Flexible 360° 5G mmWave small cell coverage through WDM 4x1 Gb/s Fiber Wireless fronthaul and a Si3N4 OADM-assisted massive MIMO Phased Array Antenna

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Abstract: Four Wavelength Division Multiplexed 1Gb/s QAM16 streams are transmitted through 10km fiber, an Optical Add/Drop Multiplexer and a V-band beamsteering antenna with 90° steering, demonstrating the first 5G Fiber-Wireless A-RoF architecture with 360° coverage.
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1. Introduction

At the dawning of 5G era, the growing demand for ubiquitous high-bandwidth connectivity through enhanced mobile Broadband and Fixed Wireless Access [1]-[4] are driving a transformation of mobile networks towards increased densification [3] and Centralized Radio Access Network (C-RAN) architectures [4], while promoting the use of millimeter wave (mmWave) directional beams for higher spectral bands and user rates [5]. In turn, this necessitates the development of Point-to-Multipoint (PtMP) configurations with high-densities and high-capacities, placing tremendous load on the underlying hardware of the fronthaul network and raising serious concerns whether CPRI will impose a hard limiting network bottleneck [6]. Analog Radio over Fiber (A-RoF) stand out as a promising candidate solution for spectrally efficient transportation of radio signals without extra bandwidth overhead [6], however profound demonstrations of such high-capacity FiWi links of up to 24 Gb/s [7] are relying on static horn antennas that are better tailored for single Point-to-Point (PtP) backhaul communication. A few recent 5G prototype Phased Array Antennas have recently managed to merge A-RoF with flexible beamsteering, yet either limited in wired setups [8] or single beams only [9][10] that still favor simple PtP configurations. To date, PtMP FiWi configurations have been presented only using a Leaky Wave Antenna [11], which is limited to fixed directions due to passive frequency selective steering without achieving to showcase a truly flexible PtMP architecture.

Aiming to extend fiber-connected PAAs in true PtMP architectures and further enhance the number of transported beams, introducing optical multiplexing in the fronthaul adds another dimension in traffic parallelization. In this direction, Wavelength Division Multiplexing (WDM) of 24 carriers [12] and 25GHz spacing [13], Space Division Multiplexing in 7-core fibers [14], Mode Division Multiplexing of 4 modes in few mode fibers [12] or Polarization Multiplexing [16] are being investigated, with WDM requiring optical multiplexing devices at the antenna site rather than installation of any new special fiber. While there is a consensus that any multiplexing provides enhanced flexibility and coverage, allowing to assign various streams at individual antenna sectors or beams [13], most multiplexing demonstrations still deploy wired setups [12][13][16], static PtP horns [14] or unitary beams only [15].

In this paper, we present a 4λ Optical Add/Drop Multiplexer (OADM) followed by 4x steerable 60GHz beams of a 32-element PAA to experimentally demonstrate the first multi-wavelength FiWi PtMP architecture for 5G small cell environments, as conceptually depicted in Fig.1. The OADM is fabricated on low-loss Si_3N_4/SiO_2 TriPleX platform [17], capable to demultiplex four 100GHz C-band wavelengths. The FiWi links extend across a 10km Single Mode Fiber (SMF) distance and 1m V-band link, transmitting four 250MBaud QAM16 signals through mmWave beams of 10° width steered across a 90° sector. The present architecture leads to 1Gb/s user rate anywhere in the four sectors, being the first OADM-assisted PAA with complete 360°-coverage for mmWave 5G small cell.

