Integrated Metro and Access Network: PIEMAN

(Invited)

Giuseppe Talli[1], Chi Wai Chow[1], Paul Townsend[1], Russell Davey[2], Tine De Ridder[3], Xing-Zhi Qiu[3], Peter Ossieur[3], Heinz-Georg Krimmel[4], David Smith[5], Ian Lealman[5], Alistair Poustie[5], Sebastian Randel[6], Harald Rohde[7]

[1] Photonic Systems Group, Tyndall National Institute and Department of Physics,
University College Cork, Cork, IRELAND
Tel.: +353 214904874, Fax: +353 214904880, E-mail: giuseppe.talli@tyndall.ie

[2] BT, [3] INTEC/IMEC, [4] Alcatel-Lucent, [5] CIP, [6] Siemens AG, Corporate Technology,
[7] Nokia Siemens Networks GmbH & Co.

We describe progress to date on the IST project PIEMAN (Photonic Integrated Extended Metro and Access Network, www.ist-pieman.org), which aims to build a radically new photonic (all-optical) communication system integrating metro and access networks, thereby greatly simplifying the network architecture and significantly reducing the cost to deliver future broadband services to all residential and SME customers. The optical fibre system being developed will also allow individual customers to directly access bandwidths of up to 10 Gbit/s upstream and downstream. Some of the key physical layer design issues are outlined and the solutions studied within the project are also described.

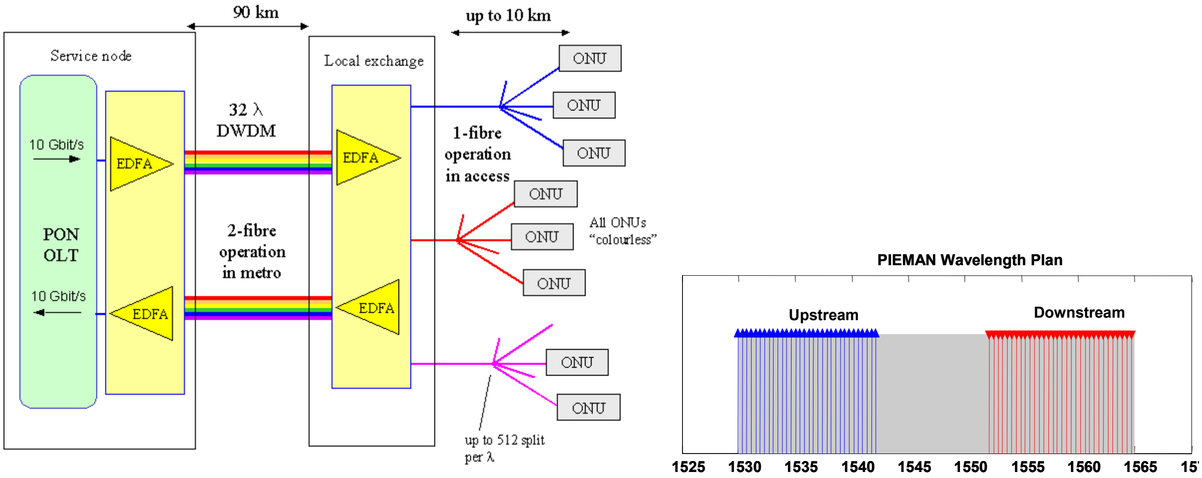
1. Introduction

In the state-of-the-art, the access and metro portions of the network are provided by separate systems. As bandwidths grow this traditional approach of separate access and metro networks will become prohibitively expensive [1]:

- from a capex viewpoint due to the large number of network elements and interfaces to interconnect them;
- from an opex viewpoint due to network design complexity, large number of network elements, large footprint and high electrical power consumption.

