Experimental Demonstration of Multiband Comb-Enabled mm-Wave Transmission

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***Abstract*— A novel system architecture to realize multiple synchronized sources for multiband millimeter-wave (mm-Wave) transmission has been designed and experimentally demonstrated in two of the *W*-band subbands at 100 and 112.5 GHz. The technique converts a distributed electro-optic comb, generated off-site, to a local electrical comb. The higher frequency tones in the resulting comb are extracted and used as mm-Wave oscillator sources. Thus, the architecture provides a method to generate multiple frequency-synchronized sources, using only a single electronic oscillator, with exceptionally low phase noise for simultaneous multiband mm-Wave transmission. Additionally, a lower frequency tone at 6.25 GHz is broadcasted over the air, providing synchronization reference between the mm-Wave transmitters and receivers.**

***Index Terms*— Data transmission, frequency comb, frequency generation, frequency synchronization, microwave photonics, millimeter wave (mm-Wave), multiband transmission, phase noise.**

I. Introduction

WITH the emergence of 5G and the anticipation of future 6G networks, the capability of millimeter-wave (mm-Wave) backhaul systems will have to satisfy a large capacity requirement. To fulfill this, multiple mm-Wave frequency bands can be utilized simultaneously through the deployment of multiple transmitters (TXs) and receivers (RXs), resulting in a multiband mm-Wave link. As recently proposed in [1], the frequency bands of interest are the recently commercialized *E*-band (71–86 GHz) and the two higher frequency bands; *W*-band (92–114.25 GHz) and *D*-band (130–148 GHz).

The mm-Wave TXs and RXs commonly utilize a frequency multiplier in the local oscillator (LO) signal path. This is due to the difficulty of generating LO sources directly at mm-Wave with sufficient power levels and low phase noise. However, a frequency multiplier inherently worsens the input phase noise by a function of the frequency multiplication factor [2]. As such, the prefrequency-multiplication phase noise, in particular the wideband phase noise, of the fundamental LO is an important parameter and has been suggested as one of the key limiting attributes to the overall performance of a mm-Wave link [3]. Therefore, to realize simultaneous transmission in different mm-Wave frequency bands, multiple low phase noise and synchronized LO sources are required, which adds significantly to the system cost.

This work proposes a solution, where a single oscillator source can be simultaneously utilized in multiple pairs of mm-Wave TXs and RXs in different frequency bands. To achieve this, an unfiltered electro-optic comb is used to generate multiple synchronized LO sources. Electro-optic refers to the method of generating the optical comb (o-comb) [4], requiring only one electrical oscillator source, which determines both the frequency spacing of the comb lines and the phase noise [5]. The o-comb can either be generated locally or distributed through optical fiber, as will be demonstrated, to multiple locations. Additionally, to enable the synchronization between the TXs or RXs with access to the comb and the corresponding remote RXs or TXs, one of the lower frequency tones from the electrical comb (e-comb) is extracted and broadcasted over the air, thus eliminating the need for the TX–RX clock synchronization via GPS or other means [6].

Along with mm-Wave and terahertz radio-over-fiber [7], the utilization of o-combs to generate sources at these frequencies is well-studied. However, the existing work [8], [9], [10] focuses on the realization of a single frequency source with the state-of-the-art frequency stability and phase noise performance for instrumentation. This is usually done by filtering the o-comb to obtain two of the comb lines. After photodetection, the beating products then generate the wanted LO source at a single frequency. This is in contrast to the proposed technique, where the o-comb is not filtered, and the counterpart e-comb is generated, allowing each tone to be extracted and used as needed by filtering of the e-comb at the TX or the RX.

In [11], the technique to generate the electro-optic comb was described, allowing the distribution of RF tones with 5-GHz spacing. However, the demonstration was done at a single center frequency of 25 GHz, generated from a single sideband filtered o-comb, and simultaneous multiband transmission was not studied. This work presents a proof-of-concept application and an experimental demonstration at mm-Wave, where simultaneous synchronized transmission in two different *W*-band subbands [12] at 100 and 112.5 GHz, enabled by unfiltered o-comb with a fine frequency resolution of 1.5625 GHz, was demonstrated and compared against an existing commercially available oscillator solution.

