5G New Radio Compatible Multicarrier Signals Delivery over an Optical/Millimeter-Wave Analog Radio-over-Fiber Fronthaul Link

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Abstract

Millimeter-wave carriers with high spectral purity are paramount for carrying kHz level subcarrier spacing multi-carrier signals. This work demonstrates the successful generation of 60.6 GHz OFDM signal, with 61 kHz subcarrier spacing, in an optical heterodyne analog radio-over-fiber system using gain switched laser source.

1. Introduction

Mobile communication networks progression towards the next generation wireless technology stems from the appetite for high-speed broadband and successful deployment of many data hungry applications [1]. An optical fronthaul link [2] (connecting centralized base band unit (C-BBU) to antenna site remote radio head (RRH)) and increased bandwidth (BW) wireless signal transmission (including in the millimeter-wave (mm-wave) frequency band [1]) are key aspects for the 5th generation (5G) and beyond 5G (B5G) wireless systems. The enhanced mobile broadband services of 5G promises to provide data rates up to 10 Gb/s by transmitting higher order modulation format multi-carrier signals, of up to 400 MHz BW, in the mm-wave frequency spectrum [3]. The frequency bands beyond 60 GHz are also under intense consideration for use in B5G wireless systems for various applications [4], [5].

The poor spectral efficiency of the currently deployed digitized radio-over-fiber (D-RoF) based common public radio interface (CPRI) optical fronthaul links hinders ultra-dense deployment for carrying 5G/B5G data traffic to antenna site [2]. The enhanced CPRI (e-CPRI) [6] relaxes the BW requirement over the fronthaul link, to some extent, using the functional split of the radio access network; resulting in a potentially complex RRH architecture as more digital functions are moved to the remote antenna site. These issues can be alleviated by analog radio-over-fiber (A-RoF) [7] approach, which harnesses the spectral efficiency of wireless modulation formats and simplifies the RRH antenna site by providing RF signals which are ready for antenna transmission directly after photo-detection (PD) and amplification.

The complexity associated with the electronic generation of the mm-wave carriers can be reduced by using the optical heterodyning technique [8-9], in which two optical carriers with a spacing equal to desired RF carrier beat on a high-speed PD. Transmitting the analog-RoF data at the intermediate frequency (IF) from C-BBU to various RRH sites, coupled with optical heterodyning at the antenna site for frequency up-conversion to the mm-wave band provides a promising solution for the generation and distribution of the signals for future mm-wave wireless systems.

Most of the previous optical heterodyne A-RoF demonstrations have focused on either increasing the frequency of the mm-wave carrier to THz range [8-9] or increasing the maximum data rate that can be transmitted over such links [10-11]. In such systems, transmitting single carrier modulated signals, the effect of phase noise (PN) of the mm-wave carrier on the system performance is minimal. However, for the systems transmitting small subcarrier spacing/baud-rate multicarrier signals, such as 5G and B5G wireless systems, the PN of the photo-generated generated mm-wave carrier limits the system performance [12]. Hence, the capabilities of such system must be studied for successful transmission of kHz level subcarrier spacing multicarrier signals, as provisioned in the 5G new radio (NR) standards. The 5G NR specification advocates for the transmission, in the mm-wave band, of the orthogonal frequency division multiplexing (OFDM) signals with subcarrier baud-rates as low as 60 kHz [13].

In our previous demonstration [14] of a DSP assisted optical heterodyne A-RoF link (using independent fiber lasers each with ~1 kHz linewidth) the phase noise of the photo-generated mm-wave carrier restricts transmission of multicarrier OFDM signals to subcarrier spacing of $\geq$ 125 kHz only. The system presented in [15], with quantum dash mode lock laser optical frequency comb (OFC) source, could transmit OFDM signals with subcarrier baud-rates of 250 kbaud or higher only. The results presented in this paper, for optical heterodyne A-RoF system using a gain switched laser (GSL) OFC source, demonstrates the successful transmission of 195 MHz, 400 MHz and 800 MHz BW OFDM signal with subcarrier spacing as low as 61 kHz, in compliance with the minimum spacing specified in 5G NR recommendations [13].

Our previous system demonstration [12] with a GSL OFC source has shown how the coherence length of the high linewidth correlated optical tones require either strict path matching between the optical carriers throughout the system, or an external PN compensation mechanism, i.e. optical injection locking with a low linewidth laser [12], or a phase noise compensation (PNC) receiver [16], increasing system complexity. The presented system provides a low complexity photonic solution for the generation and distribution of 5G NR compatible mm-wave signals achieving a data transmission rate of 4.8 Gb/s.

