Transmission of Tb/s CPRI-equivalent Rate Using Coherent Digital-Analog Radio-over-Fiber (DA-RoF) System

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Abstract: A coherent digital-analog radio-over-fiber (DA-RoF) system is proposed and experimentally demonstrated. An EVM below 3.5% with a CPRI equivalent rate of 1 Tb/s is achieved using a 25 Gbaud dual-polarization signal over a 10-km distance.

1. Introduction

5G radio access networks (RAN) have been commercialized and are being deployed worldwide. In 5G fronthaul, the enhanced common public radio interface (CPRI), denoted as eCPRI, based on optical transceivers with a data rate of 25 Gb/s is employed to realize a CPRI equivalent rate beyond 100 Gb/s [1]. Towards 6G, it is anticipated that the peak rate of wireless signals will be at least ten times higher than 5G [2]. In this case, the RAN fronthaul with a CPRI-equivalent rate beyond 1 Tb/s is needed. Coherent optical transceiver with a Tb/s data rate is being developed, and it can satisfy the required data rate of digital radio-over-fiber (D-RoF) systems for 6G [3]. However, it does not meet the requirement of fronthaul in terms of cost and power consumption. On the other hand, analog radio-over-fiber (A-RoF) systems can minimize the required bandwidth of optical transceivers but they hardly meet the error vector magnitude (EVM) or equivalently signal-to-noise ratio (SNR) requirement of wireless signals especially for high bandwidth 6G signals [4]. Therefore, more efficient transmission architectures for fronthaul to improve the EVM based on low-cost optical transceivers have attracted increasing attention. For example, a phase modulation (PM) aided A-RoF system was proposed to realize a tradeoff between the spectral efficiency and SNR [5-8]. More recently, a hybrid digital-analog radio-over-fiber (DA-RoF) system was proposed and it achieved a SNR gain up to 12.8 dB at the cost of the doubled bandwidth relative to an A-RoF system [9]. Based on DA-RoF, a CPRI equivalent rate of 160 Gb/s is demonstrated with a 10-GHz intensity-modulation and direct detection (IM-DD) system [9].

In this paper, we propose and experimentally demonstrate a coherent DA-RoF system with a CPRI equivalent rate beyond 1 Tb/s. DA-RoF compatible coherent DSP is introduced and optimized. In the experiment, a 25 Gbaud coherent DA-RoF signal is transmitted over 10-km fiber with an EVM below 3.5%, achieving a CPRI equivalent rate of 1 Tb/s for 256-QAM wireless signals. We also show that the SNR of the coherent system is crucial to further improve EVM. By reducing the symbol rate to 10 Gbaud, where the SNR improves to 23.6 dB, the EVM reaches below 2.5%, which is sufficient to support 1024-QAM wireless signals.

2. Coherent DA-RoF system

Fig. 1 depicts the modulation, demodulation and DSP blocks of the coherent DA-RoF system. The wireless signals from all the antenna-carriers (AxCs) together with the CPRI control word (CW) bits are mapped and normalized to generate the analog RoF signal, which is denoted as S. The modulation and demodulation of S follow the same procedure of the DA-RoF scheme proposed in [9]. In particular, by representing $S = W_1+W_2$, where W_1 is a digital n-QAM signal after the rounding operation of S, a time-domain multiplexing (TDM) symbol sequence is generated with the W_1, W_2 and CW symbols properly scaled and then interleaved in the time domain. Note that the CW bits are mapped to 16-QAM symbols. The TDM symbol sequence then passes through a root-raised-cosine (RRC) pulse shaping filter with a roll-off factor of 0.1. Since the DA-RoF signal contains the W_2 part, which is intrinsically analog, modulation-dependent carrier phase recovery (CPR) algorithms such as digital phase-locked loop and blind phase search are no longer applicable. Therefore, we adopt the pilot tone based CPR scheme [10] and insert a pilot tone at the edge of the signal.

At the receiver, after the front-end correction, the pilot tone is extracted and used for frequency offset compensation (FOC) and CPR. Afterwards, a complex 2-by-2 MIMO filter is applied to compensate linear impairments such as chromatic dispersion (CD), polarization-mode dispersion and polarization rotation. The filter taps are updated based on the least mean square (LMS) algorithm using the W_1 symbols to calculate the error signal. Note that since the distance for fronthaul is relatively short, it is not necessary to implement a bulk CD compensator.

An additional real 4-by-4 MIMO filter is adopted to further improve system performance by compensating transmitter inphase quadrature (IQ) errors. Finally, the equalized DA-RoF symbols are demultiplexed, scaled and combined to reconstruct the analog RoF signal. In this process, the W_1 and CW symbols pass through the rounding operation and 16-QAM demodulation, respectively.

