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D4.2

System specifications for LR-PON implementation

Dissemination Level: PU

- **Dissemination level:**

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Abstract:

This deliverable will define the technologies and architecture of the work to be done in WP5 (LR-PON critical physical hardware implementation) and WP8 (Critical system test and verification). The base of these decisions will be the findings in D4.1 (Assessment of advanced LR-PON transmission technologies) and D4.3 (Integrated architecture for LR-PON supporting wireless and wire line services).

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1 Introduction

More and more it is accepted that optical networks are becoming an important factor for enhancing the economic attractiveness of cities and regions. However, the deployment of fiber infrastructures needs a large investment, slowing down the proliferation of optical networks, particularly in the access space. Today´s optical networks in the metro and access area are mostly being owned and operated by single operators or companies for a dedicated purpose. For instance, operators install and manage as separate networks fiber-to-the-home (FTTH) and fiber-to-the-building (FTTB) services as well as optical backhauling systems. However, when looking at the slow progress of fiber network deployments these business cases do not seem sufficiently compelling or are just too risky, especially in view of regulatory uncertainties [1]-[3]. The *DISCUS* architecture aims on one hand at the capitalization of the passive optical network (PON) sharing potential by increasing the number of users per PON by well over an order of magnitude, compared to current gigabit-(G)-PON values. These long-reach PON solutions can additionally be capitalized by opening the infrastructure for several service providers and network operators in an open access network business model.

In former *DISCUS* deliverables [4] we came up with network topologies enabling long-reach-(LR)-PON networks. These network scenarios have been tested in terms of signal performance and capacity as well as for usability for different kind of services such as radio backhauling / fronthauling, residential access and business access.

While optical fibre has large usable spectrum, in LR-PON this will be limited to the C/L-band if erbium-doped fibre amplifiers (EDFAs) are used to amplify the signal. In this document we draw conclusions from our studies to define architectures and EDFA parameters for the work to be done in WP5 (LR-PON critical physical hardware implementation) and WP8 (critical system test and verification). Additionally, we discuss how semiconductor optical amplifiers (SOA) can be adopted to remove spectral range constraints and thus will pave the way not only to higher network capacities, but also to utilization of LR-PON infrastructures with multiple independent systems operating in different spectral regions. To integrate such studies in the *DISCUS* project, we also draw conclusions from our studies and findings in D4.1 (Assessment of advanced LR-PON transmission technologies) and D4.3 (Integrated architecture for LR-PON supporting wireless and wire line services) to define architectures and SOA parameters to enable additional tests and hardware implementations in WP5 and WP8.

In section 2, architectures of LR access networks for wireless and wireline integration are introduced. Subsection 2.1 covers the architectural requirements for LR-PON and P2P overlay. In subsection 2.2, the wavelength plan for LR-PON and P2P overlay is discussed and in subsection 2.3, in-line optical amplification for budget extension is introduced. In section 3, specification of broadband access systems are defined. In subsection 3.1 the required budget for LR-PON and P2P overlay are discussed, in subsection 3.2 specifications of in-line amplifiers are shown and in subsections 3.3 and 3.4 the system specification are provided. Finally, section 4 concludes the deliverable.

2 Architecture of long-reach access network for wireless and wireline integration

2.1 Architectural requirements for LR-PON

The strategy of increasing infrastructure sharing and also reducing network nodes inevitably leads to the LR-PON architecture for the access and metro networks. Using a LR-PON enables sharing of fibre infrastructure as close to the customer as possible using a passive optical splitting element that can fit into existing footway boxes or pole tops if required. A specific requirement for such boxes, the optical distribution network (ODN) as well as the optical network termination (OLT) is wavelength transparency. The passive splitter requires no power and is a highly reliable component. The LR-PON uses optical amplification to support greater total split, longer reach and higher bit rates than today's PON solutions. The higher split means that it is possible to have multiple split stages to further increase infrastructure sharing and minimise cost per customer. Locations for splitting points will be the distribution points (DP) close to the customer premises, primary cross connect (PCP) or cabinet locations, typically less than 1 km from customers, and the local exchange or central office site where the optical amplifiers will also be located as this node has electrical power available. The average distance from the local exchange will be of the order 2 to 3 km but the tail of this length distribution can go out as far as 10 km so the ODN from the old local exchange (LE) site is designed to support up to 10 km [4]. For the initially installed PON topologies within the *DISCUS* project, intensity modulation, on-off-keying (OOK), is assumed, this can be extended with coherent technology as an upgrade option as capacity demands grow further in the future or increasing advances in coherent technology give the later a financial advantage over the early direct detection systems. The access techniques used is time-division-multiplexing (TDM) with a wavelength-division-multiplexing (WDM) overlay resulting in a hybrid TWDM topology. The flexible assignment of both wavelengths and TDM capacity via dynamic bandwidth assignment (DBA) within LR-PON wavelength channels can provide a very flexible capacity assignment capability that can service all types of customer from single residential users to large businesses and even service providers.

The size of the first split closest to the customer premises is a trade off of cable fibre cost, optical drop cost, optical splitter and housing cost including splices and the customer density. The optimisation of this splitter size is part of the modelling activities that is carried out within *DISCUS.* The use of a single optical amplifier in the upstream path offers the advantage of low noise contributions. Further, to locate a single amplifier after the splitter chain rather than multiple amplifiers placed closer to the customer premises avoids the issue of introducing noise funnelling. Such an approach seems to be achievable using a fibre amplifier and potentially minimises the cost per customer of the amplifier by maximising sharing of this component across a large number of customers. However this usually means using EDFA technology which limits the available optical spectrum to the C-band plus possibly the L-band. The question here is whether other amplifier technologies can be used to enable an advantageous *DISCUS* architecture with an acceptable number of active components in the field while extending the operational wavelength range available over the LR-PON infrastructure?

A long backhaul fiber connection between the metro/core (M/C) node and the LE of 90 km, a ODN of 10 km (total reach of about 100 km) and a split of 512 are the targets to be supported by the architecture. Additionally, the architecture should provide flexibility to be useful in urban as well as in rural areas where a trade-off of split size and reach may be required for sparse population areas.

2.2 Wavelength plan for LR-PON

The wavelength plan for the LR-PON strongly depends on the technology of choice, especially on the availability of optical amplifier in the desired wavelength region as already pointed out in the *DISCUS* deliverable D3.2 [4]. On one hand, for operation of long-haul networks the C-band is used because of the availability of mature components, especially, the EDFA which provides a key technology in this wavelength region. On the other hand, other wavelength regions of the fibre attract more and more attention. Here, SOA is a promising technology, because of their availability over the entire wavelength region of the fibre. From this technology point of view, the wavelength plan of the *DISCUS* project is discussed in the following in more detail.

From a practical point of view a C-band wavelength plan for the *DISCUS* architecture has the advantage of the availability of mature technologies and components, for example in terms of optical amplifiers and wavelength multiplexers. In terms of the wavelength allocation between upstream and downstream both band splitting (with, for example, the allocation of the short wavelength side of the C-band to the downstream and the long wavelength to the upstream) or interleaving of the up- and down-stream channels could be considered. In the M/C node both options could be easily supported since the wavelength routing is done by the optical switch. On the other hand, at the ONT there is an advantage in using the band splitting approach since it could relax the specifications of the tuneable component (i.e., the tuneable laser and tuneable filter), hence reducing also the cost of these components.

