28 GHz 5G Radio over Fibre using UF-OFDM with Optical Heterodyning

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***Abstract*—A 5G millimeter-wave radio over fibre optical fronthaul system based on optical heterodyning, utilising an externally injected gain switched distributed feedback laser, is successfully demonstrated. Five bands of UF-OFDM are transmitted over 25 km of fibre and a 28 GHz Vivaldi Antenna wireless link. Transmission performance below the 7% FEC limit is achieved with an aggregate total data rate of 4.56 Gb/s.**

I. Introduction

While 3G and 4G communication systems largely focused on an increase in network speeds, it has been proposed that the next generation of wireless systems (5G) will entail a complete shift in the architecture of mobile networks.

In order to facilitate ultra dense antenna deployment and to increase the centralisation of resources, the use of cloud radio access networking (C-RAN) has been proposed. Additionally, carriers in the millimeter wave (mmWave) range (28-300 GHz), where the available spectrum is plentiful, are envisioned as a means to provide high data rates to an increasing number of connected wireless devices [1]. In particular, the 28 GHz band is seen as the leading mmWave band for 5G, where some US license holders already have up to 850 MHz spectrum [2] [3].

Due to the expensive nature and complexity of generating mmWave signals using electronic components, photonic techniques to produce mmWave signals while facilitating the convergence with the optical access infrastructure have garnered much interest [4]. Radio over fibre (RoF) is of significant interest to extend the transmission distance utilising optical fibre, while concurrently benefitting from its inherent advantages, including large bandwidth and low loss. RoF allows for the centralisation of the photonic hardware while simplifying the small cell remote radio head (RRH) design. The optical link between the centralised mmWave baseband units (BBU) and the simplified RRH is known as the fronthaul.

Universally filtered orthogonal frequency division multiplexing (UF-OFDM) is an 'OFDM inspired' candidate waveform for 5G whose sub-band filtering offers increased tolerance to timing and frequency synchronisation errors and extremely low out of band emission, which is common among other 5G candidate waveforms, compared to OFDM [5]. This allows for an increase in spectral efficiency in multiband systems. Practical 5G systems will employ multicarrier transmission with subcarrier spacings in the 100's of kHz to MHz range, placing constraints on the phase noise of the RF carrier.

A number of mmWave bands such as 28 to 30 GHz, the WiGig band at 60 GHZ, and the E-band at 71 to 76 GHz, 81 to 86 GHz, and 92 to 95 GHz are known to be promising for deployment [6]. In this paper, we focus on RoF transmission over the 28 GHz band. Transmission of five bands of UF-OFDM over 25 km of fibre and a Vivaldi antenna wireless link is successfully demonstrated based on the the aforementioned optical heterodyning technique. Performance levels below the 7% forward error correction limit are achieved for all five 5G mmWave bands with error vector magnitudes (EVM) of <8%.

II. Optical Heterodyne for mmWave RoF

Many methods for the generation of low noise mmWave signals have been researched. Mode locked lasers (MLL) can be used to generate an OFC to provide two comb lines for coherent heterodyning in order to generate low phase noise mmWave signals. However, MLLs suffer cavity complexity and, as a result of a fixed cavity length, they lack tunable free spectral range (FSR). Also, there can be significant phase noise due to imperfect phase coherence of the optical tones as the optical linewidth of individual comb lines may be relatively large [7]. It is possible to generate a wavelength tunable comb which possesses variable FSR using either a single modulator [8] or multiple cascaded external modulators [9]. However, bias drift and the requirement to overcome poor modulation efficiency and insertion loss of the modulators results in a set up which can can be complex and difficult to implement due to instability. Tunable FSR can also be achieved through the beating of two independent lasers. Two 100 kHz external cavity lasers (ECL) to generate a relatively low level of phase noise on the RF signal allowing for the successful transmission of 10 GBaud 64-quadrature amplitude modulation (QAM) have been used in [10]. However, mobile data formats typically exhibit low subcarrier baud rates. This reduces the phase noise tolerance and restricts laser linewidths (potentially to sub-