II. Experimental Setup

An experimental mm-Wave wireless testbed, representing a scenario of *W*-band transmission with two pairs of TXs and RXs in different subbands (denoted W1 and W2), was built.

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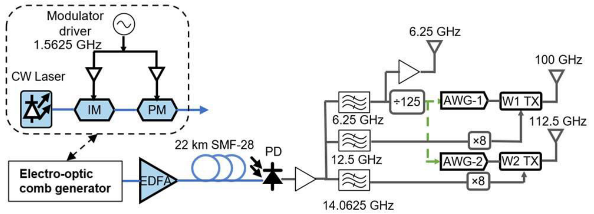

Fig. 1. Simplified block diagram of the experimental setup, TX side.

The W1 and W2 TXs have access to the o-comb, generated off-site and distributed through standard single-mode fiber (SMF-28), as simplified and shown in Figs. 1 and 2(b). The W1 and W2 RXs are shown in Fig. 2(a) and (c).

A. Overview Description

Observing Fig. 1, the o-comb is generated by the electro-optic comb generator and subsequently amplified optically by an erbium-doped fiber amplifier (EDFA). The amplified o-comb is then distributed through 22 km of SMF-28. At the mm-Wave TXs, the 7.5-dBm o-comb is converted to the e-comb using a 20-GHz InGaAs p-i-n photodiode (PD), ARx20 from APIC Corp., with 0.95-A/W responsivity. The e-comb is subsequently amplified, spectrum shown in Fig. 3, split and filtered using three different resonant-cavity bandpass filters (BPFs), centered at 6.25, 12.5, and 14.0625 GHz, to extract the three corresponding frequency-synchronized tones.

The two latter tones are amplified to 2 dBm and passed through frequency octuplers (×8), generating LO sources at 100 and 112.5 GHz for the W1 and W2 TXs, respectively. The two TXs upconvert and amplify two independent sets of baseband I and Q signals generated by the two arbitrary waveform generators (AWG-1 and AWG-2: Keysight M8190A and Rohde and Schwarz SMW200A, respectively). The W-band signals are transmitted through linearly polarized horn antennas (Flann WR10 27240) with 20-dBi gain. The antennas are oriented in orthogonal polarization, as shown in Fig. 2(b), to minimize the mutual coupling.

The former tone at 6.25 GHz, inherently frequency synchronized to the 100- and 112.5-GHz LO sources, is used as a reference source for synchronization between the two AWGs. This is done by frequency-dividing the tone to 50 MHz, a division factor of 125, using a modified Hittite HMC983LP5E. Additionally, the 6.25-GHz tone is amplified and broadcasted over the air using a WIFI dipole antenna; 6.25 GHz was chosen due to the lower propagation loss and the available components, but other e-comb tones can be used.

At the RX side, observing Fig. 2(a), the broadcasted 6.25 GHz is received and frequency divided, providing a 50-MHz reference signal to the two signal generators (LO-RX 1 and LO-RX 2: R&S SMB100A and SMF100A, respectively) and oscilloscope (Scopes 1 and 2: R&S FSW). The 2-dBm signals from LO-RX 1 and 2 are frequency multiplied by ×8 and used as LO signals for the W1 and W2 RXs, respectively. Thus, the LO signals of the four W-band TXs and RXs, the AWGs, and the Scope are all frequency synchronized. The transmitted W-band signals are received and downconverted to baseband and subsequently captured by Scopes 1 and 2.

