10 Gbit/s Bidirectional Transmission in 1024-way Split, 110 km Reach, PON System using Commercial Transceiver Modules, Super FEC and EDC

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Abstract *We report error-free transmission at 10 Gbit/s over a 110 km, amplified PON using XFP and 300-pin MSA transceivers, super FEC and EDC. Bidirectional operation is implemented over a single fibre in the access network.*

Introduction

The delivery of high bandwidth connections to end-users over the access network and the role for optical fibre is a topic of considerable interest at present. The rapid take-up of DSL lines indicates that the demand for services exists, but there is reluctance by end-users to pay proportionally more for any increase in bandwidth. To continue delivering ever higher bandwidths without eroding margins, telcos need to consider networking solutions that reduce costs.

Field deployments of systems based on passive optical networks (PONs) are already underway and there is much research interest in next generation systems. Early work [1] has demonstrated 311Mbit/s upstream (US) in an amplified PON with a split of 2048 and a reach of 100km. We have recently proposed a long reach PON (LR-PON) architecture [2], with a similar reach target, but with the goal of offering considerably higher bandwidth. The LR-PON can offer cost effective broadband service delivery by removing the need for a separate outer core or metro network tier and connecting users directly to core nodes as shown in Fig. 1. In contrast with previous work in [1], our proposal offers symmetric US and downstream (DS) capacities and does not require the optical amplifiers to be gated.

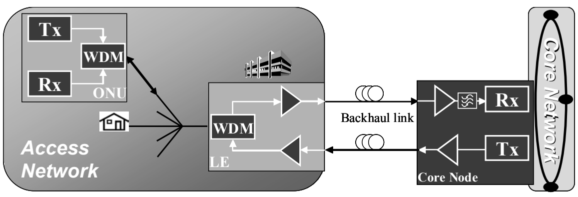


Fig. 1: Architecture of long reach amplified PON.

Experimentally, we have already demonstrated that 10 Gbit/s *upstream* transmission is possible in a 1024-way amplified PON with over 100 km reach [3]. The high aggregate data rate gives 10 Mbit/s mean bandwidth per customer, with the ability for an individual customer to utilise the full 10 Gbit/s system capacity under conditions of low traffic loading.

To make LR-PON systems practical for deployment, the optical network unit (ONU) must be made affordable for widespread use e.g. in homes and small businesses. One way to achieve this might be to use un-cooled lasers, where wavelength drifts will occur over the operating temperature range (typically ~0.1nm/ºC for a DFB laser). Such a wavelength drift has implications for optically amplified systems, where spontaneous emission (ASE) is a major system limitation, as optical filtering necessitates tight control of the Tx wavelength to align with the filter passband. Nevertheless, we have already shown in [3] that the ONU laser transmitter can be implemented by sources conforming to the CWDM wavelength grid. This removes the cost of precise laser wavelength selection and control.

Employing a single fibre in the distribution section is a requirement for deployed PON systems. To avoid crosstalk and distinguish between the US and DS data we could use the CWDM/DWDM wavelength plan shown in Fig. 2, for example.

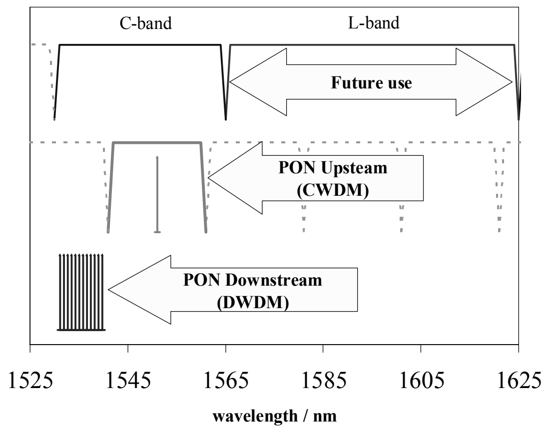


Fig. 2: Example wavelength plan for LR- PON.

We have implemented the EDFA C-band in our experimental testbed and the L-band remains open for future applications. This wavelength plan allows for bidirectional system operation, over a single fibre in the access section, by using simple WDM couplers. DWDM sources in the OLT are economically viable as the cost of this single transmitter is shared by all customers on the PON. Furthermore, one might consider adding further DWDM channels to provide extra services on a broadcast basis or via wavelength routed sub-networks on the PON.

