Multiplexing Multi-Gbps Analog Radio-over-Fiber Links over a Converged Fiber/FSO Intra-Campus Infrastructure

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***Abstract*: This paper is focused on the experimental demonstration of Analog Over Fiber systems over converged Fiber/Free Space Optical links enabling the X-haul connectivity in beyond 5G and 6G era. More specifically, we present an experimental campaign of Radio over Fiber transmission of diverse waveforms over hybrid Fiber/ Free Space Optical links scenarios. Initially, we present a brief link budget analysis for the Free Space Optical link. The performance of the end-to-end system is assessed in terms of real time error vector magnitude measurements. In parallel, by emulating a wavelength division multiplexing passive optical network topology, the RoF streams are also multiplexed with mobile traffic of an installed X-haul topology, produced by Small Form-factor Pluggable transceivers, and their performance over the converged fiber/FSO architecture is experimentally demonstrated.**

Keywords—5G, Analog-RoF, B5G, EVM, FSO, X-haul connectivity

I. Introduction

Towards the arising 6G era, vast user and multiple device connectivity dictates the evolution of transport networks not only to meet enormous bandwidth requirements, but also in terms of flexibility and interoperability for the delivery of services with largely different Key Performance Indicators (KPIs) [1]. This network densification calls for a drastic transformation of the X-haul (backhaul/fronthaul) transport networks, urgently calling towards high capacity, spectrally efficient yet flexible solution that can effectively transport multiple high-bandwidth streams across different network segments [2]. For this transformation of the X-hauling, analog Radio-over-Fiber (RoF) solutions have been proposed to overcome the bandwidth limitations imposed by digital X-haul connectivity [3]. The analog RoF X-haul links have been demonstrated in support of multi-Gbps links using multiband transceivers collaborated with millimeter-Wave (mm-Wave) radio technologies [3], while they have been also successfully validated in application layer through realistic 5G services [4]. Despite the progress in mm-Wave Radio Frequency (RF) communications [5] and the emerging sub-THz bands which can efficiently integrated with fiber X-haul scenarios [6],[7] a radio-based X-haul might not suit the capacity requirements since its capability to haul tens of GHz-scale wideband signals is limited by the system bandwidth and propagation effects.

As a natural evolution step for replacing the mm-Waves and sub-THz bands in the analog X-hauling, Free-Space Optical (FSO) communications, can act as an enabler for the flexible deployment of such links – provided that the associated optical sub-systems are very cost-efficient, they are compatible with the fiber-optics transceiver equipment, and they can be easily deployed in a seamless way with the existing fiber-based networks. Through the literature, analog Radio-over-Air experimental links have been demonstrated showing robust operation for local Cloud-Radio Access

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Network (C-RAN) applications [8]. In [9] the use of optical wireless links as a robust outdoor backhaul solution for small radio cells, such as WiFi, Long Term Evolution (LTE) and 5G has been conducted, focusing on the link availability, and the achieved network metrics such as data rate and latency. FSO links have also been successfully demonstrated as fronthaul network extensions being compatible with 4G/5G systems while they can support hybrid fiber-wireless scenarios [10]. In [11] a flexible bidirectional fiber-FSO-5G wireless convergent system with sub-6 GHz and mm-Wave 5G hybrid data signals was successfully demonstrated. Very recently, 5G New Radio (NR) Fiber-Wireless systems including FSO systems have been demonstrated showing high and flexible transmission capacity [12].

With this work we contribute to the research field of analog RoF systems over converged fiber/FSO links by demonstrating transmission experiments over a deployed intra-campus infrastructure in National Technical University of Athens (NTUA). We present an experimental campaign of analog RoF transmission over hybrid fiber-wireless scenarios for Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM) and 64-QAM modulation types. Multi-band QPSK-modulated radio waveforms carrying 10Gbps data rates with acceptable Error Vector Magnitude (EVM) values were also verified over the converged fiber/FSO links. The presented analog RoF systems were also demonstrated with mobile traffic accommodating the needs of an installed X-haul topology over a Wavelength Division Multiplexing (WDM)-enabled topology which was implemented via WDM multiplexers/demultiplexers.

