Synchronising Clock and Carrier Frequencies with Low and Coherent Phase Noise for 6G

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***Abstract*— Using radio over fiber techniques, we generate, transmit and receive a highly accurate 5-GHz spaced frequency comb, with carriers of extremely low phase noise. The carriers are used in an over the air transmission experiment, demonstrating lower phase noise than a commercially available PLL. The low phase noise and scalability of the design offer a new method of carrier and low-jitter clock distribution satisfying the stringent demands of future 6G systems. We demonstrate the efficacy of the method by over the air transmission of 128-QAM signal at 25 GHz. The recovered signal shows the advantage of low phase noise carriers even at received powers approaching -50 dBm**

Keywords — microwave photonics, clock synchronization, wireless transmission

I. INTRODUCTION

The 6G envisages new services such as connected car fleets, virtual reality, remote healthcare, massive Internet-of-thing (IoT) and holography streaming on-demand [1-3]. In addition to communications, the ubiquitous wireless networks are also anticipated to facilitate sensing and precise location services for applications including industrial manufacturing, security and wireless robot control [4]. These visions require future 6G infrastructure to provide accurate clock and timing to the end users together with high throughput data connections [1-4].

Current Cloud-user synchronization is implemented using synchronous ethernet (Sync-E) [5] and precision time protocol (PTP) [6] through fiber links in the radio access networks (RAN), where Sync-E disseminates the reference clock and the PTP provides a time stamp. Nevertheless, the clock extracted from Sync-E has a limited accuracy of about ±10ns due to the relatively high frequency wander in the clock recovery modules, unable to support the 6G vision that demands sub-nanosecond accuracy. Further, the carrier frequencies generated using this high noise clock, either using phase lock loop (PLL) or frequency multipliers, result in high phase noise carriers that fundamentally limit the wireless transmission capacity [7]. Moreover, the unsynchronised carrier frequencies between different base stations impose challenges in cooperative radio and limit the sensitivity of radio sensing using wireless infrastructures [7]. Thus, techniques to achieve low-phase noise clock and carrier synchronization between different base stations are crucial to enable the 6G vision.

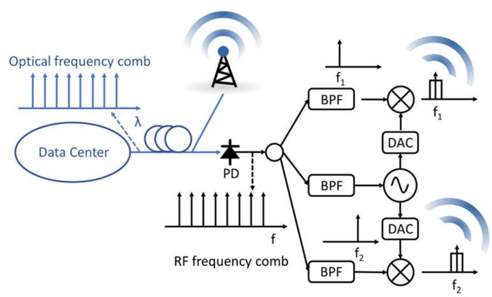

Fig. 1. Conceptual diagram of the proposed system [8].

Here we experimentally demonstrate low-phase noise clock and carrier synchronization over more than 20 km standard single mode fiber (SSMF) using a single-sideband optical frequency comb, proposed in [8]. In particular, the phase noise performance of each tone in the comb is demonstrated at different fiber lengths. We develop an optoelectronic frequency comb [9] that features a flat spectrum, low phase noise and high power per tone. As shown in Fig.1, the optical tones are converted to 5-GHz-spaced RF carriers with low phase noise (<100 fs jitter integrated for 1kHz-10MHz) and coherent RF tones up to 25 GHz. By filtering one sideband of the frequency comb, we overcome the frequency fading induced by the fiber dispersion, achieving stable RF power delivery for base stations of different distances. In our design, the lowest frequency carrier is divided to a <100-fs-jitter 50 MHz reference clock that drives high resolution signal generators and detectors, permitting 1.4 Gb/s real-time wireless transmission using 128 QAM.