To facilitate the use of lower cost components in the price sensitive ONU, we employ electronic techniques to overcome system impairments. We use forward-error-correction (FEC) coding and electronic dispersion compensation (EDC) to permit the use of “off-the-shelf” transceivers without using optical dispersion compensating modules. Additionally, EDC could allow, in principle, adaptable compensation for individual transmitters to account for differing ONU-LE distances, wider Tx chirp tolerances and time-varying ISI from PMD, for example. We also expect that ONU cost reduction can be gained from the use of standardised (e.g. based on MSAs) transceiver modules designed for mass manufacture.

In this paper, we report for the first time, the practical implementation of several new features in an amplified LR-PON system. Firstly, we demonstrate simultaneous transmission of US and DS data using CWDM and DWDM channels respectively. We also show the use of standardised transceiver modules for the US and DS transmitters. A pluggable transceiver based on the XFP platform (Fig. 3(a)) is used for the customer ONU and a 300-pin MSA compliant unit (Fig. 3(b)) is used for the OLT transmitter. Finally, super-FEC coding and EDC have been combined in the US to enable error-free operation to be demonstrated.

(a) (b)

Fig. 3: Intel 10Gbit/s modules, (a) pluggable XFP and (b) 300-pin MSA, C-band tunable DWDM transponder.

Experiment

Fig. 4 shows the experimental configuration. In the US direction, the ONU Tx at 1555 nm consists of an integrated DFB laser/electroabsorption modulator (EML) in an XFP module [4]. The driving conditions of this module were optimised in situ for high output power in exchange for reduced reach, as EDC can compensate for reach limitations.

The US and DS signals run over a single access fibre and are separated using a 1551 nm CWDM add/drop multiplexer (ADM). Data at 9.953 Gbit/s is super FEC encoded and applied to the XFP transceiver at 10.709 Gbit/s. The FEC encoding is achieved using an Intel® IXF30009 Optical Transport Processor, configured with a 7% overhead code, with an expected 6.8 dB net coding gain at 10^{-10} BER [5]. The launch power from the transceiver at the ADM input is +3.2 dBm. The ONU Rx is a PIN device (lower cost than an APD) with a sensitivity of -18.5 dBm at 10^{-10} BER (NRZ data format).

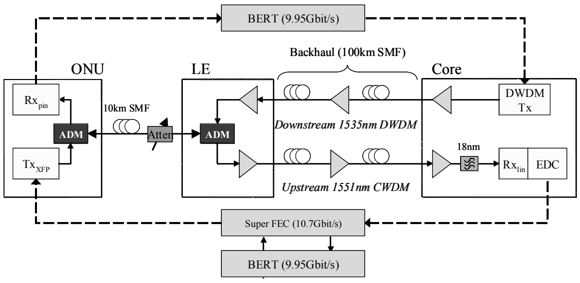


Fig. 4: Layout of LR- PON system experiment

The access network is simulated by 10 km of standard single-mode fibre (SMF, G.652) and a variable optical attenuator (VOA) to account for the PON splitter loss and additional losses from deployed fibre cable. Splitter excess losses of 0.5 dB per 1×2 split are assumed and conservative field fibre losses are taken as 0.35 dB/km.

At the local exchange, a second CWDM ADM is used to separate the US and DS signals. The US signal is amplified by a dual stage EDFA (G=46 dB and NF=4.7 dB). This amplifier is nominally wavelength unflattened with a filter at the mid-stage to suppress ASE below 1535 nm. In the reverse direction the DS signal is amplified by a dual stage EDFA to +21.3 dBm at the ADM input.

The US and DS signals are transported over two separate 100 km fibre links that represent the backhaul connecting the access network to the core. In both directions, this link consists of two 50 km spans of SMF and an intermediate optical amplifier. The span losses are built out with lumped attenuators to give a mean fibre loss of 0.35 dB/km.

At the OLT, the US data is amplified by an optical pre-amplifier and filtered by a 1551 nm CWDM, 18 nm width, bandpass filter. The Rx is a PIN device followed by a linear transimpedance amplifier for use in conjunction with the subsequent EDC.

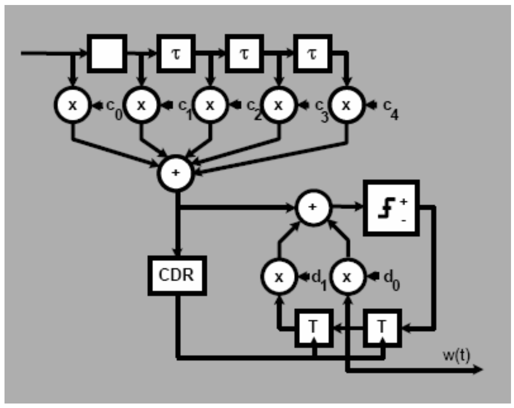


Fig. 5: Block diagram of electronic dispersion compensation chip.