The remainder of the paper is structured as follows: Section II focuses on the converged fiber/FSO network topology deployed in the campus infrastructure and presents in detail the FSO system parameters and link budget calculations. Section III provides a detailed presentation for the experimental layout while section IV includes the obtained results from the different setup configurations. Finally, section V summarizes and concludes the manuscript.

II. Converged Fiber/FSO network topology & Link budget calculations

A. *Architecture Layout*

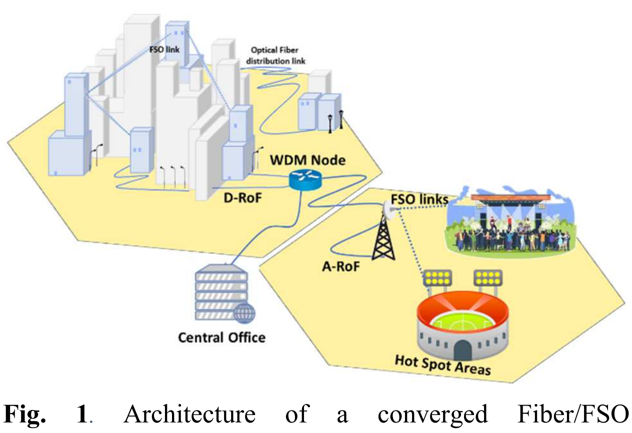

Fig. 1. Architecture of a converged Fiber/FSO infrastructure where D-RoF/A-RoF streams are multiplexed.

Fig. 1. showcases a cutting-edge multi-technology converged Fiber/FSO architecture, which utilizes flexible optical interconnections between various Mobile Network Operators, Distributed Units (DUs) and Centralized Units (CUs). The proposed architecture draws inspiration from the proven principles of Wavelength Division Multiplexing-Passive Optical Networks (WDM-PON) networking and strategically harnesses the potential of optical switching and wavelength aggregation units to optimize the transport segments of the RAN.

This approach capitalizes on the remarkable advantages of WDM nodes, including low-loss, protocol agnosticism, and Software-Defined Network (SDN) compatibility, to seamlessly aggregate disparate optical transmission schemes such as Digital/Analog Radio-over-Fiber (D-/ARoF) and various modulation formats. As a result, the architecture enables heterogeneous deployments, incorporating both fiber and converged Fiber/FSO lanes. This co-hosting capability facilitates the cooperative interaction of heterogeneous fronthaul segments and radio terminals. As a result, the envisioned AN ensures robust support for access connectivity requests with diverse KPIs. Moreover, it achieves enhanced capacity through the utilization of analog wired-wireless directional lanes, capitalizing on the exceptional bandwidth potential of FSO technology while simultaneously accommodating the legacy traffic. To realize this concept, the proposed hybrid optical RAN architecture facilitates dynamic interconnections between central offices and Remote Radio Heads (RRHs) via both digital and analog paths. An optical node employing SDN-compatible Wavelength Selective Switch (WSS) serves as a foundation for WDM and SDM functionalities, dynamically distributing the traffic. In particular, the architecture embraces the coexistence of two fronthaul implementations:

· Legacy DROF connectivity, where data transmission occurs through SFPs. The resulting data stream can be multiplexed with other network traffic, switched in Ethernet switches, and routed in IP routers, supporting technologies like LTE/4G and 5G.

· B5G A-IFoF implementations, which offer spectrally efficient transport schemes capable of supporting extremely high capacities, catering to the demands of next-generation wireless services.

B. *FSO Link modeling and characterisation*

An essential aspect of optimizing FSO technology lies in effective link modeling and characterization. This process involves creating a comprehensive mathematical model to estimate the loss in FSO link as a function of wireless distance. A systematic methodology for this estimation helps in understanding the behavior of the optical signal over different atmospheric conditions and distance parameters, thus providing crucial insights to enhance the overall efficiency of the system. Under this viewpoint, in what follows, we present a brief modeling approach for our FSO link. The overall channel loss A_{CH}, for the 50 m FSO link was modeled for the wavelength of 1550 nm as follows:

$$A_{ch} = A_A + A_{Geo} + A_C \qquad (1)$$

The channel absorption loss A_A(dB) for a link distance z depends on the absorption coefficient A(λ) for a specific wavelength λ and can be modeled as [13]:

$$A_A = 10 \cdot log_{10}\left(10^{-A(\lambda)\cdot z}\right) \qquad (2)$$

The geometrical loss A_{Geo} (dB) corresponds to the efficiency due to geometric characteristics of the receiver (i.e., Rx

