-RAT technologies across different mmWave bands.

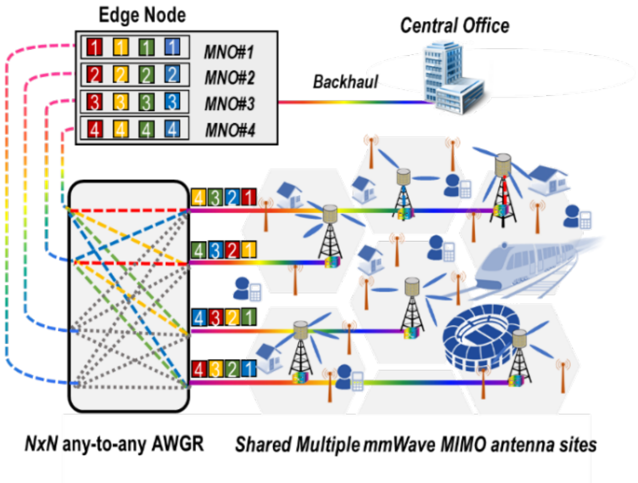

Fig. 1. Conceptual schematic of the proposed point to multi-point FiWi C-RAN architecture including four Mobile Network Operators (MNOs) transmitting over a shared 4λ-WDM FiWi fronthaul with PAA systems

III. Experimental Setup Based On The Phased Array Antenna With RF Beamsteering

The physical layer of the proposed any-to-any FiWi interconnect architecture was validated using the setup shown in Fig. 2, which emulates a 4λ WDM-transmission from the Edge-Box, followed by the AWGR–based wavelength routing operation and the mmWave wireless transmission through a 4×1 coupler and modulated by a $LiNbO_3$ Mach Zehnder Modulator (MZM), by an IFoF radio signal.

The signal was generated by an Arbitrary Waveform Generator (AWG). The 4λ-WDM output of the MZM was connected to a 32×32 AWGR with 100 GHz channel spacing, while each input port can demultiplex the traffic to four outputs. The AWGR optical output then propagated through 1km of fiber before reaching a 10 GHz InGaAs Avalanche Photodiode (APD), where it was opto-electronically converted. The output of the APD was fed to the PAA system with up to 90^o degrees beam-scanning range in the horizontal plane.

The PAA integrates 32 radiating elements with 6dBi gain, each of them connected to a phase shifter and a Power Amplifier (PA). Adjusting the values of phase shifters, a scanning range of 90^o is achieved for the utilized PAA at an operational IFoF bandwidth between 3-5GHz. The PAA acting as a Tx antenna was placed 1m away from a portable mmWave Rx horn antenna, which was used to receive the mmWave signal after the FiWi downlink transmission, where it was then down-converted back to IF and fed to the Signal Analyzer for monitoring purposes. After performing fiber only and FiWi mmWave transmission, we could evaluate the signal degradation across the various network stages of the proposed FiWi fronthaul link.

The current experimental setup is based on a prior detailed experimental characterization of the FiWi mmWave link using the V-band PAA, supporting RF beamsteering across a 90^o degree sector [17]. Specifically, the single FiWi link has been benchmarked across various angles using a QPSK and 16QAM modulation waveform at 100 Mbaud and 250 Mbaud, respectively. In order to achieve this, the PAA was sequentially set to operate at beamsteering angles from -45^{oo} to $+45^{oo}$ degrees with 15^{oo} angular steps, while the signal was captured at different angular positions by a portable horn antenna placed at a constant radius of 1m from the PAA. The FiWi mmWave-transmitted signals were evaluated in terms of constellation diagrams and EVM values at all angular positions and the recorded results are plotted in Fig. 2(e).

In the case of the QPSK waveform, the average EVM value is around 13.8% with a variation less than 0.5%, while for the 16-QAM waveform the average EVM value is around 11% with a variation less than 1.5%. As can be clearly seen in Fig.2(d), the performance of the PAA is nearly flat and constant throughout all angular positions, revealing that the PAA can support consistent RF beamsteering operation across the whole 90° degree mmWave sector. More details on the characterization of the beamsteering operation and linearity measurements of the PAA can be found in [17].

