D 2.3

Updates to the reference architecture

Dissemination Level:

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Abstract:

This report provides a description of the updates to the DISCUS architecture described in D2.1. This update particularly addresses LR-PON solutions for sparse rural areas, an update on amplifier node design considering the use of linear SOAs in addition to EDFAs. There are also updates on the LR-PON termination options in the metro-core node and the consideration of 1:N protection strategies for WDM devices and OLTs, LR-PON resilience options also focus on the rural design in this report. Upgrade options using coherent technology, 40Gb/s downstream and 100Gb/s point to point solutions over LR-PON infrastructure are also updated.

The metro-core node design including incorporation of flex grid technology is also updated and in the core network the use of sparse regenerators and Raman amplification for occasional extra reach requirements in the optical island are considered.

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1 Introduction

The initial proposals for the DISCUS architecture were described in some detail in D2.1 [1]. This deliverable describes the incremental updates to D2.1. A list of the references to sections in D2.1 that have been updated by sections in D2.3 is given in table 1.

Table 1 Cross-references to updated sections in deliverable D2.1

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The DISCUS architecture employs LR-PON technology in the access and metro or backhaul networks to enable local exchange/central office bypass and elimination of separate backhaul transmission systems. The LR-PON systems terminate on a small number of "metro-core nodes" which are interconnected by a flat optical core network which we called an "optical island". The concept of "optical islands" has caused some confusion and we have therefore tightened and focused the definition of an optical island as being: a set of metro-core nodes that are fully interconnected via a set of light paths so that any node can reach any other node in the optical island by a light path and there is no packet processing of the data in the light path except at the ingress and egress nodes. Light paths will pass through other nodes on route to the destination node but they stay in the optical layer and also for the majority of light paths will stay on the same wavelength channel/s. However some light paths may need wavelength conversion and possibly regeneration. These functions are allowed at intermediate nodes but these "through" light paths are not terminated on the packet processing layers in the intermediate nodes. In the metro-core node there is an optical circuit switching layer that allows interconnects between access wavelengths and terminating and packet processing equipment and also interconnection with the core light paths, if required, so that core wavelengths can pass over LR-PON infrastructure. The optical switching layer can provide fully flexible interconnect and sharing of all metro-node equipment and functions. The basic concepts of the DISCUS architecture are shown in

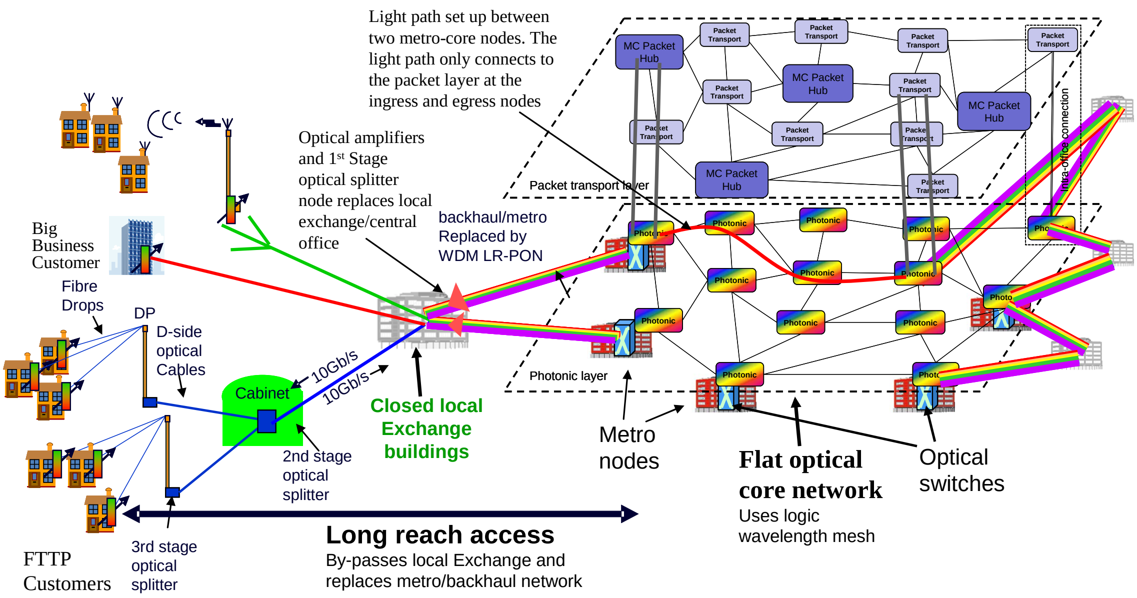


Figure 1 DISCUS end to end architecture

Figure 1 with an example light path across the core network.