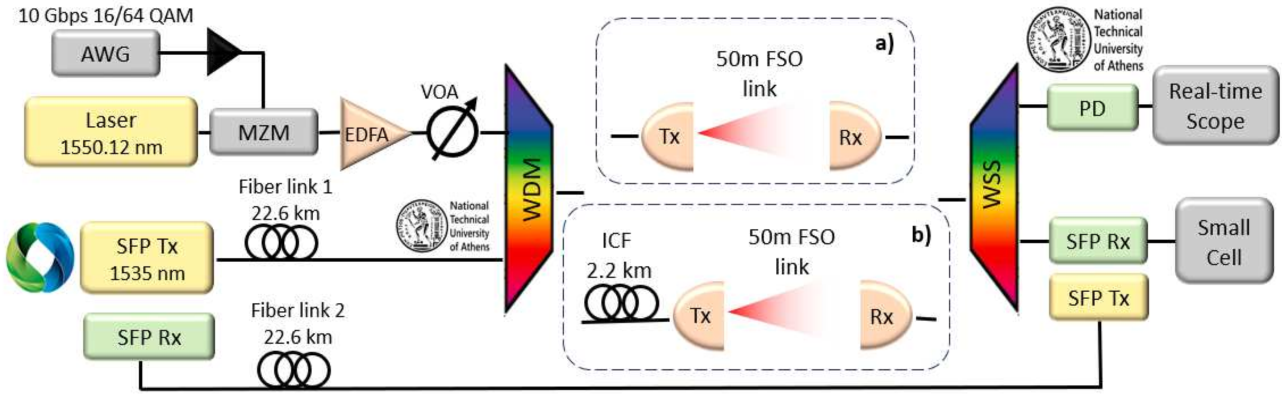

Fig. 2. Experimental setup of the co-propagation of the A-RoF and SFP data traffic over a) a 50 m FSO link and b) a converged 2.2 km intra campus fiber and a 50 m FSO link.

diameter which equals to 24 mm) whereas A_c refers to the Single Mode Fiber (SMF) coupling loss, namely the fraction of light coupled into the fiber with respect to the incident light on the Rx collimator. A_{Geo} can be calculated by the following equation [13]:

$$A_{Geo} = 10 \cdot log_{10}\left(\frac{D_{Rx}^2}{W(z)^2}\right) \qquad (3)$$

, where D_{Rx} is the receiver's aperture diameter and W(z) is the beam size at a distance z from the Tx aperture given by [9]:

$$W(z) = 2 \cdot w_0 + 2 \cdot z \cdot \tan(\theta/2) \qquad (4)$$

, where w_0 is the beam waist at the Tx aperture, $\theta = MFD/f$ is the full-angle beam divergence (in rad) and MFD denotes the Mode-Field-Diameter of an SMF, which is equal to 8 μm whereas *f* is the focal length of the receiving collimator which equals to 37.13 mm. Since the beam's spot size at 50 m was calculated to be smaller than the receiving aperture diameter (~20 mm), A_{Geo} was set to zero. The coupling loss A_c is a product of the A_{FC} and A_0. A_{FC} accounts for the effect of turbulence whereas A_0 accounts for the receiver's coupling characteristics. More specifically, A_{FC} is given by [13]:

$$A_{FC} = 10 \cdot log_{10}\left[1 + \gamma\left(\frac{D_r}{r_0}\right)^{5/3}\right]^{-\frac{6}{5}} \qquad (5)$$

, where r_0 is the Fried parameter and factor γ account the level for Adaptive Optics (AO) or tip tilt correction in the receiver subsystem (set to 1, 0.28, and 0 for no correction, tip tilt correction and full AO correction.) In our case since we applied no correction, we set γ equal to 1. To account for the optical efficiency and the focal length of the receiving collimator, the optical coupling efficiency A_0 is included as in [14].

$$A_0 = 10 \cdot log_{10}\left(2\left(\frac{e^{-\beta^2}}{\beta}\right)^2\right) \qquad (6)$$

with

$$\beta = \pi \frac{D_r}{4\lambda}\frac{MFD}{f} \qquad (7)$$

Since the FSO link is located in an indoor environment the value of Cn^2 has been set to a low value of $10^{-15}m^{-2/3}$, which is turn yields a low Fried parameter value according to [13]. Therefore, the value of A_{FC} is calculated to be negligible (~0.02 dB). On the contrary, the fiber coupling loss due to the geometry of the collimators is the main loss factor for the specific link, reaching a value of 5.3 dB. Therefore, the overall 50 m channel link loss is calculated to be 5.33 dB.

