Wired and Wireless Convergence in Future Optical Access Networks – *Invited*

Colm Browning
School of Electronic Engineering, Dublin City University, Dublin D09W6Y4, Ireland
Email: colm.browning@dcu.ie

***Abstract*—This paper reviews recent experimental demonstrations of microwave and millimeter-wave analog radio-over-fiber fronthaul, enabled through network convergence with future optical access technologies.**

Keywords—Network Convergence, Radio-over-Fiber, Fronthaul, Optical Access, 5G, Millimeter-Wave

I. INTRODUCTION

How our society interacts with the internet, is evolving rapidly. Not only is it necessary to greatly increase future network speeds, but the unprecedented levels of flexibility required will entail a complete shift in the make-up of Radio Access Networks (RAN) [1]. Meeting the capacities envisioned for 5G communications, and beyond, will involve vastly increasing the number of mobile Base-Stations (BS), and Ultra Dense (UD) antenna deployment for a given area [2]. A centralized/cloud RAN (C-RAN), whereby consolidated network hardware is connected to remote radio units through fiber links, can help to facilitate the level of antenna distribution and dynamic resource allocation envisaged. From an optical networking point of view, a move toward such a distributive architecture brings into play a number of important system-level considerations.

Firstly, C-RANs will place a high level of importance on the fixed/optical portion of the network in order to provide x-haul (fronthaul, crosshaul and backhaul) of wireless signals between the various RAN elements. These links will be required to provide high capacity, low latency and - in order to facilitate efficient and reconfigurable networking functionality - some level of flexibility in the optical domain. Currently, connections between the Central Office (CO) a distributed antenna site consist of a propriety optical fiber link which spans just a few kilometers. Clearly, a more intelligent and efficient approach, in line with recent developments in optical short reach and access networking, would be highly beneficial for the future scaling of C-RAN.

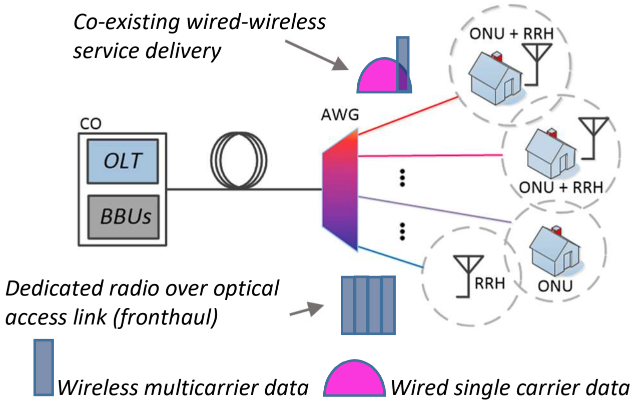

Fig. 1: Optical Access topology showing wired-wireless convergence including service co-existence. An Arrayed Waveguide Grating (AWG) is included for WDM functionality

Secondly, when designing the optical fronthaul portion of the C-RAN, i.e. the optical link between the centralized Baseband Unit (BBU) and Remote Radio Head (RRH), careful consideration must be given to the adopted functional split. This defines the demarcation point between centralized and distributed processing/hardware and has a substantial impact on fronthaul bandwidth requirements [3]. Today, optical fronthaul involves the transmission of wireless signals which have been de-modulated into sets of baseband binary IQ data. Although this technology, known generically as Digital Radio-over-Fiber (D-RoF), is mature, its requirement for binary level transmission and Analog-to-Digital Converters (ADC) at each RRH means that (in its current form) it will become unsustainable as the network scales in terms of data rate and number of users.

To address the aforementioned challenges, the recent works described in this paper focus on the *convergence* of analog wireless fronthaul links with optical access technologies used to provide wired broadband services. This allows Wavelength Division Multiplexing (WDM) functionality, and the inherent distributive nature of optical access networks, to be harnessed.

The concept of wired and wireless convergence in the optical domain extends to both (i) the use of (a portion of) access infrastructure dedicated solely for wireless service delivery, and (ii), the *co-existence* of various wired/wireless services over the same shared access transmission paths. Fig. 1 shows a converged WDM Passive Optical Network (PON)/RAN topology with the wired service Optical Line Terminal (OLT) and wireless service BBUs co-located at the CO. The network shows distributed fiber connections to (co-located) local area Optical Networking Units (ONUs) and RRHs, with figurative spectra illustrating wired-wireless co-existence, and dedicated RoF transmission provisioned through WDM.

