Simplified RF Carrier Extraction and Reuse in OFDM Radio-Over-Fiber Systems

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***Abstract*— We propose and experimentally demonstrate techniques for efficient RF carrier extraction and reuse in an orthogonal frequency-division multiplexing (OFDM) radio-over-fiber (RoF) system. In this system, an RF carrier is generated in the base station through optical heterodyning between two uncorrelated optical carriers delivered from the central office. The RF down conversion is accomplished by mixing the intermediate frequency signal with the extracted RF carrier. This not only relaxes the phase noise requirement on the RF carrier, but also minimizes signal–signal beat interference. We demonstrate an RoF network carrying 8.2 Gb/s QPSK data in OFDM modulation format for both downlink and uplink, which share the same RF carrier, which avoids the need of an additional RF oscillator in the customer unit.**

***Index Terms*— Radio-over-fiber, OFDM, radio frequency photonics, optical fiber communications, RF down conversion, uplink.**

I. Introduction

THE growing demand of bandwidth for wireless communication networks pushes the RF carrier frequencies to tens of gigahertzes, and toward the millimeter-wave (mm-wave) bands [1]. This enables gigahertz signal bandwidth to be carried on the RF carriers. Millimeter wave frequency bands are more susceptible to atmospheric absorption and rain attenuation compared to lower frequency carriers, and therefore the number of base stations (BS) has to be significantly increased with their locations closer to customer units (CU) to accommodate the reduced transmission distance. In order for such networks to be practical, mm-wave carrier generation in BSs and wideband signal delivering from the central office (CO) to BSs have to be simple and efficient. Radio-over-fiber (RoF) technology provides a viable solution by delivering mm-wave carriers and high speed data from CO to remote BSs through optical fibers [2]. This allows BSs to be located further away from the CO and minimizes complexity of BSs. At a CU, downstream baseband signal carried on the mm-wave carrier is recovered and digitally processed, and the mm-wave carrier also needs to be regenerated for upstream data transmission.

A number of techniques have been proposed for mm-wave carrier generation and wideband data transport through RoF [2]–[6]. Optical heterodyning is an attractive method which is capable of generating a wide range of carrier frequencies, limited only by the bandwidth of the photodetector. This simplifies the configuration of BSs by optically delivering the mm-wave carrier from the CO to BSs, and therefore most of the complexity is shifted from the BS to the CO. However, the phase noise of the generated millimeter-wave carrier is determined by the spectral linewidth of the lasers used, which is typically in the tens of megahertz level for a DFB semiconductor laser. Therefore, active phase-locked loop has to be applied to reduce the phase noise of the produced RF carrier [2], [3], and to ensure the quality of the wireless networks carrying phase encoded data. In order to relax the phase noise requirement of the mm-wave carrier, RF self-homodyne has been proposed [4] to down-convert the data signal from IF to the baseband, and therefore conventional DFB laser diodes can be used for optical heterodyne generation of mm-wave carriers without the need of active phase/frequency locking. However, so far, the optical heterodyning technique for mm-wave carrier generation has been used only for the downstream traffic, while the upstream link still requires high-frequency local oscillators for RF carrier generation in BSs and CUs [2], [4], [5], [7], [8]. RF carrier recovery and reuse is therefore highly desirable to realize the full potential of the optical heterodyne technique, and increase the performance-to-cost ratio of RoF systems.

In this letter, we report a technique of RF carrier recovery and reuse in a RoF network based on simple RF filtering. We define Carrier Extraction and Reuse (CER) as a RF technique in which high frequency carrier is extracted using narrowband filtering and reused by mixing it with wideband data for RF down conversion. Orthogonal frequency division multiplexing (OFDM) is used for data encoding which provides high spectral efficiency and high level of flexibility for spectral shaping [9]. This allows a narrow frequency guard band to be reserved on each side of the carrier, so that it can be selected and recovered by a narrowband RF filter. This extracted RF carrier can then be used to carry the upstream traffic. It is important to note that the multi-subcarrier nature makes OFDM modulation format susceptible to signal-signal beat interference (SSBI) when RF self-homodyne [4] is used for down-conversion from IF to the baseband. To avoid SSBI, we have modified the RF self-homodyne process by mixing the extracted carrier with the OFDM subcarriers, the technique we refer to as CER.

