Transmission of a 288 Gbit/s Ethernet Superchannel over 124 km un-repeatered field-installed SMF

P. Frascella[1], S.K. Ibrahim[1], F.C. Garcia Gunning[1], P. Gunning[2], A.D. Ellis[1]
[1]Photonic Systems Group, Department of Physics and Tyndall National Institute, University College Cork, Ireland
[2]BT Innovate & Design, Adastral Park, Martlesham Heath, Ipswich IP5 3RE, UK.   e-mail: paola.frascella@tyndall.ie

Abstract: We report the world's first transmission of a 288Gb/s Ethernet Superchannel over 124km un-repeatered link of field-installed SMF using direct-detected NRZ Coherent WDM with a 2dB OSNR transmission penalty at a FLR of 10^{-3}.

OCIS codes: (060.4510) Optical Communications; (060.2360) Fibre Optics Links and Subsystems

1. Introduction

From its invention in 1973, Ethernet has evolved and adapted to meet the increasing demands of packet-switched networks. Its low implementation cost, reliability, and relative simplicity of installation and maintenance have ensured that today nearly all traffic on the Internet starts and ends with an Ethernet connection. Ethernet's characteristics are also attractive to Internet and Network Service Providers (ISPs and NSPs) to support high-speed and low-cost packet transport over metropolitan and wide-area networks. Service demand (typically spanning the metro area) for high capacity and ultra low latency are growing for applications such as financial market transactions [1] where the elimination of memory based technologies such as FEC would minimise latency.

NSPs are anticipating bandwidth scarcity due to a continued exponential growth in data traffic [2]. This means that forthcoming Ethernet standards need to be adapted to handle both higher speeds and increased traffic volume. As the telecommunication bandwidth in optical fibres is limited, the finite limit to the information capacity that can be carried by a single optical fibre is determined by the spectral efficiency. Recently reported multi-carrier techniques, such as Coherent WDM (CoWDM) [3] and Orthogonal Frequency Division Multiplexing (OFDM) [4], lately offer the highest spectral efficiencies by exploiting sub-carrier orthogonality [5].

In this paper we report the first demonstration of an Ethernet Superchannel based on CoWDM technology. Full 288GbE transport at 1bit/s/Hz is demonstrated over un-repeatered 124km field-installed single mode fiber (SMF) link with EDFA amplification only. The directly detected NRZ-OOK CoWDM offers a low cost solution for superchannel transport, whilst the low BER enabled by phase control allows the elimination of FEC.

2. Experiments

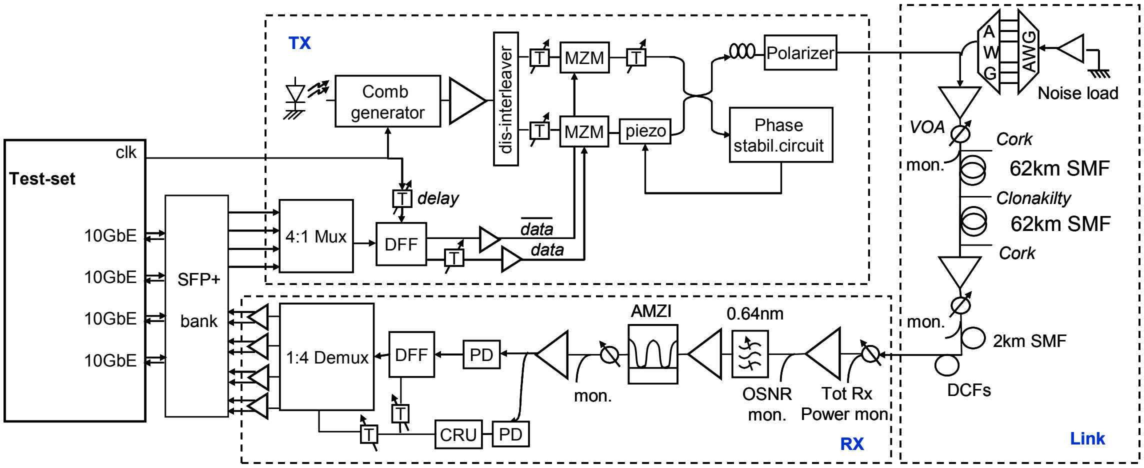


Figure 1: Experimental set-up. DFF- D-Flip Flop, AWG- Array Waveguide Grating, MZM- Mach-Zehnder Modulator, AMZI- Asymmetric Mach-Zehnder Interferometer, VOA- Variable Optical Attenuator, PD- Photodiode, CRU- Clock Recovery Unit.