II. EXPERIMENTAL SETUP

An experimental setup representing the proposed system was built and shown in Fig. 2a. The optical frequency comb dissemination system is shown in blue and the wireless transmission systems in grey. A 100-Hz narrow linewidth continuous wave (CW) laser seeds an opto-electronic frequency comb generator consisting of a phase modulator (PM) and a Mach-Zehnder modulator (MZM), both driven with a 5 GHz RF signal from the same synthesizer [9], yielding a 5-GHz-spaced optical frequency comb signal with a spectral flatness of about 6 dB. The comb signals were subsequently amplified from

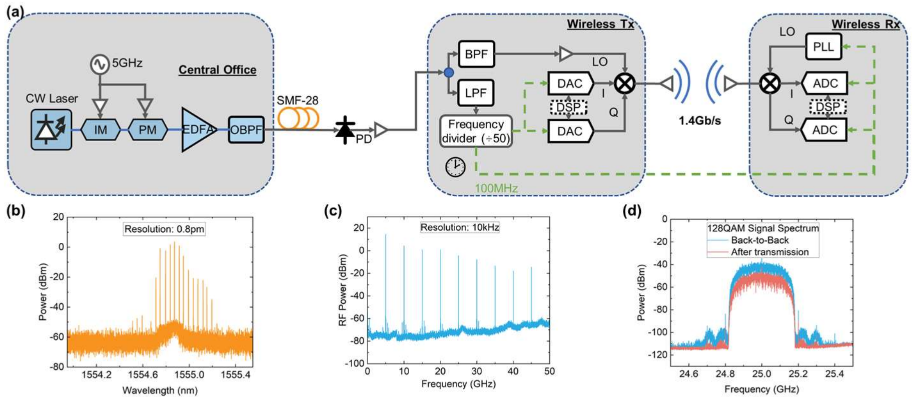

Fig. 2. (a) Experimental set-up. OBPF: optical bandpass filter, PD: photodetector, PLL: phase-locked-loop, DSP: digital signal processing (b) Optical spectrum of filtered optical frequency comb, (c) Electrical spectrum of RF frequency comb at 3.5 dBm received optical power, (d) Electrical spectrum of RF 128QAM signal at back-to-back (blue) and after transmission (red).

0 dBm to 19 dBm using an erbium-doped fiber amplifier (EDFA) of 5-dB noise figure. The amplified signal then passes through an optical band pass filter (OBPF), which transmits the upper side band of the frequency comb, as shown in Fig. 2b. The filtered comb signals were transmitted through standard single mode fibers (SSMF) to the radio unit (RU) side before detection by a 40 GHz photodetector. Different fiber lengths (6, 10, 16 and 22 km) were used to evaluate the fading due to fiber dispersion. After transmission, the coherent optical tones beat with each other and generate an RF comb signal with 5 GHz spacing, which is amplified by a 40 GHz RF amplifier with 38-dB gain. The spectrum of the disseminated RF signal is shown in Fig. 2c. The 5 GHz tone has the highest power and the powers of the high frequency tones decrease due to the reduced number of optical tone pairs with a larger frequency spacing and the frequency roll-off of the photodetector. The RF comb is used both for clock and carrier synchronization of the wireless system. To achieve this a Wilkinson power divider was used to split the signal. One output of the divider was connected to a 5.5 GHz bandwidth low pass filter (LPF) to extract the 5 GHz RF signal, which is subsequently divided to 100 MHz as the reference clock for the wireless systems, as shown by the dashed line in the experimental setup in Fig. 2a.

A 50 MHz bandwidth RF bandpass filter (BPF) centered at 25 GHz is connected to the other output of the divider extracting the 25 GHz RF tone to be used as the local oscillator of the wireless transmitter. The 1.4 Gbit/s 200 MSymbol/s 128-QAM with root-raised cosine pulse shape (0.8 roll-off factor) baseband signal was generated using two 16-bit digital to analog converters (DAC). The LO signal from the RF comb then upconverted the baseband signal to 25 GHz using an IQ mixer. The RF spectrum is shown in Fig. 2d. The RF signal is then transmitted using a horn antenna. At the receiver, another horn antenna situated 10 cm away was used to receive the wireless signal. After downconversion to baseband, the IQ signals are captured by two analog to digital converters (ADC) followed by digital signal processing and demodulation, including IQ orthogonalization, match filtering and equalization.