By using SOAs the constraint to the C-band operation can be overcome which has been indicated in the *DISCUS* deliverable D4.3 [4]. The use of wavelength regions other than the C-band can be preferable in terms of dispersion management if e.g. the O-band is used. Using an SOA approach, the above mentioned scenarios of applying a band splitting or a band interleaving would apply equally. The availability of mature transmitter and receiver components in currently almost unused wavelength bands needs to be improved to increase the attractiveness of such an approach. However, the efficient use of the wavelength domain not limited to the C-band extends the field of applications and business models. For example, the operation of an open access network implementation on the optical layer in the wavelength domain, making efficient use of the large optical bandwidth of fibres could be an option. It would allow the utilization of a single infrastructure for multiple communication purposes at the same time. The optical layer resources, such as fibres and optical spectrum, are shared among different services and operators and/or other client systems. Such a network is certainly challenging to implement and operate, but conceptually it opens attractive business opportunities. In order to allow for the most open and flexible resource utilization and to avoid the restriction to a certain modulation format or multiplexing technique, the infrastructure should remain transparent as far as possible. The basic idea of such a network concept is to establish multiple optical pipes that run in parallel through the network, within which different clients/network providers can independently allocate different kinds of service. These optical pipes are used to generate independent connections between the client equipment / networks, thus enabling a transparent optical infrastructure. The pipes can be considered as virtual "dark fibres" usable with almost any bit rate, modulation format, multiplexing technique, protocol and network topology (ptp, ptmp, mesh, ring, etc.). All-optical fibre switches will allow for a flexible reconfiguration of the virtual sub-networks, an option which is especially important for temporarily used pipes. The optical pipes are established and managed at the access points, where certain regions of the fibre transmission spectrum are administered. The fibre spectrum can be divided into a variety of wavebands with possibly unequal spectral width (a few nanometers to 20 nm, variable from fiber-to-fiber). The wavebands can carry services for residential subscribers like legacy single channel G-PON (TDM-PON) and stacked XG-PON (TWDM-PON) as well as LR-PON which would eventually replace the earlier PON systems. Wavelengths within these bands can also provided services for business subscribers such as multi-channel point to point DWDM systems (100 Gbit/s, 400 Gbit/s) [1]-[3].

2.3 In-line optical amplification for budget extension

The required power budget to establish a 100 km LR-PON network with 512 customers is about 51.5 dB in the C-band (0.2 dB/km fiber losses and 3.5 dB per splitter stage) and 69 dB (0.375 dB/km fiber losses and 3.5 dB per splitter stage) in the O-band assuming no additional power penalties along the path and no additional component losses of multiplexers/de-multiplexers and other filters in the system. Thus, in a worst case scenario, the LR-PON power budget per wavelength channel exceeds 70 dB. Assuming the input power for the acceleration of fiber non-linearities to be around 15 dBm means that each of the 32(40) upstream and downstream channels may have an OLT (optical line terminal) or ONU (optical network unit) transmitter output power of about 0 dBm, respectively. However, due to the fact that in the upstream direction, the splitter chain causes a rapidly reduction of the powers below the SBS threshold, it requires more investigation to which extend the upstream launch optical power can be increased. Currently available APD receivers have sensitivity performance of about –30 dBm at a bit-error-ratio (BER) of 10^{-3} and 10 Gbit/s OOK. A pre-amplifier can help (deployment considered at the OLT site only because of cost issues) to improve the receiver sensitivity to about –35 dBm. When coherent detection is employed, the receiver sensitivity improves to –46 dBm. Thus, the available power budget in direct detected and intensity-modulated systems using OLT pre-amplifier is about 35 dB in the downstream and about 40 dB in the upstream case only. A remedy to this deficiency is the deployment of in-line optical amplifiers. For example, EDFA, Raman amplifiers, SOA, as well as hybrid solutions of these technologies, e.g. combined SOA—Raman amplifiers [5], have been tested successfully in PON networks to extend the power budget. The advantages of the fiber amplifier technologies are a large gain, a very low noise figure, and the polarization independence of the gain. The disadvantages are the narrow gain bandwidth (if not specifically designed), the issue of availability of the units as a mass product in wavelength regions outside the C-band, and the need for additional equipment to provide burst-mode capability (for erbium-doped fibers). However, in recent years, SOA have recovered interest in the scientific and industry community, especially because of the large gain bandwidth exceeding the typical fiber amplifier bandwidth by a factor of 2, their availability virtually at any desired communication wavelength, their possibility to be integrated and their burst-mode capability [6], [7]. Additionally, so-called linear SOAs avoid inducing non-linear distortions on data signals for a large range of SOA input power levels [8].

Different optical amplifier technologies can be used for in-line amplification as discussed from an architectural point of view in the *DISCUS* deliverable D2.1 as well as in the *DISCUS* deliverable D4.3.

In principle, EDFAs show a low noise figure in the range of 4 dB and they can be operated simultaneously with a high number of wavelength channels offering a large gain (> 30 dB). This enables long-reach architectures in which a few EDFAs are deployed only at the local exchanges and the M/C node. This makes them an attractive option for an entry system albeit the wavelength band will be limited

However, recent development trends of SOA show that these devices can also offer a relative low noise figure in the range of 5 dB, a high input power dynamic range and the possibility to be cascaded for various modulation formats. A major advantage of the SOA technology compared to the EDFA technology is the availability of the gain over the entire wavelength region of the fiber and their capability to be integrated with, e.g. power splitters.

In the following sections, we come up with the required parameters for the EDFA as well as for the SOA approach to extend the power budget for the *DISCUS* network.

3 Specification of broadband access systems

3.1 Required budget for LR-PON

This deliverable is used to define the technologies and the architecture to enable the *DISCUS* LR-PON hardware implementation and the *DISCUS* LR-PON system tests and verifications. Thus, in the following, we discuss first the architecture, the budget and the enabling optical amplifier technologies, EDFA and SOA. Then, we provide the in-line amplifier parameter and finally, the system and network parameters.

The topology shown in Fig. 1 is one of the topology scenarios that have been analysed in terms of power and OSNR budget in the *DISCUS* deliverable D2.1 [4]. This topology refers to a densely populated area where a large number of customers are grouped within a short distance (10 km in this figure) and can be served by a single local exchange, which can be located up to 90 km distance from the metro core node.

The analysis of the power and OSNR budget has been performed under the assumption that within *DISCUS* the linear burst-mode receiver (LBMRx) technology developed by the Tyndall research group will be employed. The LMBRx requires 15 dB OSNR at dynamic range of 20 dB to achieve BER=10^{-3} (at 10 Gbit/s OOK). Hence, for this initial study we used 15 dB as the minimum (end of life) OSNR target. Another assumption in this analysis is that FEC will be used in the upstream. All the component losses used are derived from the G-PON standard in the ODN and from datasheet of commercial components for the LE and backhaul link.

The results from the power and OSNR modelling suggest that a split of 512 can be supported with OOK modulation of the optical signals at 10 Gbit/s in both directions with 2.5 dB OSNR margin in the upstream. The architecture in Fig. 1 is fully reconfigurable as it does not restrict in any way the wavelength allocation to and from the ONUs.

It should be noted, however, that due to the long metro section (90 km) the upstream launched power from the LE should be relatively high in order not to incur an OSNR penalty. Due to the high dynamic range introduced by the differential ODN loss the single channel power for a loud packet would be in the order of +15 dBm, which could cause issues in terms of non-linearities in the metro fibre. The launched power from the LE into the access section is also high (+15 dBm) due to the high split ratio and an APD would be required in the ONT for the downstream receiver.

