1.92-Tb/s CPRI-Equivalent Rate Direct Detection Transmission based on ANN Pre-Equalization for Digital-Analog Radio-over-Fiber Mobile Fronthaul

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Abstract: We experimentally demonstrate a 1.92-Tb/s CPRI-equivalent data-rate supporting 1024-QAM OFDM signal in a direct-detection-based digital-analog radio-over-fiber mobile-fronthaul link using ANN for signal pre-equalizations. Performances of pre-equalizers or post-equalizers based on different methods are also studied. © 2024 The Author(s)

1. Introduction

The surge in bandwidth demand in the radio access network (RAN), driven by 5G/6G networks, high-resolution video streaming, and mobile X-haul, is reshaping the industry. Cloud Radio Access Network (C-RAN) with Baseband Unit (BBU) and Remote Radio Unit (RRU) is widely adopted [1]. Small cells at higher frequencies divide into Centralized Unit (CU), Distributed Unit (DU), and Radio Unit (RU). Mobile fronthaul (MFH) is crucial for the DU-RU connection, supporting heavy data traffic demands due to the functional split among network elements [2]. In the Digital-Radio-over-Fiber (D-RoF) context, Common Public Radio Interface (CPRI) offers high fidelity (SNR > 80 dB) but is bandwidth-inefficient due to multiple quantization bits [3]. To combine the spectral efficiency of Analog-RoF (A-RoF) and fidelity of D-RoF, Digital-Analog RoF (DA-RoF) is introduced [4]. It divides the wireless waveform into quantized digital and analog parts, resulting in a significant gain compared with A-RoF.

In this paper, we experimentally demonstrate the high-speed DA-RoF mobile fronthaul transmission in C-band using intensity modulation and direct-detection with nonlinearity pre-compensation based on ANN. With 64-Gband subcarrier modulation, 32-GHz 1024-QAM OFDM signal is successfully transmitted over 500-m standard single-mode fiber (SSMF) with EVM below 2.5% threshold. The CPRI-equivalent data rate reaches a new record for 1024-QAM OFDM signal, which can be calculated as 48 (sampling rate) × 2 (IQ) × 15 (resolution) × 16/15 (CPRI overhead) × 10/8 (8b10b encoding) = 1.92 Tb/s. Different pre- and post- equalization methods are also comprehensively studied. This provides an ultra-fast, cost-effective solution for future 5G-advanced and 6G mobile fronthaul.

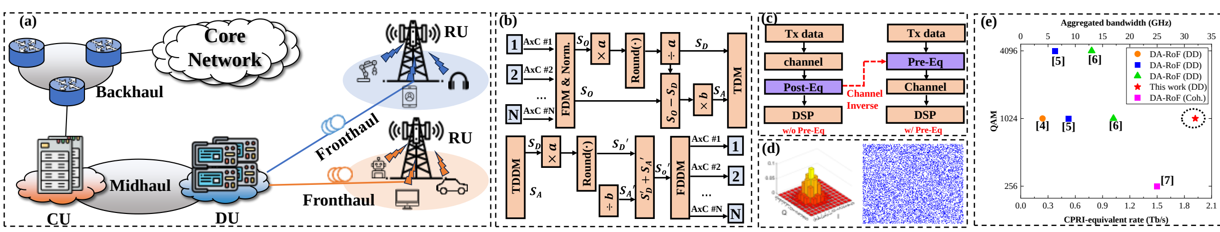

Fig. 1. (a) The structure of RAN. (b) The principle of DA-RoF modulation and demodulation. (c) the principle of channel estimation for equalization (d) constellations of digital and analog part of DA-RoF signal, respectively. (e) CPRI-equivalent data rate and aggregated signal bandwidth versus QAM order in recent radio-over-fiber transmission experiments. DD: direct detection; Coh.: coherent;

2. Principles

The mobile fronthaul links connect the DU and RU shown in Fig, 1(a). Multiple wireless signals corresponding to different antenna carriers (AxC) are combined via frequency division multiplexing (FDM) shown in Fig. 1(b). After amplitude normalization, the original wireless signals, S_O, are separated into digital (S_D) and analog (S_A) parts, as shown in Fig.1 (d). The S_D is calculated by rounding operation as $S_D = round(a \cdot S_O)/a$, where a is rounding factor. It determines the constellation of S_D. The S_A is obtained by subtraction operation as $S_A = b \cdot (S_O - S_D)$, where b is scaling factor. It determines the power ratio of S_D and S_A and. The power ratio plays a significant role in performance of DA-RoF. In DA-RoF demodulation, S_D and S_A are separated by time division demultiplexing (TDDM). Then, the recovered digital ($S_D{}'$) and analog ($S_A{}'$) parts are $S_D{}' = Round(a \cdot S_D)$ and $S_A{}' = S_A/b$. The recovered signal is $S_o{}' = S_D' + S_A{}'$.