Since PAA performance was identified to be similar with small variations across the sector, a single angular position of 0o degrees angle was selected and kept constant and fixed in the AWGR-based FiWi transmissions of the next section, in order to maintain a constant reference and evaluate the performance and degradation of the AWGR-switching node only.

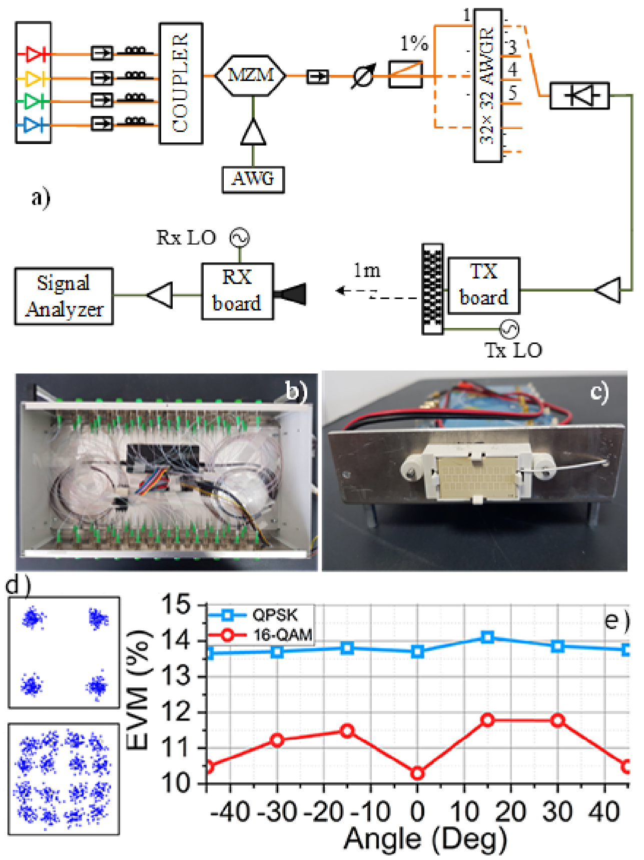

Fig. 2. a) Experimental setup used for the evaluation of the FiWi fronthaul, b) photo of deployed AWGR used in the experiment, c) photo of the deployed 60GHz Phased Array Antenna, d) experimental characterization measurements on a single channel FiWi transmission through the PAA using 100 Mbaud QPSK modulation waveform and 250 MBaud 16QAM waveform, including indicative constellation diagrams and e) EVM measurements across a sector range from -45° to +45° steering angle with a step of 15° degrees

IV. Experimental Results on the AWGR-based Reconfigurable FiWi Fronthaul

A. *Characterization of the AWGR*

Initially, we evaluated the transfer function of the AWGR and performed a static characterization, by feeding Amplified Spontaneous Emission (ASE) noise to input port 1 of the AWGR and captured the outgoing signals at all output ports and the polarization dependence. The average losses of the AWGR were found to be only 4 dB, with a polarization dependence of ¡0.8 dB, indicating that it can be accommodated in fiber-access and fronthaul links with challenging power budgets.

The transfer function for the four chosen channels is shown in Fig. 3(a), at wavelengths 1554.0 nm, 1554.8 nm, 1555.6 nm, and 1556.4 nm, confirming a flat top response with a 3 dB bandwidth of around 0.6nm. Next, four coupled continuous wave (CW) lasers were connected to input 1 and the outgoing signals of four respective output ports (P#3 to P#6) were recorded. As can be seen in Fig 3(b), the signals are successfully demultiplexed by the AWGR with the channel crosstalk being below -20 dB, which is expected to have a non-detectable effect on the ARoF signal quality.