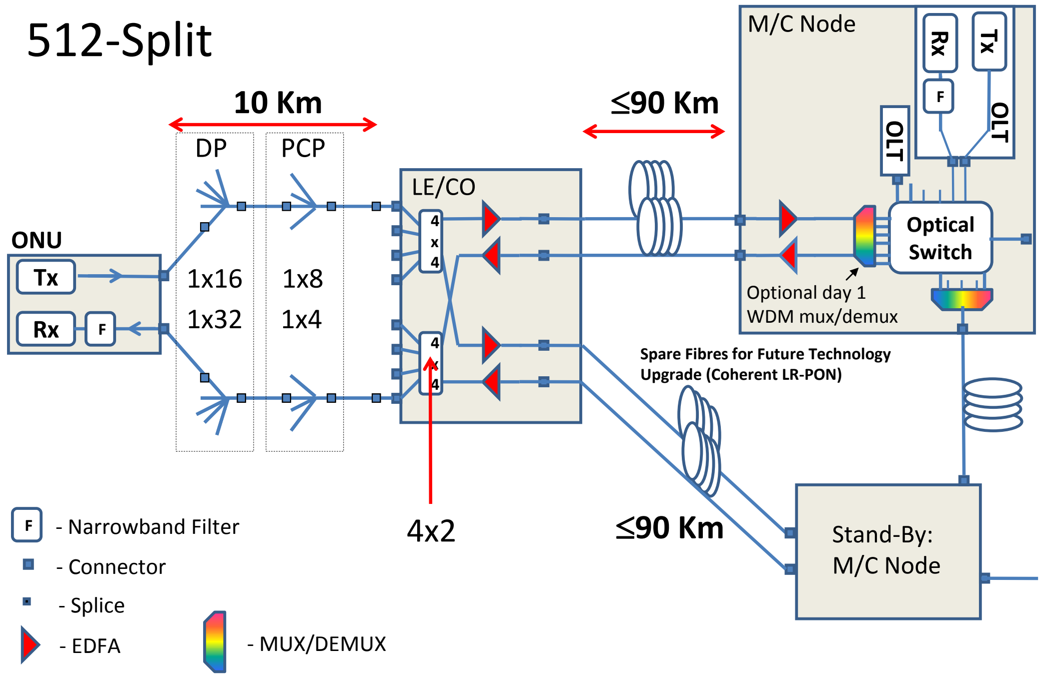

Fig. 1: Basic single wavelength LR-PON using 1xN splitters and two fibre working in access and backhaul.

One way of increasing the ODN feeder length to service sparser rural areas would be to trade off backhaul length for ODN reach, effectively moving the amplifier node towards the metro node. Such an option (analysed in the *DISCUS* deliverable D2.1) is shown in Fig. 2 where the ODN reach has been increased to 80 km and the backhaul reach reduced to 20 km. In practice however this has limited application due to the relationship between ODN reach and LR-PON split for a given power budget. If the ODN length is increased to 80 km then the total split would reduce to approximately 8 which would be not practical from an economic point of view. However this scheme may be applicable to some very sparse areas where the total reach is not so demanding. For example if the ODN reach in Fig. 2 was halved to 40 km the LR-PON split would be 64 way which is comparable to currently deployed short-reach PONs.

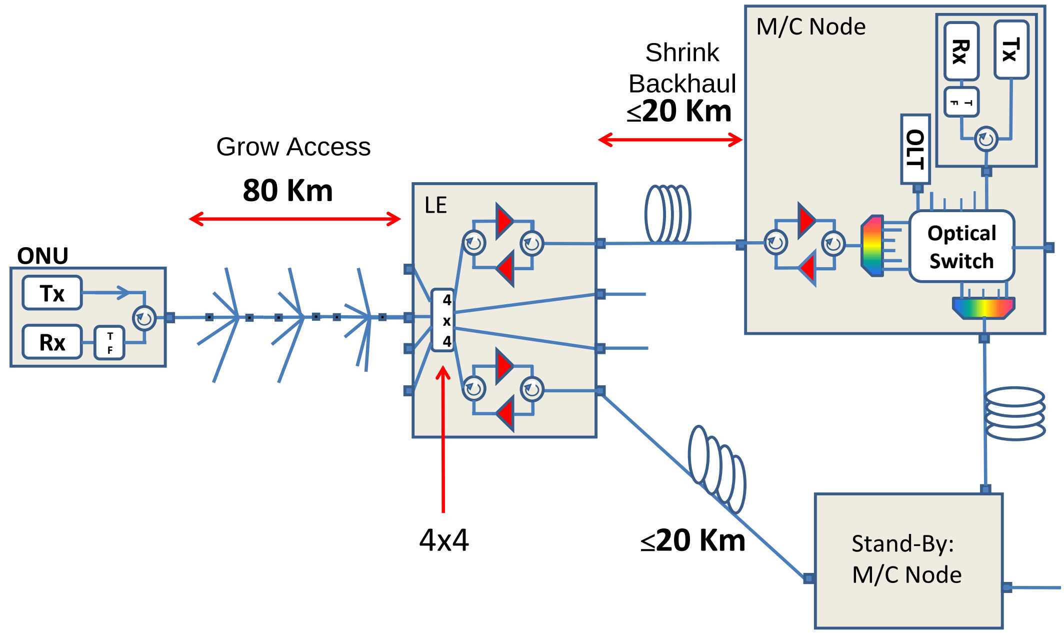

Fig. 2: Sparse rural region, simple solution - grow access, shrink backhaul.

An alternative architecture is shown in Fig. 3. In this approach the backhaul is subdivided into a number of shorter sections and a number of amplifier nodes are providing a proportion of the LR-PON split along the length of the PON. This can be considered to be a more flexible version of the simple solution shown in Fig. 2. In practice this would be a chain of old local exchange sites that the backhaul network of the LR-PON traverses along its path. At each local exchange an amplifier node is placed and an ODN extends from it to capture customer within the local exchange vicinity. Note that one of the amplifier node splitter ports provides the feeder fibre for the next amplifier node in the chain hence avoiding noise funnelling.

For the particular example chosen in Fig. 3 a 640 split would be feasible with a maximum dynamic range of 14 dB and a 4.4 dB OSNR margin in the upstream direction. It should also be noticed that the required launched power from the LE would be reduced in this case, +7 dBm per channel for the loud packet, which would greatly reduced the impact of fibre non-linearities.