The three major challenges facing future communications networks are the drivers for the objectives of the DISCUS architecture, these challenges are:

- To remain economically viable while user bandwidth grow by 1000 times or greater over the next decade
- To reduce power consumption by at last 95% compared to growing today's networks.

- To avoid the digital divide by redistribution and reduction of costs to enable FTTH solutions for sparse rural areas.

More work has been carried out on LR-PON designs and also rural solutions and is described in section 3.1. The early work on optically amplified LR-PON focused on EDFA amplifier technology because of the high linearity, high saturated output power and low noise figure. Although EDFA amplifiers remain the focus for the design of the first installed systems, the improvements in linear SOA technology warrants a fresh look at their suitability for LR-PON solutions this work is described in section 3.2. A major advantage offered by SOAs over EDFAs is the ability to exploit other optical windows in the fibre transmission spectrum.

Developments in the LR-PON design options are described in section 3. This looks at the design for sparse rural areas, the alternative use of SOAs to open up further optical windows, resilience options and analysis of the LR-PON options discussed including the sparse rural designs.

The next three sections (4, 5 and 6) give updates on the use of coherent technology to increase performance and capacity of LR-PON systems, the designs for 40Gb/s upgrade for the downstream direction and the favoured design option for 100Gb/s over the LR-PON fibre infrastructure. The section on 40Gb/s upgrade will look at the prognosis for achieving 512 way split, matching the design target for the 10Gb/s wavelengths.

The development of the metro-core node design is described in section 6, this discusses the design of the packet processing layer and its interconnection to both the access and core transmission networks. The optical switching layer is also discussed and its relationship to flex-grid transmission system functionality. Developments on the design of the control plane are also briefly described.

The final technical section is a description of the developing ideas for core transmission within and “optical island”. The concept of translucent network with sparse regenerators is presented as an alternative to transparent optical islands. The advantages of this network concept are also presented together with the idea of “transparent network with sparse Raman links” as an evolution of the transparent optical island. The need for regeneration will only be required occasionally on particularly difficult routes and extending the definition of optical islands to include translucent networks is more in line with the original concept of a flat circuit switched optical core network where a light path between any ingress and egress pair of nodes only has packet processing at those end nodes and not at any intermediated nodes that the light path traverses. The use of sparse regenerators also enables wavelength conversion using optical to electronic to optical technology (OEO) when required to avoid wavelength path blocking.

2 DISCUS architecture specification, targets and state of the art

This section describes the target parameters or specification for the discus architecture and also shows where the DISCUS architecture goes beyond the state of the art established by previous projects such as PIEMAN [2], OASE [3] and ACCORDANCE

[4]. We will start at the access network and work through to the metro-core nodes and the core network.

The overall objectives of the DISCUS architecture is to find solutions to three of the major problems facing future networks, as mentioned above i.e. to find economically viable solutions that enable three orders or more bandwidth growth while bridging the digital divide to enable sparsely populated areas to have access to the same network capability and services as urban areas and also massively reducing power dissipation within the network as the capacity grows.

In D2.1 it was shown that to meet the first challenge of future networks that is; remaining economically viable as bandwidths increase by 1000 times or more over the next decade, two major approaches to the design of the future architecture are required. The first was to minimise electronics systems and OEO conversions, this would be mainly applied to the traffic processing nodes in the network and the backhaul and core transmission networks. The other was to maximise sharing of network resources to minimise cost per customer of the remaining network equipment.

In order to achieve these targets DISCUS adopted an end to end design philosophy which is a major differentiator compared to previous projects which generally tackled problems in only one network area e.g. access, metro or core. By taking an end to end approach DISCUS is attempting to avoid problem transfer where solving a problem in one part of the network only transfers problems to other parts. Any solution that tries to solve the above problems must be scalable and evolvable and be able to adapt to future technologies as they emerge. Also for a complete network solution all layers of the network should be considered as part of the design process this would include layers 4 and up in the OSI model. Detailed design of these higher layers is beyond the scope of DISCUS but in order to enable future evolution of these higher layer and also new transport protocols that could eventually replace legacy protocols such as Ethernet and IP/TCP etc, DISCUS introduces an optical switching layer to separate the physical optical transmission layers from the electronic traffic processing layers. This can enable radically new and even experimental systems to be running alongside legacy systems. If these new systems are successful they will gracefully displace the legacy and grow while the legacy can wither and die. It is only by considering the end to end design aspects that such opportunities can be designed into the solutions.

