Real-Time 3Gb/s 16QAM-Encoded Optical OFDM Transmission over 75km MetroCor SMFs with Negative Power Penalties

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Abstract

Real-time optical OFDM(OOFDM) transceivers with advanced channel estimation are experimentally demonstrated, which support 3Gb/s over 75km SMF transmission with negative power penalties of -2dB in directly-modulated-laser-based IMDD systems without in-line optical amplification and dispersion compensation.

Introduction

Since the first proposition of the concept of optical orthogonal frequency division multiplexing (OOFDM) in 2005 [1], great effort has been expended on experimentally demonstrating real-time OOFDM transceivers, as such transceivers are vital for not only rigorously validating the OOFDM technique but also establishing a strong platform for evaluating the feasibility of the technique for practical implementation in high capacity optical networks of various architectures. Recently, we have made a significant breakthrough in experimentally demonstrating the world-first real-time OOFDM transceivers using off-the-shelf components [2]. The transceivers support real-time end-to-end transmission of a 1.5Gb/s DQPSK-encoded OOFDM signal over a directly modulated DFB laser (DML)-based 500m OM1 MMF system incorporating intensity-modulation and direct-detection (IMDD).

To further improve the transmission capacity of the real-time OOFDM transceivers, one of the most effective approaches is to employ high signal modulation formats such as M-ary QAM. In M-ary QAM systems, channel estimation influences the system performance to a great extent. It is well known [3] that, conventional channel estimation techniques widely adopted in wireless communications channels suffer strong trade-off between accuracy and pilot bandwidth usage due to the time-variant and frequency-selective nature of the channels. In addition, the conventional techniques are just capable of supporting low signal bit rates. Owing to the fact that optical communications systems are relatively stable and operate at very high signal bit rates, the conventional techniques are, therefore, not suitable for optical communications systems.

In this paper, an advanced pilot subcarrier-assisted channel estimation technique is, for the first time, proposed and successfully implemented in the real-time OOFDM transceivers. The proposed technique has unique advantages including high accuracy, low complexity, buffer-free data flow and extremely low pilot bandwidth usage.

Proposed channel estimation technique

In the transmitter, pilot subcarriers are diagonally embedded in the time-frequency OOFDM symbol space, as mathematically expressed below

$$X_{m,k} = \begin{cases} p_{m,k} & (m-k) = qN_s \\ d_{m,k} & (m-k) \neq qN_s \end{cases} \qquad q = 0,1,2,\cdots \tag{1}$$

where m is the index of the OOFDM symbols; k is the index of the information-bearing subcarriers; $p_{m,k}$ and $d_{m,k}$ are the complex values taken on the pilot and information-bearing subcarriers, respectively; N_s is the total number of information-bearing subcarriers. The pilot subcarriers are set to a constant value, which corresponds to a constellation point of the largest amplitude of the 16QAM constellation considered.

In the receiver, at the output of the FFT, the identification of the received pilot subcarriers is first made by conducting the following two operations to subcarrier 1 of different symbols:

$$D_{m,1} = \chi_{m,1}\chi^{*}_{(m+N_s),1} \tag{2}$$

$$Q_{m,1} = \frac{1}{C}\left|\sum_{i=0}^{C-1} D_{(m+iN_s),1}\right|^2 \tag{3}$$

where $\chi_{m,1}$ ($\chi^{*}_{(m+N_s),1}$) is the received complex (complex conjugate) value of subcarrier 1 of the m-th [(m+N_s)-th] symbol. C is the preset integer number. Complex values encoded using random data sequences are taken onto the information-bearing subcarriers, giving rise to minimized Q values. Whilst each of the pilot subcarriers has a fixed complex number,causing the occurrence of a Q peak corresponding to a symbol with its subcarrier 1 being the pilot subcarrier. Experimental measurements show that C=16 is sufficiently adequate. By making use of one of the generated N_s symbol-spaced Q peaks, subcarrier 1 of the corresponding symbol can be regarded as a pilot subcarrier reference, based on which all other pilot subcarriers in subsequent symbols can also be identified.

Making use of the assigned and received pilot subcarriers, the frequency domain channel transfer function, H_k (k= 1, 2, …N_s), can be computed by

$$H_k = \frac{1}{M}\sum_{i=0}^{M-1}\frac{R_{(k+iN_s),k}}{p_{(k+iN_s),k}} = \frac{1}{M\cdot \mathrm{P}}\sum_{i=0}^{M-1} R_{(k+iN_s),k} \tag{4}$$

where $R_{(k+iN_s),k}$ ($p_{(k+iN_s),k}$) is the received (assigned) complex value of the k-th pilot subcarrier of the $\left(k+iN_s\right)$-th symbol. P is the fixed value taken on the pilot subcarriers in the transmitter. To effectively reduce the noise effect, pilot subcarrier averaging is also performed over M received pilot subcarriers of the same frequency. Experimental measurements show that M=32 can be used. Channel equalization is finally conducted following well-known procedures described in [3].

