100G FSO Transmission Using 3-Bit DAC and Self-Coherent Detection

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Abstract: Using a virtual-carrier-assisted self-coherent system aided by a digital resolution enhancement technique, we experimentally demonstrate 100 Gbps FSO transmission over an outdoor 42 m link, supported by a single photoreceiver and a simplified transmitter with a 3-bit DAC.

1. Introduction

Optical wireless communications are currently under the spotlight of the research community, which is eagerly seeking to exploit its superior bandwidth potential to leverage the development of numerous novel communication scenarios, including both terrestrial (e.g. 6G, intra-datacenter and last-mile access) and space (e.g. LEO-to-earth, feeder links and satellite-to-satellite) applications [1]. In this regard, the use of coherent communications, together with free-space optics (FSO), has recently been employed to achieve record wireless transmission demonstrations, with per-channel bit-rates spanning from 400 Gbps [2] up to 1 Tbps [3, 4]. Despite the tremendous capacity demonstrated by these fully-coherent FSO systems, their practical applicability might be limited by the required high cost and power consumption. Therefore, several reduced-complexity quasi-coherent approaches have been proposed to optimize the balance between hardware complexity and achievable bit-rate. Following this need, we have recently demonstrated 200 Gbps FSO transmission using a Kramers-Kronig (KK) self-coherent receiver [5], which allows replacing the full coherent receiver by a single photodiode, while still being compatible with phase-preserving receiver-side processing and advanced modulation, such as probabilistic constellation shaping (PCS) [6]. Noteworthy, this simplified coherent FSO architecture has attracted significant attention, being subject of several recent studies on achievable capacity [7, 8].

Despite the significant complexity reduction enabled by the KK-FSO system, there are still important hurdles to overcome in terms of cost and power consumption. Namely, at the transmitter, additional hardware has been required to optically generate the KK carrier. In addition, the KK transform at the receiver requires significant digital oversampling and high carrier-to-signal power ratio (CSPR). In order to tackle this challenge, in this work we propose a novel self-coherent FSO system that further simplifies the KK-FSO system at several levels:

i) at the transmitter side, we replace the optical carrier by a virtual carrier [9], added directly to the signal in the digital domain, thus avoiding any extra hardware to generate and lock the optical carrier with the signal;

ii) still at the transmitter side, we apply a digital resolution enhancer (DRE) technique [10] to make feasible the use of very low resolution digital-to-analog converters (DACs), with as low as 3 physical number of bits (PNOBs), thus greatly reducing the cost and power consumption;

iii) at the receiver side, we replace the KK transform by our recently proposed DC-Value method [11], which allows to reduce both the oversampling and CSPR requirements, thus improving the energy efficiency.

Using this simplified self-coherent FSO transceiver, we demonstrate the transmission of a 100 Gbps PCS-36QAM signal over a 42 m outdoor link, resorting to the use of a low-resolution 3-bit DAC and a single photodetector receiver, thus effectively contributing to lower the commercial entry barrier of high-capacity FSO systems.

2. Experimental Setup

This section presents the experimental setup for the DRE enhanced virtual carrier assisted self-coherent transceiver, see Fig. 1. At the transmitter side, the random bit sequence is generated and mapped into M-QAM PCS symbols. The symbols are then passed through the root-raised cosine (RRC) filter with a 0.2 roll-off. Following that, a virtual carrier sitting at the right edge of the information spectrum is added in the digital domain. The carrier power is kept sufficiently high such that it can satisfy the minimum phase condition upon square-law detection. Following that, we apply the DRE method which performs the quantization noise shaping by employing dynamic quantization [10]. The DAC used for the experimental setup is powered by the Keysight M8194A arbitrary waveform generator (AWG) with 8 PNOB, a sampling rate of 120 GSa/s, and an analog bandwidth of

