End-to-End Real-Time Demonstration of 128-QAM-Encoded Optical OFDM Transmission with a 5.25bit/s/Hz Spectral Efficiency over IMDD Systems

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Abstract: Real-time optical OFDM transceivers with 128-QAM encoding are experimentally demonstrated, for the first time, which enable 5.25Gb/s end-to-end transmission with the highest spectral efficiency of 5.25bit/s/Hz over 25km(500m) SMF(MMF) IMDD systems involving directly modulated lasers.

OCIS codes: (060.2330) Fiber optic communications, (060.4080) Modulation, (060.2430) Fibres, single mode.

1. Introduction

To satisfy the exponentially increasing end-users' demands for broadband services, Optical Orthogonal Frequency Division Multiplexing (OOFDM) has widely been considered as one of the strongest contenders for practical implementation in various cost-sensitive network scenarios such as access networks and Local Area Networks (LANs) [1]. Recently, in Multi-Mode Fiber (MMF)-based LANs [2] and Single-Mode Fiber (SMF)-based access networks [3], we have made significant breakthrough in experimentally demonstrating world-first 3Gb/s real-time OOFDM transceivers based on off-the-shelf components. To further improve the transmission capacity of the real-time OOFDM transceivers, one of the most cost-effective approaches is to employ high signal modulation formats such as M-ary QAM. This approach is extremely valuable for MMF-based transmission systems owing to their lower bandwidths.

The use of high signal modulation formats, however, inevitably imposes a number of technical challenges in the real-time OOFDM transceiver design. The challenges are summarized as followings: 1) high Optical Signal-to-Noise Ratio (OSNR), 2) increased susceptibility to unwanted Digital-to-Analogue/Analogue-to-Digital Converter (DAC/ADC) impairments, 3) increased requirements on accuracy of real-time DSP algorithms, channel estimation and symbol synchronization, and 4) increased requirements on linearity of electrical-to-optical converters such as Directly Modulated DFB Lasers (DMLs).

In previously reported works, the highest signal modulation format used commonly on all the subcarriers within an OOFDM symbol is 64-QAM in an intensity-modulation and direct-detection (IMDD) OOFDM system [4]. Although 128-QAM was also used in a system of such type [5], the signal modulation format, however, just occupies a small portion of the signal spectral region due to the utilization of adaptive bit-loading algorithms. More importantly, all those experimental works [4,5] have been undertaken using off-line DSP approaches, which do not consider the limitations imposed by the precision and speed of practical DSP hardware for realizing real-time end-to-end transmission. The thrust of the present paper is to explore experimentally, for the first time, the feasibility of implementing 128-QAM in real-time OOFDM transceivers with channel estimation for transmitting OOFDM signals over simple IMDD SMF/MMF systems involving DMLs.

2. Real-time experimental system setup

Fig.1 shows the real-time experimental system setup, in which use is made of the real-time OOFDM transceiver design similar to that reported in [2,3]. The transmitter consists of an Altera Stratix II GX FPGA, which performs the real-time DSP on the data source and outputs four 8-bit samples in parallel at a rate of 0.5GHz. These samples are fed to an 8-bit DAC running at 2GS/s. The analog electrical signal with a 1GHz bandwidth is attenuated by a variable attenuator to adjust the modulating current injected into a 1550nm DML having a modulation bandwidth of 10GHz. The converted OOFDM signal emerging from the DML is then coupled into an EDFA with a 15dB optical gain and a 5dB noise figure. After passing through a 0.8nm optical filter, the amplified optical signal is coupled into a 25km MetroCor^{TM} SMF. The optical power injected into the SMF is fixed at 7dBm. For investigating the performance of the OOFDM signal over a 62.5/125μm OM1 MMF having a 3-dB optical bandwidth of approximately 675MHz·km and a linear loss of 0.6dB/km, the MetroCor^{TM} SMF is replaced by the MMF, into which the optical signal is coupled via a mode-conditioning patch cord.

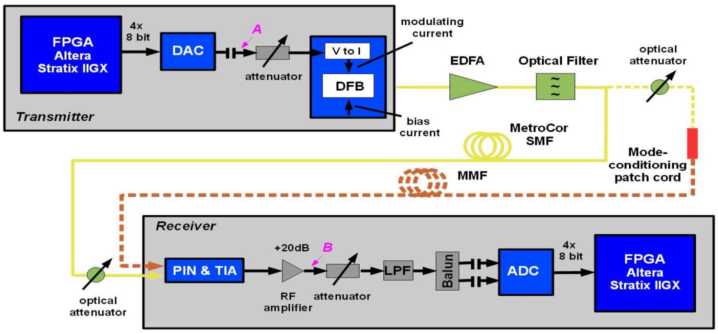

Fig. 1. Experimental transmission system setup.