PIEMAN therefore proposes a new generation of photonic communication system which integrates access and metro into one system. In order to achieve this for European national geographies requires a reach of ~100 km from the customer to the major service node. There will be ~100 major service nodes in a typical European network. The ~100 km reach is necessary to enable full coverage and the option of dual parenting for resilience. To deploy point-to-point fibre from each customer to the service node up to ~100 km away would be prohibitively expensive. PIEMAN will therefore use multi-wavelength, high split passive optical networks (PONs) to make efficient use of fibre. While the first generations of PONs are now standardized and commercially available [2], the most advanced of these (GPON and GE-PON) typically offer 2.4 Gbit/s or 1 Gbit/s downstream and ~1 Gbit/s upstream, shared between 32 customers via passive optical splitters and a time-division multiple access (TDMA) protocol, over a reach of up to 20 km. PIEMAN is performing physical layer research aimed at a new generation of PON with features totally beyond the capability of today's PONs:-

- bandwidth per customer of up to 10 Gbit/s downstream and 10 Gbit/s upstream
- each 10 Gbit/s wavelength is shared by up to 512 customers
- significant use of DWDM to provide further fibre efficiency in the metro with up to 32 wavelengths each carrying 10 Gbit/s – the project will therefore take a hybrid WDM/TDMA approach
- all-optical reach of 100 km using optical amplifiers – no use of optical-electrical-optical conversions at intermediate locations.



(a) (b)

Figure 1: (a) High level view of PIEMAN target system architecture and (b) wavelength plan.

Figure 1(a) shows a high level view of the PIEMAN system architecture. While the PIEMAN architecture will support fibre-to-the-premises, it will also, as an evolutionary step, be capable of feeding hybrid architectures such as fibre-to-the-cabinet. The focus of the PIEMAN project is in the physical layer where some major challenges lie. Higher layer and MAC protocols are being studied in parallel within the complementary IST project MUSE.

The remainder of the paper will summarize progress to date against some of the key physical layer design issues in the project.

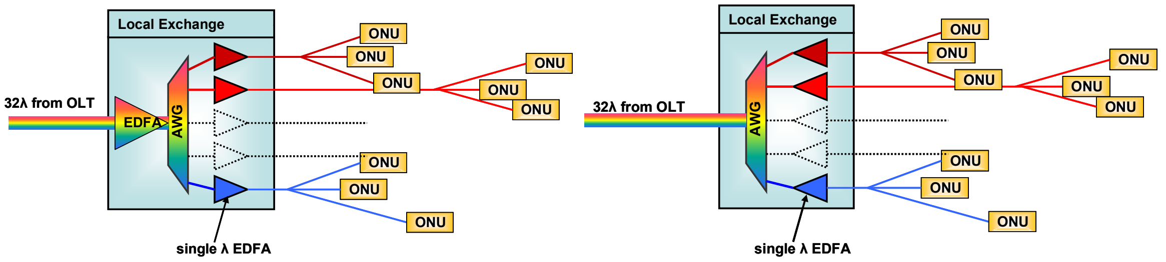
2. Target system architecture

An important design decision is the DWDM wavelength plan to use on the "backhaul" fibre between the service node and local exchange. A pure C-Band design, covering 32 wavelengths for the upstream and 32 wavelengths for the downstream on a 50 GHz grid, was found to give the optimal compromise between technical complexity and price. Figure 1(b) depicts the PIEMAN wavelength plan with the downstream wavelengths in the red part of the C band, the upstream wavelengths on the blue side of the C-band spectrum and a 10 nm guard band in between. The video overlay, present in some current PON deployments, was omitted in PIEMAN in favour of an easier and cheaper realization of the overall system which will carry video on IP broadcast channels rather than on an additional analogue optical carrier.

To avoid inventory issues associated with having 32 different types of ONU – each with different upstream wavelengths – PIEMAN implements "colourless" ONUs. The upstream wavelength for the respective ONU is determined by the OLT, either by optically delivering a wavelength-specific carrier which is then re-modulated (reflective ONU), or by programming the tunable laser of the ONU. As both approaches are technologically challenging for the given bit rates and power levels, it is not yet clear which is the preferable solution and thus both are being studied within the project.

Within the local exchange node, several possible configurations of the amplifier placing are possible. The configuration chosen in PIEMAN for the downstream direction is shown in Figure 2(a). The downstream WDM signal from the OLT is first re-amplified after the 90 km of standard single mode fibre from the OLT, demultiplexed into its single wavelengths by an arrayed waveguide grating (AWG) and each of the wavelengths is then amplified by a single-wavelength EDFA. This configuration proved to give the best performance and cost compared to the options of having one powerful EDFA before the AWG which delivers the energy for all the 512×32 users, or just having individual wavelength post-AWG boosters.

