OFDM Baud Rate Limitations in an Optical Heterodyne Analog Fronthaul Link using Unlocked Fibre Lasers

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Abstract— **The phase noise (PN) of a photo-generated mm-wave carrier, resulting from frequency and phase fluctuations of uncorrelated laser sources, limits the performance of heterodyne/millimeter-wave analog radio-over-fibre links. This work analyzes the effect of subcarrier baud rate and frequency offset (FO) variations on the performance of a 60 GHz OFDM signal generated using unlocked fiber lasers. Conventional digital techniques for FO and PN compensation, in a 25 km mm-wave A-RoF heterodyne system, are shown to overcome relatively large FOs and to enable the successful transmission of kHz range sub-carrier baud rates – in line with recent 5G recommendations.**

Keywords— Millimeter Wave, Radio-over-Fiber, Optical Fronthaul, Fiber-Wireless, 5G

I. INTRODUCTION

The appetite for high speed broadband due to the successful deployment of a wide range of data intensive applications has fuelled the continuous technological advances in mobile cellular networks. Future network requirements can be fulfilled by the ultra-dense deployment of small cell antenna sites and increased signal bandwidth – which can be aided by moving toward millimeter wave (mm-wave) frequencies (30-300 GHz) in conjunction with a centralized radio access network (C-RAN) architecture as envisioned in 5th generation (5G) technology [1]. C-RAN advocates for the functionality split, of the base station, into centralized base band unit (C-BBU), at the central station (CS), and simpler remote radio head (RRH) unit, at the antenna site, connected by fibre - termed as fronthaul. Currently deployed common public radio interface (CPRI) fronthaul links use a digitized baseband-over-fibre (DBBoF) approach which digitizes the analog signal resulting in higher fronthaul bandwidth and complex RRH architecture. An analog radio-over-fibre (A-RoF) approach retains the inherent bandwidth efficiency of the wireless signal over the fronthaul link and simplifies the RRH site architecture by avoiding the use of expensive analog-to-digital and digital-to-analog converters [2].

Optical heterodyning, wherein two optical carriers with a spacing equal to the desired frequency beat on a high-speed photodetector, has been studied extensively for the generation of mm-wave carriers [3], [4]. It also facilitates the distribution of mm-wave carrier to RRH sites through compatibility with optical fronthaul. Our previous work has combined the use of A-RoF with remote heterodyning using a gain switching comb source [4]. Mm-wave phase noise, resulting from the combined linewidths of the optical tones, is shown to be a major performance limiting factor in analog RoF systems [5] due to the relatively small subcarrier baud rates/bandwidths associated with multicarrier mobile waveforms – potentially as low as 15 kHz [11].

Previous optical heterodyne demonstrations have focused on getting more stable optical tones and low phase noise through the use of dual mode lasers [6], optical frequency combs [5], optical injection [7] or RF envelope detectors [8], [9]. These methods either require non-commercially available lasers or result in additional optical/electrical complexity in the system design. These issues have motivated this work which seeks to demonstrate A-RoF mm-wave fronthaul using 'off-the-shelf' lasers without any requirement for optical locking or coherence in the transmission system. Clearly, moving to this type of implementation introduces the critical issues of relative frequency drift of the optical carriers, and generated mm-wave phase noise resulting from the heterodyning of un-correlated sources. These performance limiting factors are addressed through digital FO and PN compensation using the 'Schmidl and Cox' (S&C) [10] and decision directed least mean square (DD-LMS) algorithms, in a 60 GHz orthogonal frequency division multiplexing (OFDM) A-RoF heterodyne transmission system.

We have simulated, in our previous work [5], the effect of optical linewidth variation on the performance of a 2 Mbaud subcarrier spacing multi-carrier signal. Results in [5] conclude that lasers with linewidths less than 1.5% of the subcarrier baud rate are required for the system performance to be below the forward error correction (FEC) limit employing 64-QAM modulation format on the subcarriers. The effect of FO was not considered in this simulation analysis and no extra processing was done to compensate the phase noise. For the experimental work presented in this paper we varied the baud rate of the OFDM signal, while

