All-Analogue Real-Time Filter Bank OFDM over 50 Km of SSMF using a Novel Synchronization Technique

Fernando A. Gutiérrez[1], Eamonn P. Martin[1], Philip Perry[1], Andrew D. Ellis[2], Liam P. Barry[1]

1. The RINCE Institute, Dublin City University, Glasnevin, Dublin 9, Ireland.

2. Aston Institute of Photonic Technologies, Aston University, Aston Triangle, Birmingham B4 7ET, UK.

fernando.gutierrez@dcu.ie

Abstract: A 21.6 Gbit/s 1.78 bit/s/Hz OFDM signal is transmitted over 50 Km of fiber without using DSP in the transmitter or the receiver. The synchronization scheme only requires one PLL to synchronize all the subcarriers.

1. Introduction

The rapid growth of Internet data traffic has translated into an increasing interest and research effort in short reach optical interconnects. Recently, a new technique based on a purely analogue orthogonal subcarrier multiplexing (OSCM) of broadband subchannels has been introduced [1]. Leveraging the maturity of broadband microwave components, OSCM can potentially meet all the requirements of short reach electro-optical transceivers. Firstly, it makes use of orthogonal subchannels achieving high spectral efficiencies. Secondly, the all-analogue nature of the solution translates into a low power consumption and latency. Moreover, due to the multicarrier approach, tolerance to dispersion is guaranteed. Finally, the solution can modulate subcarriers with baseband data signals of Gbit/s, allowing an easier integration with modern electrical interfaces. The use of monolithic microwave integrated circuit (MMIC) technology can integrate all the electrical processing in a single chip [2], allowing OSCM to benefit from reduced transistor sizes and to compete with solutions based on digital signal processing (DSP).

Previous experiments have demonstrated that OSCM can be successfully combined with wavelength division multiplexing (WDM) schemes based on optical frequency combs [1]. This paper demonstrates that OSCM is a reliable technique for intra data center and access networks distances. It also shows that through the utilization of electrical frequency combs, synchronization can be substantially simplified using only one phase locked loop (PLL) for all the subchannels, in contrast with previous SCM solutions which require one PLL per subcarrier.

2. Orthogonal subcarrier multiplexing experiment

OSCM relies on filter bank multicarrier (FBMC) theory [3] to transmit broadband orthogonal subchannels without using DSP. According to [3], orthogonal quadrature amplitude modulation can be achieved using a specific phase alignment in the baseband data pairs and the local oscillators (LO) of the IQ mixers, and using matched square root raised cosine (SRRC) filters in the transmitter and the receiver.

The OSCM scheme implemented to transmit four orthogonal 2.7 Gbaud QPSK subchannels located between the second and the fifth harmonics of the data rate (5.4 GHz, 8.1 GHz, 10.8 GHz and 13.5 GHz) is illustrated in Fig. 1. All the LOs in the transmitter were generated with an electrical comb based on a step recovery diode (SRD) which was fed with an input reference of 2.7 GHz. The electrical data signal had an overall data rate of 21.6 Gbit/s and a spectral efficiency of 1.78 bit/s/Hz. Note that the use of SRRC filters with a roll-off factor equal to 0.5 constrained the bandwidth of the baseband data to ≈2 GHz. Eight uncorrelated pseudo random binary sequences of 2^{15} bits were generated with a field programmable gate array (FPGA). The baseband filters in the transmitter compensated the sinc spectrum associated with the square shape of the generated bits to obtain a pure SRRC at their output. A pilot tone of 2.7 GHz was also multiplexed in the transmitted signal to simplify synchronization in the receiver. The pilot tone, the sourced data and the LOs in the transmitter were locked to the same master reference. The power of the pilot tone was 20 dB below the total power of the rest of the signal. A hybrid splitter was employed to generate the Hilbert transform (HT) of the electrical signal.