The EDC circuit was implemented in a SiGe technology and its functionality is illustrated in Fig. 5.

It incorporates a 5-tap feed-forward filter, a 2-tap decision feedback equaliser and clock/data recovery. In the experiment, the tap coefficients and input slice level are manually adjusted for minimum BER, but ultimately this could be performed using an automated algorithm. The output of the EDC is connected to the FEC board for decoding prior to BER measurements.

In the DS direction, the OLT transmitter is a 10 Gbit/s, 300-pin MSA transceiver [6] incorporating a full C-band tunable laser and a Mach-Zehnder modulator with a 2000 ps/nm dispersion tolerance. This emits a 1535.04 nm signal, modulated at 9.953 Gbit/s with a 2^{31}-1 PRBS. This is amplified to +11 dBm prior to launch into the first 50 km span of the backhaul link.

Results

To characterise the performance of the FEC encoding and EDC circuit, the BER vs. OSNR at the US receiver was measured. These measurements were performed with a 2nm bandwidth optical filter and the results are shown in Fig. 6.

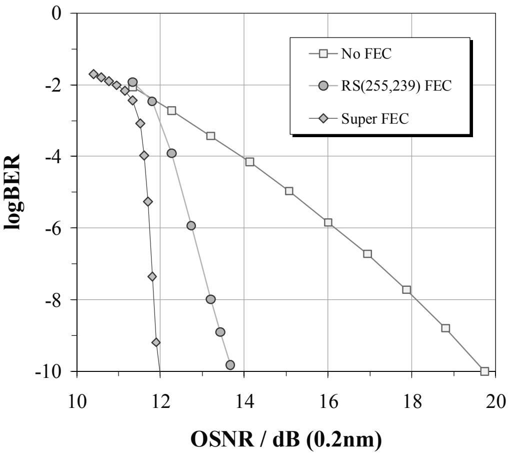


Fig. 6: BER vs. OSNR for various FEC configurations as measured over upstream LR-PON path.

The FEC chip was measured in three configurations: FEC disabled, standard G.709 FEC mode and super FEC mode. All measurements were conducted at the 10.7Gbit/s rate. The Super FEC can be seen to give a coding gain of 7.8dB at 10^{-10} BER; a 1.7dB improvement over the standard RS code.

The results for the measurement of the complete system BER (with 18 nm OLT Rx filter) versus the access network loss are shown in Fig. 7. Satisfactory performance is achieved simultaneously in both directions for an access network loss of 39 dB (equivalent to 1000-way split). The US BER shows a steep slope due to the strong FEC code for which we measured a pre-FEC BER =3.3×10^{-3} for a post-FEC BER=10^{-10} (G.983.1 target BER for PONs).

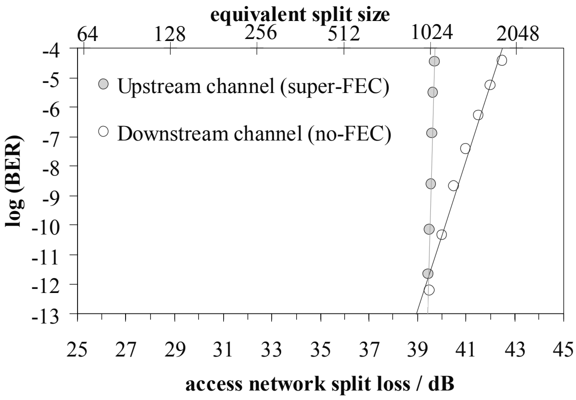
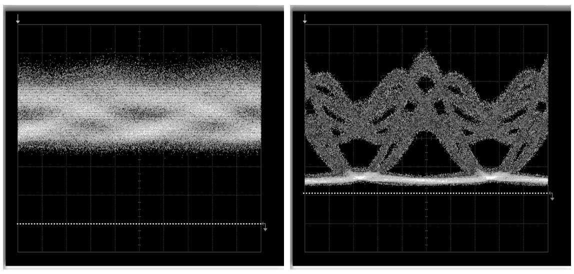


Fig. 7: BER vs. access network loss, for both upstream and downstream channels in LR-PON.

The US channel is largely OSNR limited from the large loss prior to the first EDFA (40.9 dB for 1000-way split, including the ADMs). However, an additional 0.35 dB penalty is imposed on the US channel due to the counter propagating DS channel. This is attributed to ASE crosstalk at the LE ADM. The US channel ran for 18 hours without error with the 1000-way split. The eye diagram for the US channel as recorded at the OLT Rx input is shown in Fig. 8(a).