Fig.1 – Conceptual schematic of the proposed 5G FiWi small cell architecture

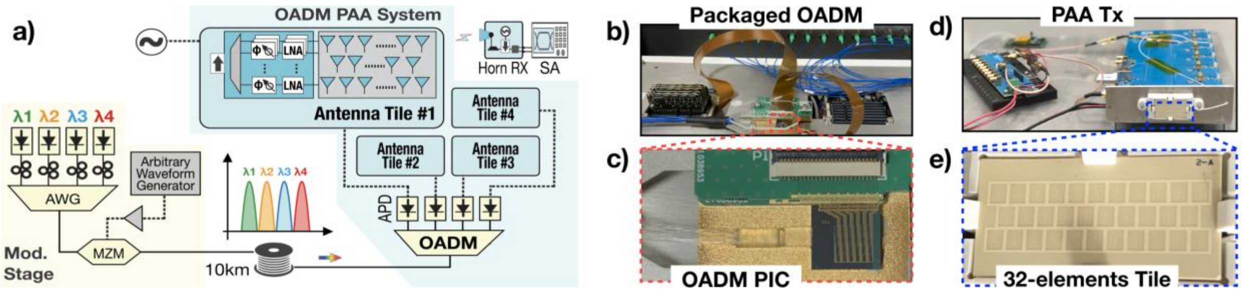

Fig. 2 – a) Experimental setup. b) Packaged OADM photo. c) OADM PIC Zoom-in. d) PAA transmitter photo. e) 32-elements Tile zoom-in.

2. Devices and Experimental Setup

The experimental setup used for the evaluation of the proposed 5G FiWi small cell architecture is shown in Fig. 2(a), comprising four FiWi links including 4λ-WDM A-RoF streams and 4x V-Band wireless links. Specifically, four Continuous Wavelengths (CWs) at λ_{1-4} of 1545.6nm, 1546.4nm, 1547.1nm and 1548nm, produced by Tunable Laser Sources, are wavelength multiplexed through an Arrayed Waveguide Grating (AWG). The CWs are fed to a $LiNbO_3$ Mach Zehnder Modulator (MZM), driven by an Arbitrary Waveform Generator. A 250 MBaud QAM16 was synthesized, upconverted at 5.8GHz IF and amplified to 5V to drive the MZM operation, imprinting the data to the 4λ optical carriers. The WDM A-RoF traffic is transmitted over a 10km-long SMF spool with typical dispersion D=17 ps/nm/km, emulating typical Mobile Fronthaul lengths and decorrelating the 4λ A-RoF waveforms.

When the 4λ A-RoF stream reaches the antenna site, it gets demultiplexed by the OADM into the four individual optical carriers with 100GHz spacing. The OADM design relies on a MZI-based cascaded interleaver layout, as described in detail in [19], where each interleaver output is either dropped towards one set of sectorized PAA elements to form one beam or propagated to the next interleaver stage to reach the next sectorized PAA segment. The OADM is fabricated on an ultra-low loss Si_3N_4/SiO_2 TriPleX platform, fully assembled on a TEC-controlled PCB, electrically and optically packaged, as shown in Fig. 2(b) and (c). Each wavelength output with an average power of around -4dBm is sequentially connected to a 10GHz Avalanche Photo Diode (APD) photo-receiver for o-e conversion and to the V-band PAA system for wireless transmission across 1m link at 61.3GHz. The data signal is received by a portable Rx antenna, featuring a 22.5dBi gain pyramidal horn, an integrated down-conversion stage and a dedicated 10GHz local oscillator to generate a baseband signal that is evaluated using a Signal Analyzer (SA).

The PAA is shown in Fig. 2(d) consists of a 32-element 60GHz beamsteering antenna system, as well as a Control PCB board. It consists of a Tile Feed PCB board that hosts also the antenna tile with the 32 radiating elements at the frontpanel, as shown in Fig. 2(e). The Tile Feed PCB integrates an RF IC with an upconversion stage, that multiples the external 10GHz clock in the 60GHz band and multiplexes it with the IFoF data received from the APD Rx, followed by a 1:32 splitter that splits to 32 channels, each including a φ-phase shifting element and Low Noise Amplifiers (LNAs). On the other hand, the Control PCB board allows selectively activating or deactivating each antenna element, as well as tuning the phase shift applied per channel, in order to perform beamforming and beamsteering. Owing to the high frequency targeted, the substrate of the Tile PCB is based on low-temperature ceramics, while each radiating element comprises a dipole with 6dBi gain, designed for broadband operation in the 57-64 GHz range and a radiation pattern of 120_o, when only one is actively radiating. When all 32 elements are activated, the antenna form a beam with a 10_o width that can be steered across 90_o, powered by 5.3V and 1.6A.