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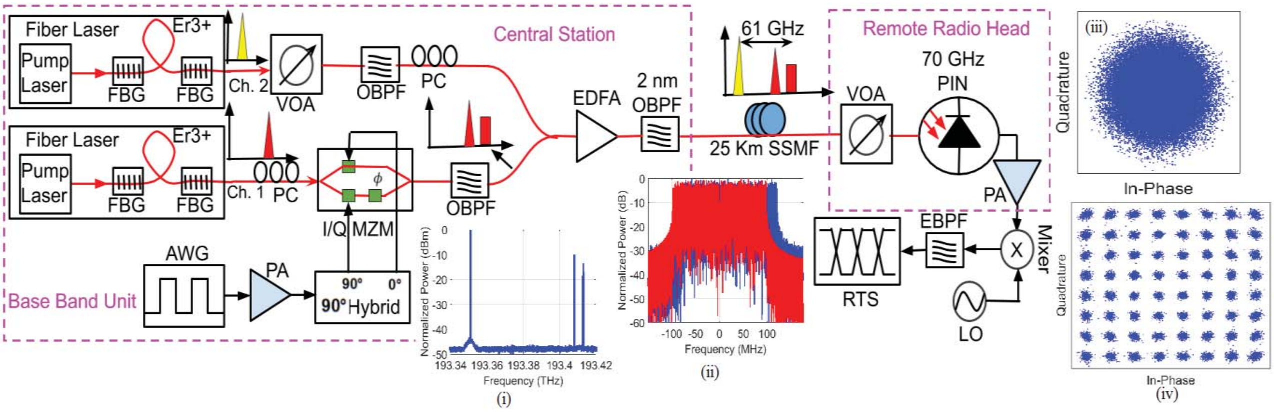

Fig. 1: Optical heterodyne mm-wave A-RoF experimental setup including figurative optical and electrical spectra along the system path. The inset shows (i) the measured optical spectrum at the output of the transmitter, (ii) transmitted (blue) and received (red) base band spectra, constellation of a received signal (iii) without FO and PN compensation and (iv) after all DSP processes.

maintaining constant lasing conditions of two independent fiber lasers which exhibit un-correlated phase noise and a relative FO. Results presented show how the performance of a 61 GHz OFDM signal varies as we reduce its subcarrier baud rate below 2 MHz – with successful transmission demonstrated at baud rates as low as 125 kHz when FO/PN compensation is used.

The fiber lasers used in this experimental work exhibit a maximum relative drift of ~6 MHz over several signal captures, and results show that it is completely compensated by the digital algorithms used. To extend the testing of the receiver FO compensation in this heterodyne context, performance is also evaluated when an additional FO is introduced in the system by varying the receiver mm-wave local oscillator (LO) frequency. The novel combination of un-locked, commercially available small form factor lasers with well-established digital processing in a heterodyne A-RoF system represents a robust and deployable system for future mm-wave fronthaul networks.

II. EXPERIMENTAL DETAILS

A. Schematics Details

The schematic of the experimental testbed is shown in Fig.1. Two low noise fibre lasers each with output power of +10.5 dBm and linewidth of ~1 kHz are used at the CS. The carrier in Ch.1 (red carrier in Fig. 1) was modulated with ~200 MHz bandwidth variable subcarrier baud rate OFDM signal, at an intermediate frequency (IF) of 5 GHz. The OFDM signal was generated in the electrical domain using an arbitrary waveform generator (AWG) operating at 20 GSa/s. More details of the OFDM signal parameters for different baud rates are given in subsection B. Optical single sideband (O-SSB) modulation was performed using an electrical 90^{o} hybrid coupler and I/Q Mach Zehnder Modulator (MZM). The OSSB modulated carrier was combined with the un-modulated carrier from Ch. 2 (yellow carrier in Fig. 1), which is 56 GHz away from the Ch. 1 carrier, and transmitted through 25 km of standard single mode fibre (SSMF) after amplification by an Erbium doped fibre amplifier (EDFA). A variable optical attenuator (VOA) was used in Ch. 2 to equalize the optical power differences (due to I/Q MZM insertion loss and OSSB modulation loss in Ch. 1) between the two optical paths at the transmitter. Inset (i) in Fig. 1 shows the spectra of the signal after a 2 nm optical band pass filter (OBPF), which is used for filtering out-of-band amplified spontaneous emission (ASE) noise.

Beating of the un-modulated carrier (yellow carrier of Ch2 in Fig. 1) and data sideband (red data of Ch1 in Fig. 1) on a 70 GHz PIN photo-detector at the 'RRH' site generates the OFDM data band at 61 GHz, which can be directly transmitted to the wireless user using antenna elements after amplification. A VOA was used to control the power falling on the PD. It is worth mentioning that wireless transmission of the mm-wave signal was not carried out in this experiment. The 61 GHz OFDM signal was frequency down converted to the IF band using a 56 GHz external LO and mixer. The frequency of this LO was intentionally varied in order to introduce additional FOs. This allowed the capabilities of the S&C FO compensation algorithm to be tested for FOs beyond those caused by the relative drift of the lasers alone (~6 MHz). A real time oscilloscope (RTS) operating at 50 GSa/s was used to capture this IF data. Offline digital signal processing (DSP) algorithms (described below) are applied to the captured OFDM signal in Matlab before performance is evaluated through bit error rate (BER) and error vector magnitude (EVM) calculations.