The optical link was established using an external cavity laser (ECL) as the optical source. An optical IQ modulator was fed with the desired signal and its HT pair in order to perform an optical single sideband (OSSB) modulation [4]. The optical spectrum can be observed in the inset in Fig. 1. OSSB modulation allows a closer allocation of optical channels in WDM solutions [5] and ensures increased tolerance against dispersion. The optical signal at the output of the modulator had an average power of -3dBm and was transmitted through 50 km of standard single mode fiber (SSMF). A pre-amplified receiver consisting of an Erbium doped fiber amplifier (EDFA) and a photo-receiver was used to recover the electrical FBMC signal.

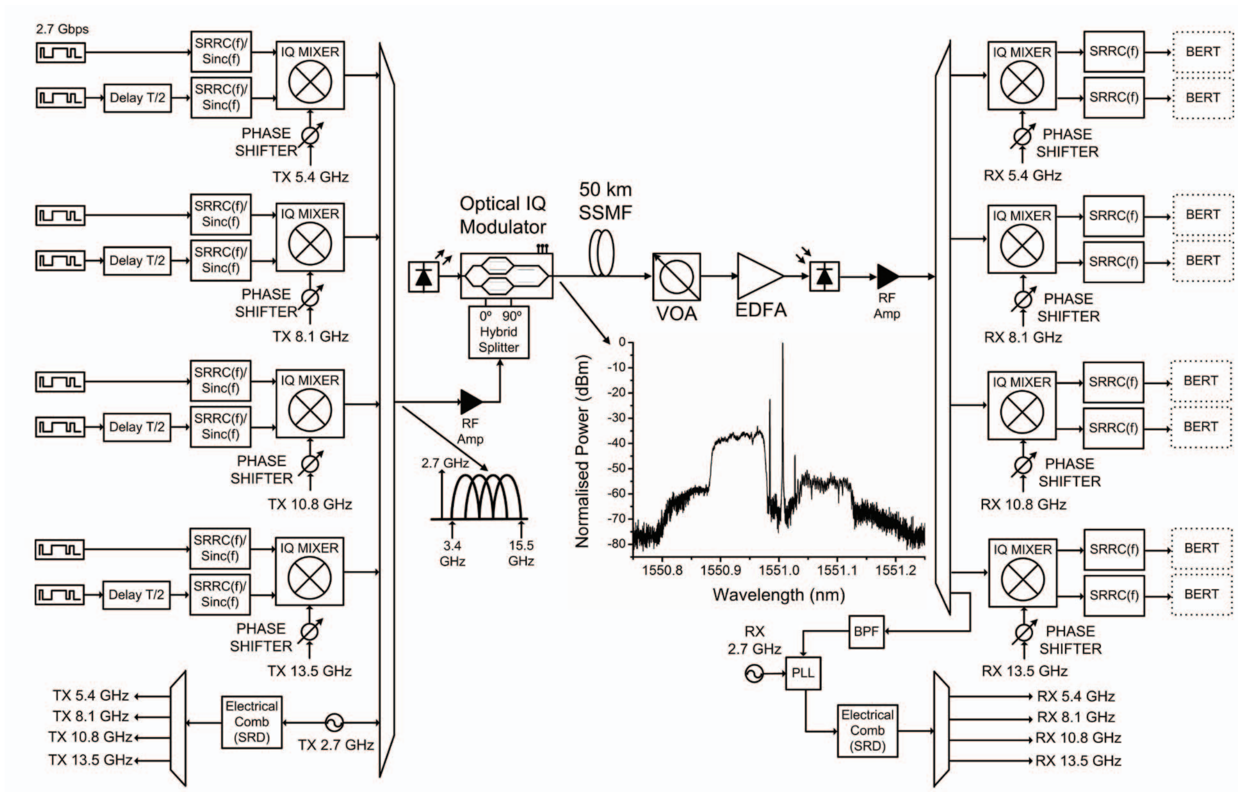

Fig. 1. Real-time OSCM link consisting of four orthogonal 2.7 Gbaud subchannel and based on an optical IQ modulator. Synchronization achieved with only one PLL for all the subchannels. Inset shows the optical spectra at the output of the optical modulator when CSPR≈18 dB.

