Role of Analogue Radio-over-Fibre Technology Beyond 5G

Liam P. Barry*, Amol Delmade, Devika Dass and Colm Browning
School of Electronic Engineering, Dublin City University, Glasnevin, Dublin D09W6Y4, Ireland
*liam.barry@dcu.ie

Abstract: Photonics-based mm-wave communication systems employing optical heterodyning can enable high-capacity wireless networks for systems beyond 5G. This work presents photonic, optoelectronic and signal processing technologies to overcome phase/frequency noise issues associated with photonics-based mm-wave systems.

OCIS codes: (060.4510) Optical communications; (060.5625) Radio frequency photonics.

1. Introduction

The requirement for new wireless network technologies which can provide increasing bandwidths, stems from the advent of many data hungry applications such as virtual reality (VR), live ultra-high definition (UHD) video streaming and autonomous driving [1]. The move towards 5th Generation (5G) mobile communication networks promises to provide data rates up to 10 Gb/s by using techniques such as higher-order modulation formats, massive multiple-input multiple-output (MIMO) antenna technology and wide channel bandwidth (BW), in conjunction with a centralized radio access network (C-RAN) architecture (Fig. 1). C-RAN simplifies the antenna site by moving the constituent parts of the baseband processing unit (BBU), i.e., the Central Unit (CU) and Distributed Unit (DU), to a centralized location, and using an optical fiber based fronthaul link for the connection to the antenna site Remote Unit (RU) [2]. The fiber link can employ either digital radio-over-fiber (DRoF) or analog radio-over-fiber (ARoF) approach, with ARoF technology having characteristics that make it suitable for specific applications in beyond 5G wireless systems, namely that it retains the inherent bandwidth efficiency of wireless signals over the fronthaul link and simplifies the RU site architecture by avoiding the use of expensive analog-to-digital (A/D) and digital-to-analog (D/A) converters [3]. However, ARoF systems do require higher SNR and linearity specifications in comparison to DRoF systems.

As outlined earlier, wider channel bandwidths are also imperative to increase capacity in future wireless systems, however, their allocation may be very challenging given the current spectral scarcity in wireless networks. This has led to the emergence of millimeter-wave (mm-wave) communications [4]- which can facilitate wider channel bandwidths by moving the carrier to the 30–300 GHz frequency band - as a key enabling technology for future wireless systems. The higher losses associated with wireless propagation of mm-wave carriers will result in the need for ultra-dense (UD) deployment of the RUs; requiring spectrum and cost-efficient fronthaul links for data delivery to and from these antenna sites over optical fiber. These requirements strengthen the case for a migration to an ARoF approach in future RANs. In this paper we will describe ARoF and its role in providing an efficient optical fronthaul solution for future high speed mobile access communications, and then focus on issues concerning the practical generation/distribution of mm-wave signals based on optical heterodyning.

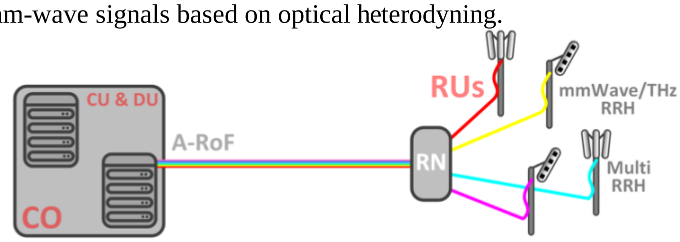

Fig. 1 Centralized radio access network (C-RAN) architecture using ARoF for fronthaul transmission from CO to RU