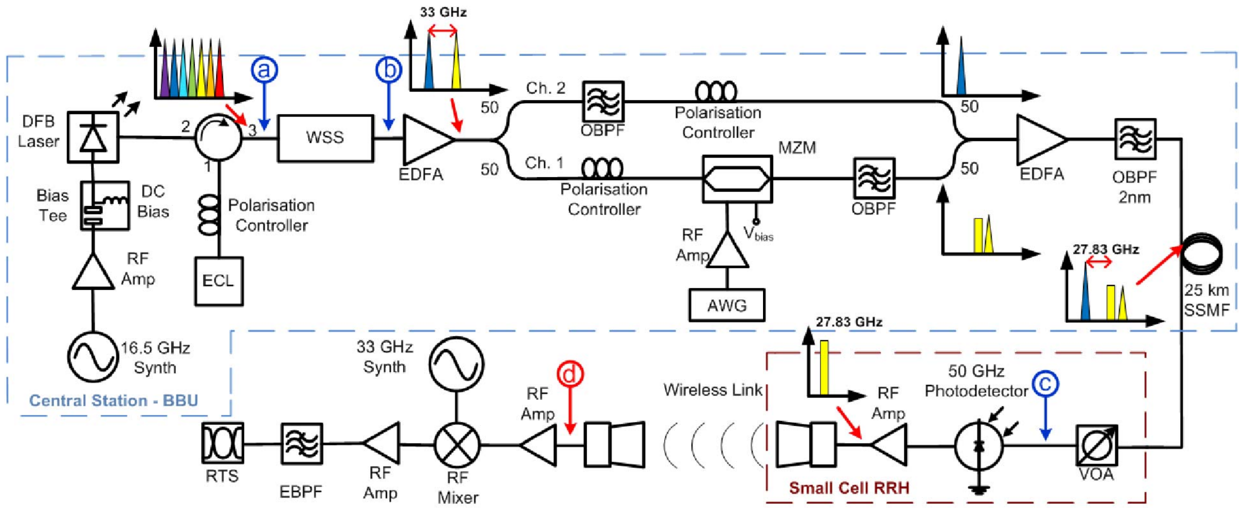

Fig. 1. 5G mmWave fronthaul experimental setup based on an externally injected gain switched DFB laser.

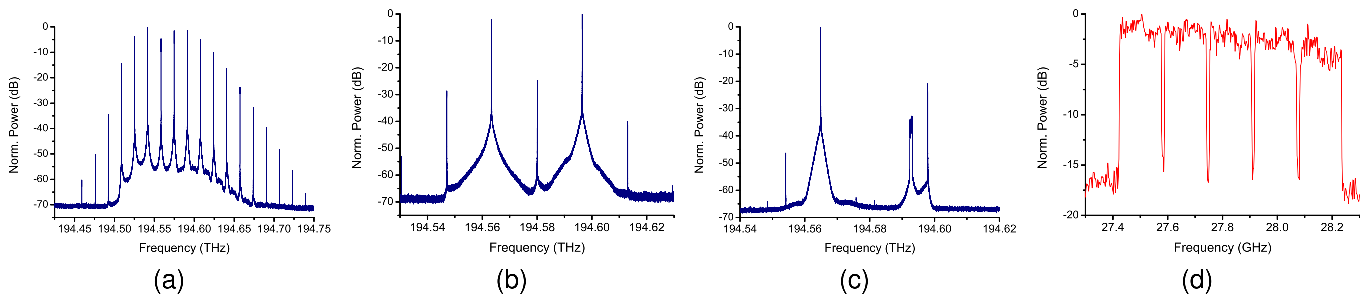

Fig. 2. Optical spectra: (a) optical frequency comb; (b) filtered comb lines separated by 33 GHz; (c) re-coupled channels subsequent to the modulation of Channel 2. Electrical spectra: (d) received 28 GHz UF-OFDM data after wireless transmission.

kHz levels) rendering this technique difficult and costly to implement.

In this paper, a 28 GHz 5G RoF system based on an OFC generated by an externally injected gain switched distributed feedback (DFB) laser is proposed [11]. This technique offers a flexible FSR as well as tunable wavelength and excellent signal to noise ratio (SNR). The tunability of the wavelength and the flexibility of the FSR allows for the reconfigurable generation of data signals across the mmWave range without the need for system upheaval and costly electronics.