II. Experimental Setup

A. Downlink Transmission

Our experimental setup is based on the system as schematically shown in figure 1. In the CO, single sideband (SSB) OFDM signal is digitally generated, in which an 8.32 Gb/s serial data is QPSK modulated and loaded onto 48 subcarriers by serial-to-parallel conversion. IFFT operation is performed on a block of length 256. OFDM signal is created by first

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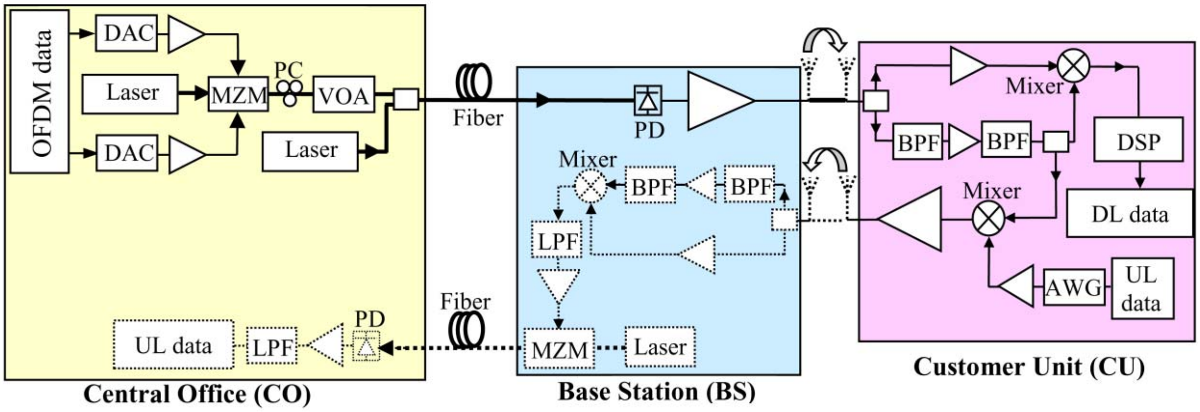

Fig. 1. Experimental setup for the mm-wave OFDM-RoF system. UL: up-link, DL: down-link, PC: polarization controller, VOA: variable optical attenuator, BPF: band-pass filter, LPF: low-pass filter, AWG: Arbitrary waveform generator, PD: Photo detector, MZM: Mach-Zehnder modulator. Dotted lines indicate functions not implemented in the experiment but needed for a full duplex system.

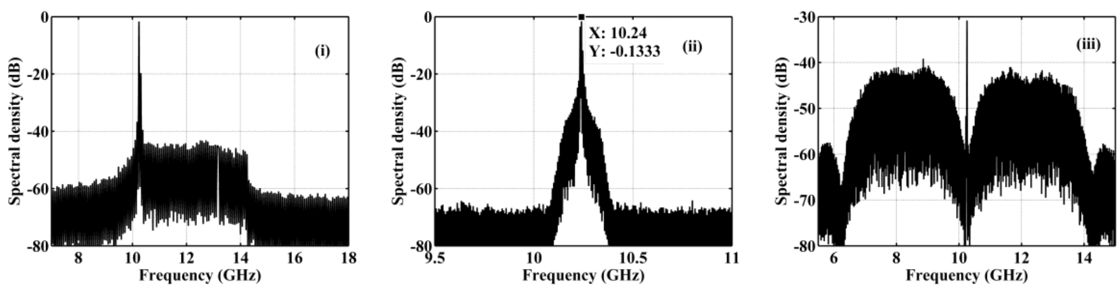

Fig. 2. RF spectra in downlink and uplink paths, measured after photodetector in BS (i), of the extracted carrier used in CU (ii), and uplink data (iii).

considering 64 subcarriers and later padding some subcarriers with zeroes to get the desired transmit signal. Each subcarrier occupies rows 1– 64 while the complex conjugate of the OFDM subcarriers are loaded into rows 193 – 256 in a reverse sequence. This data mapping insures that the time-domain signal has real values after the IFFT operation. Rows 65–192 are padded with zeroes to fill up the entire IFFT window. This ensures 2 times oversampling, which takes 4 samples per OFDM period using the 21.418 GSa/s DAC. Hilbert transform is used to generate an electrical SSB OFDM signal after the parallel-to-serial conversion.