B. Electro-Optic Comb Generator

The o-comb is generated by using the electro-optic method, as shown in Fig. 1 (top-left corner). A 100-Hz linewidth continuous-wave seed laser at 1550 nm is modulated with an intensity modulator (IM) followed by a phase modulator (PM), both driven by a low-noise 1.5625-GHz tone, generated by Signal Core SC5511A (phase noise: −137 dBc/Hz at 10-kHz offset from 1 GHz). The ultranarrow linewidth laser ensures high coherence between the o-comb tones, thus minimizes the noise of the e-comb after SMF-28 distribution and photodetection. The intensity profile of the o-comb tone is controlled by the IM. The frequency of the driver determines the frequency spacing between adjacent o-comb lines and the fundamental frequency of the e-comb through the PM. After photodetection, the extracted tones, circled in red in Fig. 3, at 6.25, 12.5, and 14.0625 GHz are therefore the fourth-, eighth-, and ninth-order harmonics, respectively.

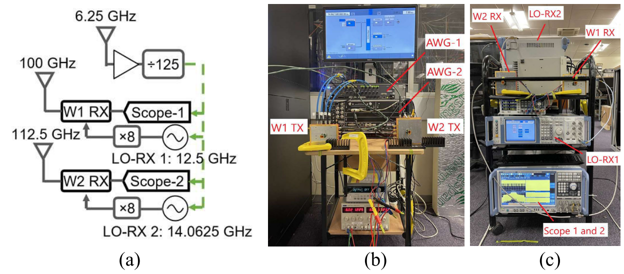

Fig. 2. Experimental setup. (a) Simplified block diagram of the RX side. (b) Photograph of the TX side. (c) Photograph of the RX side.

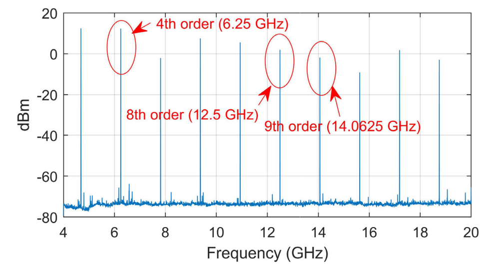

Fig. 3. Measured spectrum of the e-comb at the TXs.

C. W-Band TXs and RXs

The fully integrated W1 and W2 TXs and RXs are from Gotmic AB using GaAs pHEMT technology. The two pairs have recently been characterized and reported in [1] with two alterations: the W2 TX has been improved with a higher power power amplifier (PA) and the W1 RX is without the integrated IF amplifier.

The TXs are mainly equipped with an ×8 in the LO path, a differential IQ mixer, and a PA. W1 and W2 TXs have RF bandwidths of 86–102 and 94–116 GHz and output 1-dB compression points (P1dB) of 24 and 17.5 dBm, respectively. The RXs include an ×8, a differential IQ mixer, a low-noise amplifier, and an IF amplifier for the W2 RX. W1 and W2 RXs have RF bandwidths of 88–102 and 100–115 GHz and third-order input-intercept points of 1 and 2 dBm, respectively.

D. Baseband TXs and RXs

At the TXs, the two AWGs operating at 2.4-GHz sampling rate are generating baseband signals from two independent baseband TXs, implemented in MATLAB. The baseband signals are 16-QAM OFDM with 17 subcarriers at 3.2 Gbit/s per TX, respectively. While at the RXs, the baseband signals captured by Scopes 1 and 2 are processed offline using baseband RXs implemented in MATLAB. The OFDM RXs include standard framing and timing synchronization, linear and nonlinear equalization [13], and detection. No frequency

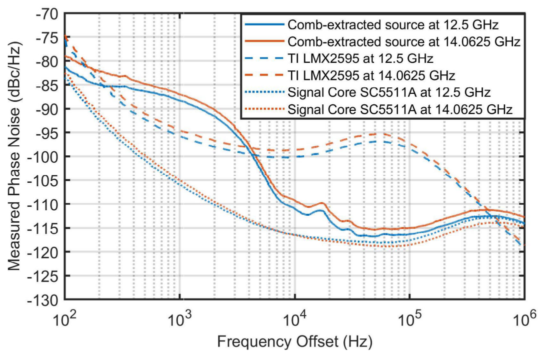

Fig. 4. Measured phase noise of the comb extracted sources, a commercially available synthesizer (LMX2595), and the o-comb driver (SC5511A).

correction was performed as this was facilitated by the broadcasted reference source from the e-comb at 6.25 GHz.