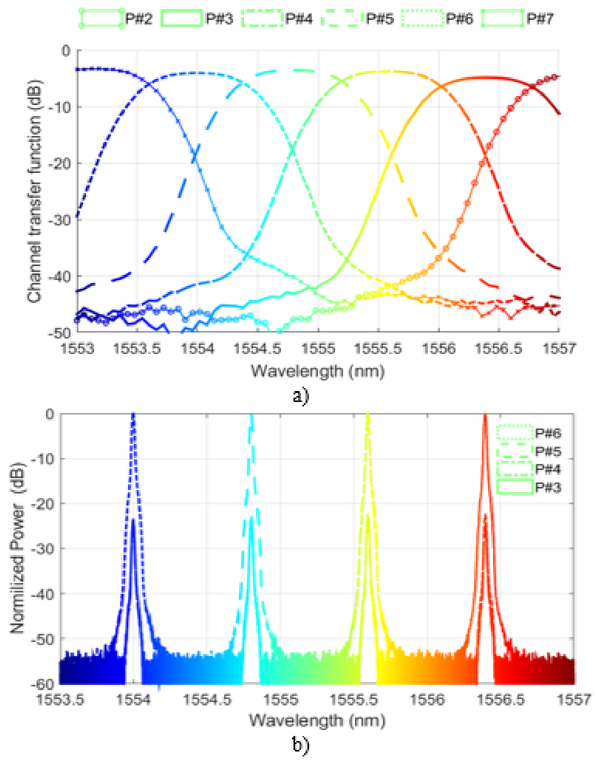

Fig. 3. a) Transfer function of the 4 used channels of 32×32 AWGR for the experiment, b) spectrum and crosstalk measurement.

B. *Fiber Wireless transmission*

To further validate the negligible crosstalk, two sets of data-transmission measurements were performed in the RoF section. The transmitted signal was a PRBS7 signal loaded on a 16-QAM 250Mbaud waveform with 0.7Vpp placed on a 4.9GHz IF carrier. Firstly, we evaluated the single wavelength fiber-optical transmission operation with wavelength tuning. Each laser-emission was activated sequentially, while the rest of the lasers were not activated yet. Thus, the recorded EVMs for this single wavelength analog RoF fiber-optical transmission are plotted in Fig. 4-top row inset, indicating a worst EVM up to 1.89%.

Next, all lasers were activated, so as to generate the 4λ-WDM traffic for fiber-optical transmission and the EVM of each output of the AWGR was recorded, resulting in a 4λ WDM ARoF setup. As clearly seen in Fig.4(b), denoted as "ARoF MUX", the performance is the same as in the case of sequential switching ON, confirming that any minimal, undesired coupling at the AWGR ports did not have any noticeable impact on signal quality, as the worst EVM channel was still in the order of 1.91%. These results indicate that the single channel of Fig. 4-top row inset and WDM analog transmission of Fig. 4- middle row inset exclusively through the fiber does not induce any significant signal degradation.

Having evaluated the co-existence of 4λ WDM IFoF/RoF streams with negligible crosstalk, we performed a 4x WDM FiWi data-transmission experiment through the PAA with mmWave transmission of the signal across a 1m V-band link, by connecting the APD output to an electrical amplifier and sequentially feeding the input of the PAA. The radiating elements were configured to transmit at an angle of 0o degree. Further measurements on the angle were performed in the work reported in [11], revealing negligible impact of the angle of the beam.

After 1m of V-band wireless transmission at a 0o degree beamsteering angle, the constellation diagrams and EVM values of the received signals at the output of the horn-Rx antenna were recorded. The received constellation diagrams after the FiWi mmWave transmission for all four channels are depicted in Fig. 4-bottom-row inset, followed by the recorded EVM values, termed as "FiWi", were at a roughly equal level for all four ports, being below the 12.5% threshold set by 3GPP [18], with clearly demodulated constellation diagrams.

Finally, to evaluate the maximum transmission capacity, the symbol rate was increased from 250 to 500 and 625 Mbaud, which corresponds to an increase in the FiWi data rate from 1 to 2 and 2.5 Gb/s, respectively. The constellation diagrams of the signals received by the horn Rx after FiWi transmission are shown in Fig. 5, featuring EVM below 12.5% for all symbol rates and meeting the respective 3GPP EVM requirements, while at the same time satisfying for the first time, to the best of the authors' knowledge, the respective 5G KPI requirement for a 10 Gb/s aggregate peak-data traffic capacity through FiWi mmWave/IFoF links with PAA beamsteering.