3. Experimental Results

The FiWi links of the proposed architecture were initially evaluated in a single user transmissions scenarios with the PAA configured either with only one radiating element being active and radiating isotopically across 120° or in a full blown mode with all 32 elements active and configured to steer a single lobe either at 0° or 45° degrees. A photo of the V-band link with the horn receiver placed at 45° degree angle is shown in Fig. 3(a). The constellation diagrams in isotopic transmission and beamsteering mode are shown in Fig. 3(b), revealing an EVM improvement of 3.4% for the beamsteering mode, which is mainly attributed to better concentration of the mmWave power in a directive beam towards the Rx antenna, while on the other hand isotropic transmission allows ubiquitously covering the whole sector area to accommodate mobile users placed everywhere within the 5G small cell. Featuring a 250 MBaud stream and a roll of factor of 1.3, resulting at a user rate of 1Gb/s and a spectral efficiency of 3.1 b/s/Hz.

The FiWi links were then evaluated a 4λ WDM and 4x beam transmission, while steering the angle of the first beam, corresponding to λ1, from -45° up to 0° and +45° degrees. The optical spectrum of the WDM transport link, is shown

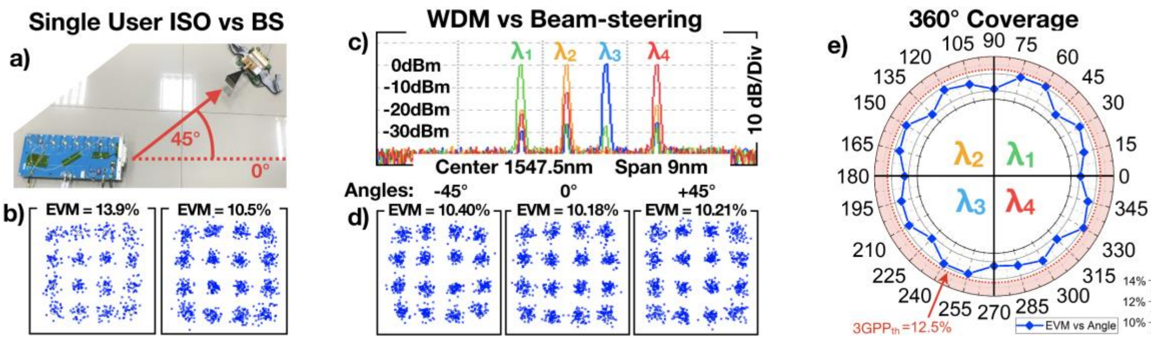

Fig. 3 – a) Top view of the 45° steered V-Band link. b) Constellation diagrams: isotropic on the left, beamsteered on the right. c) Optical spectra of the 4 demultiplexed optical signals before the APD, normalized to 0dBm peak power. d) Constellation diagrams of the received signals after optical propagation and V-Band wireless beamsteered transmission. e) Experimental EVM values for the 360° coverage.

in Fig. 3(c), depicting the superimposed channel spectra of the four A-RoF optical carriers at the output of the OADM using different coloring. As it can be seen each A-RoF channel output of the OADM features more than -13dB crosstalk from the other channels. The received signal from the beamsteered link was evaluated by means of EVM measurements, as shown in Fig. 3(d), showing clearly demodulated constellation diagrams of the QAM16 signals and almost constant EVM values of 10.4%, 10.18% and 10.21% for angles -45°, 0° and +45° respectively. The values reveal negligible impact of the steering angles while meeting the EVM requirements set by 3GPP [18].

Finally, towards evaluating the performance across a complete 360_o coverage, each of the four FiWi links were steered across the 90_o degrees of their corresponding sector, making angular steps of 15_o. At each 15_o step, the EVM values of the received signal were recorded, corresponding to 24 combinations of wavelength-and-angular locations. Fig. 3(e) depicts a polar representation of all 24 measured EVM values for the proposed 360° coverage, highlighting how each lambda serves each of the four sectors of the cell, with the inner radius corresponding to a 10% EVM and the outer to 14, while the red color show the acceptable EVM limits set by 3GPP. The plot reveals an average EVM of 11.03%, measured anywhere across the 360_o–cycle, while all values satisfy the 3GPP requirement, verifying successful 1Gb/s user rate transmission and meetings the 5G KPIs.

4. Conclusions

The first experimental demonstration of a V-band PAA system interfaced with 100GHz Si3N4 OADM concept is presented, allowing four spectrally efficient WDM A-RoF transportation of four 90° steerable mmWave beams of 250Mbd QAM16, paving the way towards 5G small cell architectures with 1Gb/s user rates and 360_o coverage.

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