II. EXPERIMENTAL DEMONSTRATIONS AND DISCUSSION

Wired and Wireless Co-Existence

Pulse Amplitude Modulation (PAM) is the leading candidate modulation format for future PONs employing advanced modulation – due to its relatively low complexity and compatibility with legacy PON [4]. Wired-Wireless co-existence in a PON employing 10 Gb/s/λ PAM-4 for downstream transmission is investigated in [5]. The 5.5 Gbaud single carrier PAM-4 signal is digitally combined with three bands of 0.6 Gb/s A-RoF multicarrier signals which are mixed to an Intermediate Frequency (IF) close to the spectral null between the PAM signal's main and side lobes (as shown in the inset of Fig. 2). This converged signal is transmitted through a 25 km PON transmission test-bed using Intensity Modulation and Direct Detection (IM/DD). Performances are evaluated where Orthogonal Frequency Division Multiplexing (OFDM), as well as future 5G candidate

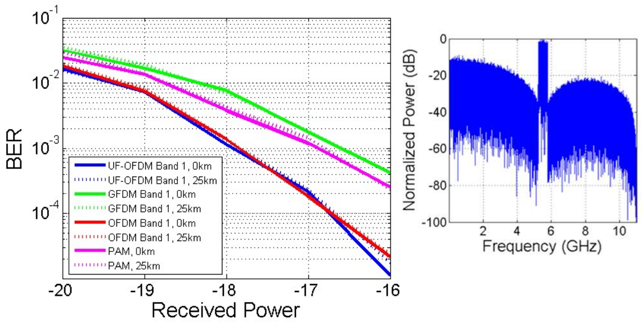

Fig. 2: BER versus received optical power [5] for converged PAM and 5G wireless. Inset shows example wired -wireless converged spectrum.

waveforms Universally Filtered OFDM (UF-OFDM) and Generalized Frequency Division Multiplexing (GFDM), are transmitted in tandem with the wired broadband PAM signal. Fig 2. Shows performance in terms of Bit Error Rate (BER) as a function of received optical power, indicating that sufficient performance can be achieved for the wired service as well as all transmitted A-RoF multicarrier signals. UF-OFDM displays a similar performance to that of OFDM when a guard band equal to 10% of the total wireless channel bandwidth is used between A-RoF channels. With UF-OFDM, this level of performance is maintained as the guard band is reduced to 3% [5]. This is due to UF-OFDM's low Out-of-Band (OOB) emission – making it an excellent candidate for accommodating co-existing wired and wireless data flows in future access networks.

Millimeter-Wave over Optical Access

The use of millimeter-wave (mm-wave) frequencies (30-300 GHz) for high speed wireless transmission is viewed as a key enabling technology for 5G communications and beyond [6]. The difficulty and expense associated with generating these frequencies by electronic means has led to the re-emergence of alternative photonic techniques (e.g. remote optical heterodyning) which are inherently compatible with optical distribution networks such as WDM-PON. Fig. 3(a) shows an example access topology whereby two optical carriers, spaced by the desired mm-wave frequency, are provisioned at the CO. One of these carriers is then modulated with wireless service data and the combined optical signal is transited through 25 km of fiber. A Reconfigurable AWG (R-AWG), or Wavelength Selective Switch (WSS), situated at a remote node is then used to route both carriers, through one of its output ports, to a distributed RHH containing a high speed Photodetector (PD). The unmodulated carrier and data sideband undergo heterodyning (photo-mixing) at the PD to produce a copy of the data signal at the mm-wave frequency. This signal is then amplified and can be fed to an antenna (array) for wireless transmission.

