Single-carrier 26.88 Tbps CPRI-equivalent data rate and 14151 dB·GHz PSAB for 1024 QAM signals using time-interleaved DA-ROF and MCF

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***Abstract*—We introduce a time-interleaved (TI) digital analog radio over fiber (DA-RoF) scheme and demonstrate hardware-efficient compensation of the dynamic transmission impairments, i.e., phase noise and polarization rotation, in a high baud coherent transmission system. In the proof-of-concept experiment, we demonstrate a record CPRI-equivalent data rate of 26.88 Tbps for 1024-QAM wireless signals transmitted over 42 km of weakly-coupled 7-core fiber, achieving the highest product of SNR and aggregated bandwidth (PSAB) of 14151 dB·GHz to our knowledge. The experimental results show the potential of the TI coherent DA-RoF system in realizing high-speed, high-fidelity, and scalable mobile fronthaul transmission systems using multicore fiber.**

Keywords—radio over fiber, multicore fiber, time-interleaving, CPRI, SNR.

I. Introduction

The fast-growing mobile telecommunication traffic poses the demand for high-speed and high-fidelity optical fronthaul transmission schemes. The digital radio-over-fiber (D-RoF) scheme based on the CPRI protocol suffers from low bandwidth efficiency due to a high quantization resolution required to mitigate the quantization noise and spectrally-inefficient binary modulation format. In comparison, the analog RoF (A-RoF) scheme offers much-improved bandwidth efficiency due to the direct up-conversion of the wireless signal into the optical domain. However, the limited SNR of the A-RoF scheme impedes the use of high-order modulation formats, which is needed in order to scale the throughput of the end-users. Recent A-RoF demonstrations achieved a maximum SNR of 24 dB [1,2], falling short of the 32 dB SNR threshold (equivalent to <2.5% EVM) needed for the adoption of *1024 quadrature amplitude modulation* (QAM) signals according to 3GPP standards [3].

Trading spectral efficiency for the highest possible SNR has received increasing interest, presenting the opportunity to support high-order and spectrally-efficient modulation formats while achieving high capacity in the fronthaul transmission system. The phase-modulation (PM) A-RoF scheme obtains a 6 dB SNR gain for every halving of the spectral efficiency and demonstrates the transmission of high-order QAM signals, such as 1048576-QAM [4]. By expanding the signal bandwidth through four-wave mixing, the PM A-RoF scheme demonstrates an 8.8 dB SNR gain at 1/3 of the spectral efficiency in a testbench transmitting 1024-QAM signals [5]. Furthermore, the DSP-assisted digital-analog RoF (DA-RoF) scheme demonstrates a 12.8 dB SNR gain at half of the spectral efficiency, reaching a CPRI-equivalent data rate of 160 Gb/s for 1024 QAM signals in an IMDD system [6,7]. By adopting coherent detection with quadrupled spectral efficiency owing to phase- and polarization diversity, a higher CPRI-equivalent data rate of 400 Gb/s is reported for 1024-QAM signals [8]. More recently, self-homodyne coherent DA-RoF has been demonstrated by remotely sending a co-propagating local oscillator (LO) in a dedicated core of a 2 km 7-core fiber (MCF) and achieves an aggregate 10.5 Tb/s CPRI-equivalent data rate for 1024-QAM signals [9]. However, the random birefringence of the fiber requires dynamic polarization control of the remotely sent LO, resulting in additional system complexity as well as reliability concerns for the practical implementation of remote radio units (RRU).