A commercial CIENA optical transmitter, which was originally designed for 10 Gb/s SONET systems with electrical-domain pre-compensation (eDCO) [10], is used to generate the optical SSB signal. This card is equipped with two DACs with 21.418 GSa/s sampling speed at 6-bits resolution. It also has a tunable DFB laser ($\lambda_1 = 1530.720$ nm) with approximately 10 MHz spectral linewidth, and a balanced dual-drive MZM. The two arms of the electro-optic modulator are loaded with parallel-to-serial converted IFFT output and the imaginary part of its Hilbert transform respectively. The bias of the dual-drive MZM was set at the quadrature point for optical SSB generation. Another optical carrier from a separate tunable laser at wavelength $\lambda_2 = 1530.780$ nm is combined with the SSB optical signal through an optical coupler before launching into the transmission fiber. Optical heterodyning between the two optical carriers is performed by the photo-detector in the BS which up-converts the OFDM signal onto a high frequency RF carrier at $\Delta\text{f} = 10.24$ GHz (shown in Fig. 2(i)), along with a baseband replica. This RF carrier frequency of 10.24 GHz in our experiment is chosen to demonstrate the system concept because of the availability of RF filters in our laboratory. As Δf is equal to the frequency difference of the two optical carriers, it can be easily changed to the commercial 60 GHz and 70/80 GHz bands by tuning the optical carriers for mm-wave high data rate applications.

The up-converted RF signal in the BS is then amplified by 30 dB with a wideband (SHF, 30 KHz-40 GHz) amplifier and sent across to the CU. As a proof of concept, an RF cable is used in the experiment in place of the wireless transmission between the BS and CU. Therefore, the impairments of wireless propagation are not included. To recover the data at CU, CER is performed by first splitting the high frequency signal using an RF power splitter (Narda, 2 GHz-18 GHz). At one of the splitter outputs, the RF carrier is selected by a narrowband filters (RLC electronics, 10.24 GHz central frequency, 210 MHz bandwidth) and amplified using an RF amplifier (JCA, 24 dB, 10-20 GHz). The spectrum of the extracted RF carrier is shown in Fig. 2 (ii), which provides an RF local oscillator. This local oscillator is mixed with the high frequency signal at the other output of the power splitter using a mixer (Miteq DMX0418L) to down-convert it to the baseband, which is then recorded using a digital oscilloscope with 20 GSa/s sampling rate and 6 GHz bandwidth. Offline Matlab signal processing is used for synchronization, FFT, equalization and demodulating the QPSK downlink data [11].

Even though the bandwidth of the analog-to-digital convertor (ADC) in scope allows us to perform experiments over a 6 GHz spectrum, the intermediate frequency (IF) bandwidth of the available mixer further limits the usable spectrum to 4 GHz. We incorporate this constraint by reducing the number of OFDM subcarriers from 64 to 51, which reduces the actual data rate to 8.7 Gb/s. Moreover, in order for the carrier to be recovered simply by RF filtering, we reserve an approximately