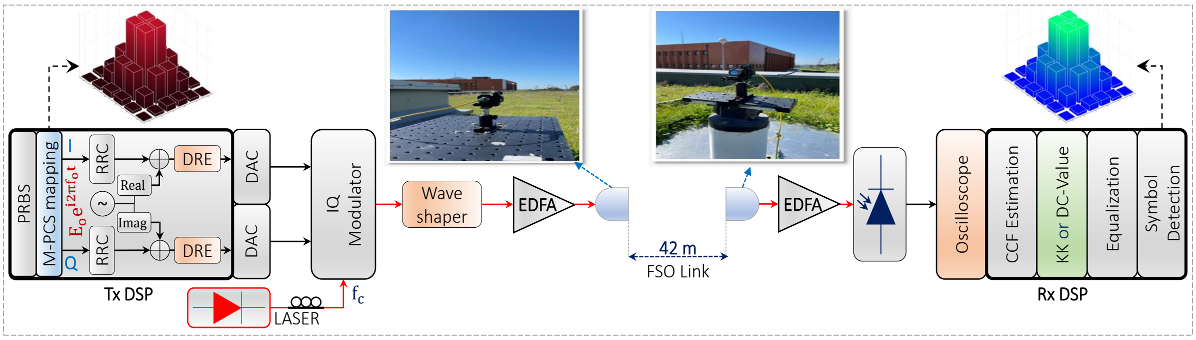
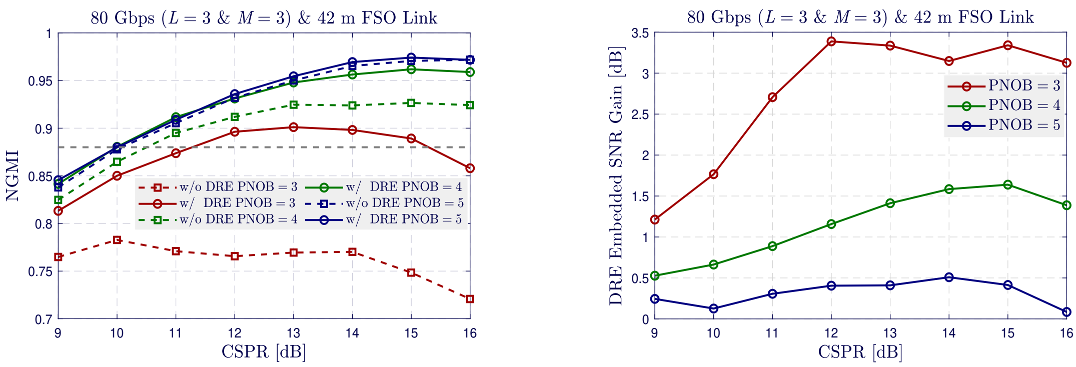


Fig. 1: Enhanced virtual carrier assisted self-coherent transceiver employing DRE.

~ 45 GHz. Notice that the PNOB configurations can be changed by rounding-off operations in the digital domain before sending it to the DRE algorithm. In this experimental analysis, we employed 3, 4, and 5 PNOBs configurations for both w/ and w/o DRE scenarios for the performance assessment. The output of the DAC is applied to the IQ Mach-Zehnder modulator (MZM) to modulate the signal into the optical domain. Following the IQ MZM, the optical signal is passed through a waveshaper to remove out-of-band noise and then amplified by a booster amplifier before applying it to an optical collimator (F810APC-1550) for outdoor FSO transmission. At the receiver end, the optical signal beam is collected through a receiver collimator located 42 m away from the transmitter collimator. The received signal is then amplified by an optical preamplifier and detected using a single photodetector. The photodetector output is then captured by a Tektronix real-time oscilloscope (RTO) and processed offline. In the receiver DSP (Rx-DSP), first, the carrier contribution factor (CCF) estimation is carried out. The CCF is an important parameter in the DC-Value method as it is used to apply the minimum phase condition in the optical field reconstruction process. Unlike the Kramers-Kronig method, the optical field reconstruction process in the DC-Value method can be operated at the Nyquist sampling rate [11]. Throughout this work, we used the DC-Value method for the optical field construction. Following that, the reconstructed signal is passed through the DC remover and then down/upconverted to get the baseband signal with zero intermediate frequency (IF). Subsequently, the equalization is carried out before symbol detection.

3. Results and Discussion

This section presents the obtained experimental results of the FSO self-coherent transceiver shown in Fig. 1. At the transmitter side, the launched power over the FSO link is fixed to 7 dBm in the experiment. At the receiver side, an optical preamplifier operating in an automatic power control (APC) mode outputs a constant 3 dBm power. Results shown in Fig. 2 presents the obtained results in terms of normalized generalized mutual information (NGMI) and corresponding SNR gain provided by DRE as a function of CSPR. Note that in the DRE algorithm, the memory order and the number of quantization possibilities are defined by L and M, respectively, as discussed in [10]. For the performance assessment, we considered 3, 4, and 5 PNOB DAC configurations. Note that the obtained results shown in Fig. 2 correspond to the 30 GBaud 36QAM-PCS signal supporting a net 80 Gbps bitrate with 20 % overhead. Fig. 2a presents the NGMI vs CSPR for 3, 4, and 5 PNOB DAC configurations.



(a) (b)

Fig. 2: Performance of DRE enhanced self-coherent transceiver over 42 m FSO link for different PNOB configurations. (a) NGMI vs CSPR, (b) SNR gain vs CSPR. (FEC limit @ $\text{NGMI}_{\text{th}} = 0.88$ with 20% overhead).