TABLE I. Comparison of different RoF demonstrations

	CPRI-equivalent rate (Tbps/λ)	*Modulation Format*	*PSAB (dB·GHz/λ)*	*Reach (km)*
IM/PM A-RoF [1]	1.03	64-QAM	393	20
PM A-RoF [4]	1.05	256-QAM	770	42
IM-DD DA-RoF [6]	0.16	1024-QAM	148	/
Pilot-assisted DA-RoF [8]	0.4	1024-QAM	812	10
Homodyne DA-RoF [9]	1.80 (*10.5 for MCF*)	1024-QAM	969 (*5814 for MCF*)	2
TI-DA-RoF (this work)	3.84 (*26.9 for MCF*)	1024-QAM	2064 (*14151 for MCF*)	42

In this paper, we present time-interleaved coherent DA-RoF scheme (TI-DA-RoF), that can compensate for the dynamic transmission impairment and eliminate the need for a co-traveling LO alongside the hardware for dynamic polarization control. Our scheme also avoids the SNR penalty induced in digital tone-assisted carrier phase recovery. We achieve a record single-wavelength CPRI-equivalent data rates of 26.88 Tb/s for 1024-QAM OFDM signals and 31.08 Tbps for 256-QAM OFDM signals, both transmitted over 42 km of weakly-coupled 7-core fiber. In order to eliminate the impact of the varied oversampling ratio (1:1 and 3:2 as adopted in [8] and [9]) and to make a fair comparison, we introduce a performance metric that evaluates the capacity of different RoF demonstrations based on the *product of the SNR and the aggregated bandwidth (PSAB)* of the demodulated wireless OFDM signal. We show in Table I that we achieve the highest PSAB value of 14151 dB·GHz for 1024 QAM signals over 42 km of MCF, which shows the potential of the proposed scheme for high-speed and high-fidelity mobile fronthaul connections.

II. Principle of the TI-DA-RoF Scheme

Figure 1(a) demonstrates the principle of the TI-DA-RoF scheme, where each OFDM sample is split into a digital sample (N^2-QAM signal) and an analog sample. The analog sample is obtained by subtracting the digital sample from the original sample, and it is scaled by a factor of β (N-1) to align the peak values with the digital sample. An unbalanced factor α is introduced to adjust the power ratio between the digital and analog samples. Fig. 1(b) shows the demodulation process where the decision results of digital samples are combined with the analog samples in order to reconstruct the original OFDM sample. Fig. 1(c) illustrates the time-interleaving and deinterleaving procedures. Interleaving the digital and analog symbols enables compensation for the transmission impairments since the dynamic channel impairments are tracked using the digital symbols and subsequently corrected for both the digital symbols and the adjacent analog symbols. The variation of phase noise and polarization rotation is assumed as a relatively static process for neighboring symbols which holds true for systems operating at a high symbol rate as required to handle the growing capacity demand of mobile fronthaul.

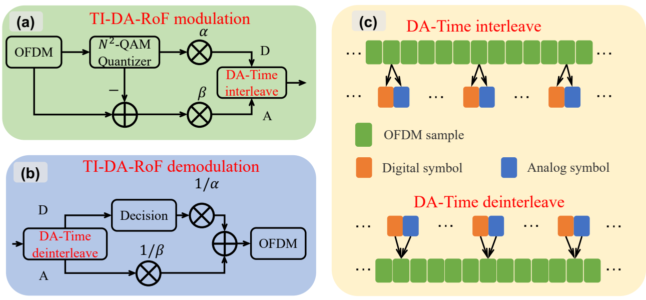

Fig. 1. (a) TI-DA-RoF modulation diagram. and (b) TI-DA-RoF demodulation diagram, (c) DA time interleave and deinterleave diagram.

III. Experimental Setup

Figure 2 illustrates the experimental setup and DSP blocks. The transmitter DSP employs a 720-point inverse fast Fourier transform (IFFT) to generate OFDM symbols consisting of 470 modulated subcarriers and appended with 48 cyclic prefixes (CP) samples. To improve spectral efficiency (SE), the OFDM waveform is down-sampled by a factor of 3:2 before the TI-DA-RoF modulation block [9,10]. The resulting OFDM signal is then divided into analog and digital symbols. These symbols are time-interleaved and up-sampled to 2 samples per symbol (SPS) for pulse-shaping using a raised-cosine (RC) filter with a roll-off factor of 0.1. Subsequently, the shaped signal is resampled to match the sampling rate of a 65 GHz bandwidth arbitrary waveform generator (AWG) operating at 128 GSa/s. Following digital-to-analog conversion, four tributaries of RF signals drive a dual-polarization Mach Zehnder modulator (DP-MZM) to imprint the TI-DA-RoF signal onto an optical carrier at 1550 nm generated by a laser with a 100 kHz linewidth. The modulated optical signal is then amplified by an erbium-doped fiber amplifier (EDFA) and split into seven branches using a power splitter due to the lack of seven optical transmitters. These branches are coupled into a fan-in module of a weakly-coupled 7-core multi-core fiber (MCF) with inter-core crosstalk below -40 dB and transmitted over a distance of 42 km.

