Impact of Crosstalk on Multi-Wavelength High Split PON Networks

Bart Baekelandt1, Cedric Mélange1, Peter Ossieur2, Johan Bauwelink1, Tine De Ridder1, Xing-Zhi Qiu1, Jan Vandewege1, David Smith3, Russell Davey4

1 Ghent University, INTEC/IMEC, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium, Bart.baekelandt@intec.ugent.be
2 Postdoctoral fellow FWO Vlaanderen, 3 The Centre for Integrated Photonics Ltd, 4 British Telecommunications plc

Abstract

The IST-PIEMAN multi-wavelength high split long reach PON (passive optical network) integrates access and metro network in one operational system, thereby greatly decreasing the cost to deliver future broadband services to customers.

In-band crosstalk arising from imperfect interburst suppression of upstream transmitters can impose significant limitations on the split factor in multipoint-to-point PON networks. Simulations are presented which show how OSNR requirements depend on interburst suppression.

Introduction

The technical objective of the FP6 IST project PIEMAN (Photonic Integrated Extended Metro and Access Network, www.ist-pieman.org) is the development of a radically new optical broadband access and metro network with reach and capacity far exceeding current state-of-the-art, at a reduced cost. The main interest of PIEMAN is to perform physical layer research aimed at 10 Gbit/s upstream bandwidth per wavelength shared by up to 512 customers over 100 km reach.

Figure 1: PIEMAN target system top level architecture. (OLT: optical line terminal; EDFA: erbium doped fibre amplifier; ONU: optical network unit; DWDM: dense wavelength division multiplexing)

Figure 1 depicts the target system architecture of the PIEMAN network. This next generation PON still contains the traditional PON architecture in the access part, however signals to and from different PON-like subnetworks are optically amplified and DWDM is used in a metro part which extends the network reach to a total of 100 km.

The PON systems that are currently being deployed work at upstream bit rates of 1.25 Gbit/s, serve up to 32-64 customers, and have a reach of 10-20km. The features of the PIEMAN network far exceed those of traditional PON networks:

- PIEMAN network contains maximum 32 PON subnetworks, each with a maximum split factor of 512, so a total of 16384 customers can be supported.
- Each PIEMAN network has 32 downstream wavelengths and 32 upstream wavelengths in a pure C-Band on a 50 GHz grid in a DWDM scheme [1].
- Bandwidth per customer is maximum 10 Gbit/s upstream and 10 Gbit/s downstream.
- In the upstream direction, DWDM/TDMA (time division multiple access) is used. Upstream traffic is in burst mode and the modulation format is NRZ (non-return-to-zero).
- 100 km reach can be obtained by using optical amplifiers without optical-electrical-optical conversions at intermediate locations. The entire fibre span is all-optical.

This integration of access and metro network enables a typical European network to attain full coverage from around 100 service nodes. This allows for significant cost savings, both in CAPEX (capital expenditures) and OPEX (operating expenditures) [2]-[3].

Upstream system architecture

Figure 2 shows the upstream transmission path in detail. An upstream burst will first encounter the high losses of the access portion of the network (dominated by the splitter loss), before amplification by an EDFA in a local exchange. This EDFA should provide a high gain with low noise to compensate for the high losses of the access portion. Because of the bursty nature of the upstream signal, the
gain of the EDFA should be independent of the input signal power within the burst. Therefore burst-mode EDFA gain stabilization and compensation schemes have been investigated [1].

The burst mode upstream signals of the different subnetworks are then wavelength multiplexed onto the feeder fibre using a 50GHz AWG. This puts stringent requirements on the wavelength stability of the upstream ONU transmitter. After optical preamplification, the channels are wavelength demultiplexed before reception by an OLT burst mode receiver.

**Colourless ONUs**

The PIEMAN architecture requires the ONU to be capable of transmitting 10 Gbit/s NRZ data over 100 km of standard optical fibre and able to select from 32 wavelength channels spaced by 50 GHz. Two colourless ONUs’ are being developed within PIEMAN:

1. The tunable ONU approach consists of a hybrid tunable laser diode, integrated with an EAM (electro-absorption modulator) and a post-amplifier SOA (semiconductor optical amplifier). A reflective SOA gain block is coupled to an external cavity with wavelength selective element optimized for the intended low cost application – i.e. “set and forget” rather than wavelength agility.
2. PIEMAN is also considering a reflective ONU approach to reduce the cost of the ONU by removing the need for an internal wavelength referencing and control function. The reflective ONU under development in PIEMAN is based upon monolithically integrated combinations of EAMs and SOAs.