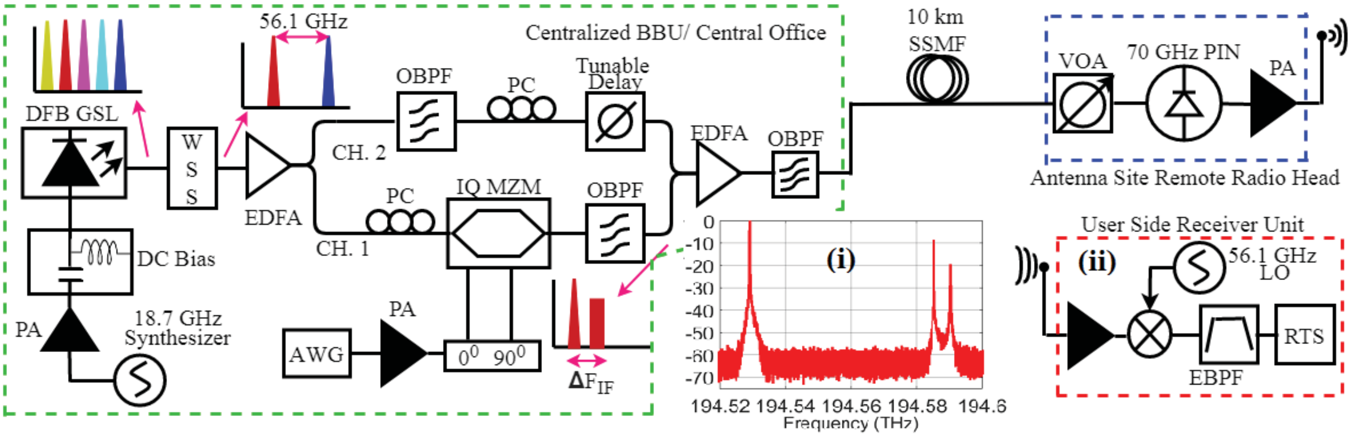

Fig. 1: GSL OFC based Optical heterodyne mm-wave A-RoF experimental setup with inset (i) showing the measured optical spectrum at the output of the transmitter and (ii) showing the architecture of the user side receiver unit.

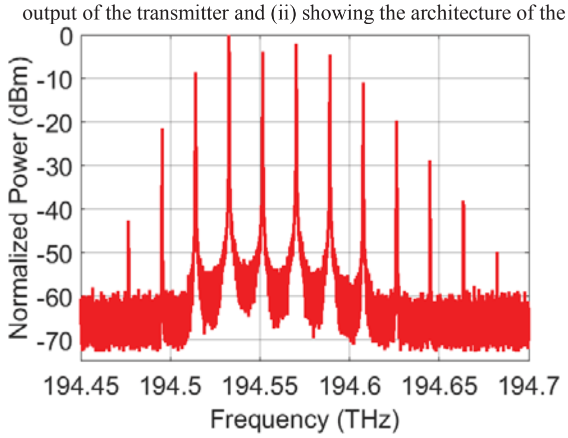

Fig. 2: Output spectrum of GSL OFC with an FSR of 18.7 GHz obtained with 62.5 mA bias current and 20 dBm RF drive.

2. Optical Heterodyne A-RoF Setup

The schematic of our experimental testbed with figurative spectra along the system path is shown in Fig.1. At the Central Station (CS) or C-BBU transmitter site, a distributed feedback (DFB) laser was gain switched by applying a sinusoidal RF signal of 18.7 GHz frequency from a synthesizer. The DC bias current and RF power of the modulating signal were adjusted to get only four lines, within 3 dB, from the GSL OFC source as shown in the spectra of Fig. 2. The total output power, and linewidth of each tone, from the GSL OFC were measured to be +8 dBm and ~20 MHz, respectively. A wavelength selective switch (WSS) was used to select two lines, which were close to the desired mm-wave frequency (56.1 GHz in this case), from the output of GSL OFC and was followed by an erbium doped fiber amplifier (EDFA) to boost the power of these carriers as shown in the setup of Fig. 1.