Another major area where DISCUS goes beyond the state of the art of previous projects is to tackle up front the issue of the digital divide where current broadband role out and performance favours citizens living in dense urban areas and neglects those living in sparse rural regions. In D2.1 the rational for the DISCUS architecture was described leading to the conclusion that long reach access (to eliminate local exchanges or central offices) coupled with a flat optical core was necessary to meet the DISCUS objectives. The long reach access technology chosen is long reach passive optical networks (LR-PON). In past projects designs for LR-PON have centred around what has become to be known as the “lollipop” model which has a long feeder fibre length between the metro-core node and the amplifier node at the old local exchange/central office site and then a relatively short (up to 10 km optical distribution network (ODN). This model works well for urban areas but is not optimal for sparser rural areas where the split portion of the LR-PON needs to be distributed over larger geographical areas. A focus in DISCUS is therefore to develop designs and fibre splitter layouts that reduce costs and are more suitable for these sparse rural areas. These options are described in more detail in this deliverable.

A further development in DISCUS of the design of the LR-PON is the dynamic use of the wavelength domain initially the C-band using EDFA technology in the amplifier nodes but also introducing the use of SOAs to extend capacity availability outside the C-band to the other fibre windows. The LR-PON infrastructure design is also taking into account the need for bespoke network configurations and point to point optical paths at rates up to 100Gb/s and possibly beyond for large business customers and special services including Service Provider connections. At the metro-node the optical switch configuration and the interconnection of the electronic processing equipment forms a major part of the metro-core node design. Options for embedded functionality and stand-alone functions interconnected via "grey" optical ports will be compared. These features of the architecture go beyond the work of previous projects, for example we compare the use of separate OLT racks and shelves versus embedded OLTs in the access switch. Further features of the metro-core node design with the optical switch is the ability to have 1 to N sharing of protection equipment which can be augmented by utilisation of the LR-PON dual parenting mechanism to enable traffic off load to minimise standby protection equipment at the metro-core nodes,

The core network is an evolvable hybrid with coexisting fixed grid and flex-grid technologies. Economics and traffic demands will determine the technology of choice. The core network itself is a flat optical core with transparent optical light paths interconnecting the metro-core nodes in a full logical mesh configuration. Although the DISCUS objective is to have fully transparent light paths in the core network wherever possible, sparse regenerators for extremely demanding links will also be considered.

To summarise this section DISCUS extends the designs of the LR-PON to include all geo-types including sparse rural and flexible wavelength assignment for both bespoke and LR-PON protocol enabled wavelengths.

The metro-core node is a flexible design with an optical switching layer to enable flexible protection mechanisms and graceful evolution including displacement of legacy protocols and technologies.

The core network is a flat optical core with transparent light paths to minimise OEO conversions and packet/traffic processing. It enables the coexistence of fixed grid and flex-grid technologies allowing economics to determine the technology of choice.

These design principles we believe will realise the following target performance for the DISCUS network:

- Reduction in buildings housing electronic switching/routing/transmission equipment by closure of the majority of LE/COs and simplification of the core network ~98%
- Reduction in customer network ports (cf. xDSL) ~99.8% (by increasing LR-PON split to ~500 ways)
- Reduction in network port cards ~70% (by elimination of metro network and using flat optical core)

- Reduction in network power consumption (neglecting CPE) with respect to Business as Usual (BAU) ~95% (from elimination of LE/COs, backhaul transmission systems and flat circuit switched optical core to minimise packet processing)
- 10Gb/symmetrical basic rate per LR-PON (in principle allowing 10Gb/s PIR if network and customer ports allow)
- 40Gb/s downstream enhanced rate for LR-PON
- 100Gb/s symmetrical for point to point bespoke optical light paths over LR-PON infrastructure
- Scalable to >1000 times today's ADSL broadband capacity.