III. Results

A. Measured Phase Noise

The phase noise of the LO sources extracted from the e-comb is measured using R&S FSWP phase noise analyzer from 100-Hz to 1-MHz offset frequency, as shown in Fig. 4. For comparison, a candidate commercially available synthesizer, 20-GHz Texas Instrument LMX2595, is also measured at the same power level of 2 dBm. The unit was chosen due to its commercial availability, while covering the same frequency range as the PD used in the experiment. On the other hand, the phase noise of the Signal Core SC5511A, the o-comb driver, is also measured, thus allowing the penalty of the whole o-comb distribution and e-comb processing chain to be deduced.

The performance difference between 12.5 and 14.0625 GHz is marginal in all three sources. Against the LMX2595, the proposed method performed better in the near-carrier region below 200-Hz offset but exhibited a slight disadvantage from 200 Hz to 4 kHz. Beyond which, the comb performs significantly better. Against its driving source, the comb exhibited expansion of the phase noise in the region below 30 kHz. This is an anticipated effect from the distribution through the dispersive SMF-28 and the beating of the unfiltered o-comb at the PD [5], [14]. However, the wideband phase noise performance in the >30-kHz region matches closely with the low phase noise of the driver, making the approach suitable for wideband mm-Wave transmission.

B. Data Transmission

The data transmission experiment was performed in-lab, representing an indoor cluttered environment with line-of-sights for both pairs of TXs and RXs. The distance between the W-band TXs and RXs was varied from 2 to 8 m with a 1-m step size by relocating the RXs on the trolley shown in Fig. 2(c). The received power spectral densities (PSDs) at 5 m for both bands are shown in Fig. 5 along with the PSDs of the ideal noise-free signal as a reference. Fig. 5(a) shows the received PSD of the W1 TX–RX pair, while Fig. 5(b) shows that of the W2 TX–RX pair. The roll-off response in the W1 band corresponds with the reported gain profile (see Fig. 4 in [1]).

The transmission performance was characterized using the error-vector magnitude (EVM). The number of bits transmitted per TX–RX pair was 4 406 400 bits. To minimize the effect of antenna misalignment and uncontrolled variations in the test

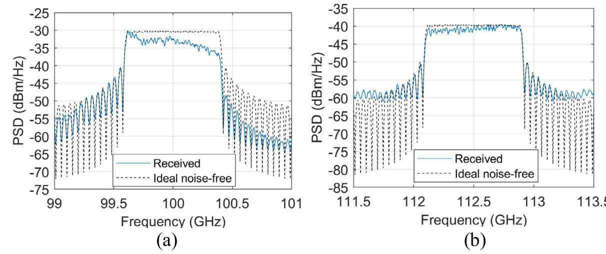

Fig. 5. Received PSDs at 5 m along with those of ideal noise-free signals as reference. (a) W1. (b) W2.

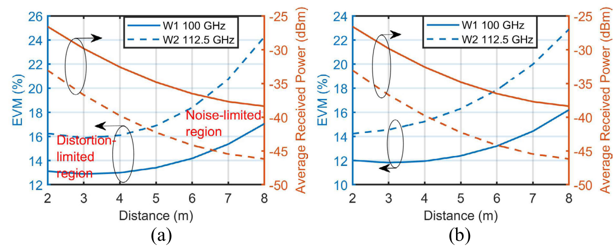

Fig. 6. Experimentally obtained EVM results and the average received power. (a) Received. (b) After the nonlinear equalizer.