Externally injecting the gain switched DFB laser with a low linewidth laser significantly reduces the phase noise of the comb source. Such a highly coherent low linewidth OFC renders a higher tolerance to the time delay induced between the two tones after fibre propagation thereby resulting in negligible phase noise on the resultant mmWave signal [12]. These factors result in a stable, cost efficient and highly effective system for 5G mmWave fronthaul.

III. Experimental Setup

The experimental setup, with figurative spectral representations, illustrated in Fig. 1 is used to achieve transmission of five 5G bands of UF-OFDM on a mmWave signal over 25 km of fibre and a Vivaldi Antenna wireless link utilising a gain switched DFB laser with external injection [11] [4]. The DFB slave laser is gain switched using a 16.5 GHz sinusoidal RF signal with an amplified RF power of 15 dBm. The DFB slave laser is externally injected using an ECL, with a linewidth of 100 kHz, and the master laser is tuned to match the wavelength of the slave laser. A polarisation controller is used to match the polarisation of the master laser to that of the slave laser. This generates an OFC with an FSR of 16.5 GHz, the spectral output which is shown in Fig. 2 (point (a) in Fig. 1).

TABLE I
UF-OFDM Transmission Parameters.

Bandwidth	152 MHz
Subcarriers	312
Modulation	64 QAM
Data rate	0.912 Gb/s
Subcarrier baud-rate	487 kBaud
Channel guard band	15 MHz

All but two tones separated by 33 GHz are suppressed using a wavelength selective switch (WSS), Fig. 2b (point (b) in Fig. 1). An Eribum doped fibre amplifier (EDFA) is used before the optical paths are split to amplify the two tones. The optical tone in channel 1 (Ch. 1) is externally modulated with a Mach-Zehnder modulator (MZM). Five bands of UF-OFDM were generated digitally and output from a single arbitrary waveform generator (AWG) operating at 20 GSa/s. The data is amplified before being fed into the MZM. Each individual band is comprised of a 152 MHz bandwidth, 312 subcarriers with 64 QAM format on each subcarrier, a subcarrier baud rate of 487 kBaud and a total data rate of 0.912 Gb/s. A guard band of 15 MHz is placed between the wireless channels. These transmission parameters are summarised in Tab. I. The RF center frequency of this block of 5G bands is 5.168 GHz and the aggregate net data rate is 4.56 Gb/s. The output from the MZM consists of the optical carrier and two sidebands which contain the five 5G bands. This signal is then passed through an an optical bandpass filter (OBPF) in order to suppress unwanted neighbouring tones from the OFC and to partially suppress the optical carrier and the higher frequency sideband in order to improve beating efficiency on the photodetector between the free channel and the 5G data channel separated by 27.83 GHz. In channel 2 (Ch. 2), an OBPF is used to further suppress the neighbouring unwanted tones and the polarisation of the two split channels are rematched using a polarisation controller.

The two channels are recombined, amplified, and an OBPF is utilised to reject out of band amplified spontaneous emission (ASE) and the two channels are transmitted over 25 km of single mode fibre (SSMF). The optical spectra after fibre transmission is shown in Fig. 2c (point (c) in Fig. 1). The optical signal consists of the optical carrier and the five bands of 5G data separated by 27.832 GHz and the unwanted optical tone. The optical power launched into the fibre from the baseband unit (BBU) in the central station is 8 dBm.

In the small cell RRH, a variable optical attenuator is employed to vary the input optical power for bit-error rate (BER) measurements. After photodetection on a 50 GHz photodetector, the electrical signal contains the desired mmWave UF-OFDM bands centered at 27.83 GHz generated through the beating of the optical carrier and the 5G bands separated by 27.83 GHz in optical frequency. The 5G mmWave signal is amplified utilising a broadband RF amplifier before being transmitted over a 10 cm Vivaldi Antenna wireless link.

The received 5G mmWave signal is shown in Fig. 2d (point (d) in Fig. 1). An additional broadband RF amplifier is placed directly after the receiver. The electrical receiver noise figure could be improved by additional mmWave amplifiers and band pass filters in the electrical architecture which would also allow maintaining the BER measurements below the FEC limit for longer wireless transmission. However, these were not available.