The preferred solution for the upstream is shown in Figure 2(b). Each wavelength is amplified by a dedicated EDFA prior to multiplexing by the AWG onto the upstream fibre. Each single wavelength EDFA is actively stabilized against the transients introduced by the bursty nature of the traffic. A common upstream WDM EDFA is not used in the local exchange in order to avoid transients introduced by neighbouring channels.



(a)

(b)

Figure 2: PIEMAN local exchange node amplifier placing for the downstream direction (a) and for the upstream direction (b).

3. Burst-mode optoelectronics

The PIEMAN upstream link design requires a 10 Gbit/s burst-mode receiver (BM-RX) including a burst-mode transimpedance amplifier with PIN photodiode (PIN-TIA) and a burst-mode post-amplifier (BM-PA), as shown in Figure 3. The BM-RX located at the service node receives optical packets from all active subscribers in fast succession, with varying signal level and phase. The design of the BM-RX in PIEMAN is extremely challenging due to the high bit rate targeted, 10 Gbit/s, the high dynamic range imposed by the high split and the ASE introduced by the amplifiers.

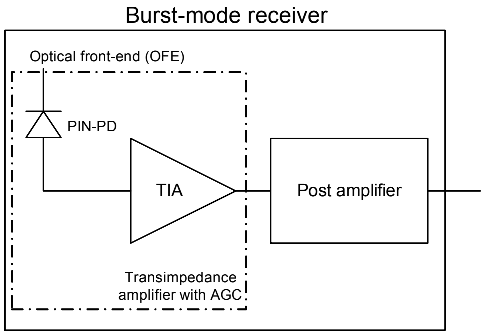


Figure 3: BM-RX and BM-PA.

Modulation format		NRZ
Min. sensitivity	dBm	-16
RX dynamic range	dB	16
Overhead length	Ns	40.8
Guard time	Ns	25.6

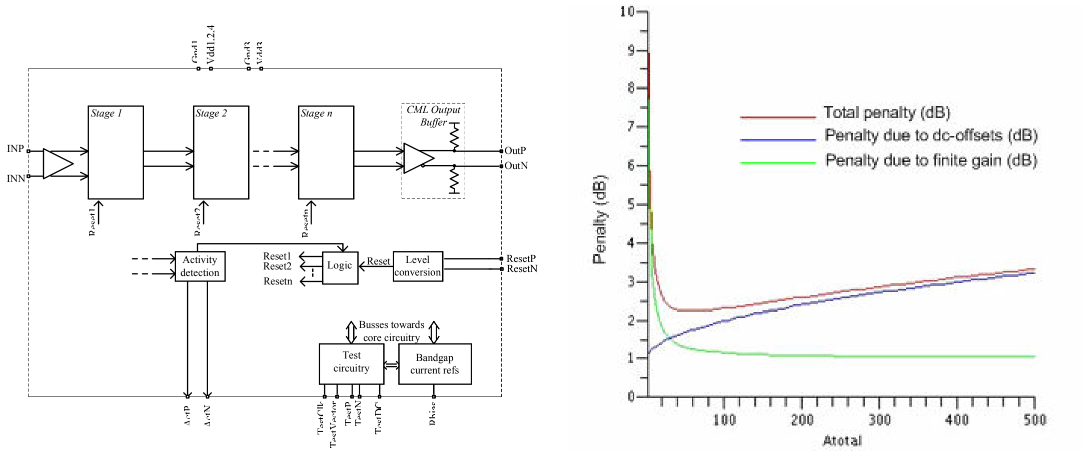
Table 1: Main target specifications BM-RX.

Table 1 gives the main specifications of the BM-RX. The dynamic range of the input levels is mainly caused by differences in attenuation of the optical distribution network), tolerance on the power launched by the ONU and residual gain variation of the EDFAs. The overhead length, which should be short to maintain high traffic throughput, is used for automatic gain control (AGC) settling, threshold and phase recovery.

Several alternative BM-PA implementations were investigated. A frequently used architecture at 10 Gbit/s is the optical differential receiver [3]. It offers the advantages of simple electronics, short overhead length and intrinsic rejection of residual EDFA transients. However, it was found that it does not achieve sufficiently high sensitivity and is not suitable for NRZ modulation due to error propagation. Receiver structures based upon explicit threshold extraction are now widely used for EPON and GPON applications [4-6]. Using the feedback type [4], it became clear that it is difficult to combine both fast AGC and threshold recovery, rendering achievement of a high dynamic range difficult. A combined feedback/feedforward type was presented in [5], however this receiver needs sophisticated digital control circuitry, and requires dark windows in the upstream traffic, reducing transmission efficiency. Finally, it was decided to use a multistage feedforward architecture, in which dc-offsets are gradually reduced along a chain of amplifiers. Figure 4(a) shows the architecture of the BM-PA.