V. Conclusions

A 4λ-WDM Fiber Wireless fronthaul that can steer up to 10 Gb/s peak data traffic through an AWGR-based any-to-any optical interconnect and a mmWave antenna with beamsteering capabilities is presented, allowing to steer and allocate the peak data traffic at any congested antenna site in an all passive manner, based only on the wavelength properties. To the authors' knowledge, this is the first time that a peak aggregate 10 Gb/s FiWi mmWave/IFoF data traffic through Phased Array Antenna is presented, meeting the aggregate peak data traffic of 5G KPIs.

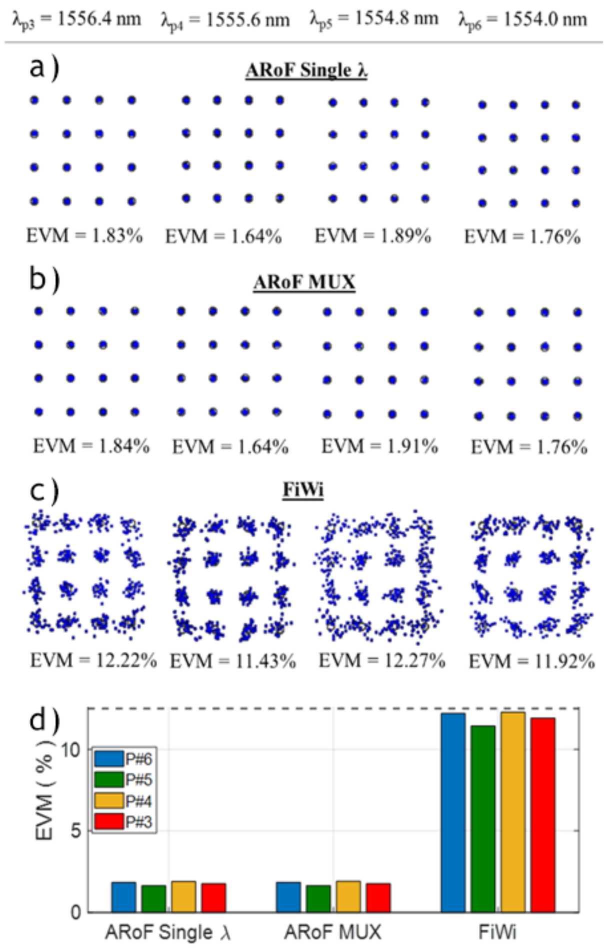

Fig. 4. Constellation diagrams of all four channels of the 4λ WDM FiWi 16-QAM 250 Mbaud transmission, including a) single channel ARoF fiber-optical (only) channel transmission at an IFoF, b) WDM multiplexed A-RoF fiber-optical (only) data transmission at an IFoF, c) FiWi mmWave transmission across 1m V-band link over the air through the PAA system, and d) detailed evaluation of the captured EVM values of the transmitted fiber-only ARoF and FiWi mmWave signals.

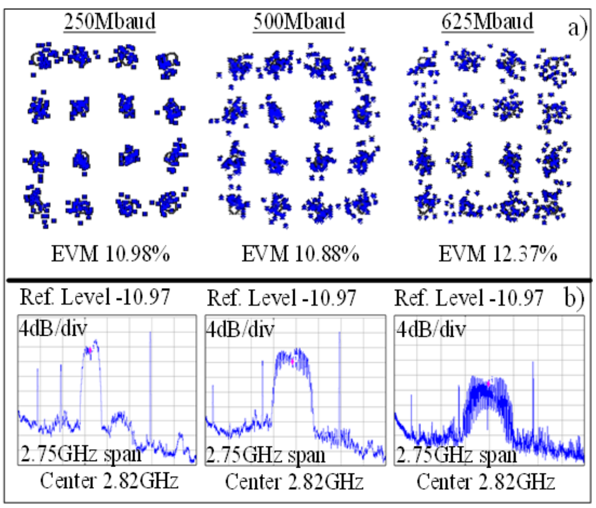

Fig. 5. Constellation diagrams and the corresponding RF spectrum of the 16-QAM signals for increasing symbol rates of 250 Mbaud, 500 Mbaud, and 625 Mbaud.

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