At the receiver, a 12GHz bandwidth PIN with a TIA (-17dBm receiver sensitivity) converts the received optical signal to the electrical domain. The electrical signal is amplified by a 2.5GHz, 20dB RF amplifier and attenuated as needed to adjust the signal amplitude. The low-pass-filtered, single ended electrical signal is converted via a balun to a differential signal to feed an 8-bit ADC operating at 2GS/s, whose digital interface format is identical to the DAC input in the transmitter. Finally, the digital samples are fed to a second Altera Stratix II GX FPGA, which performs the real-time DSP on the received symbols and determines the BER. Detailed descriptions of the system setup and the real-time OOFDM transceivers with channel estimation have been reported in [2,3].

3. Experimental results

With the 50MHz FPGA operating speeds and the 2GS/s sample rates of the DAC/ADC, 5.25Gb/s OOFDM signals of spectral bandwidths of 1GHz are produced when 128-QAM is taken on all the 15 information-bearing subcarriers in the positive frequency bins. To our knowledge, this gives the highest ever OOFDM spectral efficiency of 5.25bit/s/Hz.

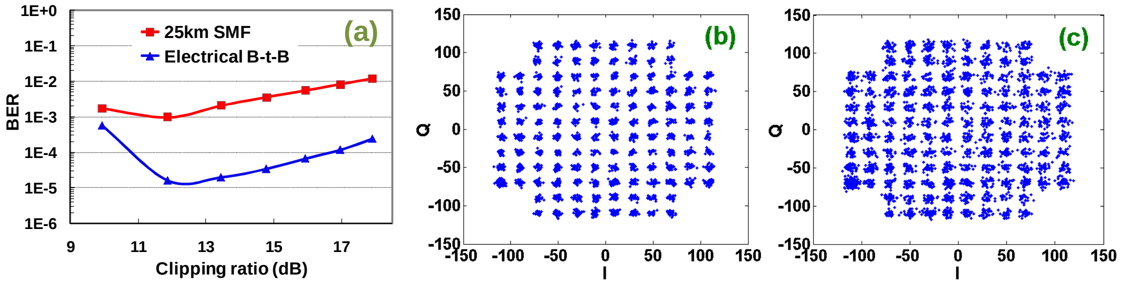

Fig. 2. Optimization of signal clipping ratio (a), corresponding signal constellations after channel equalization at lowest BERs for the electrical B-t-B case (b), and for the 25km SMF transmission case (c).

It is well known that the DAC-induced signal clipping effect is more pronounced for high signal modulation formats. To distinguish the signal clipping effect induced by the DAC from those induced by optical components, BER versus clipping ratio is explored first for the analogue electrical Back-to-Back (B-t-B) and the 25km MetroCor^{TM} SMF transmission cases. In the electrical B-t-B case, the electrical signal from the DAC (point A) is directly connected to the attenuator in the receiver (point B) without optical components being involved, as shown in Fig. 1.

As seen from Fig. 2(a), an optimum clipping ratio of 11.9dB is identified, which corresponds to the lowest BERs of 1.6×10^{-5} for the electrical B-t-B case and 9.7×10^{-4} for 25km MetroCor^{TM} SMFs transmission. The corresponding signal constellations are shown Fig. 2(b) and Fig.2(c) for both cases. When clipping ratios are smaller than the optimum value, the signal is clipped considerably, thus resulting in distorted signal waveforms; whilst when clipping ratios are higher than the optimum value, the signal is quantized at a wide quantization step size over an enlarged dynamic range, thus producing large quantization noise. Furthermore, the similarities of the BER evolution curves and in particular, optimum clipping ratios, between the two different configurations considered, indicate that DML nonlinearities do not considerably alter the signal waveform. However, subcarrier × subcarrier intermixing upon direct detection in the PIN causes the occurrence of an unwanted spectral distortion region in the vicinity of the optical carrier frequency [6]. As a direct result of the effects of subcarrier intermixing and noises associated with the PIN, the minimum BER of 1.6×10^{-5} observed in the analogue electrical B-t-B case is increased to 9.7×10^{-4} observed in the 25km MetroCor^{TM} SMF transmission case.