Several sources of burst-mode penalties can be recognized such as, fast threshold acquisition [7], Dc-offsets in the signal path and slow tails in the burst. The finite gain of the post amplifier can also give rise to a penalty, which becomes smaller with increasing post-amplifier gain. A trade-off can be recognized in which increasing BM-PA gain increases penalty due to dc-offsets and reduces penalty due to limited post amplifier gain. Hence, an optimum overall gain exists, as shown on an example in Figure 4(b).

A PIN-TIA is used as front-end to reach the 10 Gbit/s speed and a sensitivity of -16 dBm. High dynamic range will be ensured using an AGC operating on packet-by-packet basis.



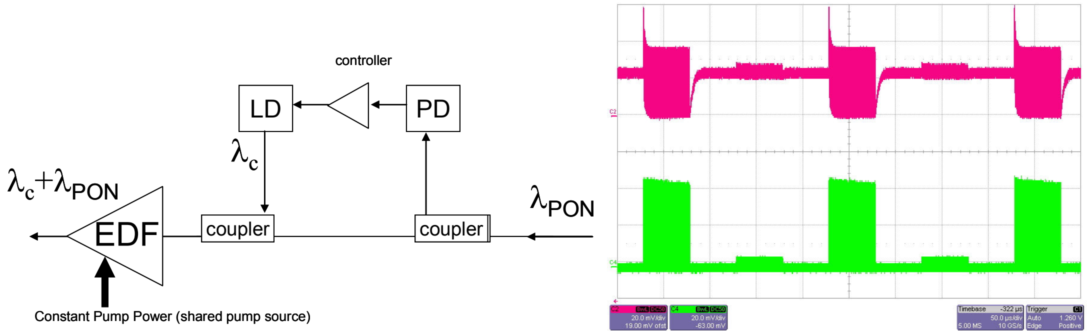
(a) (b)

Figure 4: BM-PA architecture (a) and penalty (dB) as a function of BM-PA gain (Atotal) (b).

4. Optical amplifier design for burst-mode operation

The demanding optical attenuation budget of the high-split approach requires optical amplification in the downstream and especially in the upstream direction. The power-splitting approach further requires the TDMA mode of operation which generates bursty upstream traffic patterns. The long upper level lifetime prevents a simple usage of EDFAs in the same way as in the continuous downstream. Significant impact from varying burst power levels and traffic gaps onto the momentary optical gain would be observed without a stabilization for the elastic EDFA optical gain in saturation. A consequence would be a negative impact on burst mode receiver sensitivity even though the number of cascaded EDFAs is low in this application. To avoid such a penalty, which would reduce the feasible splitting factor, the target is to stabilize the EDFA gain under single-lambda operation to within 1 dB.

Several techniques to stabilize EDFA gain under varying input power conditions are known, which range from optical gain clamping to pump power variation. To achieve a premium pump efficiency and non-degraded maximum output power in conjunction with an unaffected noise figure, an optical compensation scheme for a constant amplification has been chosen. In this scheme, an auxiliary wavelength λ_c is sent through the EDFA together with the payload wavelength(s) λ_{PON}. Active circuitry senses the payload signal and keeps the total input power constant within the response bandwidth of the signal. As shown in Figure 5(a), the input signal is tapped and converted into an electrical signal by a photodiode (PD). A controller derives a suitable compensation signal, which is converted into the optical domain by a laser diode (LD) and re-combined with the payload signal. After joint amplification in the EDFA the compensation signal is stripped off again, e.g. by the subsequent multiplexing stage. The extra EDFA cost is split among up to 512 subscriber stations.



(a) (b)

Figure 5: (a) Hybrid stabilization circuit using an auxiliary local light source and (b) time domain behaviour of stabilized burst EDFA with 10 dB strong/weak burst difference and 50 μs duration bursts and gaps

With the auxiliary local lightsource technique, a stabilized two-stage, single- pre-mux amplifier has been realized with a constant gain for input powers up to −22 dBm. The behaviour depicted in Figure 5(b) shows the result with an unstabilized preamp stage and a stabilized, signal-saturated power stage. The upper trace shows the intermediate compensated signal and the payload output is in the lower trace. Bursts and gaps are of 50μsecs duration. Alternative approaches are also currently under investigation with respect to cost and operational aspects.