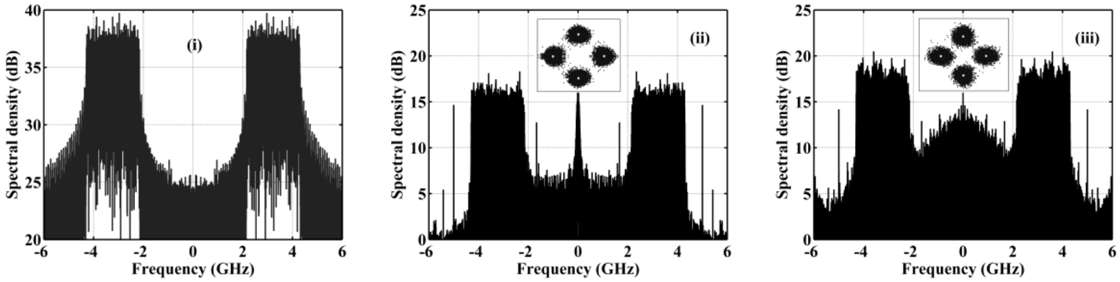

Fig. 3. OFDM spectra with 50% guard band, generated at the CO (i), measured at the CU using CER (ii) and measured at the CU using self-homodyne (iii). The insets in (ii) and (iii) show the respected received constellation diagrams.

300 MHz guard band by zero-padding the first 3 OFDM subcarriers which are adjacent to the carrier. This further reduces the overall data rate to 8.2 Gb/s.

B. Uplink Transmission

The RF carrier extracted in the CER process and shown in Fig. 2(ii) is used to carrier the uplink traffic so that a separate RF oscillator is not required in the CO. The uplink data is a 4 GHz OFDM signal with 3 subcarriers generated by an arbitrary waveform generator (AWG) with 25 GSa/s sampling rate and 10-bit resolution (Tektronix AWG70002A). After mixing with the recovered RF carrier at 10.24 GHz, the uplink RF spectrum transmitted to the BS is shown in Fig. 2(iii).

At the BS, CER can again be used which down converts the uplink data to the baseband. This uplink data can then be modulated onto an optical carrier through an electro-optic modulator or using direct modulation on a laser diode if the data rate is low enough. The uplink data is finally recovered in the CO after direct detection and applying similar signal processing routines as in the CU. As the same carrier frequency is used for both the uplink and downlink, time division, or space division multiple access may have to be used to avoid interference in full duplexing [12].

III. Results and Discussion

In this section, we present the experimental results which compare two techniques of RF frequency down conversion in the downlink path to obtain baseband signal, namely CER and self-homodyne [4]. In self-homodyne, RF signal mixes with itself which is essentially a squaring operation. Whereas in CER, the IF signal mixes with the RF carrier selected by a narrowband filter, which not only provides RF carrier recovery but also avoids SSBI when multi-carrier modulation format is used. We evaluate system performance using Error vector magnitude (EVM) as the performance metric, which is essentially a measure of spreading of received constellation points. EVM has shown to be a reliable metric for high level modulated optical signals including linear and nonlinear impairments [13]. This comparison is performed primarily for the downlink path using OFDM SSB signals with and without a 50% guard-band to show the impact of SSBI. Parameters of the OFDM signals transmitted in these cases are summarized in table 1.

A. OFDM With 50% Guard-Band

To observe the effect of nonlinear mixing among subcarriers on the received spectrum, we first consider an OFDM signal that occupies a 2 GHz bandwidth. Fig. 3(i) shows the data

TABLE I
OFDM Signal Parameters

Parameters	50% guard band [units]	w/o 50% guard band [units]	Uplink [units]
	Downlink		
No. of subcarriers	24	48	3
Δf_{sc}	83.66 [MHz]	83.66 [MHz]	1 [GHz]
Unused subcarriers	1-27 and 52-64	1-3 and 52-64	
Data rate	4.18 [Gbps]	8.2 [Gbps]	6 [Gbps]

Δf_{sc} = separation between OFDM subcarriers

spectrum digitally generated by a Matlab program which drives the transmitter MZM after DAC and RF amplification. In this spectrum, 2 GHz guard band is reserved on each side of the carrier to elaborate the effect of nonlinear mixing in this region. This is done by forcing the subcarriers 1–27 and 52–64 to zeroes, which is commonly referred to as band offset modulation. Fig. 3(ii) and 3(iii) show the received baseband spectra at the CU using CER and self-homodyne, respectively, measured with a real-time sampling oscilloscope, and a FFT and frequency equalization process is applied using offline Matlab program. Comparing the two received spectra shown in Fig. 3(ii) and 3(iii), we see distinct contamination of the spectrum due to SSBI in the 0–2 GHz band when self-homodyne is used. The nonlinear mixing shows a typical triangle shape in the spectrum close to the carrier shown in Fig. 3(iii). Here since the 2 GHz guard band is reserved between the carrier and the signal sidebands, the SSBI crosstalk does not affect the receiver performance, and the average EVM of 24 OFDM subcarriers are approximately 15% for both techniques. However, the reduced SSBI in the guard band shown in Fig. 3(ii) implies that CER technique does not need this 50% spectral guard band, and thus full bandwidth utilization would be possible for the OFDM signal.