III. Experimental Layout

The overall experimental setup is depicted in Fig. 2. An Arbitrary Waveform Generator (AWG) was used to provide the QPSK, 16-QAM and 64-QAM modulated data signals, at symbol rates up to 4 GBd. The data signals were digitally up-converted at IF frequencies up to 4GHz prior to transmission through the AWG's DAC output. A tunable laser centered at 1550.12 nm was fed to a Mach Zehnder Modulator (MZM), which was responsible for the electro-optic conversion of the IF modulated data. The produced signal was amplified with the use of an Erbium-Doped Fiber Amplifier (EDFA) and

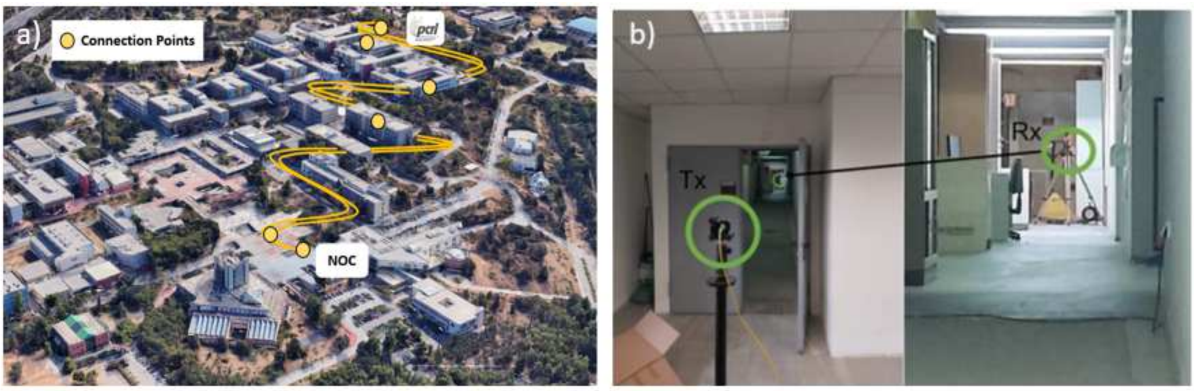

Fig.3. a) The 2.2 km deployed IC fiber loop over NTUA campus. b) Indoor 50 m FSO link

consequently attenuated by a Variable Optical Attenuator (VOA) enabling the precise control of the A-RoF signal's optical intensity. Concerning the 4G RAN architecture of the mobile infrastructure, COSMOTE (largest Greece's Network Operator) houses the Evolved Packet Core (EPC), while the mobile cell is hosted in National Technical University of Athens (NTUA) premises. These two components are interconnected using Small Form-factor Pluggable (SFP) transceivers (Metrodata GIG-E SM 80km) which emit a modulated signal at 1535 nm with an approximate power of +1.7 dBm. After the 22.6 km transmission over a deployed fiber across Athens (Fiber link 1 in Fig. 2), the received optical power of the downlink channel is measured to be -11.5 dBm at NTUA premises. The uplink channel is transmitted via a second separate 22.6km fiber connection link, as depicted in Fig. 2. At this point, the A-RoF signal was multiplexed with the SFP downlink signal using a low loss (Insertion Loss (IL) = 1.3 dB) two port WDM module centered at 1550.12 nm. For the de-multiplexing a Flexgrid WSS was used (IL = 3.5 dB) with 3x12.5 GHz (0.3 nm) spectral slices for each signal respectively. The A-RoF signal was then directed to a Photoreceiver, whereas the SFP downlink signal was connected to the Aruba SFP switch Rx connection, for the downlink EPC-small cell interconnection. The output of the photoreceiver was fed to a Real-Time Oscilloscope (RTO), where a Vector Signal Analyzer (VSA) software was used for signal retrieval.

