

60 GHz 5G Radio-Over-Fiber Using UF-OFDM With Optical Heterodyning

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Abstract—Millimeter-wave communications may be harnessed to help meet future 5G network bandwidth requirements, but the generation of these frequencies in the electronic domain can be difficult and costly. Photonic techniques, such as optical heterodyning, can be exploited to generate millimeter-wave frequencies in a manner which is efficient and compatible with fiber transport infrastructure. In this letter, analog radio-over-fiber transmission of five bands of UF-OFDM, with optical heterodyning around 60 GHz, is experimentally demonstrated over 25 km SSME, and performance well below the forward error correction limit is achieved for an aggregate raw bit rate of 4.56 Gb/s. Additionally, the importance of precise optical phase correlation in these systems is highlighted with respect to future 5G system requirements.

Index Terms—Radio-over-fiber, fronthaul, millimeter-wave, optical access, optical heterodyne, UF-OFDM.

I. INTRODUCTION

RATHER than a straight-forward increase in network speeds, 5G communications systems entail a complete shift in the make-up of mobile networks. Ultra dense antenna distribution, increased centralization of resources through cloud radio access networking (C-RAN), and the use of millimeter (mm)-wave carrier frequencies are envisioned as a means of providing high data rates to a vastly increased number of connected devices [1]. Furthermore, 5G communications will place a high level of importance on the optical transport portion of the network as the high capacities and low latencies on offer are exploited; allowing efficient optical front/back/mid-haul (x-haul) of wireless signals between radio network elements [2].

It has been proposed that 5G systems avail of free spectrum at frequencies in the mm-wave range from 28–300 GHz [3], [4]. Due to the cost and complexity associated with electronic components which operate in this band,

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there has been much interest in the use of photonic techniques which can produce mm-wave frequencies and facilitate ease of convergence with optical access infrastructure [5], [6]. To date, the study of photonic based mm-wave transmission has focused on maximizing throughput using broadband RF multi [6], [7] and single [8] carrier data. However, as narrower band 5G systems will employ subcarrier baud rates of 100s kBd to several MBd, constraints are placed on the allowable level of RF phase noise generated by photo-mixing of the optical carriers, which is not addressed by the aforementioned studies.

Universally filtered orthogonal frequency division multiplexing (UF-OFDM) is an ‘OFDM inspired’ waveform whose sub-band filtering offers extremely low out-of-band (OOB) emission, compared to OFDM [9], allowing for increased spectral efficiency in multi-band systems. In this work, 60 GHz radio-over-fiber (RoF) transmission of five bands of UF-OFDM, over 25 km of standard single mode fiber (SSMF), is demonstrated successfully utilizing an optical heterodyne technique. Multi-carrier properties such as bandwidth and subcarrier number/baud rates are chosen to align with what is envisioned for 5G systems at 60 GHz [10]. The high level of phase correlation required, given the relatively low subcarrier baud rates associated with multi-carrier mobile signals, is investigated and results highlight design parameters which must be taken into account given particular laser and signal characteristics. Additionally, de-correlation pre-compensation is employed to achieve error vector magnitudes (EVM) <5%.

II. 5G OPTICAL-WIRELESS TECHNOLOGIES

A. UF-OFDM

UF-OFDM - an in-depth discussion of which can be found in [9] - is considered to be a candidate waveform for 5G networks. Like OFDM, it is a multi-carrier modulation format whose digital implementation is based on the (inverse) fast Fourier transform (IFFT). UF-OFDM subcarriers are subdivided into bands known as resource blocks, and linear filtering of each resource block is employed in order to shape the signal spectrum and lessen subcarrier orthogonality requirements. Filtering in this way leads to much lower OOB emission, compared to OFDM, and indeed other 5G candidate waveforms such as generalized frequency division multiplexing (GFDM)/circular filter-bank multi-carrier (C-FBMC) whose circular filtering implementation leads to truncated