The output of EDFA is split into two channels for data modulation on one carrier. An I/Q Mach Zehnder Modulator (MZM) and electrical 90^{o} hybrid coupler were used, in the Ch. 1, to generate an optical single sideband (OSSB) OFDM signal. Initially 195 MHz bandwidth (BW) OFDM signals with different subcarrier baud-rates were generated in the electrical domain, at an intermediate frequency of 4.5 GHz, using an arbitrary waveform generator (AWG) operating at 20 GSa/s. The number of data subcarriers were increased, from 100 to 3200, as the subcarrier baud-rate was reduced, from 1.95 Mbaud to ~61 kbaud. A 195 MHz BW OFDM signal with 64-QAM data modulated subcarriers result in a raw data rate of ~1.17 Gb/s. The un-modulated carrier was attenuated using the programmable WSS at the output of GSL OFC, to equalize the optical power between the two optical paths due to relative path losses. Optical bandpass filters (OBPF) were used in both channel paths to remove the unwanted components of the carriers and signal. A tunable optical delay line was used in Ch. 2 to pre-compensate the path length difference and swept to study the limitations [12].

The OSSB modulated carrier (red carrier in Fig.1) was combined with the un-modulated carrier (blue carrier in Fig. 1) from Ch. 2 and transmitted through 10 km of standard single mode fiber (SSMF) after amplification by EDFA. The optical spectrum of the transmitted signal is shown in inset (i) of Fig. 1. The photo-mixing of combined transmitted signal, on a 70 GHz PIN PD at RRH antenna site, generates mm-wave OFDM signal at 60.6 GHz frequency. A variable optical attenuator (VOA) was used to control the power falling on the PD. This photo-mixing generated mm-wave signal can be directly transmitted to the wireless end user using antenna elements, after amplification as shown in the blue colour RRH box in Fig. 1. It is worth mentioning that wireless transmission of mm-wave signal was not carried in this experiment.

The photo-mixing generated 60.6 GHz OFDM signal was frequency down converted to the original IF frequency using a 56.1 GHz external local oscillator (LO) and mixer as shown in the inset (ii) of Fig. 1. A real time oscilloscope (RTS) operating at 50 GSa/s was used to capture this IF data. Offline processing was applied on the captured signal using Matlab to evaluate the bit error rate (BER) and error vector magnitude (EVM) performance. In order to demonstrate the BW capabilities of the system, we also demonstrated the transmission of 400 MHz and 800 MHz BW OFDM signals carrying the raw data rates of 2.4 Gb/s and 4.8 Gb/s, respectively.

3. Results and Discussion

In optical heterodyne analog-RoF systems, with an OFC source, the effective path length difference between the beating tones and fiber dispersion in the system results in decorrelation at the receiver – producing mm-wave carriers with high level of phase noise [12]. In order to study the effect of mm-wave signals PN, the performance of 195 MHz BW OFDM signal with a subcarrier baud-rate of 61 kbaud was analysed in our system. Fig. 3(i) shows the EVM performance of the mm-wave optical heterodyne A-RoF link with varied

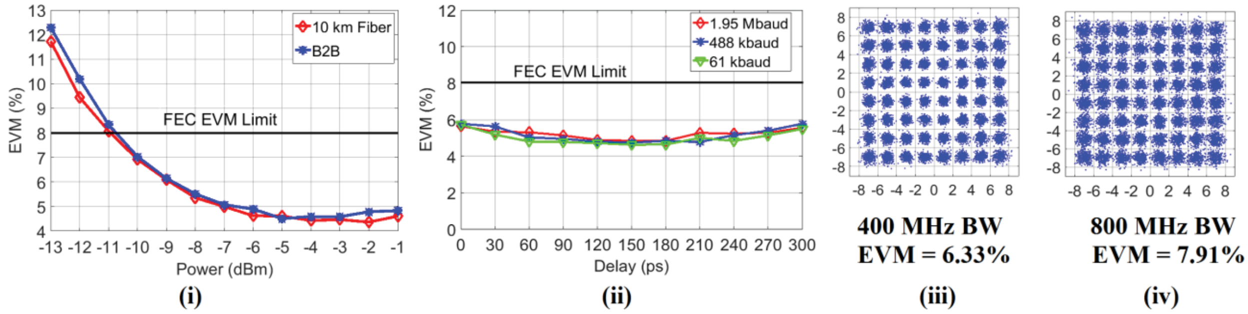

Fig. 3: Performance of low subcarrier spacing OFDM signal over mm-wave optical heterodyne A-RoF link with (i) received optical power variation, (ii) relative optical delay variation; Constellation of the (iii) 400 MHz BW and (iv) 800 MHz BW received demodulated signal.

received optical power on PD for back-to-back and 10 km fiber transmission case. The figure shows that there is no penalty due to fiber transmission and performance stays within the FEC limit for optical power as low as -11 dBm. For a received power of -1 dBm a BER of 2.48×10^{-6} and EVM of ~4.61% are obtained - indicating excellent performance. The performance degradation at lower power levels is attributed to the thermal noise of photodetector and quantization noise of the RTS. The received power variations from -1 dBm to -12 dBm result in EVM variation from ~4.61% to ~12%.