Subsequently, the 28 GHz 5G signal is down-converted with a 33 GHz sinusoidal RF signal utilising an external mixer. The data signal centered at 5.168 GHz is filtered with an electrical band pass filter (EBPF) before being sent to a real time scope (RTS) with a sampling rate of 50 GSa/s. Digital signal processing (DSP) including time synchronisation, channel estimation, EVM and BER calculations are performed offline.

A. Wireless Antenna

Vivaldi antennas were employed on either side of the link because they offer wide bandwidth as well as good directional features which have the potential to be suitable for mmWave 5G communications [13]. The Vivaldi antenna is fed using

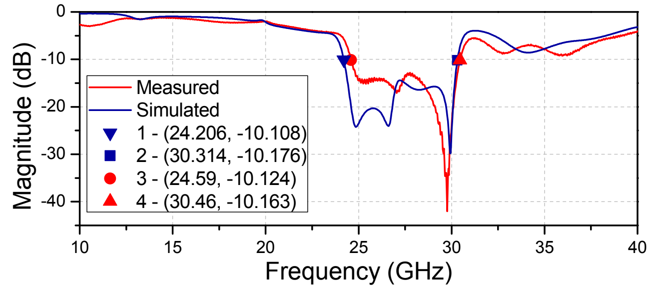

Fig. 3. Measured and simulated S11 (matching) for the Vivaldi antenna showing good matching from 24 GHz to 30 GHz.

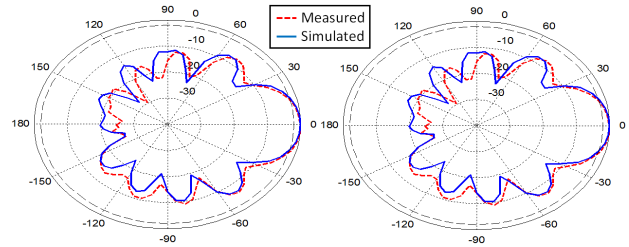

Fig. 4. Radiation patterns for XZ Plane (Φ = 0°) and YZ Plane (Φ = 90°). Red - Measurement, Blue - Simulation.

TABLE II
UF-OFDM OPTIMUM PERFORMANCE PER CHANNEL.

Ch.	Freq. (GHz)	EVM (%)	BER
1	28.168	5.50	2.52×10^{-5}
2	28	6.17	7.11×10^{-4}
3	27.832	7	2.53×10^{-3}
4	27.664	7.18	3.11×10^{-3}
5	27.496	6.3	6.06×10^{-4}

a microstrip line on the rear of the board which excites the tapered slot. The line matches to 50 Ω at the SMK connector. The antenna was fabricated on Rogers 5870 substrate, 0.38 mm thickness and of dimension 32.8 mm×15.0 mm. The two arms of the Vivaldi structure have the length of a half of a wavelength at center design frequency (28 GHz). The simulated and measured S-parameters of the 5G antenna are illustrated in Fig. 3. The reflector and additional 5 directors play a significant role to increase antenna gain. The random spline curves at the edge of the ground plane lengthen the rearward current path, widen the bandwidth and spread the radiated energy (caused by the rearward current path) into various directions in space to maintain the boresight gain and to increase the antenna resilience to rear proximity effects. The simulated and measured radiation patterns for both the XZ Plane (Φ = 0°) and YZ Plane (Φ = 90°) are shown in Fig. 4. The measured and simulated gain was 12.1 dBi.

IV. Results

The system was analysed for transmission over 25 km of SSMF and a wireless link. The performances achieved on all mmWave UF-OFDM channels when the received optical power (RoP) is 3 dBm are displayed in Tab. II. Considering a hard-decision FEC code with a 7% overhead, the threshold of acceptable BER is 3.8×10^{-3} [14]. Performance below the FEC limit is achieved for all five channels. The worst