In this work, pre-equalization and post-equalization methods using Volterra series or ANNs are applied to the DA-RoF system. Fig.1 (c) illustrates the channel estimation principle. Initially, unprocessed Tx data is sent through the channel. On the receiver side, post-equalization is performed after resampling and synchronization to protect channel information. Post-equalization acts as a signal recovery aid, with the amplitude frequency response as the inverse transfer function of the channel. The equalizer stabilizes during training, providing weight coefficients or the equalizer model for pre-equalization. Optimizing pre-equalization signal amplitudes is crucial to avoid overshoots and high peak-to-average power ratio (PAPR), which can impact system performance. To avoid this problem, we define an optimization parameter g to quantify the extent of pre-equalization and its impact on the PAPR of the transmitted signals [8]. Assuming the raw data without pre-equalization are $s(n)$ and the fully pre-equalized data are $d(n)$, the real transmitted data is $t(n) = s(n) + g\big(d(n) - s(n)\big)$, where n is the time index. Properly adjusting the g ratio is crucial to achieve suitable pre-equalization.

3. Experiment and Discussions

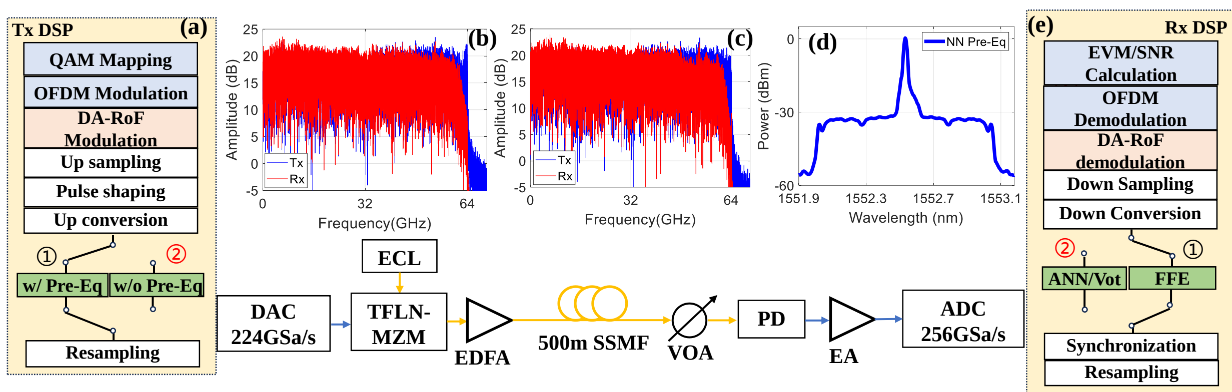

Fig. 2 Experimental setup of the DA-RoF system, (a) and (e) are the Tx and Rx DSP. (b) is the spectrum of the transmitted (Tx) signal w/ pre-eq and received (Rx) signal. (c) is the spectrum of the transmitted (Tx) signal w/o pre-eq and received (Rx) signal. (d) is the measured optical spectrum w/ pre-eq.

Fig. 2 shows the experimental setup of the DA-RoF system. At the transmitter side, the bits are first mapped into 1024-QAM symbols. OFDM modulation is used to simulate aggregated wireless signals. The FFT size is set as 2048. Then, the OFDM signal is modulated by DA-RoF modulation. After 4-times up-sampling, pulse shaping with 0 roll-off and digital up-converted, the transmitted signal, whether pre-equalized with ANNs or Volterra series or not, is generated and sent to a 224-GSa/s digital-to-analog converter (DAC). The baud rate of the signal is set at 64 Gbaud. A Thin-Film Lithium Niobate Mach-Zehnder modulator (TFLN-MZM) with 60-GHz bandwidth is employed to modulate the optical carrier from external cavity laser (ECL), whose center wavelength is 1552.52 nm. An Erbium-Doped Fiber Amplifier (EDFA) is employed to amplify optical signal. The transmission link is 500-m standard single-mode fiber (SSMF).

At the receiver, a variable optical attenuator (VOA) is placed to adjust the received optical power (ROP). The received optical signal is detected by 100-GHz photodiode (PD). Then, a 55-GHz electronic amplifier (EA) is employed to amplify electrical signal. The electrical signal is captured by analog-to-digital converter at 256 GSa/s. For the offline processing, the signal is re-sampled to 4 samples-per-symbol. Synchronization is achieved by identifying the peak of the cross-correlation between the received signal and the synchronization sequence. Without pre-equalization, post-equalization uses a 3rd-order Volterra or ANN equalizer to remove ISI and nonlinearity and train the channel model. With pre-equalization, only an FFE equalizer is used. Fig. 2 (b) shows the spectrum of the transmitted (Tx) signal with pre-equalization and received (Rx) signal. Fig. 2 (c) shows the spectrum of the transmitted (Tx) signal without pre-equalization and received (Rx) signal. The 3rd-order Volterra equalizer uses RLS for tap updates, with tap lengths of 201, 21, and 19 for different orders. The ANN includes input, two hidden, and output layers with 201, 20, 20, and 1 node, employing ReLU activation in the hidden layers. The 3rd-order Volterra equalizer requires 4654 multiplications per symbol, while the ANN needs 4481 multiplication. The complexity of the 3rd-order Volterra equalizer is slightly higher than that of the ANN equalizer but comparable. Afterwards, the signal is down-converted and down-sampled to 1 sample-per-symbol. After DA-RoF demodulation, the OFDM signal is recovered by FFT. The EVM and SNR are calculated based on the recovered constellation.

