ASE Source enabled 2 Tb/s CPRI-Equivalent Rate 1024-QAM DA-RoF Transmission

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Abstract: We demonstrate unprecedented 2nm broadband ASE source-enabled digital-analog radio-over-fiber mobile fronthaul system with joint force of SOAs for intensity noise suppression and multicore fiber for self-homodyne detection. We achieve 35GHz(=7core×5GHz) aggregated bandwidth with 2Tb/s CPRI-equivalent data rate supporting 1024-QAM signal.

1. Introduction

As a critical link connecting central units (CUs) and remote radio units (RRUs), fiber-based mobile fronthaul plays a pivotal role in the rapid and seamless delivery of data in telecommunication. Towards the era of 5G and beyond, in an attempt to boost capacity and reduce latency, several radio-over-fiber (RoF) schemes have been brought up (D-RoF [1], A-RoF [2], etc.). Among them, the recently proposed digital-analog radio-over-fiber (DA-RoF) scheme comes into prominence as it has outstanding strength in ensuring high fidelity and large capacity at the same time [3]. Most DA-RoF schemes rely on the utilization of narrow-linewidth lasers as light source [4-5].

Broadband light sources, on the other hand, as opposed to narrow-linewidth lasers, draw attention due to their low cost and cost-effective manufacturing. However, their intensity noise sets an upper limit on the achievable signal-to-noise ratio (SNR), making them unsuitable for most fiber communication scenarios, including mobile fronthaul, which favors advanced 5G modulation formats such as OFDM-1024-QAM and requires high SNR [6].

Another challenge associated with using broadband light sources is the stringent requirement for time delay. In self-homodyne scenarios, the path difference between the signal and the local oscillators (LOs) must be kept within the coherence length of the broadband light source. For example, for a 1 nm broadband light source, the coherence time is 5 ps [7]. Yet for the single-mode fiber (SMF), the relative time delay variation can be up to 15 ps in 2 h measurement, making coherent transmission impossible for the broadband light source [8].

For the first time, here we present a self-homodyne coherent DA-RoF transmission using a broadband ASE source with a 2 nm bandwidth. This achievement is attributed to two essential factors: (1) The utilization of two cascaded semiconductor optical amplifiers (SOAs), operating in a saturated state, plays a pivotal role in effectively mitigating the intensity noise of broadband ASE source and enhancing the SNR. This improvement addresses a critical limitation on broadband sources in scenarios that demand high-order modulation formats and SNR, such as in the context of mobile fronthaul. (2) Our approach incorporates an 1 km 8-core fiber, where one core transmits the local oscillator (LO), and the remaining cores handle the signals. This implementation offers dual advantages. Firstly, the use of a multicore fiber (MCF) ensures a stable time delay between the LO and the signal since they share the same fiber and are subject to the same environmental conditions [9], ensuring stable transmission and detection of signal and LO. Secondly, it significantly enhances the capacity of coherent transmission using space division multiplexing (SDM), meeting the growing demand for mobile fronthaul transmission. Here we realize a CPRI-equivalent rate of 2 Tb/s with 1024-QAM using a super broadband ASE source of 2 nm. Remarkably, an SNR gain reaches a surprising 19.4 dB, thanks to the joint effort of 2 SOAs and the DA-RoF scheme. This innovative approach paves the way for the extensive deployment of cost-effective, broadband light sources in large-scale fronthaul networks.