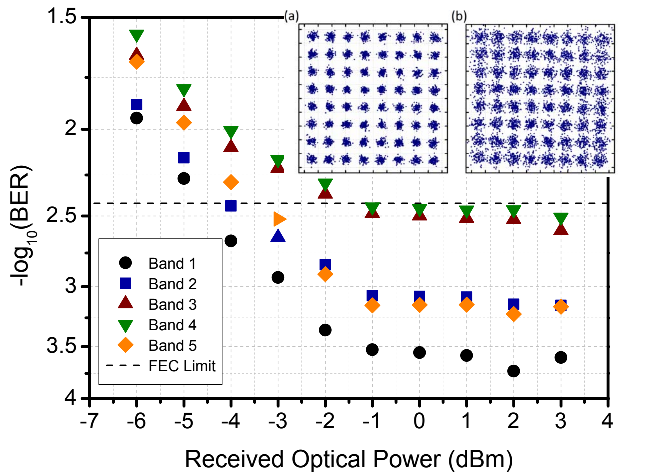

Fig. 5. -$\log_{10}$(BER) v RoP (dBm) for 25 km of fibre and wireless transmission with a constellation plot inset at 3 dBm for Ch. 1.

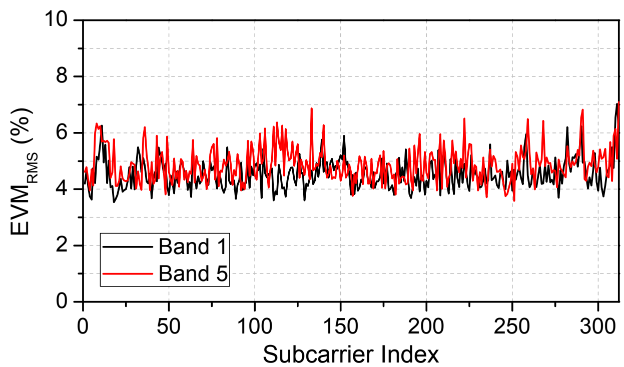

Fig. 6. EVM per subcarrier for Ch.1 and Ch. 5 at a RoP of 3 dBm.

performing channels are Ch. 3 and Ch. 4 with EVMs of 7% and 7.18% respectively. Attenuation at the higher frequencies due to the optical filtering and bandwidth limitations of some of the RF amplifiers degrades performance of the higher frequency channels, as seen in Fig. 2. In addition the central bands are also more affected by additional composite triple beat (CTB) mixing products.

The results obtained for all five bands are illustrated in Fig. 5, with -$\log_{10}$(BER) plotted against against RoP. The constellation for Ch.1, inset (a) of Fig. 5, clearly demonstrates good performance at a RoP of 3 dBm. Inset (b) of Fig. 5 illustrates the constellation for Ch.1, at a RoP of -5 dBm, where the BER is just below the FEC limit and the degradation in system performance and in SNR is apparent. Examining the results at the FEC limit, it is evident that there is a $\sim$3.8 dB penalty between Ch. 1 and Ch. 4. As mentioned previously this is due to electronic attenuation and CTB mixing products. The error floor in these measurements is expected to be as a result of nonlinearities in the RF amplifier and photodiode at higher signal levels. The EVM per subcarrier is shown in Fig. 6 for the two outermost channels, Ch. 1 and Ch. 5. This demonstrates the suitability of the bandpass of the antenna for transmitting the 5G data.

V. Conclusion

An externally injected gain switched DFB laser generates a low linewidth coherent comb source which is utilised to demonstrate a 28 GHz 5G mmWave RoF system. Transmission of a 28 GHz 5G signal, consisting of five bands of UF-OFDM, over 25 km of SSMF and a wireless link is achieved. Performance below the FEC limit is achieved on all five channels. The proposed system is based on an externally injected gain switched laser used to generate an OFC with tunable FSR and wavelength. This allows for the stable and flexible operation across the mmWave range. Furthermore, the discrete components used in the experimental setup could be integrated to develop a small form factor transmitter and receiver making this system a cost-effective solution for mmWave 5G fronthaul.

Acknowledgments

This research was supported in part by a research grant from Science Foundation Ireland (SFI) and is co-funded under the European Regional Development Fund under Grant Number 13/RC/2077. The work has also been jointly supported through the SFI US-Ireland project (15/US-C2C/I3132) and IPIC (12/RC/2276) research grants.

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