Fig. 3(a) shows the measured SNR versus the combinations of the rounding factor (a) and the scaling factor (b) for the 64-Gbaud DA-RoF signal with FFE post-equalization at back-to-back (BTB). The maximum recovered SNR value is 30.9 dB, which is achieved at the optimal combination of (a, b) is (5, 5). Fig. 3 (b) show the measured SNR versus the ratio of NN pre-equalization g. When $g = 0.2$, we get best NN pre-equalizer. Insets (i) and (ii) are the transmitted signal in time domain with NN pre-equalization under different ratio. We find the PAPR of (ii) is significantly higher than that of (i), leading to the degradation in system performance.

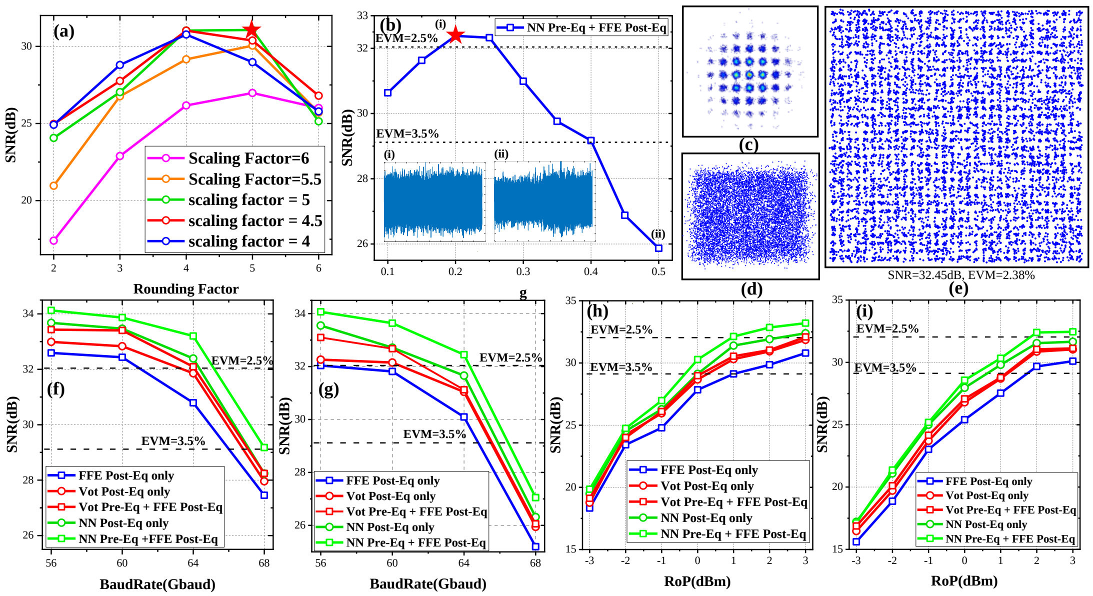

Fig .3 (a) Measured SNR versus the rounding factor and scaling factor. (b) Measured SNR versus NN pre-equalization ratio g. Measured SNR versus baud rate with (f) at BTB and (g) after transmission. Measured SOP sensitivity with (h) at BTB and (i) after transmission. (c), (d) and (e) are constellations of digital part, analog part and 1024-QAM

The SNR performances of 56, 60, 64 and 68-Gbaud DA-RoF signal for different transmission cases are presented in Fig. 3 (f) and (g), which are at BTB and after 500-m fiber transmission. The NN pre-equalization has the best performance among the five schemes. After transmission, only NN pre-equalization can reach the 2.5% EVM threshold at symbol rate of 64 Gbaud, whose measured SNR is 32.45 dB. NN pre-equalization, NN post-equalization, Volterra pre-equalization, and Volterra post-equalization signals can all reach the 2.5% EVM threshold at symbol rate of 60 Gbaud after transmission. Fig. 3(g) and (i) show the measured SNR versus received optical power (ROP) at symbol rate of 64 Gbaud. NN pre-equalization, NN post-equalization, and Volterra pre-equalization signals can reach the 2.5% EVM threshold at BTB, whose ROP sensitivities are 1.0, 2.3 and 3.0 dBm, respectively. But only NN pre-equalization signal can reach the 2.5% EVM threshold after transmission, whose ROP sensitivities is 1.8 dBm. Finally, we successfully realize 64 Gbaud, corresponding to 32-GHz aggregated bandwidth, 1024-QAM DA-RoF signal transmission. Fig. 3(c), (d) and (e) show the constellations of digital part, analog part and 1024-QAM when ROP is 3 dBm.

.4. Conclusion

We report a 1024-QAM DA-RoF system in the IM-DD experiment for future mobile fronthaul. Using NN pre-equalization, we successfully demonstrate a record 1.92-Tb/s CPRI-equivalent data rate fronthaul link, supporting the 1024-QAM format after fiber transmission. Different pre- and post- equalization methods are also comprehensively studied. This provides more effective solutions for the future mobile fronthaul applications of DA-RoF systems.

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