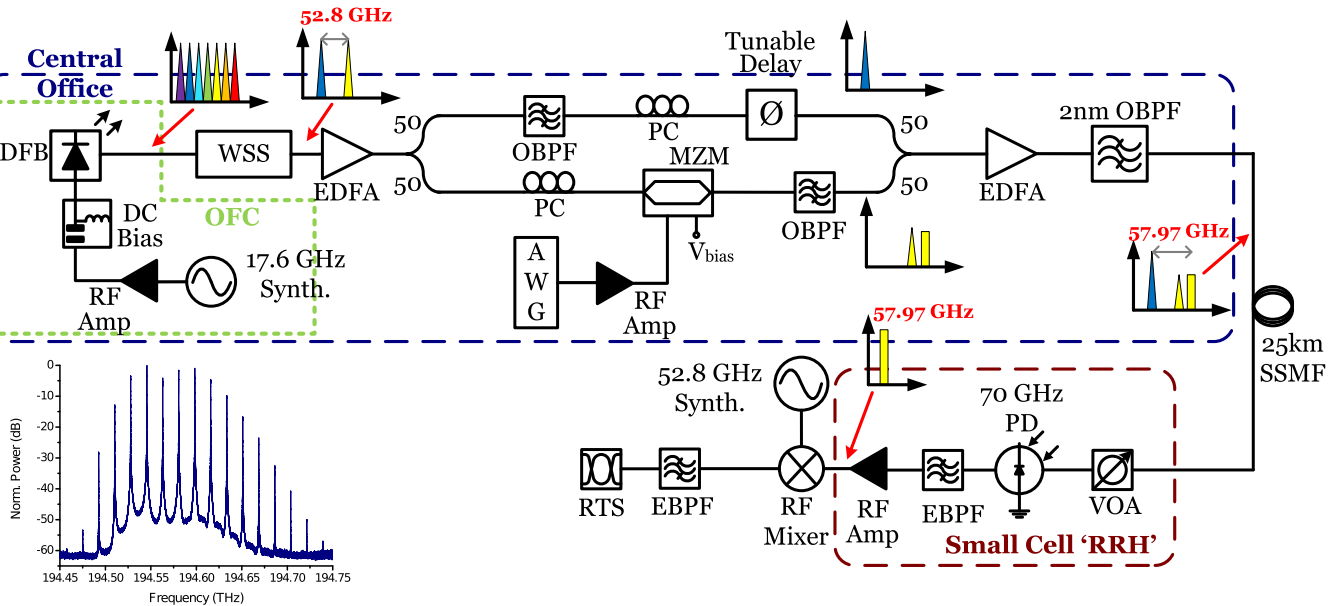


Fig. 1. 5G mm-wave fronthaul experimental setup.

subcarrier filter responses resulting in a 'sinc'-like shaping of the spectrum and relatively high OOB emission [9]. We have previously demonstrated UF-OFDM's advantage over other waveforms in the optical access domain where spectral containment of the signals is required in order to reduce interference between different services [11]. For these reasons UF-OFDM is chosen in order to construct an efficient multi-band mm-wave system.

B. Optical Heterodyne for mm-Wave RoF

Optical heterodyning involves the transmission of optical carriers spaced by a given frequency. The beating of two carriers on a photo-diode results in an electrical component whose frequency is equal to the difference of the two. By introducing wavelength tunability to the optical source, data signals can be generated across the mm-wave range without the use of costly electronics.

Recent optical heterodyne demonstrations have proposed the use of two independent external cavity lasers (ECL) as tunable sources [8]. The relatively low level of RF phase noise produced after beating of these two 100 kHz linewidth sources allows for successful transmission of 10 GBaud 64-quadrature amplitude modulation (QAM). However, mobile data formats typically exhibit low subcarrier baud rates. This reduces phase noise tolerance and restricts laser linewidths (potentially to sub-kHz levels) rendering this technique both difficult and costly. Other recent demonstrations employing dual wavelength fiber lasers [12] and optoelectronic cross injection-locking [13] show low RF beat linewidth/excellent phase correlation. However, these methods involve complex setups and, in the case of [12], the requirement for guard bands due to frequency drift at mm-wave frequencies.