2. Experimental setup

The experimental setup of the reduced-intensity noise broadband light source-enabled SDM self-homodyne DA-RoF fronthaul link is illustrated in Fig. 1.a. At the transmitter (Tx), the broadband ASE source is generated with a center of 193.400 GHz. It is subsequently amplified by two cascaded SOAs, both operating in a saturated state, to ensure the maximum suppression of intensity noise [10]. Then, the optical signal is divided into two parts using a 50:50 coupler, one for signal modulation and the other one serving as LO. In the signal modulation section, we employ a single-polarization (SP) IQ modulator for coherent transmission with the signal generated from a 100 GSa/s 35 GHz arbitrary waveform generator. It's worth noting that we only demonstrate SP coherent transmission due to instrument limitations. Polarization division multiplexing (PDM) can be further realized with a double-polarization IQ modulator. The modulated signal is then split by a 1:8 coupler and injected into core No. 2-8 of a 1 km uncoupled 8-core MCF. The MCF's insertion loss is approximately 5 dB due to the fan-in/ fan-out, the inter-core crosstalk is <-30 dB. All cores of the MCF present good consistency according to former tests. The time delay between core 1 and the others is 10 to 425 ps and the relative time delay fluctuation is observed to be kept within 2 ps during the experiments. At the receiver side (Rx), the LO first passes through a tunable optical delay line to compensate for the path difference between the signal and LO. Both the signal and LO undergo second-order dispersion compensation using Waveshapers before they are mixed in the coherent receiver and detected using an 80 GSa/s 33 GHz real-time oscilloscope.

The DSP procedure is depicted in Fig. 1.b., with a focus on two key processes. For details, see reference [3]. The first is the DA-RoF modulation, where the signal is modulated into DA-RoF symbols. This is achieved by dividing it into digital component, $S_D = B \cdot \text{Round}(A \cdot S_0)/A$, and analog component, $S_A = (S_0 - S_D/B) \cdot 2A$. These components are then cascaded in a time division multiplexing (TDM) manner. The rounding factor A, which determines the SNR gain of the digital component, and the scaling factor B, which controls the amplitude ratio of digital to analog component, have been pre-optimized with specific values of 4.3 and 1.7, respectively. Another procedure we stress is the simplified receiver DSP, which leaves out the Carrier Phase Estimation (CPE) and Frequency Offset Estimation (FOE) thanks to the self-homodyne architecture enabled by MCF.