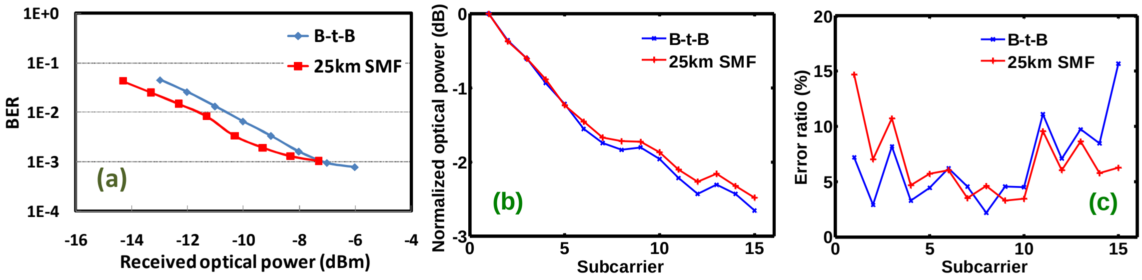

Fig. 3. BER performance of 5.25Gb/s 128-QAM-encoded OOFDM signals over SMF (a), normalized system frequency response (b), and error distribution (c).

Making use of the identified optimum clipping ratio, experimental measurements are performed of the transmission performance of real-time 5.25Gb/s 128-QAM-encoded OOFDM signals in DML-based 25km MetroCor^{TM} SMF IMDD systems without in-line optical amplification and chromatic dispersion compensation. The measured BER as a function of received optical power is shown in Fig. 3(a). As seen from Fig. 3(a) that, a BER of 1.0×10^{-3} (7.8×10^{-4}) is achieved at a received optical power of -7.3dBm (-6.0dBm) for 25km MetroCor^{TM} SMF (optical B-t-B) transmission. Very similar to those corresponding to real-time 3Gb/s 16-QAM-encoded OOFDM signals [3], a negative power penalty of approximately -0.5dB are observed in Fig. 3(a). The physical mechanism underpinning the negative power penalty is that the negative chromatic dispersion parameter associated with the MetroCor^{TM} SMF can be compensated by the positive transient frequency chirp associated with the DML [3].

In Fig. 3(a), error floors start to develop at BERs of approximately 1.0×10^{-3}. It is worth addressing, in particular, that the occurrence of the error floors is not due to the real-time DSP functionalities and digital-to-analogue/analogue-to-digital conversions, as indicated clearly in Fig.2. The cause of the error floors is the subcarrier intermixing effect. This can be understood by considering Fig. 3(c), where the error ratio, which is defined as the percentage ratio between the number of error bits on a given subcarrier and the total number of error bits on all the subcarriers at a BER of 1.0×10^{-3}, is presented to quantify explicitly error distributions for various scenarios. It can be seen in Fig. 3(c) that, almost uniform error ratios occur over the entire subcarriers, even though, according to Fig. 3(b), the low frequency subcarriers experience SNRs roughly 2dB higher than those experienced by the high frequency subcarriers. This implies that the subcarriers in the positive frequency bins suffer right triangle-shaped spectral distortions, which offset the channel frequency response-induced SNR variations. All the above-mentioned characteristics are in line with those associated with subcarrier intermixing. It has already been experimentally verified [3] that, the subcarrier intermixing effect is negligible for transmission of 3Gb/s 16-QAM-encoded OOFDM signals over MetroCor^{TM} SMFs of up to 75km. Of course, the use of a spectral guard band can reduce such an effect. However, the approach decreases the signal spectral efficiency and increases the transceiver complexity.

In addition, investigations are also undertaken of the transmission performance of real-time 5.25Gb/s 128-QAM-encoded OOFDM signals in the MMF systems. For the case of 500m (100m) MMF transmission, a minimum BER of 9.3×10^{-4} (9.7×10^{-4}) is achieved at a received optical power of -6.0dBm (-6.2dBm). Power penalties of approximately 0.5dB at BERs of 1.0×10^{-3} are observed for both systems, which originate from the co-existenceing effects of Differential Mode Delay (DMD) and modal noise.

3. Conclusions

The feasibility of implementing 128-QAM in off-the-shelf component-based real-time OOFDM transceivers at 5.25Gb/s has been explored experimentally, for the first time, in DML-based IMDD 25km SMF (500m MMF) transmission systems. The highest ever spectral efficiency of 5.25bit/s/Hz has also been successfully achieved. This work suggests that it is possible to implement real-time OOFDM transceivers running at 40Gb/s for cost-sensitive access and local area networks, if use is made of multiband transmission [7] and higher DAC/ADC sample rates.

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