For the work described below, an 'off-the-shelf' distributed feedback (DFB) laser was gain switched [6] producing an optical frequency comb (OFC) which consisted of a number of

correlated optical tones whose frequency spacing can be tuned. Two of these tones were independently filtered and used for the optical heterodyne technique. The phase de-correlation between the two optical tones, induced by path length differences and chromatic dispersion, are pre-compensated by way of a tunable delay line; resulting in a stable, cost efficient and highly effective system for 5G mm-wave fronthaul.

III. EXPERIMENTAL SETUP

The experimental setup, with figurative spectral representations at various points along the setup, is shown in Fig. 1. The test bed was designed to emulate a fronthaul architecture where optical and RF hardware, as well as baseband processing, are consolidated at a central office (CO) which is connected to a small cell remote radio head (RRH) site through 25 km of fiber. An OFC (the spectrum of which is shown as an inset in Fig. 1), with a comb spacing of 17.6 GHz is generated by gain switching a DFB with an RF sinusoid. A wavelength selective switch (WSS) is used to suppress all but two carriers which are spaced by 52.8 GHz. These two carriers are amplified using an Erbium doped fiber amplifier (EDFA) and then the optical path is split in two, where one carrier is externally modulated using a 10G single-ended Mach-Zehnder modulator (MZM). Five bands of UF-OFDM, each with properties outlined in Tab. I, a channel guard band of 15 MHz

TABLE I
UF-OFDM PROPERTIES

Bandwidth	152 MHz
Subcarriers	312,
Sub-bands	13,
Modulation	64-QAM,
Raw data rate	0.912 Gb/s,
Subcarrier baud-rate	487 kBaud

TABLE II
UF-OFDM OPTIMUM PERFORMANCE PER CHANNEL

Ch.	1	2	3	4	5
mm-wave (GHz)	57.632	57.8	57.968	58.163	58.304
EVM (%)	4.67	4.82	5.6	6.3	6.1
BER	1.2×10^{-5}	4.6×10^{-5}	3.1×10^{-4}	6.9×10^{-4}	6.1×10^{-4}

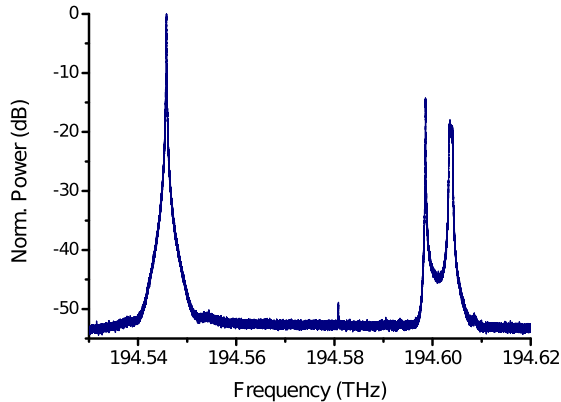


Fig. 2. Optical spectrum showing an un-modulated carrier and carrier-suppressed SSB signal before the 70 GHz photodiode.

and a peak-to-average power ratio (PAPR) of between 11–12.5 dB (after 80% hard clipping), are generated digitally and output from a single arbitrary waveform generator (AWG) operating at 20 GSa/s. The RF center frequency of this block of five UF-OFDM bands is 5.168 GHz, and the aggregate net data rate is 4.56 Gb/s. The composite UF-OFDM signal is electrically amplified with a highly linear RF amplifier and used to modulate one of the optical carriers. A tuneable optical band-pass filter (OBPF) is used to fully suppress one of the data sidebands and decrease the carrier power to generate a carrier suppressed single-sideband (CS-SSB) signal. This operation is necessary in order to avoid unwanted beating terms falling in-band, and to optimize the carrier-to-signal ratio for efficient photo-mixing, at the receiver. An additional OBPF was required in the un-modulated arm in order to fully reject adjacent side modes which were present due to the relatively low filter rejection associated with the WSS (30 dB).