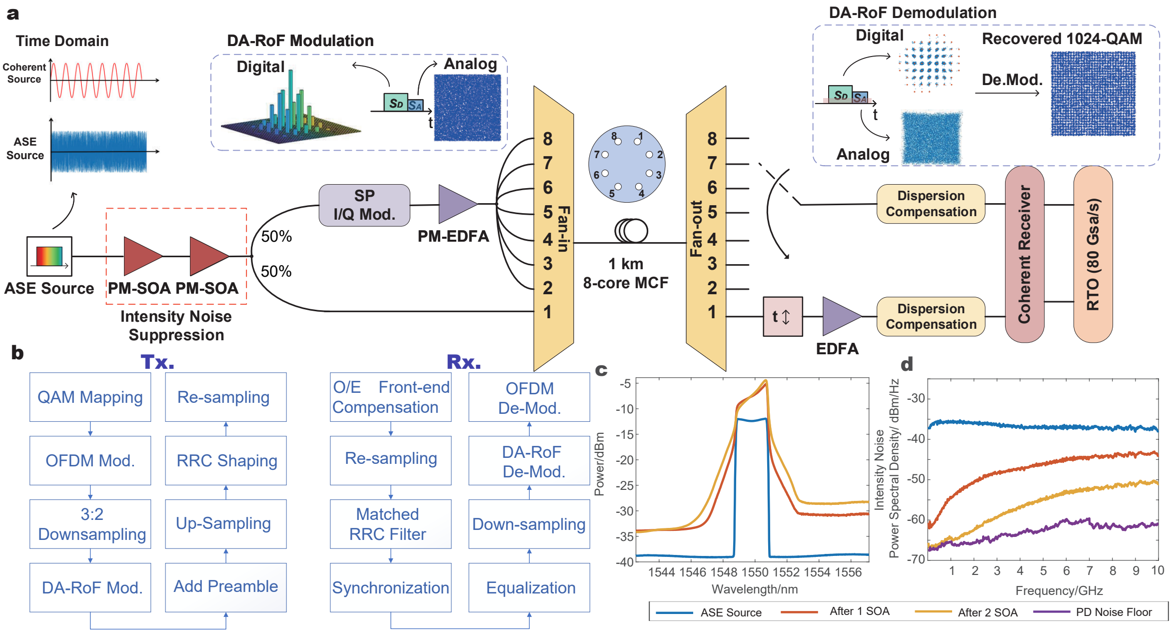

Fig. 1. (a) Experimental setup, (b) DSP procedure, (c) Spectrum and (d) Intensity Noise Power Spectral Density of ASE source without SOA , with 1 SOA and with 2 SOAs. The purple line is PD noise floor.

3. Results and Discussions

We firstly demonstrate the intensity noise mitigation effect of the SOAs. In Fig. 1.c. and d., the spectrum and the intensity noise power spectral density (PSD) of the broadband source, the output of a single SOA, and the output of two cascaded SOAs are shown. Notably, a distinct dip near DC and an overall reduction in intensity noise are clearly observable in Fig. 1. d. [11]. This verifies the SOA's ability to reduce the overall intensity noise, with a particularly pronounced effectiveness in reducing low-frequency noise.

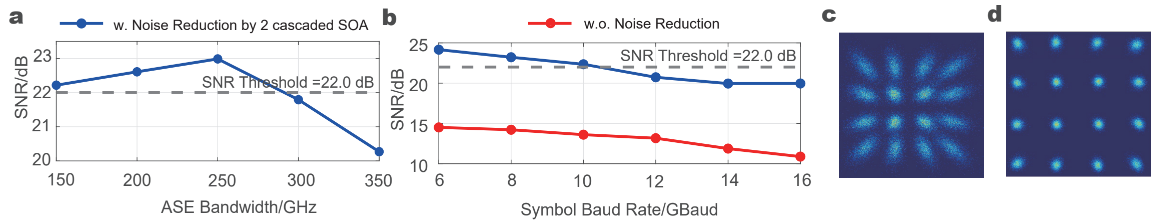

Fig. 2. (a) SNR versus ASE bandwidth of 16-QAM coherent signal of Core 4, (b) SNR versus symbol baud rate of Core 4, and 16-QAM constellation (c) without SOA and (d) with 2 cascaded SOAs.

To achieve the highest SNR and optimal transmission capacity, it is crucial to initially set the proper bandwidth of the broadband ASE source and the signal baud rate. Regarding the former, there is a tradeoff between the SNR and the effects of dispersion. A narrower bandwidth results in a lower initial SNR, whereas a wider bandwidth is more susceptible to the effects of dispersion. This is because only the second-order dispersion with the average value of each core is compensated, while the residual differences of second-order dispersion among each fiber core and the higher-order dispersion remain uncorrected. Therefore, the optimal value of the broadband source bandwidth must be determined by parametric sweeping. Regarding the latter, the SOA can only suppress intensity noise significantly within a certain frequency bandwidth, as evident in Fig. 1.d. This limitation imposes the upper limit on the signal baud rate [12]. In order to attain an optimal SNR and reach maximum capacity, we must first find out the optimal values of these two parameters.

To characterize the SNR indices, we first transmit the 16-QAM coherent signal. Given the consistent performance across all eight cores, we choose core 4 as our representative. We first use a 10 GBaud 16-QAM signal to determine the optimal bandwidth. As depicted in Fig. 2.a., the broadband source with a bandwidth of 250 GHz, equivalent to 2 nm, demonstrates the highest SNR. Following that, we employ a 2 nm broadband source to determine the optimal baud rate. Given that a 1024-QAM signal requires an error vector magnitude (EVM) of 2.5% [13], corresponding to a SNR of 32.0 dB, and building upon previous research mentioning that the DA-RoF scheme can provide an approximate 10 dB SNR gain [3], we determine that the initial SNR must be no less than 22.0 dB. As seen in Fig. 2.b., the maximum achievable baud rate is 10 GBaud, which meets the SNR threshold. The SNR gain with an average of 8.7 dB is evident, thanks to the utilization of cascaded SOA. It's essential to emphasize that it is the deployment of SOAs that enables the SNR to meet the 1024-QAM threshold. Fig. 2.c. and Fig. 2.d. illustrate the clear reduction of intensity noise in the 16-QAM constellation.