Transceiver architecture and system setup

Fig.1 shows the off-the-shelf component-based real-time OOFDM architectures with channel estimation. The experimental system setup is illustrated in Fig.2.

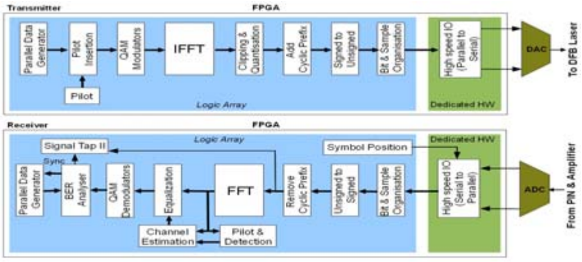

Fig. 1. Real-time OOFDM transceiver with channel estimation.

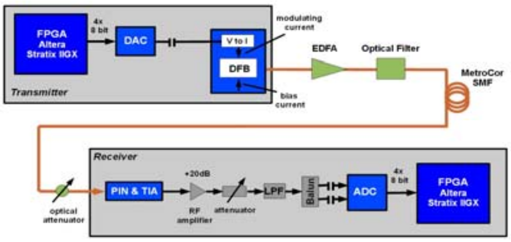

Fig. 2. Experimental system setup.

The real-time OOFDM transmitter consists of an Altera Stratix II GX FPGA. 14 parallel pseudo random bit sequences of lengths of 354000 are employed as information data. One extra sequence of a fixed 4-bit pattern is used for pilot data. Together with their conjugate counterparts and zero power subcarriers, 32 ($2N_s$+2) 16QAM-encoded OOFDM subcarriers are input to the IFFT. At the output of the IFFT, 13.8dB clipping and 8-bit quantization are applied to the signed, real-valued OOFDM symbols. A cyclic prefix of 8 samples is then added to each symbol, resulting in 40 samples per symbol. The internal system clock is set to 50MHz, which is equal to the symbol rate. After converting the signed samples to unsigned values and performing sample ordering and bit arrangement, the unsigned 40 samples are streamed to the DAC interface at 2GS/s. An entire symbol is fed in parallel to 32 high speed 10:1 dedicated hardware serialisers. The DAC generates an analogue electrical OOFDM signal having a maximum peak-to-peak voltage of 636mV. The signal is, together with an appropriate DC bias current, injected into a 1550nm DML with a 3-dB modulation bandwidth of approximately 10GHz. After passing through an EDFA and a 0.8nm optical filter, a fixed optical power of 7dBm is coupled into MetroCor SMFs of different lengths.

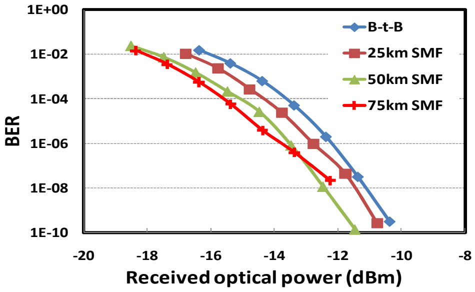

Fig. 3. BER versus received optical power for 3Gb/s 16QAM-encoded OOFDM transmission over DML-based IMDD MetroCor SMFs of different lengths.

In the receiver, after passing through an optical attenuator, the transmitted OOFDM signal is converted into the electrical domain using a 12GHz PIN with TIA. The electrical signal is amplified with a RF amplifier. The low-pass filtered signal is converted via a balun to a differential signal and then digitized by a 2GS/s, 8-bit ADC. Finally, the digital samples are fed, via a digital interface identical to that corresponding to the DAC, to a second Altera Stratix II GX FPGA.

Symbol alignment and BER measurements are conducted according to the procedures presented in [4]. Clock synthesizers based on a common reference clock are used to generate the system clocks for both the transmitter and the receiver.

Experimental results

Under a DFB laser a bias current of 35mA, the measured BER as a function of received optical power is presented in Fig. 3 for four different scenarios including optical back-to-back and SMF transmissions of 25km, 50km and 75km. Record low BERs of approximately 1.0×10^{-10} are obtained at received optical powers of -10.3dBm (optical back-to-back), -10.75dBm (25km) and -11.4dBm (50km). Whilst for the 75km case, a BER of 3.98×10^{-7} is measured at -12.26dBm, which is due to the limitation on the maximum optical power received under the current operating conditions. No error floors are observed for all these four cases, indicating high accuracy of the proposed channel estimation technique.

It is very interesting to note in Fig.3 that, for all the SMFs, negative power penalties are observed, whose absolute values at BERs of 1.0×10^{-4} increase almost linearly with transmission distance, and a -2dB power penalty is obtained for the 75km SMF case. The negative power penalty is due to the fact that the positive transient frequency chirp associated with the DML is compensated by the negative chromatic dispersion parameter associated with the MetroCor fibre [5].

References

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