In the un-modulated path, a tuneable optical delay line is added so that effective optical path length differences between the optical carriers can be pre-compensated; ensuring ideal phase correlation between optical tones and the mitigation of RF phase noise when the optical signals beat at the 70 GHz photodiode (PD). The two optical paths are recombined with an optical coupler, and an EDFA is used to set the total optical launch power to 5 dBm. A 2 nm optical filter is used to filter amplified spontaneous emission (ASE) from the EDFA before transmission is carried out over 25 km SSMF. The optical spectrum, showing the un-modulated carrier along with the CS-SSB UF-OFDM data signal measured at the output of the fiber, is shown in Fig. 2. The beating, on the 70 GHz PD, between the data bands and the un-modulated carrier which are separated by 57.97 GHz, results in mm-wave

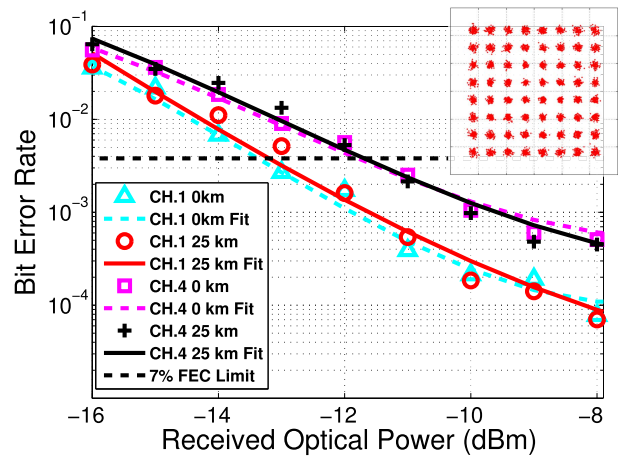


Fig. 3. BER versus received optical power for 0 and 25 km transmission.

UF-OFDM bands centered at 57.97 GHz. The mm-wave signal is transmitted through 1 m RF cable - wireless transmission is not performed in this work. A 52.8 GHz local oscillator (LO) is used to mix the UF-OFDM data down to its original intermediate frequency of 5.168 GHz before being sampled by a Tektronix DPO71254C real time oscilloscope (RTS) operating at 50 GSa/s. Channel estimation and equalization, as well as EVM and bit error rate (BER) measurements, are performed off-line.

IV. RESULTS AND DISCUSSION

Tab. II summarizes the optimum performance achieved on all mm-wave UF-OFDM channels, where precise phase matching is obtained using the tuneable delay, and the received optical power is ~ -6 dBm. Ch. 1 exhibits a BER of 1.2×10^{-5} , and performance well below the 7% forward error correction (FEC) limit of 3.8×10^{-3} are achieved on all channels. Differences in performance between the channels are due to a combination of the electronic attenuation profile across the band, and the fact that each UF-OFDM channel exhibits a different value of PAPR which influences the level of interference experienced by each channel.

Fig. 3 shows BER vs. received optical power for the best (Ch. 1) and worst (Ch. 4) performing channels. The inset shows the total 64-QAM constellation received on Ch. 1 at a power of -8 dBm. As mentioned, the 1.2 dB penalty between these channels (at the FEC limit) is caused, mainly, by electronic attenuation emanating from the RF mixer. No penalty is observed after 25 km fiber transmission compared to the 0 km case indicating UF-OFDM's ability to effectively handle fiber chromatic dispersion in this fronthaul architecture.