At the receiver end, the optical signal in each core of the MCF is received using an integrated coherent receiver (ICR) and sampled using a real-time oscilloscope (RTO) with a sampling rate of 256 GSa/s. In the receiver DSP, the received signal is resampled to 2 samples per symbol (SPS) and fed into a real-valued 4x4 linear MIMO equalizer for polarization derotation and inter-symbol interference (ISI) removal. The MIMO equalizer is updated only at the digital samples and directly applied to the analog samples due to nearly identical channel responses experienced by the adjacent digital and analog samples at a symbol rate of 64 and 74 Gbaud in 1024-QAM and 256 QAM transmission, respectively. After equalization, FFT-based frequency offset compensation (FOC) is performed using the 1 SPS digital symbols while excluding the analog symbols. The estimation of phase noise is achieved using a blind phase search algorithm (BPS) that processes the digital symbols using a sufficiently long noise rejection window in order to mitigate performance degradation caused by probabilistically shaped digital symbols. The estimated phase error is then directly applied to the adjacent analog samples for phase recovery.

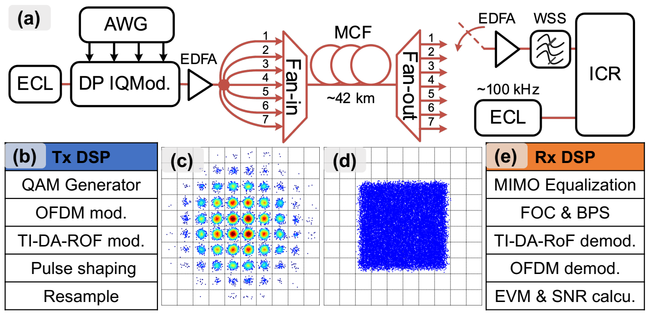

Fig. 2. (a) Experimental setup, (b) transmitter- and (e) receiver-side DSP, (c) constellation of the received 100-QAM digital symbols before the decision, (d) constellation of the received analog symbols.

IV. Results and Discussions

We first conduct parametric testing for the TI-DA-RoF scheme by sending 1024-QAM OFDM signals with a DA symbol rate of 54 GBaud. We measure the SNR of the wireless OFDM signal using different unbalanced factors α and different resolutions of the digital part, i.e., from 81-QAM to 144-QAM. The results are depicted in Figure. 1. The figure shows that the SNR of the recovered signal initially increases and then decreases as the unbalanced factor α increases in all digital resolution conditions. A lower α results in a lower SNR of the digital part, causing more decision errors and reducing the SNR of the recovered OFDM signal. A higher α can reduce decision errors, but it also decreases the SNR gain resulting from the decision operation. The optimal setup is the digital resolution of 100-QAM and unbalanced factor α of 1.7, achieving the highest SNR of 33.86 dB.

For higher transmission capacity, we test a higher DA symbol rate from 54 GBaud up to 66 GBaud in 1024-QAM transmission. As Fig. 4 shows, the SNR of 64 GHz 1024-QAM is higher than the SNR threshold of 32 dB.