B. OFDM Signal With Full Bandwidth Utilization

To measure and compare the impact of SSBI on the received signal with CER and self-homodyne techniques without the 50% spectral guard, we evaluate the EVM for each subcarrier. The transmitted signal in this case occupies the frequency band of 300 MHz – 4.3 GHz consisting of 48 orthogonal subcarriers as shown in Fig. 4(i) (generated in Matlab). We reserve a small guard band (0-300 MHz) to isolate the carrier component so that it can be extracted simply with narrowband filtering.

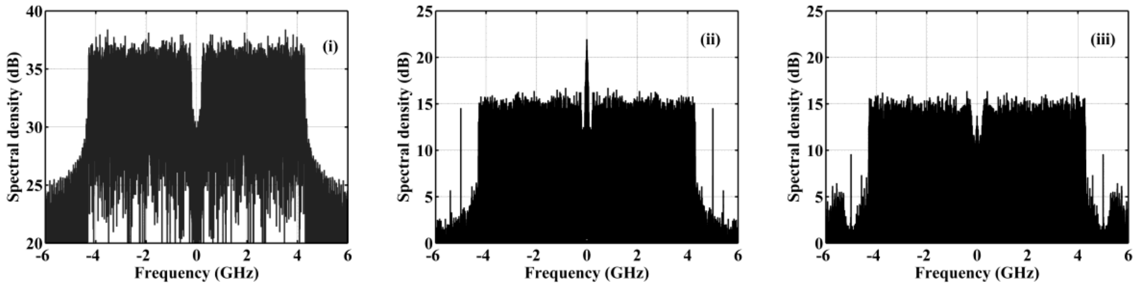

Fig. 4. OFDM spectra without 50% guard band, generated at the CO (i), measured at the CU using CER (ii) and measured at the CU using self-homodyne (iii).

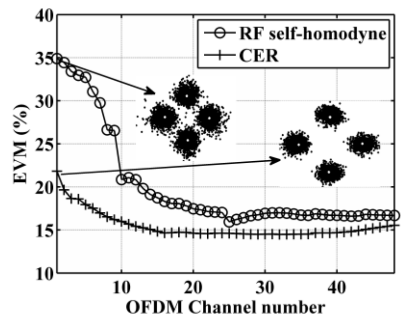

Fig. 5. Relative system performance for two RF down conversion techniques for each subcarrier. The insets show the received constellations diagrams for the first subcarrier for each technique.

The corresponding output spectra at the receiver after CER and RF self-homodyne measured using oscilloscope are shown in Fig. 4(ii) and 4(iii), respectively. Although the shapes of these two spectra look similar, SSBI introduced by nonlinear mixing can be significantly different, especially for the subcarriers adjacent to the carrier. Figure 5 shows EVM measured as a function of OFDM channel number (1 to 48) for the two RF mixing techniques. It is observed that the performance of CER is substantially better than self-homodyne, for channel numbers lower than 24 indicated by the reduced EVM values. In fact, channels 1 to 24 occupy the 300 MHz to 2.3 GHz region in the spectrum which is expected to be contaminated by triangle-shaped SSBI shown in Fig. 3(iii). The EVM of channel 1 (closest to the carrier) for the self-homodyne technique is about 13% higher than that for the same channel when CER is employed. The relative difference in EVM values decreases for subcarriers further away from the carrier. It should be noted that the EVM values from channel 25 to 48 for both techniques were expected to be the same. The small degradation of EVM of self-homodyne at high channel indices is attributed to the slight length imbalance between the two arms leading to the mixer and the introduced phase mismatch before mixing. In addition, for CER the moderate EVM increase for the first 10 subcarriers near the carrier is due to the phase noise of the RF carrier which is generated by heterodyne mixing between two free-running lasers. As both CER and self-homodyne techniques rely on self-mixing between different components of the heterodyne RF spectrum, their requirements on the frequency stability of the two lasers are expected to be comparable, as has been analyzed in [6] for the downlink path. However, further analysis is still needed for the uplink to understand the impact of laser stability using CER.