The electrical receiver performed the demodulation of every electrical subchannel. The LOs in the receiver must be synchronized in frequency and phase to the incoming subcarriers. Different PLL techniques have been traditionally used in SCM links, but always relying on one PLL per subcarrier [6]. In this case the generation of the LOs in the receiver was substantially simplified. The received pilot tone was filtered with a bandpass filter (BPF), and a PLL was used to lock a 2.7 GHz reference to the pilot tone. The locked reference was fed to an electrical comb (SRD) that generated all the required LOs. This method locks any practical number of LOs in the receiver to the ones in the transmitter using the smallest number of components of any solution presented to date. The recovered baseband data was evaluated with a bit error rate tester (BERT) that measured performance in real-time.

3. Results

In the presented direct detection (DD) link there is a trade-off between various parameters. The optical modulation index (OMI) of the optical modulator must be high to reduce carrier to signal power ratio (CSPR) and improve sensitivity [4]. However, higher OMIs also result in higher nonlinearities [4] which are enhanced during the transmission over fiber [7]. In this particular case, the second order intermodulation products also reduced the carrier to noise ratio of the received pilot tone affecting synchronization. Performance was measured as BER versus average optical power at the input of the optical pre-amplified receiver for different values of CSPR. Results are illustrated in Fig. 2 for all the subchannels. For a 7% hard decision forward error correction (HD-FEC) code with a BER limit of $3.8\cdot10^{-3}$, a CSPR of 18 dB was found to be optimum considering all the subchannels. The worst case of sensitivity was -19.5 dBm in subchannel 4. This was a consequence of the limitations of the microwave components at the highest frequencies. Some components had higher attenuation at higher frequencies and the phase noise at the output of the receiver SRD was also higher for higher frequencies. For the CSPR of ≈18 dB, performance was compared with the back to back case (BTB). As expected, the highest penalty due to fiber transmission occurred in subchannel 1 (3 dB), the most affected by nonlinearities, in contrast with subchannels 3 and 4 that presented the lowest penalty (<0.5 dB) as they were not affected by second order intermodulation distortion.