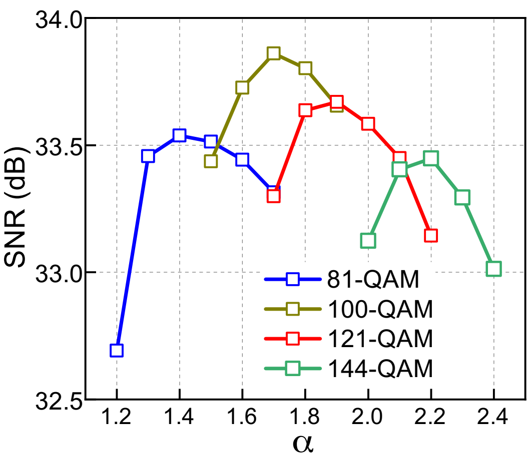

Fig. 3. SNR of recovered 1024-QAM versus α for different digital resolutions.

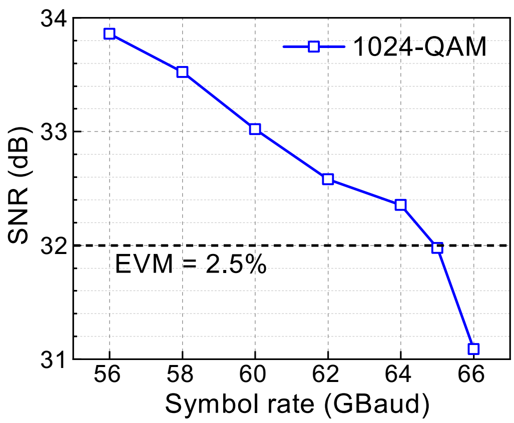

Fig. 4. SNR versus different DA symbol rates.

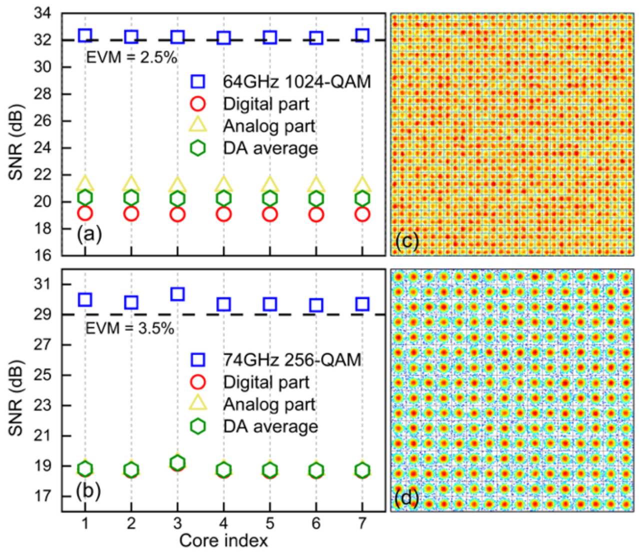

Fig. 5. SNR of (a) 64 GHz 1024-QAM and (b) 74 GHz 256-QAM in 7-core MCF, a constellation of recovered (c) 1024-QAM and (b) 256-QAM.

Figure 5(a) depicts the SNRs achieved in 64 GHz 1024 QAM transmission in all cores of the 42 km 7-core MCF. It is seen from this figure that the EVM threshold of 2.5% for 1024-QAM is satisfied in all cores. The 1024-QAM system achieves the CPRI-equivalent rate of up to 26.88 Tbps (= 64/2 × 2[polarizations] × 2[I and Q quadratures] × 7[core] × 3/2[resample] × 15 × 16/15 × 10/8 Gbps) and PSAB of 14151.38 dB·GHz (= 64GHz/2 × 2[polarizations] × 470/480 × 32.26dB × 7[core]). Next, we test the SNR of 74 GHz 256-QAM OFDM signal in the 7-core MCF, as shown in Fig. 5(b). With the 3.5% EVM threshold, the CPRI-equivalent rate of 31.08 Tbps and PSAB value of 15131.35 dB·GHz are achieved.

V. Conclusions

The proposed TI-DA-RoF enables the highest single-wavelength CPRI-equivalent data rate of 26.88 and 31.08 Tbps for 1024- and 256-QAM OFDM signals over 42 km of 7-core MCF. Additionally, we achieve the highest PSAB of 14151 dB·GHz for 1024-QAM OFDM signals, which indicates the potential of the proposed scheme in high-speed and high-fidelity mobile fronthaul communications.

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