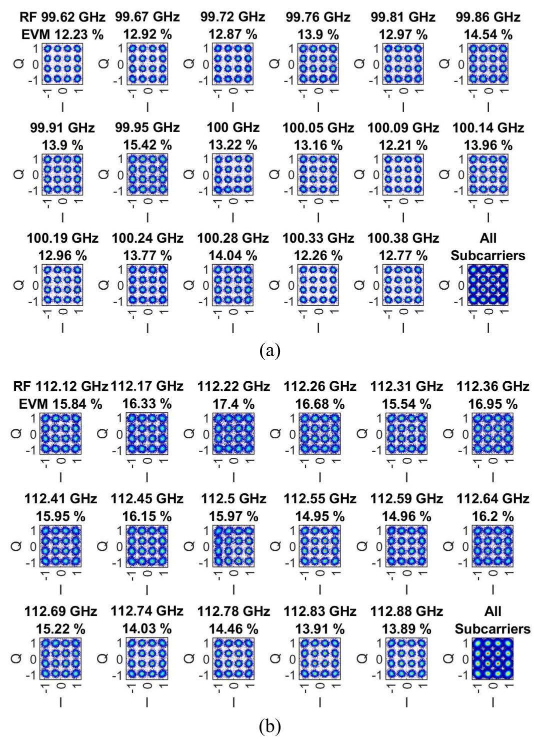

Fig. 7. Received constellation diagrams of each subcarrier at 5 m with the corresponding EVM and RF. (a) W1. (b) W2.

environment, multiple sets of measurements were performed for each distance and the measured EVMs are used to extract the EVM results shown in Fig. 6. The average received power levels at each distance are also included. Fig. 6(a) shows the received EVM (with minimal signal processing), while Fig. 6(b) shows the EVM after nonlinear equalization.

Observing Fig. 6(a), the difference in the average received power between W1 and W2 is due to the higher propagation loss and the lower transmitted power used at W2 to account for the lower P1dB. Considering the profile of the received EVM as a function of distance reveals the noise-limited region from 3 m onward. On the other hand, in the range below 3 m, distortion limited profile, where noise is relatively low and nonlinear distortion is relatively high, can be observed.

The optimal received power appeared around 3 m for both bands. By using the nonlinear equalizer, as shown in Fig. 6(b), the EVM is improved in all cases and the profile of the results below 3 m is improved, as seen clearly in the W2. No indication of phase-noise limited performance is observed.

For illustration, the constellation diagrams of each subcarrier along with the corresponding instantaneous EVM and RF are shown in Fig. 7. The results indicate successful utilization of the comb-generated sources to simultaneously transmit data in the two frequency bands, together with frequency synchronization capability between and within the TX and RX.

IV. Conclusion

Simultaneous data transmission in different mm-Wave frequency bands using a single oscillator source has been experimentally demonstrated at 100 and 112.5 GHz. The technique utilizes the source to generate an o-comb, which can be distributed to multiple locations. In the demonstration, after receiving the distributed o-comb through 22 km of optical fiber, an e-comb with a fine frequency resolution is subsequently generated. As all the tones in the e-comb are frequency synchronized, the required frequency source for each mm-Wave TX can then be extracted as needed. A lower frequency source was also broadcasted over the air to provide frequency synchronization to a remote location, e.g., the mm-Wave RXs, thus eliminating the need to provide frequency synchronization by other existing techniques. The phase noise property of the extracted tones was compared against that of a commercially available oscillator and the oscillator used to generate the comb. Only a slight penalty in the frequency region close to the carrier results from this implementation and no penalty was observed in the region further away.

The technique provides an effective and scalable solution to the mm-Wave phase noise challenge, e.g., the 11th-order harmonic at 17.1875 GHz in the demonstrated electronic comb can be used with a frequency octupler to generate an additional frequency-synchronized source at 137.5 GHz in the *D*-band. Furthermore, with the increasing commercial availability of high-frequency PDs, multiple mm-Wave tones may be generated based on this technique directly, foregoing the requirement of a frequency multiplier, ultimately enhancing the phase noise performance.

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