2. Analog Radio-over-Fiber

Analog radio-over-fiber schemes transmit RF data signals over fiber, in their native analog form, after modulation onto an optical carrier. This increases the bandwidth efficiency and reduces the latency in wireless networks by avoiding the use of A/D and D/A converters at the RU. Typically, ARoF system demonstrations require optical components that work at the bandwidths of the carrier frequencies and involve direct or external modulation of a single mode laser with the RF data signal. Direct/external laser modulation becomes challenging as wireless systems move to the mm-wave or sub-THz bands. To overcome these issues, optical heterodyning, wherein two optical carriers with a desired mm-wave frequency difference beat on a high-speed photodetector (PD), provides a promising solution for the generation/distribution of such mm-wave carriers. This technology is also compatible with the C-RAN architecture that employs optical links for fronthaul transmission. In the optical heterodyning scenario, the RF data signal is initially modulated onto an optical carrier at a lower intermediate frequency (IF), suitable for direct/external laser modulation, before being coupled together with a CW laser source. The CW laser operates at the specific frequency to generate the required mm-wave RF signal after beating of the modulated optical signal and CW signal on a high speed photodiode at the RU. By tuning the frequency separation between the unmodulated and modulated optical carrier it is possible to generate RF signals from 10s to 100s of GHz, and a number of photodiode technologies that can operate in these systems have been proposed and demonstrated over the past decade [5]. In terms of the optical sources employed, an important operating principle in heterodyne systems is that, for independent sources, the phase noise (PN) and frequency fluctuations of the generated RF beat signal will be determined by the sum of the PN and frequency fluctuations of the individual optical sources. If we consider the use of commercial tuneable lasers currently employed in coherent transmission systems, for heterodyne ARoF systems, this would result in RF carriers with linewidths in the order of 100’s of kHz and frequency offset (FO) fluctuations of 10’s of MHz. These phase and frequency fluctuations can be extremely problematic for systems employing A-RoF transmission. In particular, these issues become highly exacerbated when considering the ARoF transport of the multi-carrier signals synonymous with 5G (and potentially beyond 5G) such as orthogonal frequency division multiplexing (OFDM), given their kHz-level subcarrier spacing (requiring low phase noise) and strictly defined RF channel bandwidths (requiring very stable operating RF frequency). To overcome these limitations, we can consider the use of advanced optical, optoelectronic and digital processing technologies to facilitate the use of ARoF in 5G and beyond 5G wireless systems.

3. Phase noise and frequency offset issues in ARoF systems

As outlined above, the use of independent discrete laser sources for optical heterodyning in ARoF system results in significant PN and FO fluctuation on the generated RF signal. One approach to significantly reduce the relative frequency variations between the independent laser sources (and ensure a stable RF beat signal) is to integrate two tunable lasers in a single photonic integrated circuit (PIC) that is temperature controlled with a single thermoelectric cooler (TEC). To overcome *both* PN and FO fluctuations issues simultaneously, it is necessary to employ techniques such as the use of an optical frequency comb (OFC) source [6] or optical phase/injection locked sources [7] to correlate the frequency and phase fluctuations of the beating optical carriers. These techniques ensure that stable, low phase noise RF signals are generated; providing the spectral purity to enable the transmission of multi-carrier mobile signals with subcarrier baud rates down to the kHz range (as currently specified in the 5G New Radio (NR) standards).

To demonstrate the PN and FO issues that occur when different optical sources are employed in a heterodyne ARoF system, we have measured the RF beat spectra using discrete fiber laser and external cavity laser (ECL) sources, an integrated dual laser source [8] and a gain switched laser source [6]. For this work we set the spacing between the two optical lines from the various sources to be 48 GHz so the spectrum analyzer could characterize the beat signal without the need for frequency downconverters, but the results are independent of the frequency spacing. As we can see in Fig. 2 (a), when using two discrete ECLs and the two carriers from an integrated dual laser source, the RF beat signals have linewidths around 80 kHz and 34 kHz, respectively, corresponding to optical linewidths of ~40 kHz for the ECL and ~17 kHz for the dual laser source. When using fiber lasers, the RF linewidth is around 2 kHz as these sources have optical linewidths of ~1 kHz. When selecting two lines from the gain-switched laser the RF linewidth is

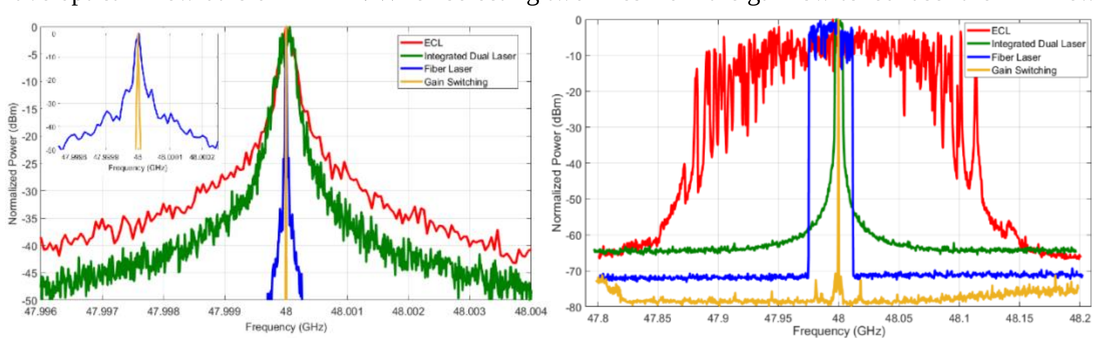

Fig. 2 (a) RF spectra of beat signal using various optical sources for signal generation round 48 GHz (b) RF spectra taken with maximum hold on spectrum analyzer demonstrating large frequency offset fluctuation with discrete sources.

several Hz, even though the optical linewidths are 10’s of MHz. This is because the optical lines have correlated phase noise after being generated in the same laser active region through the gain-switching process. Fig. 2(b) presents the frequency offset fluctuation results and here it is observed that the use of the discrete sources results in very large FO, 250 MHz and 70 MHz, respectively, which is clearly problematic in the context of provisioning multi-carrier mobile signals over a mm-wave/THz enabled C-RAN. The use of single TEC with the integrated dual laser source keeps the frequency fluctuations to several MHz, while the gain switched source enables frequency fluctuations of several Hz.