B. Baud Rate Specifications

Variable subcarrier baud rate OFDM signals were generated by changing the IFFT size and keeping the baseband sampling rate constant. To keep the signal bandwidth constant, the number of 64 QAM data modulated subcarriers were also increased in proportion to the IFFT size. 100 subcarriers out of 256 were modulated by 64 QAM data to get a baud rate of ~ 2 MHz resulting in a raw data rate of 1.2 Gb/s. Both IFFT size and the number of data subcarriers were increased by a factor of 2 with respect to previous values to reduce the baud rate by a factor of 2 each time. OFDM signals with subcarrier baud rate values of 2 MHz, 1 MHz, 500 kHz, 250 kHz, 125 kHz and 62.5 kHz were generated, and their performance was analyzed upon transmission over the 25 km SSMF based mm-wave A-RoF heterodyne system. These signals were up-sampled and digitally mixed with a 5 GHz IF carrier before being loaded to the AWG.

C. DSP for FO and PN compensation

Uncorrelated fluctuations in the carrier frequencies (yellow and red carriers in Fig. 1) of the two free running fibre lasers changes the frequency spacing between them.

This results in different IF center frequency of the captured signal leading to frequencies offset as shown in the frequency down converted signal spectra (inset (ii) in Fig. 1). As explained previously, these random fluctuations result in the random relative phase variations between LO and 61 GHz generated mm-wave signal giving rise to phase noise in the system. The FO and PN need to be compensated for the reliable detection of the transmitted data.

The captured signal from the RTS was processed for FO and PN compensation after resampling and frequency down conversion to baseband. Direct ODFM demodulation of this frequency down-converted baseband signal, without application of any compensation algorithms, results in the constellation as shown in the inset (iii) of Fig. 1. It is impossible to retrieve the data due to the FO and PN effects without the application of the DSP algorithms. Searching for a special symbol with two identical halves, i.e. preamble as defined in the S&C algorithm [10], in the frequency down converted signal helps with the timing synchronization along with FO estimation. This preamble was transmitted at the start of the OFDM data signal for each baud rate case. Using the preamble, FOs that were a fraction of the baud rate (subcarrier bandwidth) were corrected by estimating the phase shift caused by the received signal FO [10]. The remaining integer (subcarrier index) FO was detected by cross correlation of the transmitted and received preamble, instead of using a second preamble as described in S&C algorithm. The detected data is counter rotated in the frequency domain by a number of samples equal to the integer FO to completely correct for the FO. To determine the amount of FO that can be compensated by this algorithm, we have introduced an additional FO by varying the mm-wave LO in 20 MHz steps for some of the baud rates, and the results are discussed in section III.

Phase correction is applied by employing the least mean square phase tracking which compares the FO compensated data with the standard 64-QAM constellation points. As this technique is blind and depends on the squared error with the ideal constellation points, it leads to a phase ambiguity resulting in a fixed phase shift in the symbols. This fixed phase was estimated by using pilots placed along the sub-carriers of the OFDM data. Inset (iv) in Fig. 1 shows the constellation of the OFDM demodulated signal after employing all necessary digital post-processing.

III. RESULTS AND DISCUSSION

EVM performance of the transmission system described is measured with variable baud rates and FO under the influence of uncorrelated fluctuations of the two optical carriers used in this experiment. Transmitted data can be correctly retrieved by applying the DSP compensation algorithms described earlier, as can be seen from the constellation diagrams transformation from the one shown in inset (iii) to that in inset (iv) after the relevant DSP is implemented. This constellation diagram corresponds to the 2 MHz subcarrier baud rate OFDM signal and represents a received EVM of 4.76% with measured BER to be 3.13×10^{-5} for a received optical power of -2 dBm. We have also observed that there is no penalty due to 25 km fibre transmission. The excellent performance obtained for this mm-wave A-RoF link is attributed to the good quality of fibre lasers with SMSR > 50 dB and RIN better than -140 dBc/Hz.

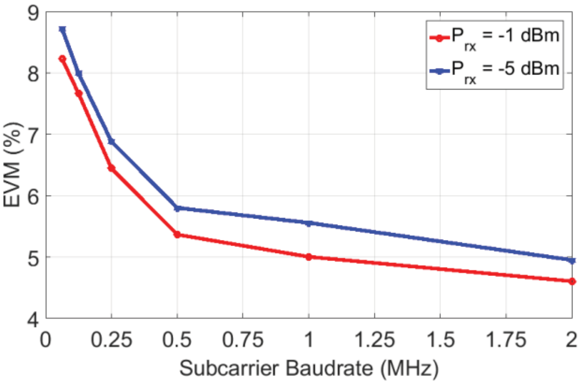

Fig.2: EVM versus subcarrier baud rate for DSP compensation based 61 GHz OFDM mm-wave A-RoF system.