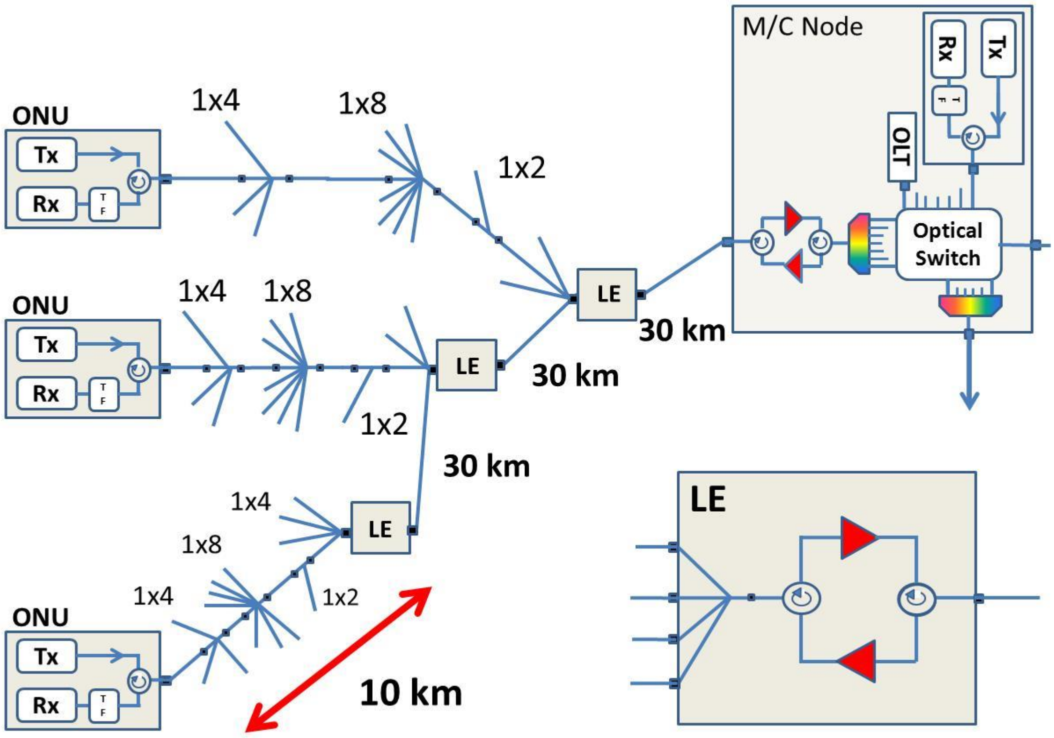

Fig. 3: Distributed amplifier node solution for rural areas.

The use of SOA as in-line amplifiers has been studied in the *DISCUS* deliverable D4.3 for several architectures in detail. In the following, we make use of these results to optimize the tree-based LR-PON architecture (see Fig. 4) as well as the extended version of the bus-feeder and the tree-distribution-based LR-PON (see Fig. 5) in terms of power budget and OSNR. The following analysis assumes the use of TWDM technology. Given their much higher sensitivity, coherent detection based technologies can operate in the same architectures. The parameters of the different network components (Tx, Rx, SOA, splitter, etc.) are chosen identically to D4.3 and they are in-line with the intended NG-PON2 standard (I-TUT G.989.2). The already performed calculations and simulations for the architectures using SOA as in-line amplifiers are extended to the use of 32 wavelength channels in the downstream and 32 wavelength channels in the upstream direction. Additionally, the architecture 3E (see Figure 6) is optimized here for the case of different split ratios along the way (x, y in Fig. 6). The target BER is still 10^{-3} (FEC use assumed) at a bit rate of 10 Gbit/s using OOK modulation.

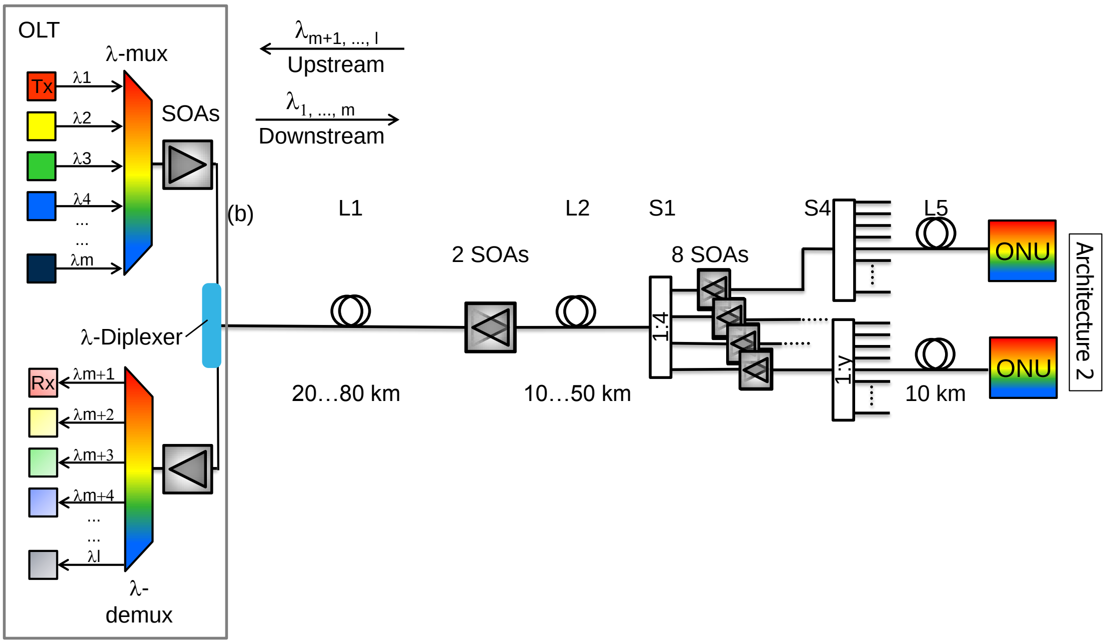

Fig. 4: Tree-based LR-PON architecture deploying 5 inline SOAs for the DS and 5 SOAs for the US (architecture No.2 from D4.3). The configuration contains also a booster and a pre-amplifier in the OLT.

The topology shown in Fig. 4 has been analysed in terms of power budget, SOA non-linear distortions, and noise funnelling in the *DISCUS* deliverable D4.3 for 4 upstream and 4 downstream wavelength channels. More than 512 customers are achievable using SOAs for 60 km of feeder fiber reach L1, 10 km L2 fiber reach and 10 km for the L5 distribution fiber. The S4 splitters offer a 1:128 split ratio each. This topology is comparable to the scenario of the Fig. 1 and it is applicable to a densely populated area where a large number of customers are grouped within a short distance (e.g. 10 km). The M/C node is located at 70 km distance from the S1-SOA-S4 splitter "box".

The following analysis of the OSNR budget is performed in-line with the linear burst-mode receiver (LBMRx) technology requirements as mentioned above. Hence, for this study a minimum of 15 dB OSNR is the target together with a low power penalty at the receiver at 10 Gbit/s OOK and a BER of 10^{-3}.

The topology shown in Fig. 4 is analysed in this deliverable in terms of power budget, OSNR, and SOA dynamic input power range for 32 upstream and 32 downstream wavelength channels. The results from the power and OSNR modelling suggest that still a split of 512 and a total reach of 80 km can be supported in both directions.

In the downstream path, it should be considered to reduce the per-channel OLT transmitter output power from +7 dBm (in total 4 channels; behind WDM MUX) to lower values of about 0 dBm (in total 32 channels) to avoid signal degradations from fiber non-linearities and to avoid SOA gain saturation. Note that more investigations on fiber non-linearities for such LR-PON networks are required before an exact number of Tx power levels as a function of the channel number can be provided. However, the per-channel OLT-Tx output power has to be sufficiently high to achieve the required ONU-Rx input power.

The OSNR in the upstream path depends on the SOA amplified-spontaneous emission (ASE) output power which is tested here for noise figure values between 3.5 dB and 13.5 dB (gain always 15 dB) and ONU transmitter output powers of +2 dBm each. Fig. 5 shows the OSNR calculation results for the upstream case. In Fig. 5(a), the noise figure as a function of the total ASE power from the SOA is shown. In Fig. 5(b), the blue curve shows the delivered OSNR in a 12.5 GHz bandwidth as a function of the total ASE power from the SOA. The difference of the delivered and required (red curve) OSNR provides the OSNR margin. Of course, the use of an SOA with a low noise figure is always preferable, but an OSNR margin of 5 dB can be achieved at the OLT-Rx with an SOA noise figure of 8 dB which is provided in today's commercial devices. A noise figure of 8 dB has already been assumed for all performed simulations in D4.3 and it is also used for further studies within this deliverable. Table 1 summarizes the calculation results and it shows that using an SOA with a noise figure of 8 dB a low power penalty of 1.5 dB can be achieved. The power penalty at the OLT-Rx is evaluated in relation to the back-to-back pre-amplifier receiver sensitivity of −33 dBm for the upstream signal. The delivered signal power per channel at the OLT-Rx is always −29.5 dBm.