5. Tunable ONU design

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. Whilst this level of performance may be achievable for transmitters engineered for long haul DWDM systems, there are significant new challenges when this has to be achieved at costs acceptable for access networks. Wavelength control introduces additional problems for a timeshared PON network because it might be necessary to build additional features into the transmission protocol to assist ONU lasers to lock to wavelength reference signals before bursting data. To avoid this problem a "set and forget" approach to wavelength tuneability is being considered within the design of the PIEMAN. To achieve the long reach required in PIEMAN it is also necessary to use external modulation to help manage dispersion.

A very wide variety of approaches to tuneable transmitters have been reported. These can broadly be divided into discrete, monolithic and hybrid schemes. With discrete devices, a DFB or DBR laser is made to tune over a sub-set of channels within the band by simple temperature tuning. To tune over half of the C band, as required by PIEMAN, either 2 or 4 lasers would be required. The monolithic approach uses more sophisticated DBR structures where several sections can each be electrically individually controlled. This approach provides the required tuning range from one device. However, the monolithic device requires a larger chip area and more intensive characterization during manufacture and extensive control systems. The third class is hybrid devices where a semiconductor optical amplifier gain block is coupled to an external cavity with wavelength selective element. In this case the design of the external cavity and tuning mechanism is crucial to the performance of the laser.

We have carried out a detailed cost comparison of alternative methods to achieve the PIEMAN requirements from a tuneable transmitter. The cost model has been built from experience gained carrying out studies on a wide range of optoelectronic components and takes into account the chip size, InP wafer size, defect density, device complexity, piece parts, packaging, test and characterization costs. Costs of additional components such as external modulators and lockers are also included when required. A useful comparison when considering alternative approaches is the cost against the yield for the individual active device elements. The results of this comparison are summarized in Figure 6, which includes two known variants of monolithic multisection DBR lasers.

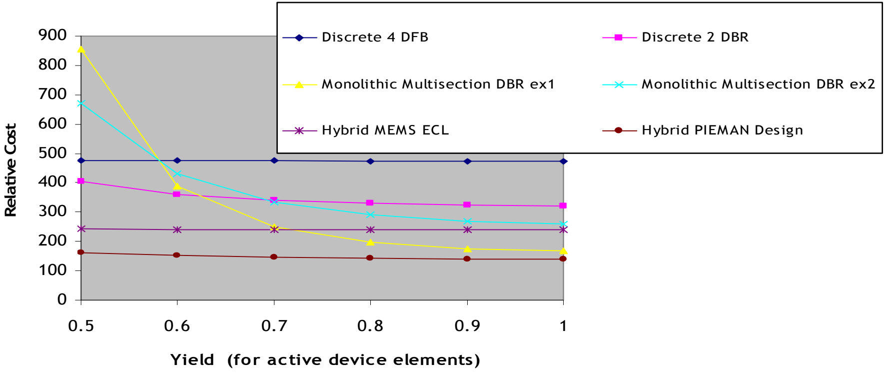


Figure 6: Comparative costs of tunable transmitter technologies.

The curves show that monolithic approaches can only compete against discrete solutions when element yield exceed between 0.6 and 0.7, and this lines up with current typical yield figures for the industry. With the hybrid solutions there is a balance between what is carried out monolithically and what is performed externally. In the PIEMAN design the integration of the modulator and gain block is monolithic to reduce piece parts but the tuneable cavity is external so it can be optimized for the intended application –i.e. “set and forget” rather than wavelength agility.