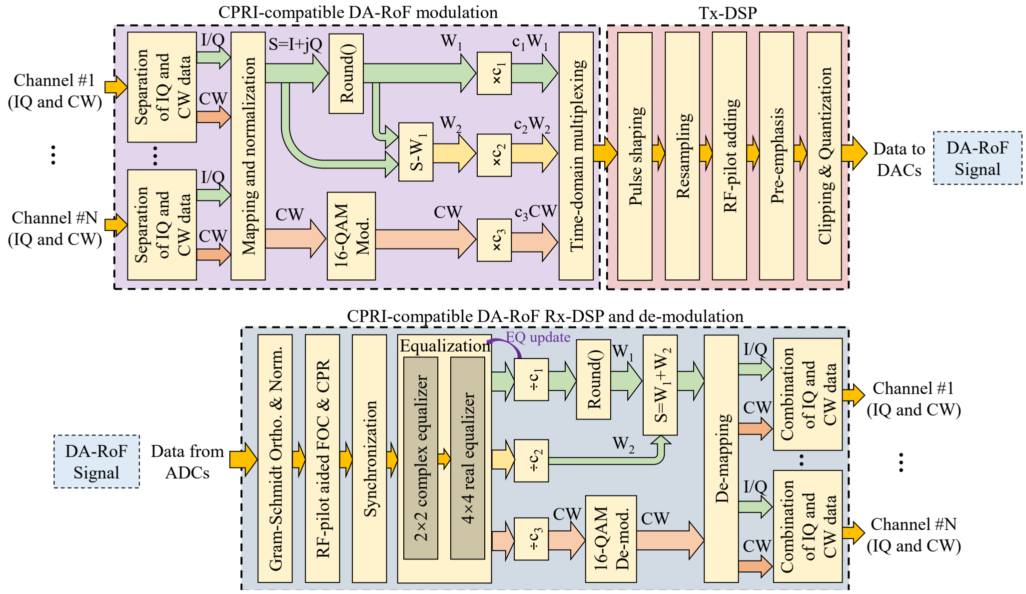

Fig. 1. The modulation, demodulation and DSP blocks of the coherent DA-RoF system.

3. Experimental setup and results

Fig. 2(a) depicts the experimental setup for the coherent DA-RoF transmission. The DA-RoF signal was generated following the procedure described in the previous section. The generated digital signals were sent to an arbitrary waveform generator (AWG) with a sampling rate of 80 GSa/s and then amplified by four radio frequency (RF) drivers. The output electrical signals were modulated by a dual-polarization (DP) IQ modulator. An external cavity laser (ECL) with a nominal linewidth of 100 kHz was adopted. The optical signal was amplified by an erbium-doped fiber amplifier (EDFA) and the launch power was -1.5 dBm. After 10 km transmission of standard single mode fiber (SSMF), a variable optical attenuator (VOA) was employed to adjust the received optical power (ROP) of the signal. Then the optical signal was received by an integrated coherent receiver (ICR) and another ECL was used as the local oscillator (LO). The output electrical signals were captured by a real-time digital storage oscilloscope (DSO) with a sampling rate of 100 GSa/s and a bandwidth of 33 GHz. For a 25 Gbaud DP DA-RoF signal, the CPRI-equivalent data rate is 1 Tb/s [9]. Similar to [9], 121-QAM was used for W_1 by performing the calculation of $round(5S/E_{max}) \cdot E_{max}/5$, where E_{max} is the maximum amplitude of S. Note that the wireless signal at the transmitter was generated without any noise. Fig. 2(a) plots the constellation of transmitted W_1 symbols.

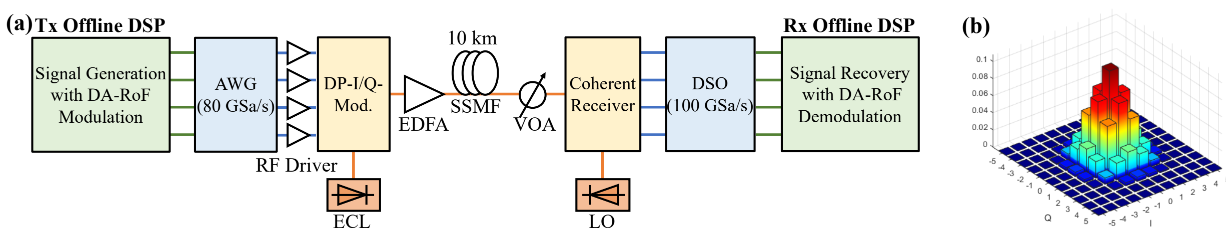

Fig. 2. (a) Experimental setup for the coherent DA-RoF transmission. (b) Constellation of transmitted W_1 symbols.

Fig. 3(a) plots the measured SNR as a function of ROP. We calculate the SNR of the received DA-RoF symbols relative to the transmitted DA-RoF symbols, and the SNR of the wireless signal after the DA-RoF demodulation. The difference between them is defined as the SNR gain through the DA-RoF demodulation. As per Fig. 3(a), the SNR gain reaches 9.7 dB when the SNR of the received DA-RoF symbols is 20.0 dB. To evaluate whether the experimental performance meets the target, we conducted simulations with a simple AWGN channel. The results in Fig. 3(b) show that at the 20 dB SNR of DA-RoF symbols, the SNR gain is 11.9 dB, which is higher than the experimental result, indicating that the experiment can be further improved. Fig. 3(b) also shows that the c_1 and c_2 should be optimized for each SNR to balance the rounding errors of W_1 and noise variance of W_2.