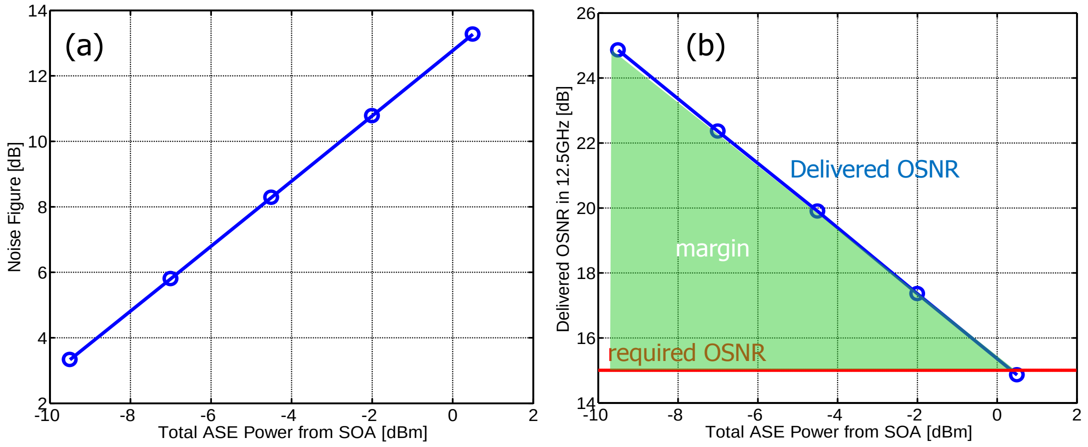

Fig. 5: OSNR for the architecture 2 shown in Fig. 4. In (a) the noise figure as a function of total ASE power (in both polarization directions) is shown, whereas in (b) the OSNR versus the total ASE power from the SOA is shown.

Total P_{ASE} in 100 nm [dBm]	NF [dB]	Power Penalty [dB]	OSNR [dB]	OSNR margin [dB]
0.5	13.5	5	14.9	0
-2	11	3	17.4	2.4
-4.5	8.25	1.5	19.9	4.9
-7	5.75	0	22.4	7.4
-9.5	3.5	0	24.9	9.9

Table 1: Summary of power budget and OSNR values for different SOA noise contributions. The power penalty at the OLT-Rx is evaluated to the pre-amplifier receiver sensitivity of -33dBm for the US signal. The delivered signal power per channel at the OLT-Rx is -29.5 dBm.

The dynamic range which the SOAs have to offer should be as large as possible. The employed SOA has a gain of 15 dB and the input power for a 1 dB gain compression is about 0 dBm (according to D4.3). Using the obtained knowledge from the LR-PON analysis, it becomes obvious that this SOA can be used for input power levels from about −27 dBm to about 0 dBm without causing significant degradation on the signal quality. This statement is still valid for an SOA cascade of few SOAs in the chain. Here, in the tree-based LR-PON architecture (No.2) (see Fig. 4) the power dynamics in the upstream path are given by the ONU transmitter output power variations and the distribution fibre length between the ONU and the 1:128 splitter. Assuming that all ONUs have identical minimum transmitter output power levels of +2 dBm and additionally all ONUs are located at a distance of 10 km to the distribution splitter, than the input power levels to the SOA in the distribution arms are −26.25 dBm / channel and the total input power is −11.25 dBm if all 32 channels are located on the same 1:4 split path. If we are assuming contrarily that all ONUs have identical maximum transmitter output power levels of +7 dBm (5 dB power variations of ONU Tx power is taken from the NG-PON2 standard) and additionally all ONUs are directly connected to the distribution splitter, than the input power levels to the SOA in the distribution arms are −17.5 dBm / channel and the total input power is −2.5 dBm if all 32 channels are located on the same 1:4 split path. The input power levels to the SOA in the feeder section can vary between −22 dBm / channel (−7 dBm total input power if all 32 channels are on) and −13.25 dBm / channel (+1.75 dBm total input power if all 32 channels are on) for the two discussed cases. Thus, the employed SOA provides approximately the required dynamic range of > 20 dB for this architecture (No.2 from D4.3).

It should be mentioned that the above discussion assumes a limitation for the differential path loss of about 4 dB only (5 dB ONU Tx power variation) compared to the 15 dB as it is intended in the standard for the NG-PON2 network (additional 5 dB of ONU Tx output power variations). In LR-PON networks, it seems to be reasonable to define new methods to limit the differential path loss and the ONU Tx output power variations.

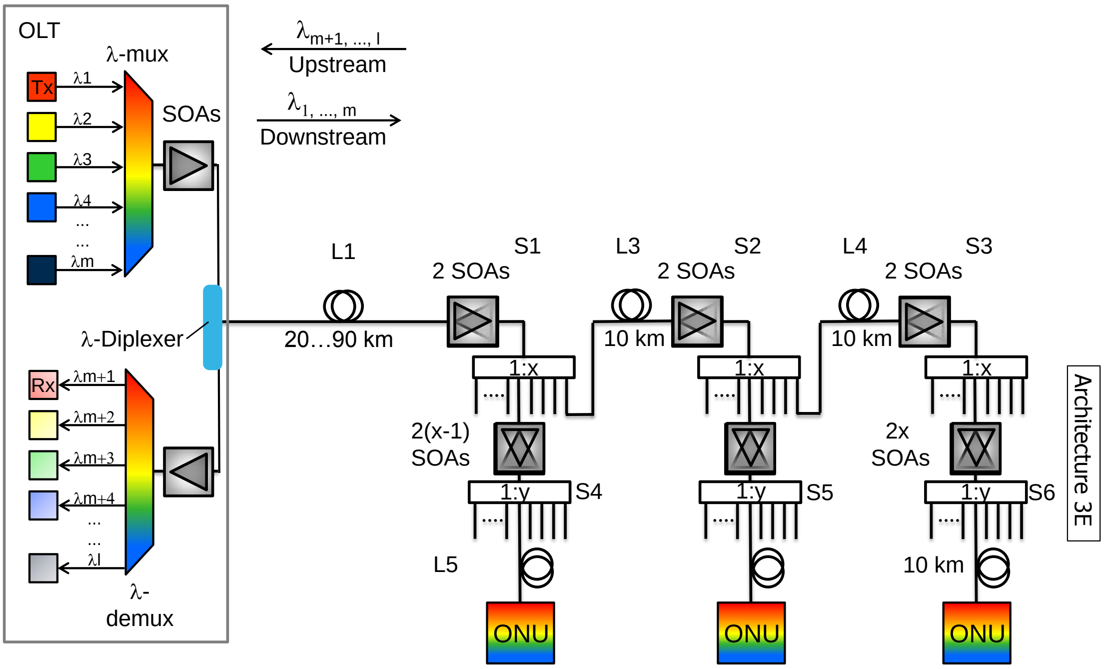

Fig. 6: Extended version of the bus-feeder based LR-PON architecture using (3x+1) in-line SOAs for the DS and US, respectively (architecture 3E from D4.3). This architecture also includes booster and pre-amplifier in the OLT.