A. *Performance with variable baud rates*

Variable baud rate signals were generated and transmitted through the 25 km SSMF mm-wave A-RoF system and performance was analyzed at two different power levels falling on the PD. Fig. 2 shows the EVM performance of the 200 MHz bandwidth OFDM signal with variable subcarrier baud rates for received powers of -1 dBm and -5 dBm. The figure shows that for the implemented system, performance degrades as the subcarrier baud rate reduces. The phase noise of the generated mm-wave carrier does not significantly affect the performance of higher baud rate signals, but as the subcarrier baud rate reduces, the phase noise on the RF beat signal (due to combined optical phase noise of the fiber lasers) starts to degrade the system performance. Performance goes above the FEC EVM limit of 8%, for 64-QAM modulated data, at the subcarrier spacing of 62.5 kHz and below. Performance degradation ≤ 0.5% in the EVM is observed when the power falling on the PD is changed from -1 dBm to -5 dBm.

We can infer that for successful transmission of the 62.5 kHz subcarrier baud rate OFDM signal, optical sources with a linewidth of <1 kHz will be required. The linewidth (~1 kHz) of the lasers used in this experiment corresponds to ~1.5% of the lowest subcarrier baud rate (62.5 kHz) used. This is in agreement with the simulation results presented in our previous work [5]. It is important to note that the simulations presented in [5] do not consider the FO effect but our DSP compensations techniques were able to overcome the FO effect and achieve close to simulation performance. Lasers with linewidths of ~225 Hz will be required for the successful transmission of 64-QAM multi-carrier signals with the lowest subcarrier baud rates of 15 kHz suggested by 5G NR physical layer specifications [11], over a mm-wave A-RoF heterodyne system.

B. *Performance with FO variations*

The fibre lasers used in the experimental setup drift by ~6 MHz over several captures. The DSP used for compensation of the FO and PN operate successfully over this range as seen from the constellation diagram of inset (iv) in Fig. 1 and the EVM performance of Fig. 2. This does not completely test the capabilities of the FO compensation algorithm. For this purpose we introduced the FO in the signal by changing the frequency of the RF (mm-wave) LO at the RRH site. Fig. 3 shows the EVM performance of the system with FO variations for three different subcarrier baud

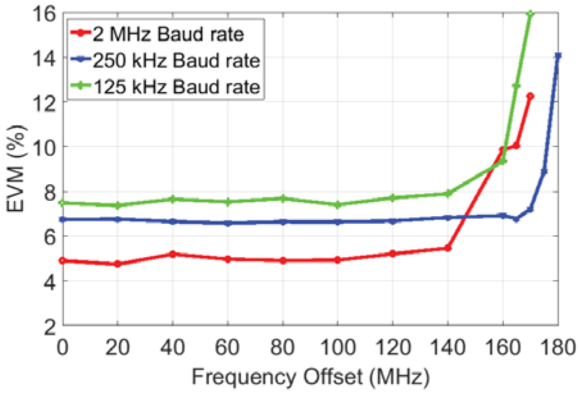

Fig.3: EVM versus LO induced frequency offset performance for DSP compensation based 61 GHz OFDM A-RoF system

rates at a received power of -1 dBm. Results shows that an LO induced frequency offset of up to 140 MHz can be compensated digitally without any significant degradation in the system performance - and it is independent of the signal's subcarrier baud rate. Degradation in the performance can be observed from this graph for FO's beyond 140 MHz, but FO's below this level should be easily achievable through the use of a number of standard laser and thermoelectric cooler technologies. Performance degradation for FOs beyond 140 MHz can be attributed to the limitations of the S&C algorithm [10].

CONCLUSION

Remote optical heterodyning can be used in future wireless systems for the generation and distribution of mm-wave analog signals over optical fronthaul networks. Low linewidth lasers in conjunction with digital processing, for compensating frequency drift and phase offset between the optical carriers, are of paramount importance for facilitating the transmission of small baud rate multicarrier signals, as envisioned in 5G technology. The results presented here demonstrate the successful transmission of 61 GHz OFDM signals with subcarrier baud rates of 125 kHz and higher, when FO/PN compensation is used, over a mm-wave A-RoF heterodyne system using unlocked fiber lasers. In the proposed system, frequency offsets of around 140 MHz and less can be compensated by using digital processing without any significant performance degradation. This paves the way for the utilization of 'off-the-shelf' fibre lasers coupled with well-established digital processing for the transmission of the low baud rates multicarrier signals over spectrally efficient mm-wave A-RoF fronthaul networks.

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