III. Results

Fig.3 shows the dispersion tolerance of the RF comb delivery. The markers indicate the experimental results at

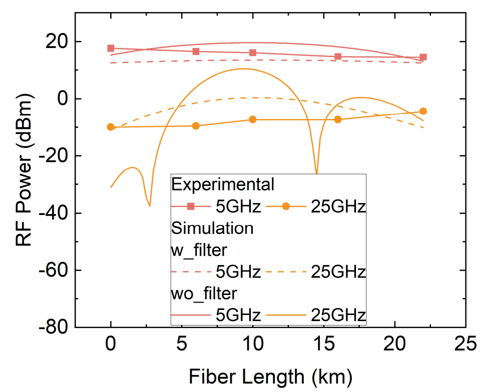

Fig. 3. Distributed RF power after transmitting over different fibre lengths

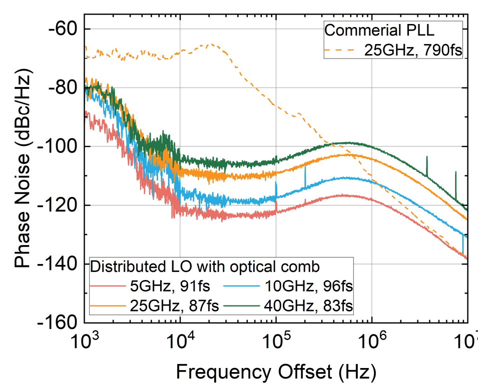

Fig. 4. Phase noise measurement of distributed RF tones after 22 km SSMF, phase noise of commercial PLL is shown as comparison

different fiber lengths (e.g. DU-RU distance) and the dashed curves show the simulation results. For comparison, we simulate the transmission of an unfiltered frequency comb and show the power fading using solid curves. Without the single side band filtering, the tones in the uppers side band and the lower side band destructively beat with each other at a certain fiber length due to the dispersion induced group velocity delay (GVD). Using a single side band of the frequency comb, the distance-associated power fading is much reduced and results in stable RF clock and RF carrier power dissemination regardless of the

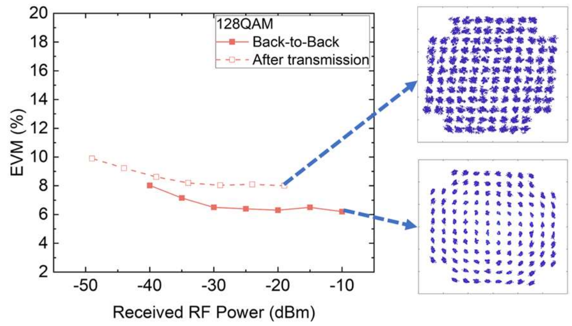

Fig. 5. EVM results at different received RF power of 200 MSymbol/s 128QAM.

in the simulation and experimental results are due to the inaccurate estimation of the fibre dispersion and the spectral shape of the filtered comb. Fig. 5 shows the measured phase noise of the distributed RF tones after transmission over 22 km SSMF, showing an integrated jitter of 87-96 fs (1kHz to 10MHz) for the distributed tones from 5-40 GHz. After transmission, the fiber dispersion introduces GVD difference to the 25-GHz-spacing optical tones pairs which leads to enhanced phase noise in the low frequency region. For comparison, we pot the measured phase noise of a commercial electronic phase lock loop (PLL) using a solid black curve, which shows a much worse phase noise in the low frequency region (<600kHz) and exhibits a large rms jitter of 790 fs. In the high frequency region (>600kHz), the phase noise of the distributed 25-GHz tone is worse than the commercial PLL due to the driver signals used for the frequency comb generation, which can be improved with lower phase noise drivers.

Fig. 5 shows the error vector magnitude (EVM) of the received wireless signals at different RF power. A back-to-back comparison was made by directly connecting the transmitted RF signals to the receiver's RF input, as shown by the solid square markers. Using 128 QAM, we obtained a clear constellation (shown as the inset) with an EVM of 6.2% at -20 dBm. After transmission through the air, the EVM degraded to 8.0% at the same receiver power. At -50 dBm received power (i.e., 30 dB loss), we can still achieve an EVM value of 10% after the wireless transmission. This means we could transmit 25-GHz centered wireless signal up to 3 meters, assuming an ideal free-space path loss, 2x20 dBi horns and perfect coupling/alignment.