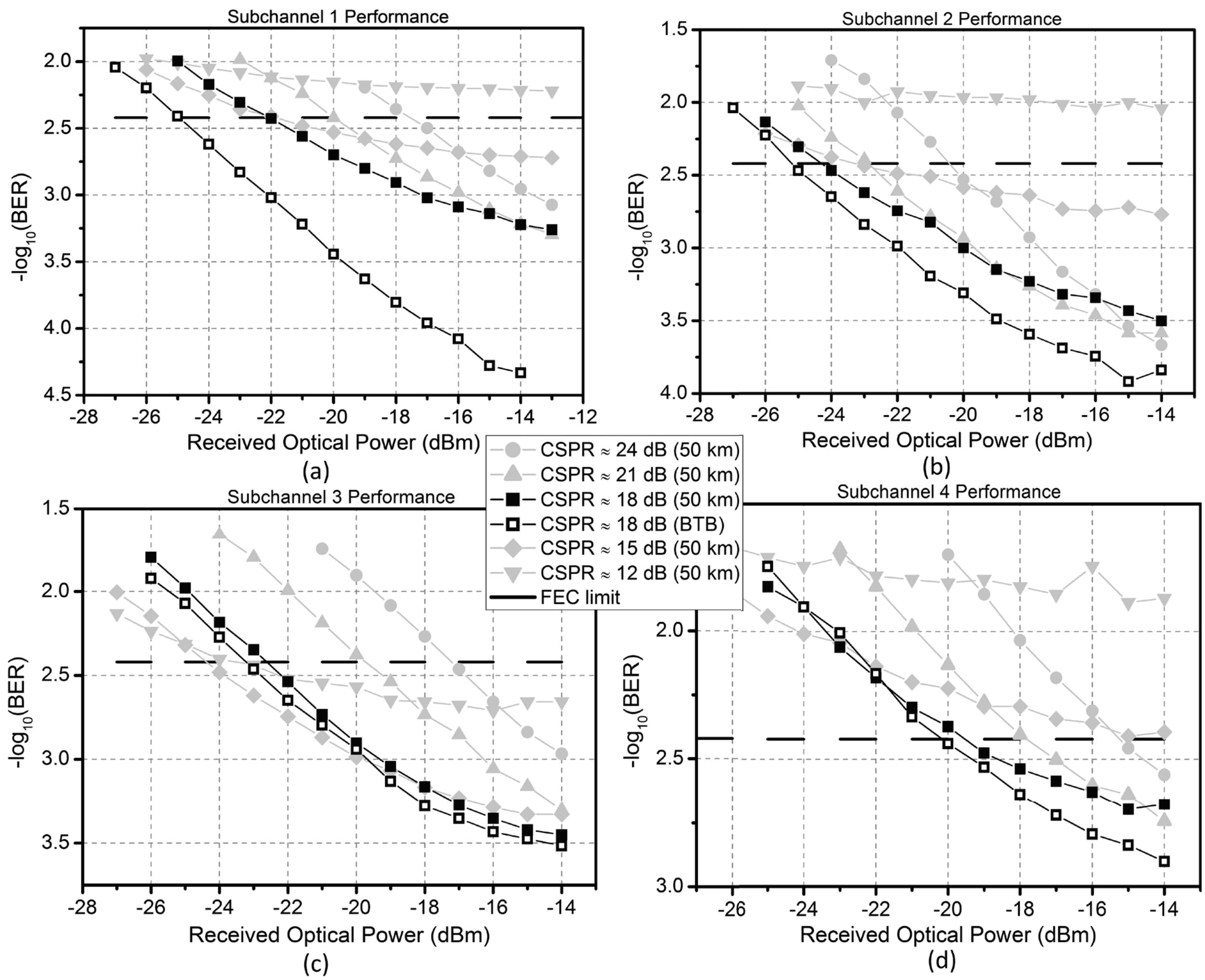

Fig. 2. Performance versus average optical input power as a function of CSPR for subchannels: (a) 1, (b) 2, (c) 3 and (d) 4.

4. Conclusions

A real-time all-analogue DD 21.6 Gbit/s OSCM 50 km link has been presented. The expected tolerance to dispersion of OSCM has been confirmed. The lowest frequency subchannel presents the highest penalty due to fiber transmission as it is the most affected by nonlinearities. A novel synchronization scheme, applicable to both traditional SCM and OSCM, has been introduced. It allows the synchronization of any number of practical subchannels requiring only one PLL. As a consequence, this synchronization method presents the lowest number of components of any analogue solution presented to date.

Acknowledgments

This work was supported in part by the EI CFTD grant CF/2011/1627, SFI grants IPIC (12/RC/2276) and CTVR (10/CE/I1853), and EPSRC grant EP/L000091/1.

[1] F. A. Gutiérrez *et al.*, "100 Gbit/s Real-Time All-analogue Filter Bank OFDM based on a Gain-Switched Optical Comb," in Proc. ECOC, 2015, p. Th.1.5.4.
[2] M. Salter *et al.*, "Circuits and system simulations for 100Gb/s optical SCM transmission," in Proc. ICECS, 2009, pp. 960-963.
[3] B. Saltzberg, "Performance of an Efficient Parallel Data Transmission System," IEEE Trans. Commun. Tech., vol. **15**, pp. 805-811, 1967.
[4] F. A. Gutiérrez *et al.,* "Optimum Bias Point in Broadband Subcarrier Multiplexing With Optical IQ Modulators," JLT, vol. **33**, p. 258, 2015.
[5] F. A. Gutiérrez *et al.,* "Impact of band rejection in multichannel broadband subcarrier multiplexing," JOCN, vol. **7**, pp. 248-252, 2015.
[6] P. Kourtessis *et al.,* "A Complete 8-GHz QPSK-MODEM Featuring Novel Subcarrier and Data Synchronization for Optical Communications," IEEE Trans. Comm., vol. **55**, pp. 987-995, 2007
[7] W. H. Chen *et al.,* "Multichannel single-sideband SCM/DWDM transmission systems," JLT, vol. **22**, pp. 1679-1693, 2004.