In this setup the SFP downlink signal and the A-RoF signal co-propagated over a) over the 50 m FSO link or b) a 2.2 km installed Intra-Campus (IC) fiber interconnecting Photonic Communication Research Laboratory (PCRL) with the Network Operation Center of NTUA, followed by the 50 m free space transmission, as depicted in Fig. 2.

For the realization of the FSO connection two small-sized air-spaced doublet collimators with a numerical aperture of 24 mm were employed, dedicated for operation within the C-band. For the alignment of the 50 m FSO link, a beacon laser at 650 nm was used. The FSO link was set up in a long corridor, as depicted in Fig 3.b, which ensured the protection of the transmission from the outdoor environment. The minimum achieved overall loss of the FSO link was measured to be 5 dB, after proper manual tip-tilt adjustments, which includes the fiber patch cords connectors as well as the coupling loss of the collimator modules. This value strongly agrees with the expected values that were provided by the link modeling of the free space channel in Section II.B.

IV. Results and Discussion

Experimental studies on A-RoF over the deployed converge fiber-FSO transmission link were performed focusing on the modulation order of the IF signal. The goal of this study was to characterize the effect of the optical-wireless channel in case that the radio signal characteristics vary. Besides, leveraging from the (Digital Signal Processing (DSP) capabilities for generating any complex modulation scheme at the transmitter side, the feasibility of increased spectrum utilization was also demonstrated. Fig. 4 shows EVM measurements and the corresponding constellation diagrams after signal detection, for QPSK, 16-QAM and 64-QAM schemes. It is shown that generating different types of complex waveforms carrying symbols rates of 2 GBd, EVM values well below the limits set by 3GPP specification were achieved [15] (with a minimum EVM margin of 8% for 64-QAM signals) for each format investigated, employing a standard 21-tap equalizer at the receiver side that was available through the VSA software. In all cases the same equalizer was used, without the need for reconfiguration of its taps for processing of the different formats. Furthermore, the impact of the deployed link's optical loss budget on the reception quality was investigated. For this test, the employed modulation scheme was 16-QAM, which is more efficient than the QPSK one and at the same time more robust, compared to the 64-QAM case, and the symbol rate was extended to 4 GBd, corresponding to bit rate of 16Gbps. More specifically, Fig. 5 presents the EVM measurements that were obtained after using a VOA, to reduce the optical power at the input of the photoreceiver. The received EVM performance indicates successful signal retrieval for optical power levels above -15.5 dBm and marginal signal performance for -18.5 dBm optical power.

The next evaluation step involves the increase of the overall bandwidth utilization for the proposed A-RoF concept

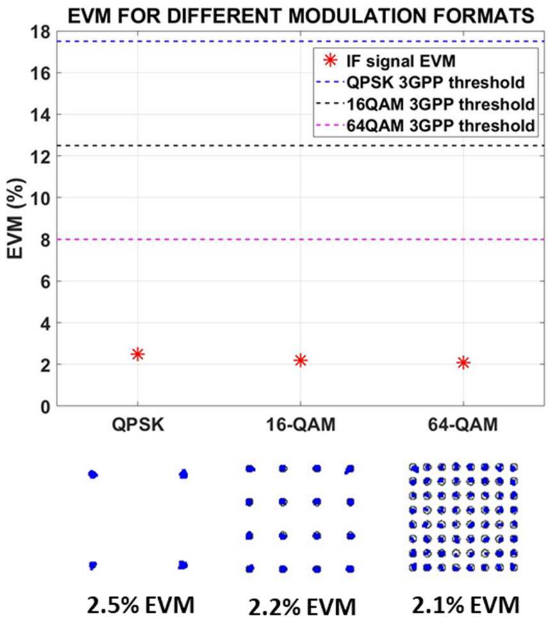

Fig. 4. Constellation diagrams and EVM measurements of the received signals at different modulation schemes.