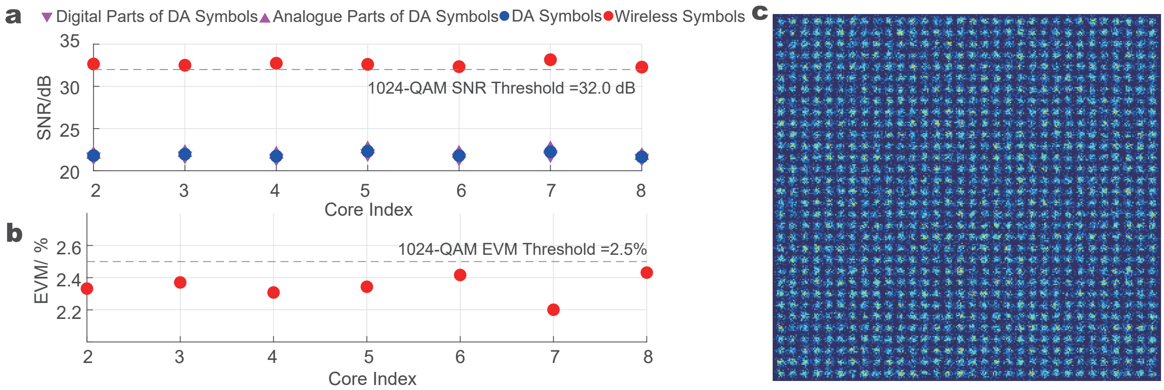

Fig. 3. (a) SNR of digital and analog parts of DA symbols, recovered wireless symbols and (b) EVM of all MCF cores used for transmission. (c) the constellation of the recovered 1024-QAM wireless signal of core 7.

Finally, we demonstrate 1 km transmission utilizing the 8-core MCF with a DA-RoF signal generated from the 2 nm broadband light source. The DA-RoF signal employs a 1024-QAM modulation format with a symbol rate of 10 GBaud, resulting in an aggregated bandwidth of 5 GHz/core. As depicted in Fig. 3.a., the use of the DA-RoF signal enables the recovered SNR to exceed the 32.0 dB threshold, with an average of 32.6 dB. The implementation of the DA-RoF scheme leads to an average SNR gain of 10.7 dB, with a remarkable consistency of 0.7 dB variation observed across different fiber cores. Fig. 3.b. demonstrates that the EVM for all cores is below 2.5%, which falls beneath the threshold for a 1024-QAM signal. In Fig. 3.c., the 1024-QAM constellation of core 7 is displayed, with the EVM of 2.20%. Consequently, the overall CPRI equivalent rate can achieve a remarkable $7\times5\times1000/1024\times3/2\times2\times15\times16/15\times10/8$=2 Tb/s, showcasing a successful DA-RoF fronthaul scheme that employs the light source with highest optical bandwidth and accurate skew matching.

4. Conclusion

In summary, we have showcased a self-homodyne DA-RoF architecture designed for cost-effective short-range fronthaul transmission, leveraging a 2 nm bandwidth broadband light source. This achievement is made possible with the assistance of two SOAs and an 8-core MCF. We've achieved an aggregated bandwidth of 35 GHz with a modulation format of 1024-QAM, resulting in a CPRI-equivalent rate of 2 Tb/s. This scheme opens up the possibility of massive usage of low-cost, broadband sources in the massive-implemented fronthaul network.

Acknowledgements

National Natural Science Foundation of China (62071010). National Key R&D Program of China 2022YFB2903500.

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