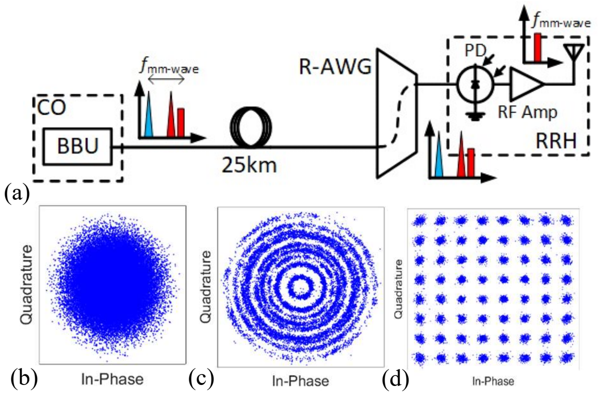

Fig. 3: (a) shows an example flexible PON topology facilitating remote mm-wave generation. Also shown are received 60 GHz OFDM constellations without compensation (b), with FO compensation (c) and with PN and FO compensation (d).

Such a system has been investigated in [7,8] where the advantages of high spectral efficiency and reduced RRH complexity associated with A-RoF is exploited in a 60 GHz mm-wave-over-access system. Where correlated optical sources (such as an optical frequency comb) are used, results in [7] shows that the level of correlation between the optical carriers at the receiver is a performance limiting factor. This ultimately places strict criteria on source linewidth and places a lower bound on the A-RoF subcarrier baud rate.

The use of independent (i.e. un-correlated) laser sources is possible, but introduces the necessity for very low (kHz level) linewidths and the complication of Frequency Offset (FO) between the optical carriers. In this scenario, [8] demonstrates how the incorporation of training sequences and pilot symbols enables the use of receiver Digital Signal Processing (DSP) to successfully track and compensate Phase Noise (PN) and FOs over values up to 70% of the channel bandwidth. Figs. 3 (b-d) show the received mm-wave OFDM constellations with/without digital compensation.

Provided the necessary signal and source requirements are fulfilled, the experimental demonstrations show that the converged A-RoF mm-wave/access systems exhibit excellent performances of ~5% error vector magnitude in the cases where correlated [7], and independent [8], sources are used.

III. CONCLUSION

Connectivity and network flexibility are critical issues for future mobile transport. High bandwidth wireless x-haul can be provided through optical networking by converging RAN and PON services and infrastructure; with flexibility offered in the optical domain through WDM access. The demonstrations discussed show successful transmission of converged A-RoF, indicating that these systems can aid the wide deployment of both microwave and millimetre-wave functionality for future high speed mobile networks.

ACKNOWLEDGMENT

This work has emanated from research supported by a research grant from Science Foundation Ireland (SFI) and is co-funded under the European Regional Development Fund under grant numbers 18/SIRG/5579 and 13/RC/2077. The author would like to acknowledge the contributions of Prof. Liam Barry, Amol Delmade and Dr. Arman Farhang.

REFERENCES

[1] J. G. Andrews et al., "What will 5g be?" IEEE Jnl. Sel. Areas in Commun., vol. 32, no. 6, pp. 1065–1082

[2] M. Agiwal *et al*., "Next generation 5g wireless networks: A comprehensive survey," Commun. Sur. Tuts., 18 (3), pp. 1617–1655, 2016.

[3] D. Harutyunyan and R. Riggio, "Flex5G: Flexible Functional Split in 5G Networks," in Trans. Netw. Service Manag., 15 (3), pp. 961-975, 2018

[4] X. Hu *et al*., "Converged mobile fronthaul and passive optical network based on hybrid analog-digital transmission scheme," OFC, Anaheim, 2016

[5] C. Browning *et al*., "5G wireless and wired convergence in a passive optical network using UF-OFDM and GFDM," ICC Workshops, Paris, pp. 386-392, 2017

[6] M. Xiao *et al*., "Millimeter wave communications for future mobile networks," J. Sel. Areas Commun., 35, (9), pp. 1909–1935, 2017

[7] C. Browning *et al*., "Gain-Switched Optical Frequency Combs for Future Mobile Radio-Over-Fiber Millimeter-Wave Systems," in J. Lightw. Technol., 36 (19), pp. 4602-4610, 2018

[8] A. Delmade *et al*. "Digital frequency/phase offset correction for 60 GHz OFDM radio-over-fibre with unlocked fibre lasers," Accepted for presentation at ECOC 2019