3 LR-PON design

3.1 LR-PON design for sparse rural areas

The difficulty for conventional PON designs in sparse rural areas is connecting a sufficient number of customers to the PON system in order to get adequate sharing of the physical infrastructure and achieve a low cost per customer. A further problem is the longer distances between splitter nodes and customers requiring longer cable lengths with higher fibre count which also increases cost per customer.

When considering LR-PON applied to sparse rural areas the small rural communities to be served can be much smaller than the total LR-PON split which would mean that the conventional "lollipop" design, with long feeder and large split within a relatively small fibre reach ~<10km, can be considerably underutilised which directly increases the cost per customer. To improve the utilisation we are considering alternative LR-PON structures for rural applications in DISCUS that utilise a "chain" of amplifier nodes. The basic concept was described in D2.1 and is shown in Figure 2. In this figure a protection path option is also shown which was not discussed in D2.1. This particular implementation is the same basic structure as the lollipop model for dense urban with the closest amplifier node to the metro-core nodes being dual parented to the working and standby metro-core nodes while successive amplifier nodes form a chain with a working path and a geographically separated protection path. However it is more appropriate to consider the whole structure as a chain with the metro nodes at the ends

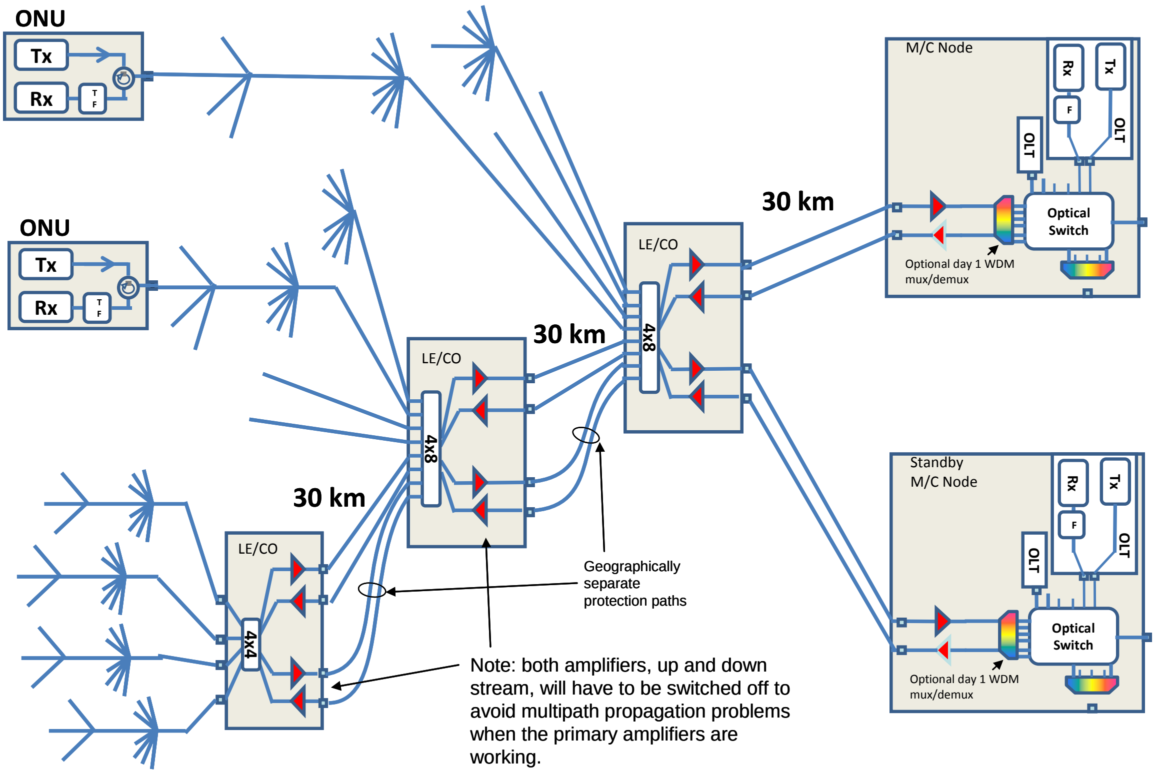


Figure 2 Distributed amplifier concept for rural areas - initially described in D2.1

of the chain, which then also maps to the metro ring topologies of today's networks where a chain can be considered to be part of a ring. When structured as a chain with the metro nodes forming the end points of the chain the structure shown in Figure 3 is obtained. The amplifier nodes for a single LR-PON are shown in a chain configuration with four fibres required between the amplifier nodes for each LR-PON chain while only two fibres are required from the primary and secondary metro-nodes to the closest respective amplifier nodes. This solution shares one OLT working and one protection OLT for all the amplifier nodes in the chain, it maintains full wavelength availability at all amplifier nodes and also works for single wavelength entry solutions. The cost penalty compared to the lollipop model is the greater number of amplifiers per customer due to the smaller split (and of course smaller number of customers) at each amplifier node. The feeder fibre and inter node fibres remain highly shared as with the urban lollipop model and should not add significantly to the cost per customer.