(a) (b)

Fig. 8: Eye diagrams of: (a) of upstream signal recorded at OLT Rx input and (b) downstream signal recorded at LE output. (Horizontal white line indicates zero level.)

In the DS direction the system BER is largely loss limited. However, the link budget is improved through dispersion induced pulse shaping resulting in a 36 ps eye width after transmission and a negative power penalty. The DS eye diagram recorded at the LE amplifier output is shown in Fig. 8(b).

Optical spectra recorded at both receivers are shown in Fig. 9 for an access network loss of 39 dB. The OSNR at the US Rx input is 17.1 dB/0.1nm and the received power at the DS Rx is -20 dBm.

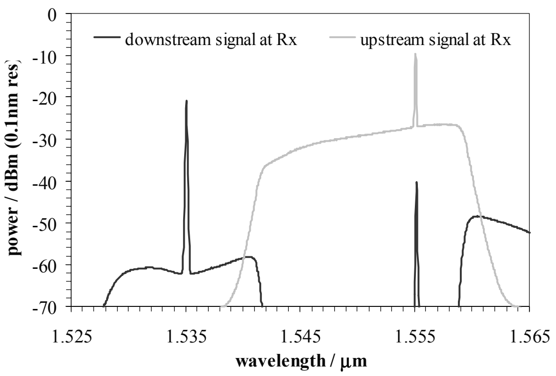


Fig. 9: Spectra recorded at receiver inputs for both upstream and downstream channels in LR-PON.

Discussion

Although this paper reports advances in the practical implementation of LR-PON systems at 10 Gbit/s, we are still only in the embryonic stages of research. We now have the confidence that one can transport bits in both US and DS directions, over 100 km, with the losses equivalent to a 1000-way split. The hurdles in the way of deploying such a system are both technical and economic.

The technical challenges include the development of a low-cost, 10 Gbit/s burst-mode Tx for the ONU. In addition one needs the complementary 10 Gbit/s burst-mode Rx and CDR at the OLT. Burst-mode receivers at 10 Gbit/s have been demonstrated in the laboratory already [7] and we eagerly await further progress and commercial availability.

We have used FEC and EDC in our experiment to show how electronics can be used to relieve some of the pressure on component specifications; however it is an area of further study to determine if this is compatible with the US data bursts on the PON. In principle, one could envisage the tap weights for an EDC circuit could be determined over multiple bursts or during a training sequence. Once determined these could be “loaded in” to match the currently transmitting ONU.

In the case of FEC, it is already defined that the Reed-Solomon (255,239) code can be used in current generation PON systems conforming to the G.984.3 standard. It is still an open question as to the most appropriate FEC code for next generation PONs and if high gain codes, such as we have used here, are suitable. Furthermore, we have assumed that FEC in the DS is undesirable as the decoding circuitry will add to the ONU cost but thinking on this is still ongoing.

Further aspects to consider with regard to the burst mode data concern the transient gain behaviour of the US EDFAs. Between data bursts and during the PON ranging window there can be long periods when no light is entering the EDFA. This is an issue we are currently studying and it is strongly coupled to the PON protocol that has yet to be defined; although we do anticipate any protocol would be broadly similar to current PON standards. Efforts to define next generation PON systems are currently ongoing within FSAN [8].

A further aspect that is subject to standardisation is the choice of wavelength plan. We have proposed a CWDM/DWDM plan (Fig. 2) as an input to this process. However, this may not be appropriate if next generation PON systems need to coexist on the same fibre as legacy PON systems, as there would be a conflict in the C-band with the current B-PON enhancement band.

The economic benefits of a LR-PON, resulting from network simplification, can only be fully realised with the reduction in the optoelectronic component costs. The transceiver at the ONU is critical in this regard as this cost is borne on a per subscriber basis. It is expected that this cost reduction will be driven by maturing transceiver technology and the enormous volumes that could be expected from a widespread roll-out of such systems.

Conclusions

We report for the first time, error-free physical layer transmission at 10 Gbit/s, over a 110 km reach PON architecture for both the upstream and downstream directions and a split size in excess of 1000. This has been achieved using commercial transceiver components in standardised form factors. High coding gain FEC and electronic dispersion compensation have been employed to overcome noise and dispersion related impairments, and thereby enable the use of a lower cost upstream transmitter, and eliminate the use of optical dispersion compensation. Furthermore, we have discussed many challenges for such systems that must be addressed to make LR-PONs a practical proposition.

References

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