The topology shown in Fig. 6 has been analysed in terms of power budget, SOA non-linear distortions, and noise funnelling in the *DISCUS* deliverable D4.3 for 4 upstream and 4 downstream wavelength channels. More than 512 customers are achievable using SOAs in this scenario for 70 km of feeder1 fibre length L1, 10 km of distribution fiber1 length L3, 10 km of distribution fiber2 length L4 and 10 km for the drop fibre length L5. The splitters S1,2,3 offered a split ratio of 1:8 each. The drop splitters (1:*y*) had been optimized in terms of optical signal-to-noise ratio (OSNR) and noise funnelling to 1:32.

The topology provides a very high flexibility because of the combination of a bus in the feeder structure and a tree in the drop fibre sections with the drawback of the requirement of in total 50 SOAs. In the present deliverable, this architecture is also analysed in terms of power budget, OSNR, and power dynamic range for 32 upstream and 32 downstream wavelength channels and as already mentioned above for optimized split ratios in the distribution and in the drop sections. The results from the power and OSNR modelling suggest that still a split of 512 and a total reach of 100 km can be supported in both directions.

In comparison to the 4 wavelength channel case in the downstream direction, the per-channel OLT transmitter output power has to be reduced from 7 dBm (in total 4 channels; behind WDM MUX) to about -2 dBm (in total 32 channels) to avoid signal degradations by SOA gain saturation. For the worst case analysis assuming high fibre losses in the range of 0.375 dB/km (O-band), there is almost no power margin which significantly changes by using an operation in the C-band.

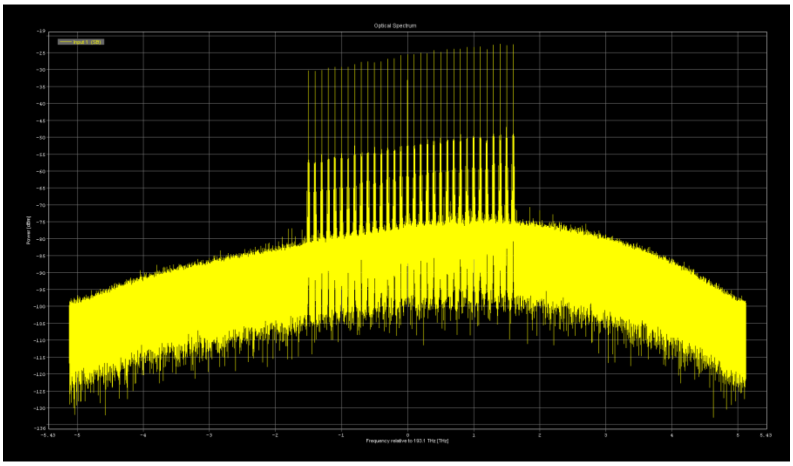

Fig. 7: Typical spectrum of the 32 wavelength channel downstream signal behind the SOAs.

Fig. 7 shows a typical spectrum for the 32 downstream wavelength channels behind the SOAs obtained using the VPI simulation environment introduced in the DISCUS deliverable D4.3.

The OSNR in the upstream path depends on the SOA ASE output power which is tested here for the noise figure value of 8 dB and a gain of 15 dB. The optimization process showed that the drop split ratio 1:y should not be too high (range of 1:32) to obtain a reasonable OSNR at the OLT-Rx. Additionally, the distribution split ratio should be “high” (compared to 1:2, 1:4, 1:8) to obtain a non-saturating input power level into the SOAs. Thus, using the above mentioned parameters an OSNR of about 20 dB has been obtained for the architecture parameters (fibre length 70+10+10+10 km; distribution splits 1:8, drop splits 1:32). The power penalty is in the range of 8 dB which is quite high, but required to counteract the signal degradations from the noise contributions.

Here, in the combined bus-feeder and distribution-tree-based LR-PON architecture (No.3E from D4.3) the power dynamics in the upstream path are given by the ONU transmitter output power variations, the distribution fibre length between the ONU and the 1:32 splitters and the location of the customer along the bus structure. Even in the case that the minimum ONU Tx output power level for the NG-PON2 standard is used, the maximum total SOA input power level is almost reached. Additionally, the per-channel power has to be sufficiently high to guarantee the required OSNR. Thus, the dynamic of the system needs to be regulated. For example, the ONU output power levels could be limited to a small power variation and additionally, wavelength bands (bundles of wavelength channels) could be defined which are than limited regionally to specific parts of the bus structure.

3.2 Specification of in-line amplification

The characteristics of the amplifiers used in the LE are extremely important in order to be able to support the long reach and the high number of users targeted by the *DISCUS* architecture. A key parameter is the noise figure of the amplifier that has to be as low as possible in order to maintain the OSNR of the upstream within acceptable level. The amplifiers should also be able to provide a high gain and high output power in order to be able to overcome the high loss of the access and the metro section of the LR-PON. Both from system flexibility and performance point of view the best option would be to use a single multi-channel amplifier for each direction in the LE.

EDFAs are the obvious choice of amplifiers due to their overall good performance in terms of low noise figure, high gain and high output power and the ability to provide these characteristics in a system with a large number of channels. EDFAs also have the advantage of being mature components in optical network which makes them attractive for deployment in an access scenario.

In the modelling work presented in this deliverable and in *DISCUS* deliverable D2.1 multi-channel EDFAs have been considered, with a noise figure of 5.5 dB and a maximum gain of around 30 dB. The maximum aggregated output power will depend on the number of channels supported by the system and also by the particular configuration deployed. As mentioned in the previous paragraph the most demanding configuration in terms of EDFA output power is the densely populated configuration with a long metro link. In this case a maximum single channel output power of +15 dBm should be supported. Considering a 20 channel system this could lead to an aggregated maximum output power of +28 dBm, considering all channels at maximum power. However, this might not be a realistic case since due to statistical multiplexing it is very unlikely that all channels will present the maximum burst power and an EDFA with lower aggregate output power could be used.

Another important aspect of the amplifiers used in the upstream direction is that they need to be able to operate with burst signals of high dynamic range. Recently EDFAs with automatic gain control able to stabilise the gain in the short timescales needed for in order not to impair the transmission in PONs have become commercially available. Within WP5 (task 5.1) such amplifiers will be characterised for the *DISCUS* architecture requirements and alternative gain stabilisation solutions will also be explored if necessary.

Another mature technology for amplification in access networks is given by SOA as already outlines above. The requirements of a low noise figure are achievable. However, typically SOA cannot provide high gain values and simultaneously high output power levels without introducing signal distortions. Thus, this way, a higher number of SOA along the chain (bus/feeder structures) are used to achieve the required budget. On the other hand, the number of cascaded SOA should be as low as possible to avoid significant OSNR degradations. The simulation and calculation results discussed in D4.3 and in the current deliverable provide some requirements for the SOA which are discussed in the following. The SOA gain should be in the range of 15 dB to avoid a too high number of SOAs in the system and to offer a sufficiently high saturation input power (1 dB) to avoid signal impairments by non-linear effects such as cross-gain modulation or four-wave-mixing. The saturation input power defined above should be in the range of 0 dBm. This way, an acceptable output power per channel in the range of 0 dBm (assuming 32 wavelength channels) can be obtained. As shown above, a noise figure of 8 dB is sufficient to support the discussed scenarios. Nonetheless, the lowest possible noise figure is always preferable. The polarization dependence of the gain should be as low as possible, thus, in the range of 0.2-0.5 dB. To amplify a high number of wavelength channels (e.g. 32) with the same gain, the gain should be constant (high gain flatness) over the entire wavelength band.