For 3 PNOB DAC configuration, the results show that without DRE, 3 PNOB DAC cannot support the error-free transmission. Nevertheless, the employment of DRE can significantly improve performance and surpasses the considered 0.88 NGMI threshold. It translates into a significant ~ 3 dB SNR gain with the employment of the DRE in the 3 PNOB DAC configuration, see Fig. 2b. Similarly, results show ~ 1 dB and ~ 0.5 dB gains for 4 and 5 PNOB DAC configurations, respectively. Further, for the same setup and configuration, we increased the net bitrate to 100 Gbps and obtained new experimental results, see Fig. 3. In this case, we used only 3 PNOB DAC configuration with and without DRE. Results show that the case of DRE with $L = 3$ and $M = 3$ provides an optimum 0.83 NGMI which is considerably far from the required NGMI threshold for an error-free transmission. Further, increasing memory order in the DRE method to $L = 5$, with $M = 3$, provides a significant performance improvement. Results presented in Fig. 3 show the obtained NGMI as a function of CSPR for three different configurations, (i) without DRE, (ii) DRE with L = 3 and M = 3, and (iii) DRE with L = 5 and M = 3. An optimum 0.9 NGMI is obtained for the case of DRE with L = 5 and M = 3, which ensures an error-free transmission with a low resolution DAC with PNOB as low as 3. Finally, we also take long term measurement to present the transmission reliability with such low resolution DAC.

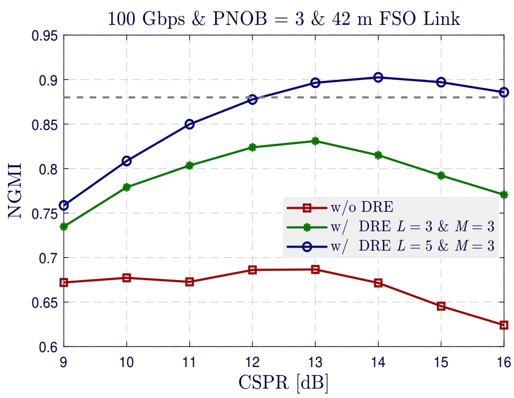
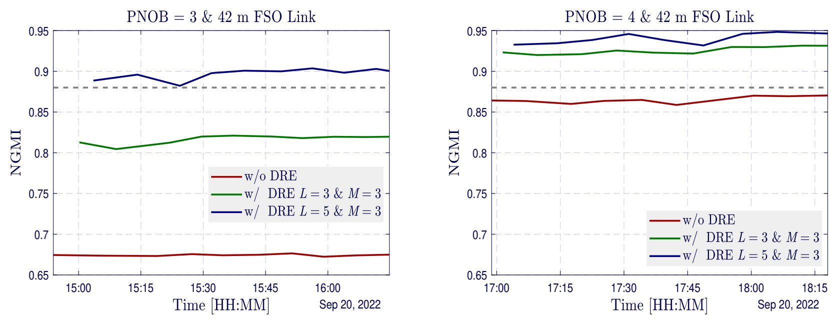


Fig. 3: Obtained results for 30 GBaud 36QAM-PCS system with a net 100 Gbps bitrate with and without DRE.

Figure 4 shows the obtained results for the net 100 Gbps bitrate during approximately 4-hours with and without DRE, in which the different measurements were taken in a time-interleaved fashion. From Fig. 4a we can conclude that stable error-free (NGMI above 0.88 threshold) FSO transmission can be achieved with a PNOB of only 3 bits, provided that DRE is employed with 5 symbols memory depth ($L = 5$) and 3 quantization possibilities ($M = 3$), which is a reasonably low-complexity DRE amenable for practical implementation [10]. Finally, in Fig. 4b we observe that error-free operation is still not possible with 4 PNOBs if no digital resolution enhancement is performed. However, a low-complexity DRE with $L = 3$ and $M = 3$ is able to safely bring the system into valid operation.



(a) (b)

Fig. 4: Four hours long transmission and performance assessment results obtained from the mentioned experimental setup in Fig. 1, for 3 and 4 PNOB DAC configurations.

4. Conclusion

In order to tackle the cost and power consumption of high-capacity coherent FSO systems, we presented the first experimental demonstration of a virtual carrier-assisted self-coherent FSO link with a low-resolution DAC enhanced by the DRE technique. Error-free transmission is demonstrated with a 30 GBaud 36QAM-PCS signal and 100 Gbps net bitrate, requiring only a single photodiode receiver and a reduced complexity self-coherent transmitter, using a virtual-carrier to avoid the requirement for any local oscillator hardware and employing a digital resolution enhancement technique to allow for the use of a very low-resolution 3-bit DAC.

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