Figure 1 illustrates the experimental configuration. An Ethernet testset generated four distinct 10GbE LAN PHY (10.3125Gbit/s) optical streams, each with frame length of 64 bytes (containing random payload, 8 byte preamble) and inter-frame gap of 12 bytes. The four tributaries were converted into the electrical domain with transponder boards and electrically multiplexed to 41.25Gbit/s. This signal was then optically multiplexed to 288.75Gbit/s using CoWDM [6] as follows. A 1556nm-centred DFB followed by two cascaded Mach-Zehnder modulators (MZM) generated a comb of 7 phase-locked optical subcarriers separated by 41.25GHz (equal to the symbol rate to enable subcarrier orthogonality). Odd and even subcarriers were dis-interleaved, NRZ data (and delayed data-bar) encoded at 41.25Gbit/s and passively recombined. An optimised phase control system (actuated by a piezo-electric fibre stretcher) was required to minimise the residual crosstalk.

The 288Gbit/s Ethernet signal was transmitted over a single loop comprising 124km of BT Ireland's field-installed SMF, between Cork City and Clonakilty (County Cork, Ireland), and post-compensating fibres with EDFA amplification only. The installed-fibre had a total insertion loss of 26dB and dispersion post-compensation consisted of an extra 2km of SMF followed by a series of Dispersion Compensating Fibre (DCF) modules. The latter had a total fibre dispersion of -1388ps/nm. The direct detection receiver comprised of an optical pre-amplification and two filtering stages for subcarrier selection: an asymmetric Mach-Zehnder Interferometer (AMZI) and a 0.64 nm tuneable band-pass filter (Fig. 1-RX). Finally, each Ethernet tributary was electrically demultiplexed and directed back to the Ethernet test set via differential limiting amplifiers (MICRAM) and SFP+ transponder boards. The performance was measured in terms of Frame Loss Rate (FLR) for the Ethernet streams where we transmitted the maximum number of frames possible on the test set (4.3×10^{9}), or a sufficient number to accumulate at least 10 frame errors, for each data point.

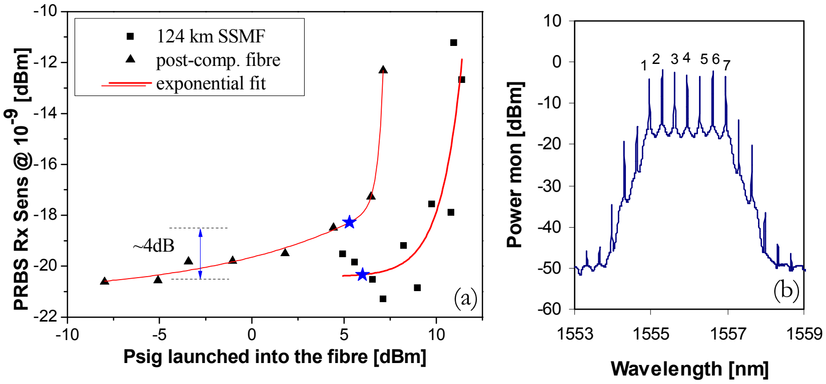


Figure 2: (a) Non-linear threshold measurements for installed fibre link (squares) and dispersion compensating fibres (triangles). Stars indicate the optimised operating powers for the Ethernet Superchannel transmission. (b) Optical spectra of the Superchannel.

In order to optimize the transmission performance with the given link, we replaced the bank of SFP+ transponders with a four channel bit error rate test set and BER measurements were performed using 2^{31}-1 Pseudo Random Binary Sequences (PRBS). Figure 2a shows the nonlinear performance of the 4th subcarrier from the 288Gbit/s CoWDM system. The receiver sensitivity (at BER = 10^{-9}) was then measured when the input power per subcarrier launched into SMF and the post-compensating fibres were changed. The launch power for the post compensating fibres was fixed at -2dBm for SMF non-linearity assessment, whilst the SMF launch power was fixed at +6dBm for the non-linearity measurements in the post-compensating fibres. As expected, non-linearities are induced in DCFs at lower signal powers than in SMF. From this data, we predicted that the optimum performance would be for input power levels of +6dBm/subcarrier and +5dBm/subcarrier into the SMF and post-compensating fibres respectively due to a trade-off between optical signal-to-noise ratio (OSNR) and the measured non-linear penalty.