For both ONU types, the light source will not be switched off between bursts, as retuning the wavelength for each burst would be prohibitively slow. Instead, the SOA will be gated, so as to limit the optical power leakage when an ONU is in off-state. This interburst suppression is not perfect, so there will always be a low amount of interburst residual output power, which can degrade network performance. Furthermore, the residual optical powers are aggregated from all connected ONU’s in off-state with the same wavelength as the signal burst, which makes it impossible to suppress it by additional filtering.

When this field impinges onto a photodiode, the resulting current is given by:

\[ I(t) = R \cdot |E(t)|^2 \]

\[ = R \cdot \left( \sum_{i=1}^{N} P_i(t) + 2 \sum_{i,j} P_i(t)P_j(t) \cos(\phi_i(t) - \phi_j(t)) \right) \]

(2)

In equation (2), the first term represents the power of the individual channels. It contains the launched upstream burst data signal (i=1), as well as offsets caused by the interburst interferers (i=2..N).

The second term contains the crosstalk contributions, where the phase noise of the lasers is converted into intensity noise. This effect is called linear in-band crosstalk, and it can seriously degrade network performance, and even impose BER (bit error rate) floors [4][5]. It was previously studied in the context of non-ideal optical WDM crossconnects. It can however also appear in the PIEMAN high split long reach PON network, where the presence of interburst residual output power of ONUs is the cause.

There are two types of crosstalk terms:

1. Terms where an interburst signal (i=2..N) interferes with the launched data signal(i=1). These terms are called signal-crosstalk beat noise.
2. Terms where interburst signals interfere with each other. These terms are called crosstalk-crosstalk beat noise. In most practical systems, these terms are negligible compared to the signal-crosstalk noise.

**OSNR requirements in the PIEMAN network**

Previous OSNR (optical signal-to-noise ratio) requirements were calculated without taking into account in-band crosstalk. For example, the required OSNR as a function of extinction ratio for different bit error rates, is depicted in Figure 3. For a target extinction ratio of 10dB, a BER of 10^{-10} can be attained with an OSNR of around 17.5dB. The OSNR in the upstream direction is mainly determined by the loss in the access portion of the network, so high OSNR requirements will impact the attainable split factor of a PON subnetwork.
Figure 3: OSNR versus extinction ratio for different BER values

While giving a good initial idea of the required OSNR, this model is only valid in cases where the interburst ONU output power is negligible. For a more accurate analysis, one needs the OSNR requirement in a network dominated by ASE (amplified spontaneous emission) noise and disturbed by in-band crosstalk.

An analytical model was conceived and simulations were performed to determine the OSNR, needed to guarantee a certain bit error rate in the presence of interburst residual output power. Figure 4 plots the OSNR requirement for a BER of $10^{-10}$ as a function of the interburst power and the extinction ratio in a nominal case, where all interferers encounter the same loss as the signal burst. The average power of the signal burst is 5 dBm.

Several conclusions can be made from Figure 4:
1. For extremely low interburst powers, the required OSNR converges to the curve in Figure 3. In this area, the network is dominated by ASE.
2. With increasing interburst power, the required OSNR steadily increases before rapidly approaching infinity. At this point, the BER floor imposed by linear crosstalk is already higher than $10^{-10}$, so even a network without ASE noise will not guarantee the envisaged BER. This is the crosstalk dominated area.
3. Extremely low interburst residual output powers are needed to guarantee a satisfactory BER performance. For an extinction ratio of 10dB, the crosstalk imposed BER floor reaches $10^{-10}$ for -39 dBm off-state power.

PON Differential loss implications

The differential nature of a PON network poses another problem: the optical signals coming from different ONUs may encounter different losses. The difference between maximum loss and minimum loss allowed in a network is called the differential loss.

From a crosstalk point of view, the worst case arises when the signal burst encounters maximum attenuation, and all interburst signals encounter minimum attenuation. Figure 5 shows the OSNR requirement in worst case, where the interferers encounter 10dB less attenuation than the signal burst. One can see that the increase of OSNR requirement with increasing interburst power comes 10dB earlier. For an extinction ratio of 10dB, the crosstalk imposed BER floor now reaches $10^{-10}$ for -49 dBm off-state power.

Figure 5: OSNR requirement in worst case, N=512

Conclusions

Linear crosstalk caused by interburst residual output power can cause significant OSNR penalties. Calculations show that the residual output power of an ONU transmitter in off-state should be very low. Challenging specifications for interburst suppression are needed, and research on the feasibility of the gated SOA approach is ongoing.

Acknowledgments

The authors would like to thank the European IST (Information Society Technologies) committee for supporting the PIEMAN research activities. This work was also sponsored in part by the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) for grants to Bart Baekelandt and Cedric Mélange.

References