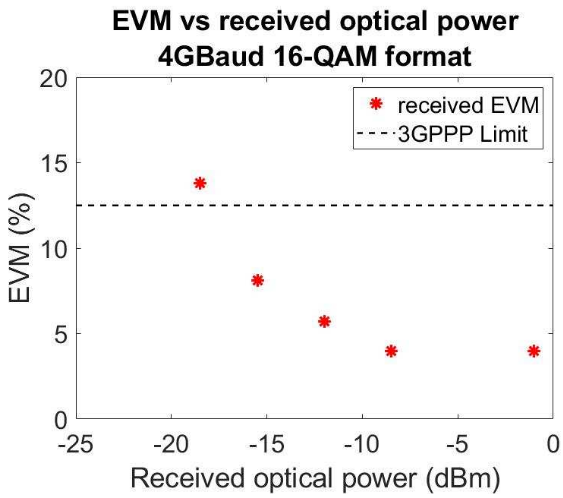

Fig. 5. EVM measurements after reducing the received optical power, in case of 16-QAM scheme transmission with 4 GBd symbol rate.

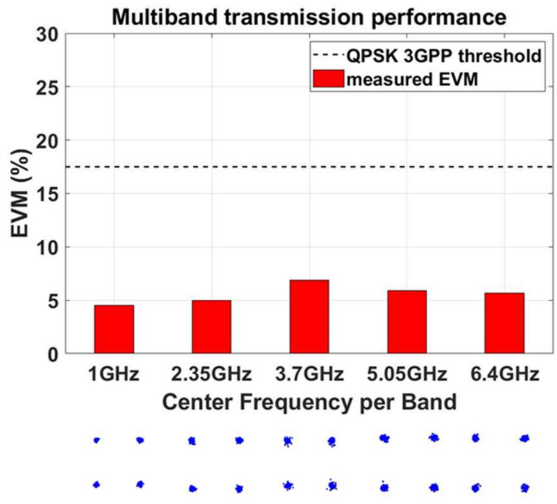

Fig. 6. EVM measurements and constellation diagrams for each sub-band of the 5-Band A-RoF link.

by introducing a digitally generated SCM signal to extend the operating bandwidth of the single carrier approach. Exploiting once more the DSP capabilities on generation of complex waveforms, five different subcarriers have been digitally synthesized, in order to generate the desired multiband radio signal. The 5 sub-bands were assigned at 1 GHz, 2.35 GHz, 3.7 GHz, 5.05 GHz and 6.4 GHz center frequencies and each of them was modulated at 1 GBd symbol rate, pulse-shaped with a root raised cosine filter ($\alpha = 0.35$), utilizing thereby a total 6.75 GHz bandwidth. Fig. 6. shows that all sub-bands have a similar EVM performance, while the central sub-band showcases maximum performance degradation with an EVM of 6.9%. Given that A-RoF scheme is highly susceptible to nonlinearities related to active RF and electro-optic units of the setup, the performance degradation of the central band may be owed to power leakage of the neighboring bands. In all cases, with EVM values below 6.9%, all QPSK, 16-QAM and 64-QAM schemes have the potential to achieve accepted performance in all the allocated spectrum bands [16].

Aside from the physical layer performance metrics of the optical-wireless link, the capability of the proposed layout to be integrated in an inhomogeneous testbed, co-supporting legacy mobile equipment was assessed. To this end, access to real-world legacy through the SFP traffic lane of the employed setup was also showcased. Specifically, Mobile User Equipment (MUE) was used to perform Iperf measurements, using Transmission Control Protocol (TCP) traffic, exhibiting 100Mbps stable connectivity. On top of that, 4K online video streaming, uninterrupted live IP-video teleconferences and web browsing were successfully demonstrated.

V. Conclusion

This paper demonstrates the experimental feasibility of analog RoF systems over converged fiber/FSO links for X-haul connectivity in the beyond 5G and 6G era. An experimental campaign of analog RoF transmission of diverse waveforms, including QPSK, 16-QAM, and 64-QAM, over hybrid fiber/FSO scenarios has been successfully conducted at NTUA premises, achieving acceptable EVM values below 3GPP specifications. The impact of optical loss on reception quality is explored, and the potential of digitally generated SCM signals to increase overall bandwidth utilization is demonstrated. This work contributes to the advancement of flexible and high-capacity X-haul transport networks, showcasing the potential of FSO communications in meeting future connectivity demands.

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