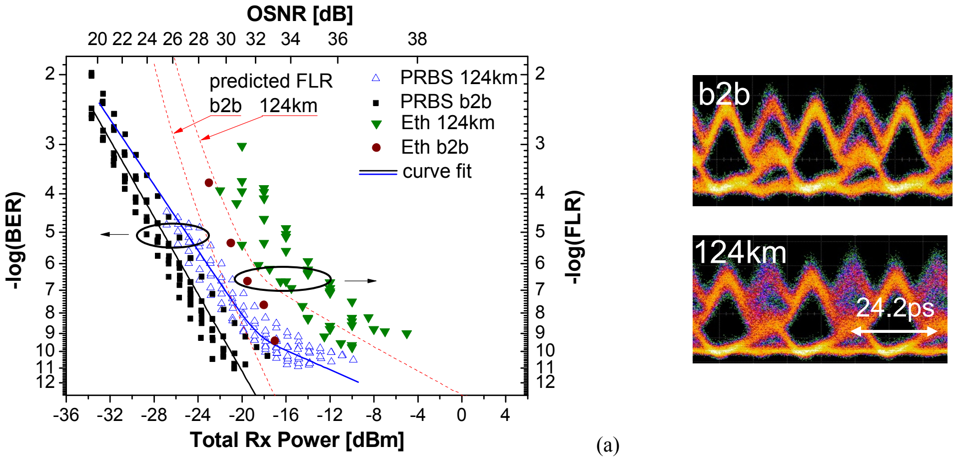
Figure 3 shows optimised results for back-to-back (squares) and transmission performance (triangles) as a function of both total received power and $\mathrm{OSNR}_{0.1\mathrm{nm}}$. Measurements of OSNR corresponding to the BER versus received power measurements gave a required OSNR of 22dB for a BER of 10^{-3} with a penalty of only 1dB. Equivalent numbers at BER of 10^{-9} were 32dB and 3.8dB respectively (cf expected penalty of 4dB from Figure 2a). For the full Ethernet superchannel, a FLR of 10^{-9} was achieved with a required OSNR of 37dB following transmission over 124km installed fibre (figure 3a), demonstrating that superchannel transmission without FEC is possible over 124 km of field installed fibre. The transmitted spectra of the 288 Gbit/s super channel is shown in figure 2b, clearly illustrating the compact spectrum achieved using orthogonal carriers, whilst the received and demultiplexed eye diagrams are shown with and without transmission in figure 3b.

Note that the removal of FEC had a significant impact on the required OSNR. This arises because one can expect the Ethernet performance to be related to the BER performance, assuming uniformly distributed and independent bit errors by:

$$(1 - \text{FLR}) = (1 - \text{BER})^{N} \tag{1}$$

where N represents the bits in the frame,. In practice, depending on the Ethernet scrambling scheme, error multiplication may occur [7], exaggerating the impact of certain error pathologies. The Ethernet Superchannel measurements are also shown in Fig. 3(a) along with the predicted FLR (dashed curves) obtained from equation (1) and the measured PRBS curve fits. As can clearly be observed, the FLR of the 288GbE Superchannel always exceeded the predicted FLR, confirming the existence of additional error multiplication mechanisms with and without transmission over the installed fibre link. In the case of installed fibre transmission the measured FLR for the Ethernet frames showed an additional penalty of up to 3dB when compared to the predicted values. For back to back measurements, the deviation was always less than 2dB. Overall, in terms of measured FLR, we observed an OSNR penalty of ~2dB at 10^{-3} (~4dB at 10^{-9}). We attribute the FLR penalty present in the back to back system to the pathological error multiplication (up to a factor of 3 in FLR), the RMS jitter (270fs) of the Ethernet clock and the additional analogue path via the limiting amplifiers and SFP+ modules. We attribute the additional 2dB transmission penalty to pattern dependent errors arising from the non-linear response of the DCFs (~1dB as observed in PRBS measurements), convolved with the analogue path, jitter and scrambling.

We anticipate that the latency could be further reduced by operating at a lower symbol rate, and utilising symbol by symbol signal processing [8] to avoid the propagation delay associated with dispersion compensating fibre.



(a) (b)

Figure 3: (a) BER and FLR performance for PRBS and Ethernet Super channel transmission. Black: PRBS back-to-back, Blue: PRBS after 124km, Red: back-to-back Superchannel (one subcarrier shown for clarity). (b) Eye diagram of one subcarrier of the Ethernet Superchannel back-to-back (top) and after transmission (bottom).

3. Conclusion

We successfully transmitted for the first time 288Gbit/s Ethernet (64-byte frames) Superchannel over a 124km installed fibre fully-compensated link with EDFA amplification only. An OSNR penalty of 2dB was observed for 288Gbit/s Ethernet Superchannel when allowing for FEC overhead, whilst a 4dB OSNR penalty was observed instead for a low latency Ethernet Superchannel. Despite the excess penalty, a FLR below 10^{-9} was achieved with an OSNR of 37dB.

The authors would like to thank J. Proudlove from Laser Physics; A. Poustie and J. Reed from CIP; D. Nesset, M. Wilkinson and K. Smith from BT Innovate & Design; and D. Cassidy, BT Ireland for continued provision of the field-installed optical fibre. This work is supported by Science Foundation Ireland under Grant 06/IN/I969.

4. References

[1] A.F. Bach, Keynote 1, IEEE Symposium on High Performance Interconnects, 2008.
[2] P. Magill, Paper OTHR1, OFC 2009.
[3] F.C.G.Guning et al., Paper CI8-5-FRI, CLEOE-IQE 2007.
[4] Y. Ma et al., Paper ThLP75, OFC 2009.
[5] R.E. Mosier et al., AIEE Transactions, vol. 76, pt. I, pp. 723-728 (1957).
[6] A.D. Ellis et al., PTL 18 (12) pp1338-1340 (2006).
[8] B. Raahemi, Proc IEEE Canadian Conference on Electrical and Computer Engineering, pp.398, 2005.
[9] J. Zhao et al., Paper Tu1.D.2 , ECOC 2008.