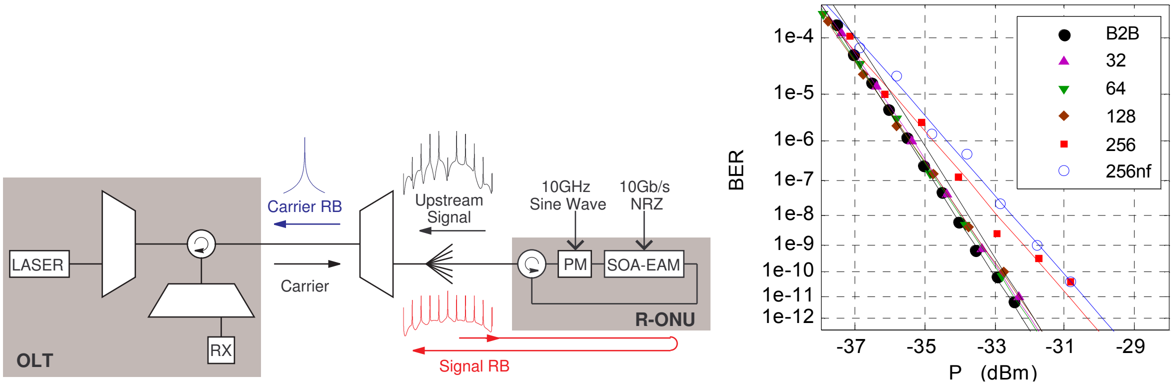
6. Reflective ONU

PIEMAN is also considering an alternative approach for provision of upstream channels, which attempts to reduce the cost of the ONU by removing the need for an internal wavelength referencing and control function. Instead, the latter is provided by means of cw optical carriers that are distributed from the service node and shared among multiple users on each individual power splitter PON. The upstream signals are generated from the cw carriers using ‘colourless’ reflective modulators that operate across the full upstream wavelength range. The reflective ONU (R-ONU) under development in PIEMAN will be based upon monolithically integrated combinations of EAMs and SOAs, or a variant of this basic configuration. These devices, which will be grown by selective area metal-organic vapour phase epitaxy, will have sufficient bandwidth and gain (~25dB) to achieve the PIEMAN upstream bit rate and launch power targets of 10Gb/s and +5 dBm respectively.

One potential disadvantage of the R-ONU approach is that at least part of the fibre path between the customer and the upstream Rx is shared by the optical carrier and the upstream signal, hence Rayleigh back-scattering (RB) and Fresnel back-reflections can lead to interferometric beat noise, which will ultimately limit the split that can be achieved in the network. While the level of back-reflection can in principle be controlled by setting appropriate return loss specifications for the various optical components employed in the network, the RB is an intrinsic phenomenon in fibre propagation and its level is fixed by the fibre type and configuration used. Hence, an important task within PIEMAN is to achieve an understanding of the fundamentals of the Rayleigh noise generation processes and develop suitable mitigation strategies. In architectures using R-ONUs we find that there are two RB contributions generated respectively by the carrier and by the upstream signal, as shown in Figure 7(a) [8].

One example of a mitigation technique that is under study in the project adds a phase modulator (PM) to the ONU to reshape the spectrum of the upstream signal. The PM is purposely overdriven with a 10 GHz sinusoid to generate multiple side-bands and to suppress the centre wavelength. This reduces the overlap with the back-reflected light and hence reduces the beat noise falling within the receiver (RX) bandwidth [9]. Another simple, but effective approach uses a second feeder fibre to deliver the optical carrier, thus reducing the total RB power at the receiver [10]. This scheme also maintains the currently-preferred low cost option of a single drop fibre to the customer.

A PIEMAN network test-bed was developed incorporating both of these techniques in order to assess the potential for split extension through Rayleigh noise reduction [11]. The upstream performance was tested by measuring the BER curves for various split ratios as shown in Fig. 7(b). Without mitigation the network split was limited to about 8. The results obtained using the mitigation schemes show that the network can operate with a negligible penalty for split ratios up to 128, while for a split of 256 a penalty of 1.6dB can be seen at a BER of 10^{-10}. The dispersion tolerance, reduced by the phase modulation technique, is still sufficient to cover the access section of the network as shown by the similar results achieved without the 12 km feeder fibre section for the maximum split of 256 (labeled ‘256nf’). Work is currently underway to determine the optimum Rayleigh mitigation approach and associated R-ONU design for the PIEMAN network.



(a) (b)

Figure 7: (a) Schematic network architecture with R-ONU using PM spectral-broadening and showing CB and SB Rayleigh components and (b) 10Gb/s BER curves

7. Conclusion

While challenging physical layer research remains to fully realise the benefits of the radical PIEMAN architecture, results obtained to date are encouraging. Further results will be obtained from the realisation of the solutions described here and will be presented through the remaining time of the project

Acknowledgements

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