IV. Conclusion

We have proposed and experimentally demonstrated a simple carrier recovery and mixing technique where the carrier is generated with optical heterodyning in the BS and extracted with narrowband filtering from the downlink path in the CU. This RF down conversion technique (CER) allows OFDM modulation format to be used but with significantly reduced SSBI compared to RF self-homodyne. Carrier recovery and reuse in the CU makes RoF systems simple and cost effective. The use of multi-carrier modulation enables high bandwidth efficiency and flexibility.

References

[1] J. Wells, “Faster than fiber: The future of multi-G/s wireless,” *IEEE Microw. Mag.*, vol. 10, no. 3, pp. 104–112, May 2009.

[2] R. P. Braun, G. Grosskopf, D. Rohde, and F. Schmidt, “Low-phase-noise millimeter-wave generation at 64 GHz and data transmission using optical sideband injection locking,” *IEEE Photon. Technol. Lett.*, vol. 10, no. 5, pp. 728–730, May 1998.

[3] L. A. Johansson and A. J. Seeds, “Generation and transmission of millimeter-wave data-modulated optical signals using an optical injection phase-lock loop,” *J. Lightw. Technol.*, vol. 21, no. 2, pp. 511–520, Feb. 2003.

[4] A. H. M. R. Islam, M. Bakaul, and A. Nirmalathas, “Multilevel modulations for gigabit access in a simple millimeter-wave radio-over-fiber link,” *IEEE Photon. Technol. Lett.*, vol. 24, no. 20, pp. 1860–1863, Oct. 15, 2012.

[5] J. O’Reilly and P. Lane, “Remote delivery of video services using mm-waves and optics,” *J. Lightw. Technol.*, vol. 12, no. 2, pp. 369–375, Feb. 1994.

[6] A. H. M. R. Islam, M. Bakaul, A. Nirmalathas, and G. E. Town, “Simplification of millimeter-wave radio-over-fiber system employing heterodyning of uncorrelated optical carriers and self-homodyning of RF signal at the receiver,” *Opt. Exp.*, vol. 20, no. 5, pp. 5707–5724, 2012.

[7] C.-T. Lin, J. Chen, P.-T. Shih, W.-J. Jiang, and S. Chi, “Ultra-high data-rate 60 GHz radio-over-fiber systems employing optical frequency multiplication and OFDM formats,” *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2296–2306, Aug. 15, 2010.

[8] T. Kuri, H. Toda, J. J. V. Olmos, and K. Kitayama, “Reconfigurable dense wavelength-division-multiplexing millimeter-waveband radio-over-fiber access system technologies,” *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2247–2257, Aug. 15, 2010.

[9] I. B. Djordjevic and B. Vasic, “Orthogonal frequency division multiplexing for high-speed optical transmission,” *Opt. Exp.*, vol. 14, no. 9, pp. 3767–3775, May 2006.

[10] J. D. Gaudette, D. J. Krause, J. C. Cartledge, and K. Roberts, “Offset sideband modulation at 2.5 GSym/s,” in *Proc. Opt. Fiber Commun. Nat. Fiber Opt. Eng. Conf.*, Mar. 2007, pp. 1–3.

[11] S. J. Savory, “Digital filters for coherent optical receivers,” *Opt. Exp.*, vol. 16, no. 2, pp. 804–817, Jun. 2008.

[12] A. Goldsmith, *Wireless communications*. New York, NY, USA: Cambridge Univ. Press, 2005.

[13] R. Schmogrow *et al.*, “Error vector magnitude as a performance measure for advanced modulation formats,” *IEEE Photon. Technol. Lett.*, vol. 24, no. 1, pp. 61–63, Jan. 1, 2012.