3.3 System specifications for TWDM LR-PON

For the broadband access part of the DISCUS network, *the baseline architecture* is shown in Fig. 1. A single fibre network is assumed here with the goal to support a 90 km feeder section and a 10 km drop section and a split of 512 in total. The OLT is connected to the feeder fiber in the metro core node. Inside the metro core node, the signals pass an optical switch and a WDM MUX/DEMUX.

In the *DISCUS* deliverable D4.3 this network and many possible variations were evaluated and optimized with a VPI simulation. The PON system is assumed to be a 4 channel TWDM-PON compliant to NG-PON2 with 10 Gbit/s per channel for upstream and downstream. For optical amplification SOAs are used instead of EDFAs. This selection and the definition of the fiber loss parameter to be 0.375 dB make sure that the results are valid not only for C and L-band, but for the entire usable spectrum of a SMF ranging from O-and to L-band. The architecture that is closest to the initial one without using in-line amplifiers is shown in Fig. 8.

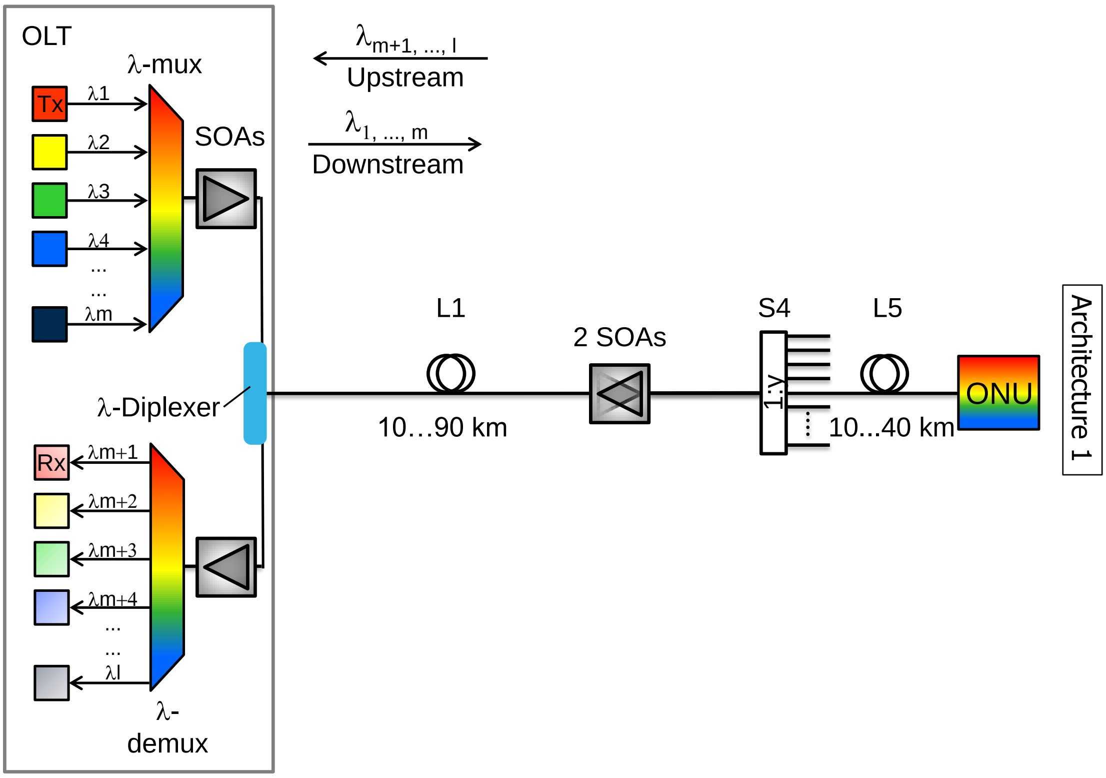

Fig. 8: Classical tree type PON network with single in-line optical amplification.

The results of the simulations show that this architecture can support up to 60 km and a split ratio of 128. This architecture uses 2 SOAs, one for US and one for DS.

A *more powerful architecture* is shown in Fig. 6. This network has a first level of a bus structure, and lower levels of amplified and unamplified splitters. In this way the impact of noise funneling is reduced to an accepatable level. Noise funneling means that preamplifier SOAs placed at the drop side of a power splitter will sum up the ASE contributions from all SOAs, whereas the signal is only contributed from one SOA. In this way the S/N of the upstream signal is drastically reduced. The network of Fig. 6 can serve more than 512 customers and support at the same time a reach of 100 km. Of course this higher performance comes for the cost of a higher number of SOAs.

In both architectures the performance was limited by the upstream. The downstream could support even higher budgets. The specification values for the OLT and ONU sided transceivers were defined similar to the E1 budget classes of NG-PON2 and are given in Table 2.

Parameter	Value
Number of DS/US wavelength channels	4/4 up to 32/32
WDM Channel Spacing in DS around 193.1THz (4 channels / 32 channels)	100 GHz / 50 GHz
Modulation format	NRZ-OOK
Bit rate per channel with PRBS of 2^{15}-1	10 Gbit/s
OLT transmitter extinction ratio of externally modulated source	8.2 dB
OLT transmitter output power per λ-channel (4 channels / 32 channels)	+7 dBm / FFS
ONU transmitter output power (4 channels / 32 channels)	+2 dBm / FFS
ONU receiver sensitivity (direct detection using avalanche photodiode (APD)) @ bit-error-ratio (BER) of 10^{-3} and 10 Gbit/s including a 50 GHz filter	– 28 dBm
OLT receiver sensitivity (pre-amplifier direct detection using avalanche photodiode (APD)) @ bit-error-ratio (BER) of 10^{-3} and 10 Gbit/s	– 33 dBm

Table 2: Specification parameters for TWDM PON 4 channels with 10G US/10G DS. FFS means for further study; here the fiber non-linearity limit for LR-PON networks needs to be identified carefully for different WDM channel loads.

For the downstream, a duo-binary signal at 40 Gbit/s is also considered as a future upgrade for TWDM LR-PON. The ONU receiver sensitivity will be of course lower in this case. If the filtering for duo-binary is mainly done on the receiver side [9], the bandwidth is adjusted to be 0.25 x bit rate. For NRZ this filter bandwidth is 0.7 x bit rate. Also the signal power is divided over two eyes in the case of duo-binary transmission. Therefore the theoretical receiver power penalty from a 10 Gbit/s NRZ receiver to a 40 Gbit/s duo-binary receiver would be 4.5 dB. As signal linearity is more critical for multilayer signals than for binary signals, a 6 dB penalty is taken as a more realistic assumption. For a single channel system, the transmitter output power can be increased by 6 dB to compensate for this penalty. Some preliminary parameter specifications are provided in Table 3.

Parameter	Value
Modulation format	Duo-binary
Bit rate per channel with PRBS of 2^{15}-1	40 Gbit/s
OLT transmitter extinction ratio of externally modulated source	8.2 dB
OLT transmitter output power	+13 dBm
ONU receiver sensitivity (direct detection using avalanche photodiode (APD)) @ bit-error-ratio (BER) of 10^{-3} and 10 Gbit/s	– 22 dBm

Table 3: Specification parameters for duo-binary downstream at 40Gbit/s.