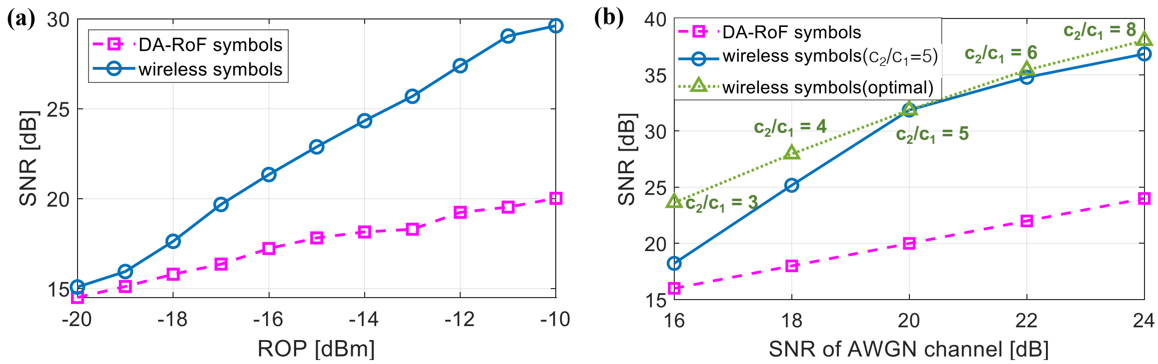

Fig. 3. (a) Measured SNR as a function of ROP in experiment. (b) Simulated SNR as a function of SNR in AWGN channel.

The SNR of coherent optical systems at high symbol rates is typically quite limited due to the various transceiver impairments including DSP implementation penalty, laser phase noise, driver nonlinearity, ADC/DAC quantization noise, and so forth. These impairments normally increase as the symbol rate increases for the same transceiver. In Fig. 4, we evaluate the performance of the coherent DA-RoF system as a function of symbol rate with -10 dBm ROP. As per Fig. 4(a), the SNR of the received DA-RoF symbols is 23.6 dB, 21.0 dB, 20.0 dB and 18.6 dB, and the corresponding SNR after the DA-RoF demodulation is 34.2 dB, 32.0 dB, 29.7 dB and 25.4 dB, respectively. The resulted EVM is plotted in Fig. 4(b). We can see that the 25 Gbaud signal reaches an EVM below 3.5% (threshold for 256-QAM), and the 10 Gbaud signal reaches an EVM below 2.5% (threshold for 1024-QAM). These results demonstrate that the coherent DA-RoF system can be a promising candidate for future 6G fronthaul, and by further improving the bandwidth and SNR of the coherent system, CPRI-equivalent multi-Tb/s fronthaul will be feasible.

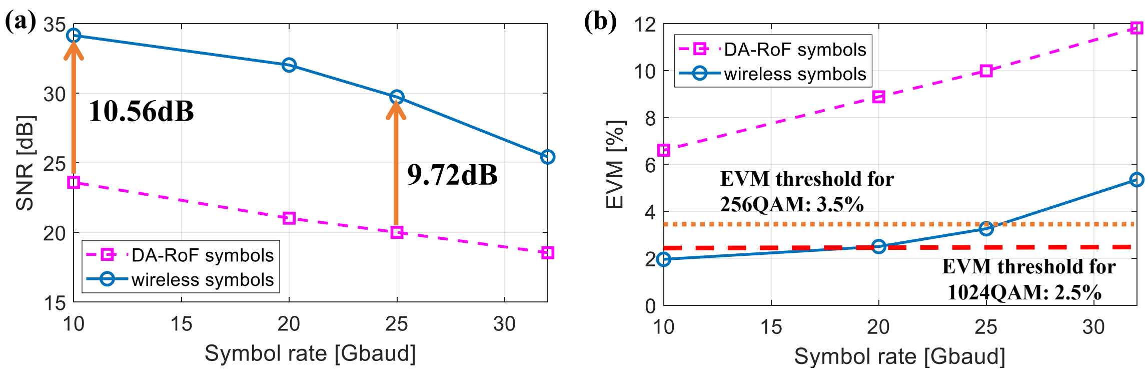

Fig. 4. Experimental results of the coherent DA-RoF system as a function of symbol rate: (a) measured SNR and (b) measured EVM.

4. Conclusion

We experimentally demonstrated a coherent DA-RoF system with a CPRI equivalent rate beyond 1 Tb/s, which can be a promising solution for 6G RAN fronthaul. In the experiment, a SNR gain of 9.7 dB was obtained for 25 Gbaud DP signals through the DA-RoF demodulation, achieving a CPRI equivalent rate of 1 Tb/s with an EVM below 3.5%. The performance of the coherent DA-RoF system was also studied for different symbol rates, indicating the importance of the SNR of the coherent system to support high fidelity wireless signals.

Acknowledgement

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