The impact of phase noise due to fiber transmissions is shown in Fig.6. With back-to-back, the distributed RF tones show similar rms jitters. As transmission distance increases, the jitter increases from 83 to 95 fs for 5 GHz, but only increased slightly to 85 fs for the 40 GHz tone. This is because the 5GHz tone results from the beating between more than 10 pairs of 5-GHz-spacing optical tones whilst there were only two pairs of 40-GHz-spacing tones in the transmitted comb [12]. The decorrelation due to the different GVD for different optical tones degrades the optical phase coherence between the tone pairs, which increased the jitter.

IV. Conclusion

Simultaneous distribution of sub-100-fs jitter clock and low noise 5-GHz spaced RF tones using a filtered electro-optic frequency comb has been experimentally demonstrated.

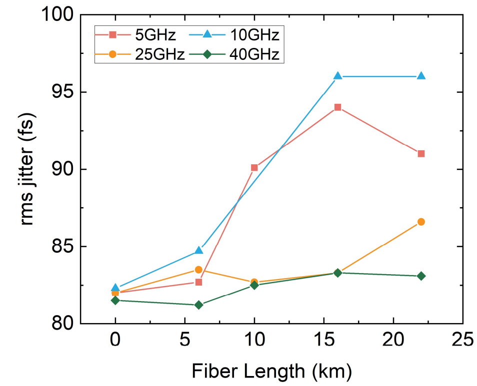

Fig. 6. Rms jitter of distributed RF carriers using filtered optical frequency comb for different fiber length.

Exceptionally the RF comb exhibited a significantly enhanced tolerance to power fading with less than 10 dB RF power variation observed. By comparing the obtained phase noise using lasers of different linewidths, it was observed that the decoherence of optical tones mainly degrades the low frequency phase noise. High performance wireless transmission of up to 1.4 Gb/s net rate was achieved using the proposed distributed carrier and clock.

Acknowledgment

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References

[1] Z. Jiang et al., "Phase-Stabilized Side-Branch RoF Link for Extensible Frequency Dissemination in Distributed Systems," in IEEE Photonics Journal, vol. 13, no. 5, pp. 1-7, Oct. 2021.

[2] M. Sung et al., "Demonstration of IFoF-Based Mobile Fronthaul in 5G Prototype With 28-GHz Millimeter wave," in Journal of Lightwave Technology, vol. 36, no. 2, pp. 601-609, Jan 2018.

[3] H. Li et al., "Analysis of the Synchronization Requirements of 5g and Corresponding Solutions," in IEEE Communications Standards Magazine, vol. 1, no. 1, pp. 52-58, March 2017.

[4] M. Koivisto et al., "Joint Device Positioning and Clock Synchronization in 5G Ultra-Dense Networks," in IEEE Transactions on Wireless Communications, vol. 16, no. 5, pp. 2866-2881, May 2017.

[5] G.8262. Timing characteristics of a synchronous equipment slave clock https://www.itu.int/rec/T-REC-G.8262-202003-I!Amd1/en

[6] G.8261. Timing and synchronization aspects in packet networks (2008).

[7] J. Chen et al., "Influence of White LO Noise on Wideband Communication," in IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 7, pp. 3349-3359, July 2018.

[8] Z. Zhou et al., "Simultaneous Clock and RF Carrier Distribution for Beyond 5G Networks Using Optical Frequency Comb," in The European Conference on Optical Communication (ECOC), Sep 2022.

[9] J. Capmany and D. Novak, "Microwave photonics combines two worlds", Nature Photon., vol. 1, pp. 319-330, 2007.

[10] H. H. Elwan, J. Poette and B. Cabon, "Simplified Chromatic Dispersion Model Applied to Ultrawide Optical Spectra for 60 GHz Radio-Over-Fiber Systems," in Journal of Lightwave Technology, vol. 37, no. 19, pp. 5115-5121, Oct, 2019.

[11] G. Qi et al., "Phase-Noise Analysis of Optically Generated Millimeter-Wave Signals With External Optical Modulation Techniques," in Journal of Lightwave Technology, vol. 24, no. 12, pp. 4861-4875, Dec. 2006.

[12] C. Deakin et a., "Phase noise of electro-optic dual frequency combs," Opt. Lett. Vol. 46, no.6, 1345-1348, 2021.