The excellent performance of the presented system for successfully transmitting low subcarrier spacing (61 kHz) OFDM signals is attributed to the high correlation between the GSL OFC tones. In our previous optical heterodyne A-RoF system demonstration [15] with mode lock laser OFC source, the low level of correlation between the beating tones, (despite exhibiting lower linewidths compared to the GSL OFC tones) limit the transmission of OFDM signals to 250 kbaud and higher subcarrier spacing only. This shows the importance of using an OFC source with high correlation in the optical heterodyne A-RoF system that is required to facilitate multi-carrier signal transmission that is compatible with 5G/B5G systems. The high correlation between the GSL OFC tones is direct consequence of using RF LO for gain switching.

In order to check the effect of relative path length difference between two channels, which results in de-correlation between the beating optical carriers, we varied the optical delay line, placed in Ch. 2, by 150 ps on either side of the optimum point and measured the performance variations for our system. Fig. 3(ii) shows the performance of demonstrated optical heterodyne A-RoF system for 195 MHz BW OFDM signal with three different subcarrier baud-rates of 1.95 Mbaud, 488 kbaud and 61 kbaud. The results in figure shows almost similar performance for all the baud-rates and the best performance of ~4.7% is obtained at the midpoint of the delay line i.e. 150 ps. EVM increases by ~1% after 150 ps delay on either side of the optimum point on the delay line. This result indicates that the link distance could be increased by up to 20 km (whose dispersion effect de-correlates the beating carriers by 160 ps) with a negligible impact on performance and without relative path delay optimization.

In our previous optical heterodyne A-RoF system experimental demonstration with GSL OFC [12], [16] ~8% EVM degradation was observed, for 1.95 Mbaud subcarrier baud-rate OFDM signals, with ~100 MHz and ~80 MHz linewidth optical carriers. However, this performance variation was reduced by either injection locking the GSL OFC with low linewidth laser [12] or external phase noise compensation mechanism [16], resulting in increased optical/electrical complexity of the system. For GSL OFCs, the selection of bias current and the power of the gain switching signal determine the number of comb lines generated and the linewidth of the tones [12]. Considering that only a small number of tones are required to obtain the desired mm-wave frequency separation, a bias current of 62.5 mA and gain switching signal power of 20 dBm are selected resulting in 4 comb lines within a 3-dB ‘flatness’ each with a linewidth of ~20 MHz. For these OFC characteristics in the system described, the performance varies by ~1% EVM, over 150 ps delay, for lower baud-rate.

In order to increase the data rate, we transmitted higher BW OFDM signals over the system and the constellation diagrams of the received demodulated signals are shown in Fig. 3(iii) and Fig. 3(iv) for 400 MHz and 800 MHz BW signals, respectively. The increase in OFDM signal BW from 200 MHz to 400 MHz degrade the EVM from 4.7% to 6.33% and further BW increase to 800 MHz degrades the EVM to 7.91% as a direct consequence of SNR degradation at a received optical power of -1 dBm. The measured BER values of 2.21×10^{-4} and 2.0×10^{-3} for 400 MHz and 800 MHz BW signals, respectively, are within the FEC limits, showing the successful delivery of 2.4 Gb/s and 4.8 Gb/s raw data rates over the optical heterodyne A-RoF system.

4. Conclusion

Remote optical heterodyning coupled with analog-RoF fronthauling can provides an efficient solution for the generation and distribution of mm-wave signals for future wireless communication systems. The results presented here demonstrate how the optical heterodyne analog-RoF system, using an optimized GSL OFC source, can successfully support 60.6 GHz OFDM signals with subcarrier baud-rates as low as 61 kbaud with bandwidths up to 800 MHz. By avoiding additional hardware (injection locking or advanced receiver architectures) or DSP requirements, the proposed system represents a low complexity photonic solution for the delivery of 5G NR compatible subcarrier spaced mm-wave signals. The potential for the photonic integration of almost all transmitter functionality can pave the way for the ultra-dense development of GSL OFC based optical heterodyne A-RoF links in future wireless communication systems.

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