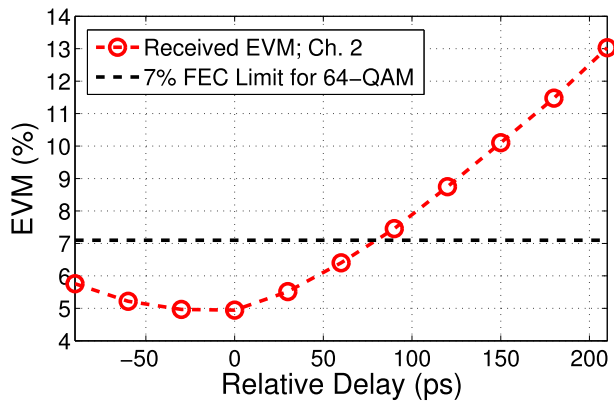


Fig. 4. Relative delay versus EVM for Ch. 2

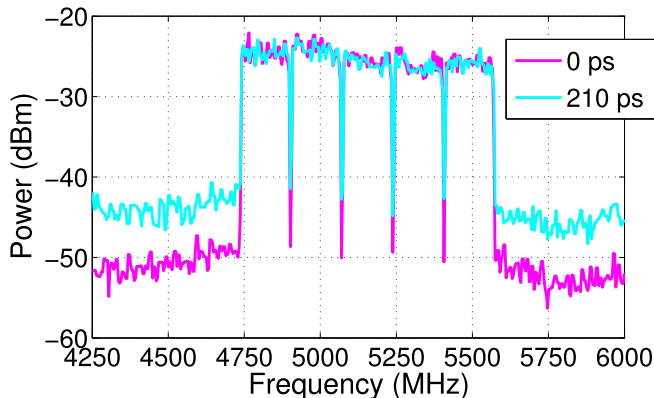


Fig. 5. Received electrical UF-OFDM spectra.

Fig. 4 shows the performance of Ch. 2 as the tunable optical delay line is tuned across its range. The total received optical power in this case was -6 dBm. Maximum correlation is reached when the effective delay experienced by both carriers is equalized (relative delay of 0 ps in Fig. 4), and EVMs $< 5\%$ are achieved. The figure shows that a parabolic relationship exists between relative delay and system performance - as the relative delay between the carriers deviates from 0 ps and the carriers lose correlation. It follows that the profile of this relationship is governed by the *linewidth* of the laser source, as it is this property which directly determines the coherence time of optical carriers; and thus the level of correlation between the carriers as they ‘walk off’ due to dispersion (or, indeed, any other path length differences in the system). Given the relatively large ~ 10 MHz linewidth DFB used in this work, Fig. 4 shows that for a relative delay between the tones of just 90 ps, EVM surpasses the 7% FEC limit as ideal correlation is lost and RF phase noise increases.

Fig. 5 shows the received electrical UF-OFDM spectra for relative delays of 0 and 210 ps. The effects of decorrelation are clear as the resultant phase noise around the bands increases by ~ 10 dB for a relative delay of 210 ps (13% EVM). Figs. 4 and 5 highlight the importance of coherence/strict phase matching in optical heterodyne systems where 5G signals, exhibiting subcarrier baud rates of 100s kHz, are transmitted.

V. CONCLUSION AND FUTURE WORK

60 GHz RoF transmission of five bands of UF-OFDM has been successfully demonstrated using an optical heterodyne technique. An aggregate bit rate of 4.56 Gb/s is achieved over an optical fronthaul architecture and the use of de-correlation pre-compensation to reduce RF phase noise allows for excellent performance of $\sim 5\%$ EVM on all channels.

Results show how correlation between optical carriers is an essential requirement for effective mm-wave 5G systems which employ photo-mixing for RF generation. Linewidth requirements for such systems, employing OFCs, can be lessened through the use of precise pre-compensation to ensure ideal correlation is maintained between the lines, as evidenced by the results presented

The proposed system utilizes gain switching of a DFB laser to generate an OFC with *tunable* free spectral range and wavelength, allowing stable and flexible operation across the mm-wave range. Furthermore, many of the transmitter elements could be integrated to develop a small form factor photonic transmitter making this system a cost-effective solution for mm-wave 5G fronthaul.

Much work in the radio research world has focused on the design of easily integrated antennae and amplifiers for 60 GHz wireless links capable of handling the signal types and bandwidths proposed in this work. An important next step will be to implement such a link in combination with the proposed hybrid transmission system.

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