The above given specifications are all related to minimum receiver power, as it is commonly done for demo systems. In practical PON systems, the dynamic range of receiver power can be quite challenging.

The reason for this dynamic is on one side the desire to build cheap ONU transmitters that will have a large output power variation (from TDM PON typically 5 dB). On the other side, not all ONUs will be connected to the ODN from the same distance and the same splitter level. For this an additional variation of 15 dB is typically attributed.

A further important aspect is the not completely switched off transmitter power of the laser, when the ONU is not sending out a burst (burst mode extinction). Considering 512 ONUs in the network makes the sum of this power a source of penalty for the upstream signal, however this will depend on the technology used for the LR-PON ONU transmitter and if necessary can be improved by using gated SOA at the ONU transmitter output.

In the case of TWDM PON, a cross-talk to other WDM channels can occur, caused by the side modes of a transmitting laser.

3.4 System specifications for coherent LR-PONs

As in section 3.3, we refer to the baseline architecture as shown in Fig. 1, showing a single fiber network with the goal to support a 90 km feeder section and a 10 km drop section and a split of 512 in total. The OLT is connected to the feeder fiber in the metro core node. Inside the metro core node, the signals pass an optical switch and a WDM MUX/DEMUX.

The coherent (UDWDM) LR-PON system is described in Deliverable D 4.1. It offers in its full extension up to 1000 symmetric wavelengths which 1 Gbit/s data rate per wavelength and an optical power budget of 43 dB. Note that budget classes of amplified TWDM LR-PON need new definitions and cannot be directly compared to presented value for the coherent approach.

The key transmission parameters of the coherent LR-PON are shown in Table 4.

Parameter	Value
Number of DS/US wavelength channels	1000
WDM Channel Spacing in DS around 193.1THz	2.799 GHz
Modulation format	DQPSK
Bit rate per channel	1.244 Gbit/s
OLT transmitter output power per λ-channel	-3 dBm
ONU transmitter output power	+3 dBm
ONU receiver sensitivity coherent reception @ bit-error-ratio (BER) of 10^{-3}	– 46 dBm
OLT receiver sensitivity @ bit-error-ratio (BER) of 10^{-3}	– 40 dBm

Table 4: Specification parameters for the coherent LR PON.

As the sensitivity of a coherent LR PON is much enhanced with regard to that of a TWDM LR-PON, in-line amplifiers can be omitted whenever the required optical power budget is less than 43 dB. However, the system has sufficient dynamic range so that the use of in-line amplifiers, as specified above in this deliverable, does not disturb the operation of the coherent LR PON. When SOAs are used as inline amplification stages, care has to be taken that the SOAs are being operated in the linear regime. However, inline amplifiers which were designed for TDM systems (as described in section 3.2) should be able to handle the traffic of coherent LR PONs without significant degradation.

4 Conclusion

In this document we defined the architectures and optical amplifier parameters of the work to be done in WP5 (LR-PON critical physical hardware implementation) and WP8 (critical system test and verification). In general, the system specifications for the optical distribution network follow the specification of the I-TUT 984.3 (GPON) as well as the I-TUT G.989.2 (NG-PON2).

Two key architectures are defined both with the goal to achieve a total reach of 100 km and 512 customers while keeping the ODN wavelength transparent. The first architecture can be used for densely (urban) populated areas where a large number of customers are grouped within a short distance. Using EDFAs in the metro/core node (in total 2 for upstream / downstream) and at the local exchange site (in total 2 for upstream and downstream (4 with protection)), a 90 km backhaul reach between the metro-core node and the local exchange is supported and a 10 km optical distribution network with a 512 total split. The requirements of optical-signal-to-noise ratio in the upstream path of 15 dB at 10 Gbit/s OOK and a BER of 10^{-3} are fulfilled so that the burst-mode capable receiver in the OLT is able to detect the signal with an acceptable quality. An additional OSNR margin of 2.5 dB is included.

The second architecture can be used for rural areas which are sparsely populated. Therefore, the ODN is increased up to 80 km and the backhaul is reduced to 20 km fiber length. This architecture is enabled by a higher number of EDFAs which are distributed along the chain. Here, a total reach of 100 km and a total split of > 512 can be supported with a dynamic range of 14 dB and a high OSNR margin exceeding 4 dB.

The EDFA parameters which enable such architectures are a high small-signal gain of 30 dB, a low noise figure of 5.5 dB and a very high output power of > 15 dBm. Additionally, in the upstream direction methods are taken to enable burst-mode capability of the EDFA by an automatic-gain control to stabilize the gain on a fast timescale.

These key architectures have been analysed in detail regarding the application of TWDM technology. The results are also applicable to coherent reception based UDWDM technology due to its higher sensitivity.

Using the SOA amplifier technology, the above mentioned architecture for the densely populated area has been investigated for two different implementation scenarios. The first one is a tree-based LR-PON. In this scenario, 32 upstream and 32 downstream wavelength channels are supported for a 70 km backhaul reach and a 10 km ODN reach for a 512 total spit ratio. The OSNR requirements are met in the upstream direction with an additional 5 dB OSNR margin and a large dynamic range > 20dB. A total number of 10 SOAs are required to support the above numbers.

The second scenario is a bus-feeder and tree-distribution based LR-PON. This architecture offers higher flexibility, but with the drawback of a total number of 50 required SOAs. This scenario supports a backhaul fiber length of 90 km and an ODN of 10 km. The total split ratio exceeds 512 it is distributed to three time a 1:8 split in the bus structure and 1:32 split in each of the distribution arms. An

OSNR of 20 dB is supported including 5 dB margins, but at the expense of a high power penalty of up to 8 dB. Additionally, the dynamics of the system need regulation.

The SOA parameters which enable such architectures are a moderate small-signal gain of 15 dB, a noise figure of 8 dB, a high (1 dB) saturation input power of about 0 dBm, a high total output power of about +15 dBm, a low polarization dependent gain of up to 0.5 dB and a high gain flatness across the upstream and downstream wavelength regions, respectively. In the upstream direction no additional methods need to be taken to make SOA burst-mode capable.

Finally, it should be mentioned that such architectures require methods to adapt the differential path loss to handle the required dynamic range and some kind of power levelling techniques at the OLT-Tx and ONU-Tx to adapt for a varying number of wavelength channels.

The above architectures, amplifier technologies, amplifier parameters and system specifications are input to the work to be done in the *DISCUS* WP5 and *DISCUS* WP8 in which the hardware implementation and experimental verifications will be performed.

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6 Abreviations

ASE	Amplified Spontaneous Emission
APD	Avalanche Photo Diode
BER	Bit Error Ratio
DBA	Dynamic bandwidth assignment
DP	Distribution points
EDFA	Erbium Doped Fiber Amplifier
FTTB	Fiber-to-the-building
FTTH	Fiber-to-the-home
ODN	Optical Distribution Network
OLT	Optical Line Termination
ONT, ONU	Optical Network Termination, Unit
OOK	On-off-keying
OSNR	Optical Signal-to-Noise-Ratio
PCP	Primary cross connect
LBMRx	Linear burst-mode receiver
LE	Local exchange
(LR) PON	(Long Reach) Passive Optical Network
ptp	Point-to-point
Ptmp	Point-to-multipoint
Rx	Receiver
S-GW	Service Gateway
SNR	Signal-to-Noise-Ratio
SOA	Semiconductor Optical Amplifier
TDM	Time-division-multiplexing
Tx	Transmitter
WDM	Wavelength-division-multiplexing
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation