Sub-THz Fiber Wireless Multi-IFoF fronthaul of a V-band massive MIMO antenna for multi-user 6G networks

M. Vargemidou(1), P. Toumasis(2), K. Kanta(2), R. Maximidis(1), G. Giannoulis(2), Z. S. He(3), Y. Leiba(4), D. Apostolopoulos(2), H. Avramopoulos(2), A. Miliou(1), N. Pleros(1), C. Vagionas(1)

(1) Department of Informatics, Center for Interdisciplinary Research & Innovation, Aristotle University of Thessaloniki, Thessaloniki, Greece, vargemim@csd.auth.gr
(2) School of Electrical and Computer Engineering, National Technical University of Athens, Greece
(3) Sinowave AB, Hovås, Sweden
(4) Siklu Communications Ltd., Petah Tikva 4959501, Israel

Abstract *Three D-band Fiber-Wireless Multi-IFoF links each with 0.5 Gb/s per beam are experimentally transmitted across a 7km fiber and a V-band MIMO antenna with 90º-degree RF-beamsteering, forming the first demonstration of a THz Fiber-Wireless X-haul of a multi-beam mmWave antenna*

Introduction

On the verge of the 6G/Beyond 5G era, there is an imperative need for a series of new Use Cases and Applications, such as Augmented/Virtual Reality, Enhanced Mobile Broadband, Industry 4.0, Fixed Wireless Access and Pervasive Connectivity to everything [1]. This has been driving a surge of the wireless traffic and the number of connected devices, with forecasts predicting 10^7 devices per km^2 at dense areas and more than 125 billion devices globally by 2030 [2], including personal devices, sensors, vehicles, fixed antennas or UAVs with user rates of 1 Gb/s and area capacities of 1 Gb/s/m^2.

Albeit, the 6G vision is expected to severely stress the already congested mobile networks. On the one hand, it drives a densification of the Radio Access Networks (RAN) to smaller cells with radii down to a few tens of meters, with massive Multiple-Input Multiple-Output (MIMO) antennas, millimeter-wave (mmWave) and directional beamforming [3] being promoted as promising enablers to boost wireless capacities. Yet, X-haulling of multiple mmWave beams still remains a daunting issue, as it typically requires hardware- and cost-expensive digitization/packet parsing in Digital Radio over Fiber (DRoF) and (e)CPRI-based solutions with increasingly more power-hungry signal processing [4][5].

On the path to higher frequency bands in 6G, analog (ARoF) and Intermediate Frequency over Fiber (IFoF) are gaining increasing attention, as they inherently allow aggregating multiple radio signal on optical sub-carrier multiplexed X-haul (fronthaul or backhaul) with high spectral efficiency, reduced hardware and cost complexity [4][5]**.** At the same time, the THz (0.3-3 THz) and Sub-THz (60-300 GHz) bands [6]-[9] are becoming appealing compared to the more expensive and less flexible fiber-deployment. Featuring large spectral resources of up to tens of GHz, high integrability to multiple radiating elements (>100) and high directivity to mitigate intercell interference and propagation losses [1],[2], THz and Sub-THz bands bear promises to unleash fiber-equivalent multi-Gb/s capacities in flexible FiWi THz X-haul links for dense 6G hotspots, as schematically depicted in Fig. 1.

To this end, global efforts in the THz/Sub-THz domain achieved to demonstrate Fiber Wireless (FiWi) links with high aggregate capacities at up to 23.1 Gb/s [6], 103.2 Gb/s [8], 352 Gb/s [7] or 1 Tb/s [9], with km-long coverage [6]. Yet, these rely in fixed Point-to-Point FiWi links and static wireless 'bridges' between two end-points [6]-[9] or with carefully-optimized heterodyne mixing of two carriers [10], without trully aggregating/de-aggregating multiple different user-radio signals. To this end, only a few recent multi-user X-haul links demonstrated true IFoF aggregation of different Point-to-MultiPoint links/beams, yet still either including cascade, exclusively fiber-optical X-haul stages [11] or four completely separate FiWi IFoF X-haul links with each beam assigned to a separate wavelength [12] or fiber-core [13].

This work experimentally demonstrates for the first time three Sub-THz FiWi fronthaul links aggregated on a single-wavelength multi-IFoF transmission to a v-band MIMO antenna with individual beamsteering in a 90º sector. It employs a pair of novel sub-THz antennas with

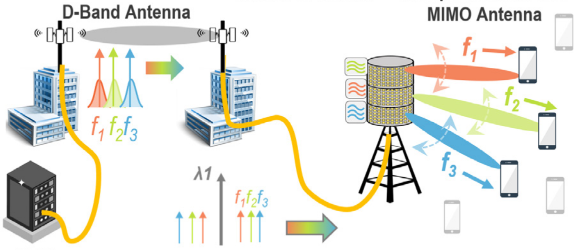

Fig. 1: Conceptual schematic of the Sub-THz FiWi X-haul

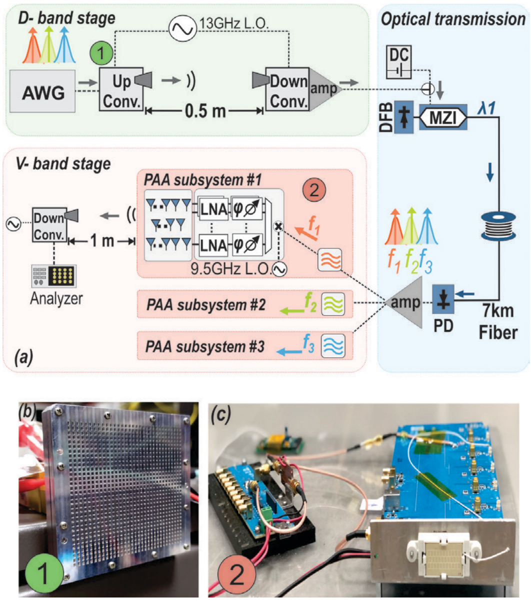

Fig. 2: (a) Experimental Setup of the proposed system including close up pictures of (b) Sub-THz (D-Band) Tx antenna and (c) V-band MIMO Tx antenna.

256-radiating elements transmitting across 0.5m distance and acting as a seamless, low-complexity wireless extension of a 7km-long fiber, which in-turn is followed by a cascaded V-band MIMO antenna with analog filtering and IF interface to handle de-aggregation of the parallel IF/beams. The end-to-end X-haul is thoroughly characterized in terms of bandwidth, modulation formats, steering angles, losses and fiber-lengths. Transporting 250 Mbd QPSK per Wireless Fiber Wireless (WiFiWi) link, each beam carries 0.5 Gb/s, forming the first demonstration of a flexible sub-THz X-haul of a mmWave MIMO antenna on a single lamda, paving the way for dense, high-capacity, multi-user 6G networks.

Experimental Setup and Devices

For the experimental demonstration of the proposed WiFiWi link, the experimental setup shown in Fig. 2(a) was implemented. A pair of high gain sub-THz antennas featuring a radiating flat front-panel of 256 elements transmitting in the 145 GHz are employed in the first wireless D-band stage. The radiating frontend forms a thin planar antenna of 40 mm×40 mm×8 mm and a 30 dBi gain, as shown in Fig. 2(b) [14], and a 16x16 slot antenna array configuration based on Electromagnetic Bandgap (EBG) concepts.

A 3-band IF signal between 0.6-5.6 GHz of 800 mV generated by an AWG was directly fed to the mixer of the Tx-antenna and up-converted at 156 GHz using an external 13 GHz clock of 7dBm. The signal was wirelessly transmitted at 0.5m and received by a similar Rx-antenna with an integrated D-band Low Noise Amplifier (LNA) with 25dB gain and down-conversion stage.

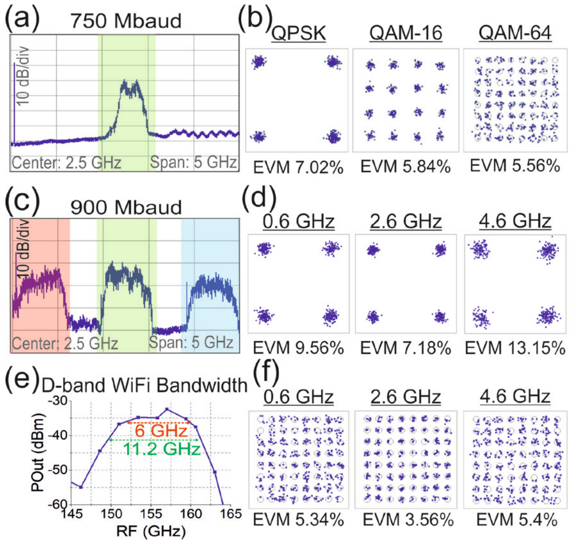

Fig. 3: Experimental results of the D-band WiFi link: (a) RF spectrum of a 750 MBd single band, (b) constellation diagrams and EVM value of QPSK, QAM-16, QAM-64, (c) RF spectrum of a 900 MBd transmission of 3 bands at 0.6 GHz, 2.6 GHz, 4.6 GHz, (d) constellation diagrams and EVM values of each QPSK-band (e) bandwidth characterization of the FiWi link, (d) three band 64-QAM transmission.

Then, the IF signal and amplified to drive an MZI $LiNbO_3$ modulator with a V_π of 7V, fed by a Continuous Wavelength (CW) optical signal at 1550 nm of a laser source. The optical IFoF signal was then transmitted through a Single-Mode Fiber (SMF) for 7 km with Variable Optical Attenuator (VOA), before entering a 10 GHz PIN Photoreceiver (PD) for o-e conversion.

The PD-signal was sequentially connected to the analog microwave filtering stage and IF input interface of a V-band MIMO Tx antenna system, comprising a control- and an antenna board, as shown in Fig.2(c). The antenna board operates between 57-64 GHz by integrating a 1:32 splitter with 32-channels of φ-phase shifting elements and LNAs that each feed a 6dBi dipole, capable of tuning the amplitude and phase of each radiating element, to perform beamforming and steering [12]. The signal was fed to the mixing stage of the MIMO to be upconverted to the V-band, featuring a x6 multiplication of an external 9.5 GHz LO. The RF was wirelessly transmitted to a V-band horn receiver at a distance of 1 m and converted back to the IF signal. The Rx was provided with an external LO signal of 9.3 GHz

Characterization of the Sub-THz FiWi link

Initially, we characterized the only the sub-THz link as shown in Fig. 3. More specifically, to determine the maximum data rate capability provided by the D-band link, single band signal transmissions of a 750 Mbaud waveforms centered at 2.6 GHz were conducted, as shown in Fig.3(a) and (b). The waveforms included

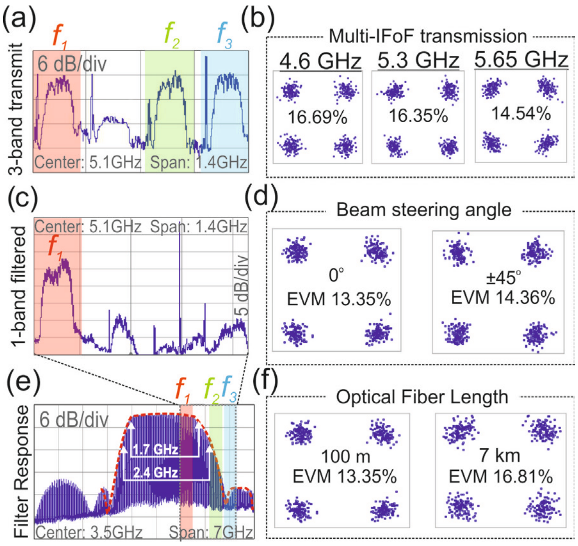

Fig. 4: Experimental results of the WiFiWi link, including: (a) RF spectrum of a 250 Mbaud 3-band transmission, and (b) respective constellation diagrams, (c) RF spectrum of the same transmission using a filter to select the first band, (e) filter's frequency response, constellation diagrams and achieved EVM values for filtered transmission, (d) with and without beamsteering and (f) at different fiber lengths.

QPSK, 16-QAM and 64-QAM formats. The achieved EVM values were 7.02% for QPSK, 5.84% for 16-QAM and 5.56% for 64-QAM, being below the respective requirements established by 3GPP for radio and RoF transmissions, resulting in a maximum data rate of 4.5 Gb/s.

Figures 3(c) and (d) depict the transmission of a 900 MBaud QPSK at three bands centered at 0.6 GHz, 2.6 GHz and 4.6 GHz. The recorded constellation diagrams and the respective EVM values were 9.56% for the first band, 7.18% for the second and 13.15% for the third, which satisfy the respective threshold requirements. We also characterized the 3dB and 10 dB bandwidths of the FiWi link, found to be 6GHz and 11.2 GHz respectively, as shown in Fig.3(e), and performed a high capacity three-band transmission. As shown in Fig.3(f), 750 MBaud 64-QAM signals at all three bands were transmitted, achieving a 4.5 Gb/s per IF/beam and 13.5 Gb/s aggregate rate.

Experimental results of the end-to-end X-haul

The second set of experimental results refers to the measurements conducted on the complete end-to-end WiFiWi link, as shown in Fig. 4. Fig. 4(a) and (b) depict the capacity of a simultaneous three-band transmission, featuring a 250 MBaud QPSK signal for each of the three bands at 4.6 GHz, 5.3 GHz and 5.6 GHz. The recorded constellation diagrams featured equal EVM of 16.69%, 16.35% and 14.54% respectively.

Afterwards, the same transmission was performed, using an analog RF bandpass filter to select and de-aggregate the first IFoF waveform

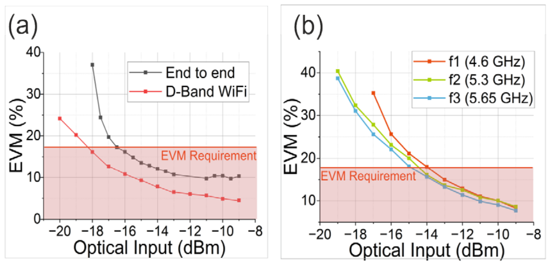

Fig. 5: Experimental characterization of the dynamic range: a) the Sub-THz FiWi link and the end-to-end WiFiWi link for a single band, and b) equal EVM-performance of the three end-to-end WiFiWi links versus the power reaching the PD.

at 4.6 GHz from the rest of the two Ifs to evaluate the beam-selectivity with individual steering of each user-beam. Fig.4(c) shows the recorded RF spectrum, showing clear separation of the first band with crosstalk less than <-15dB. The transfer function of the RF-microwave filter used is shown in Fig.4 (e), revealing a 1.7 GHz-wide flat top and a 10 dB bandwidth of 2.4 GHz.

Finally, two end-to-end experiments targeted to verify individual beam-steering of the mmWave user beams, while also increasing the distance between the V-Band Tx and Rx to 6 m. The same multi-band transmission and filtering of the first band was conducted, with the beam steered at 0° and ±45°. The results reported in Fig. 4(d) show the constellation diagrams and measured EVM values 13.35% and 14.36%, resulting in an equal performance within 90° sector (± 45°). The test was repeated after the addition of a 7 km SMF spool after the 100m-short fiber, to evaluate a long-distance fiber transmission, resulting in an EVM penalty of only 3.5%, shown in Fig.4(f).

Finally, we evaluated the dynamic range of the Sub-THz FiWi link only and the end-to-end WiFiWi X-haul link, shown in Fig. 5(a) and (b) for various power levels from -20 dBm up to -8 dBm reaching the PD. The former operated within the acceptable EVM values across at least a 9 dB dynamic range for power levels >-17 dBm, while the latter supports at least 6.5 dB dynamic range with optical power levels above -14.5 dBm.

Conclusions

The first Sub-THz X-haul link to a MIMO antenna serving three 0.5 Gb/s mmWave users with individual RF beamsteering at up to ±45°, and 6.5 dB dynamic range for up to 7km fiber-link, paving the way for multi-user 6G networks.

Acknowledgements

This work is supported by H2020 5GPPP project Int5Gent (957403), Horizon Europe Project OCTAPUS (101070009) and MSCA-PF-EF MIMOSA(101065845). The authors acknowledge Keysight support with measurement equipment.

References

[1] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, M. Zorzi, "Toward 6G Networks: Use Cases and Technologies," IEEE Communications Magazine, vol. 58, no. 3, pp. 55-61, Mar. 2020. DOI: 10.1109/MCOM.001.1900411

[2] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, P. Fan, "6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies," IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 28–41, Sept. 2019, DOI: 10.1109/MVT.2019.2921208

[3] A. Tsakyridis et al., "Reconfigurable Fiber Wireless IFoF Fronthaul With 60 GHz Phased Array Antenna and Silicon Photonic ROADM for 5G mmWave C-RANs," IEEE Journal on Selected Areas in Communications, vol. 39, no. 9, pp. 2816–2826, 2021, DOI: 10.1109/JSAC.2021.3064649.

[4] C. Lim, Y. Tian, C. Ranaweera, N. Ampalavanapillai, E. Wong, K.L. Lee, "Evolution of Radio-over-Fiber Technology" IEEE Journal of Lightwave Technology, vol. 37, no. 6, pp. 1647-1656, Mar. 2019. DOI: 10.1109/JLT.2018.2876722

[5] S. Ishimura, et al., "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, April 2018. DOI: 10.1109/JLT.2017.2787151

[6] W. Li, et. al, "23.1-Gb/s 135-GHz Wireless Transmission Over 4.6-Km and Effect of Rain Attenuation," IEEE Transactions on Microwave Theory and Techniques, article in press, DOI: 10.1109/TMTT.2023.3267547

[7] R. Puerta, et. al., "Single-Carrier Dual-Polarization 328-Gb/s Wireless Transmission in a D-Band Millimeter Wave 2 × 2 MU-MIMO Radio-Over-Fiber System," IEEE Journal of Lightwave Technology, vol. 36, no. 2, pp. 587-593, Jan. 2018 DOI: 10.1109/JLT.2017.2756089

[8] W. Li et al., "Delivery of 103.2 Gb/s 4096QAM signal over 180m wireless distance at D-band Enabled by Truncated Probabilistic Shaping and MIMO Volterra Compensation," Optical Fiber Communication Conference, San Diego, CA, USA, M1C.4, 6–10 March 2022, DOI: 10.1364/OFC.2022.M1C.4

[9] X. Li et al., "1-Tb/s Millimeter-Wave Signal Wireless Delivery at D-Band," IEEE Journal of Lightwave Technology, vol. 37, no. 1, pp. 196–204, Jan. 2019, DOI: 10.1109/JLT.2018.2871472

[10] A. Delmande, et. al. "Optical heterodyne analog radio-over-fiber link for millimeter-wave wireless systems," IEEE Journal of Lightwave Technology, vol. 39, no. 2, pp. 465-474, 15 January 2021, DOI: 10.1109/JLT.2020.3032923

[11] K. Tanaka, H.-Y. Kao, S. Ishimura, K. Nishimura, T. Kawanishi, M. Suzuki, "Cascaded IF-Over-Fiber Links With Hybrid Signal Processing for Analog Mobile Fronthaul," IEEE Journal of Lightwave Technology, vol. 38, no 20, pp. 5656 - 5667, 15 Oct. 2020, DOI: 10.1109/JLT.2020.3001930

[12] E. Ruggeri, et. al. "Flexible 360o 5G mmWave small cell coverage through WDM 4x1 Gb/s Fiber Wireless fronthaul and a Si3N4 OADM-assisted massive MIMO Phased Array Antenna," Optical Fiber Communication Conference (OFC), San Diego, CA, USA, Mar. 2020. DOI 10.1364/OFC.2020.T4A.5

[13] S. Rommel "High-Capacity 5G Fronthaul Networks Based on Optical Space Division Multiplexing," IEEE Transactions on Broadcasting, vol. 65, no. 2, pp 434 - 443, June 2019, DOI: 10.1109/TBC.2019.2901412

[14] R. Maximidis, et. al. "Demonstration of Low-Complexity D-band Extension of Fiber X-haul for 5G and Beyond Infrastructure," European Conference on Antennas and Propagation, Florence, Italy, 26-31 March 2023, Article in press