The results reveal how the laser sources used in a hybrid RoF system employing optical heterodyning determine the quality of the RF signal generated. This can be a limiting factor setting an upper bound on the modulation order deployed and hence the overall achievable capacity. To alleviate these limitations, and achieve enhanced system performance, we have developed both digital and analogue signal processing techniques to overcome some of the PN and FO issues presented. The analog mm-wave receiver approach uses the photo-generated RF carrier itself for frequency down-conversion of the signal, requiring the transmission of both mm-wave signal and a carrier (pilot tone) over the wireless channel. The demonstration of this technique was investigated employing discrete tunable ECLs as presented in Fig. 3 [9], with the PN and FO issues discussed earlier. The photo-mixing, at the RU site, generates electronic copies of a mm-wave OFDM data signal at F_S = 61 GHz and a mm-wave carrier at F_C = 56 GHz. The frequency drift of the free running ECLs will result in the equal amount of frequency shift (say δF) in both F_C ($F_C \pm \delta F$) and F_S ($F_S \pm \delta F$), after the photo-detection. The frequency shift, δF, changes over time, but the difference between F_S and F_C will remain constant at the intermediate frequency, F_{IF}, eventually making the system agnostic to the laser frequency drift and phase noise, as presented in [9]. As an alternative to this analog receiver, we have also developed a DSP based A-RoF scheme that employs existing Schmidl and Cox (S&C) and decision directed least mean square (DD-LMS) algorithms, implemented digitally, to overcome FO & PN from the laser heterodyne process [3].

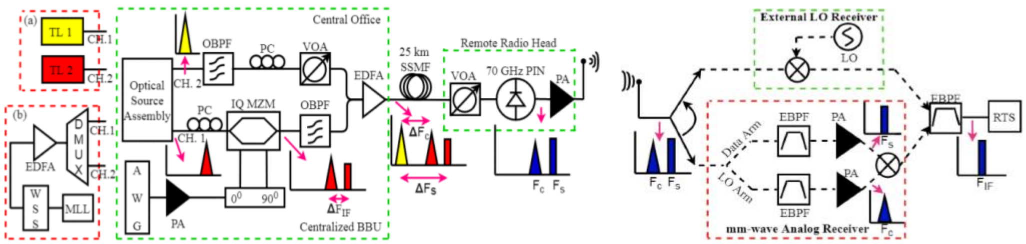

Fig. 3 Experimental setup used to investigate the performance of different optical sources in a heterodyne based ARoF fronthaul system (operating at 60GHz). Receiver side presents standard RF receiver (green box) and mm-wave analog receiver (red box).

Further simplification and enhanced performance of the ARoF system presented in Fig. 3 can be achieved by employing correlated optical carriers, potentially from an OFC such as a gain-switched source, which can ensure PN and FO comparable to RF synthesizers. In previous work we have demonstrated different methods to generate gain switched OFCs with varying bandwidths and free spectral ranges for different applications, novel technologies to simply the filtering and modulation of the comb lines for ARoF transmission systems [10] and the use of innovative waveforms that enhance system performance [6].

4. Conclusion

ARoF links based on optical heterodyning provide an efficient platform for the generation and distribution of mm-wave signals for high-capacity wireless systems. To facilitate the wide deployment of such fiber-wireless systems, techniques which ease restrictions on relative frequency drift and phase offset between the optical carriers, with minimal additional complexity, are required. In general, the optical heterodyne ARoF systems employing correlated lines from an OFC can generate a wide range of frequency stable mm-wave carriers from a single device resulting in a simple receiver architecture with reduced DSP requirements, but potentially at the expense of increased optical source complexity. Scaling up the DSP to include PN and FO compensation, or incorporating more complex electronic receiver architectures, enables the deployment of mm-wave A-RoF systems which can make use of two independent commercially available lasers. The combination of optical source and signal processing used will ultimately depend on the specific application for which the mm-wave A-RoF system will be deployed.

Acknowledgment

This work has emanated from research supported in part by a research grants 18/EPSRC/3591, 18/SIRG/5579, 13/RC/2077, 12/RC/2276_P2 from Science Foundation Ireland (SFI); co-funded under the European Regional Development Fund.

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