Protection switching is more complex than for the simple "lollipop" LR-PON model used for dense areas due to the increased number of failure modes that can occur. In the event of a break anywhere in the primary path all the amplifier nodes would switch over to the secondary path. The up stream amplifiers in the secondary path need to be

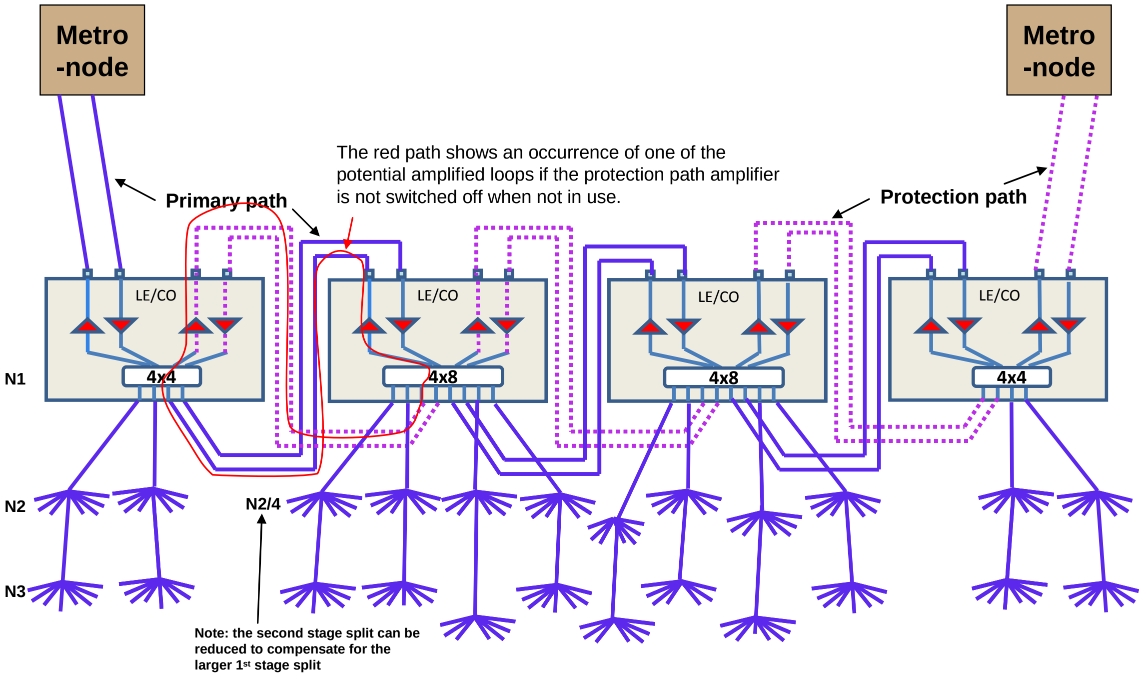


Figure 3 Chain configuration of distributed amplifier structure

off to avoided multipath propagation and an amplified loop, an example of such a loop is shown by the path highlighted in red in Figure 3. Note that the centre amplifier nodes in the chain requires 4x8 splitters to provide the chain ports to connect to their adjacent amplifier nodes, the edge amplifier nodes only require 4x4 splitters as in the usual "lollipop" LR-PON configuration.

The need to turn off the amplifiers in the protection path (to avoid the risk of amplified loops) reduces "fault coverage" because the protection path cannot pass light unless the amplifiers are bypassed with an out of band wavelength pass filter. This makes monitoring of the protection fibre path difficult when the protection path is in the "off" state. Monitoring of protection paths is an important operational requirement in order to maximise “fault coverage” and minimise the risk of switching to a faulty protection path.

The chain cable concept can also be applied to the “lollipop” LR-PON model in urban areas as shown in Figure 4. This configuration applies to denser areas where each local

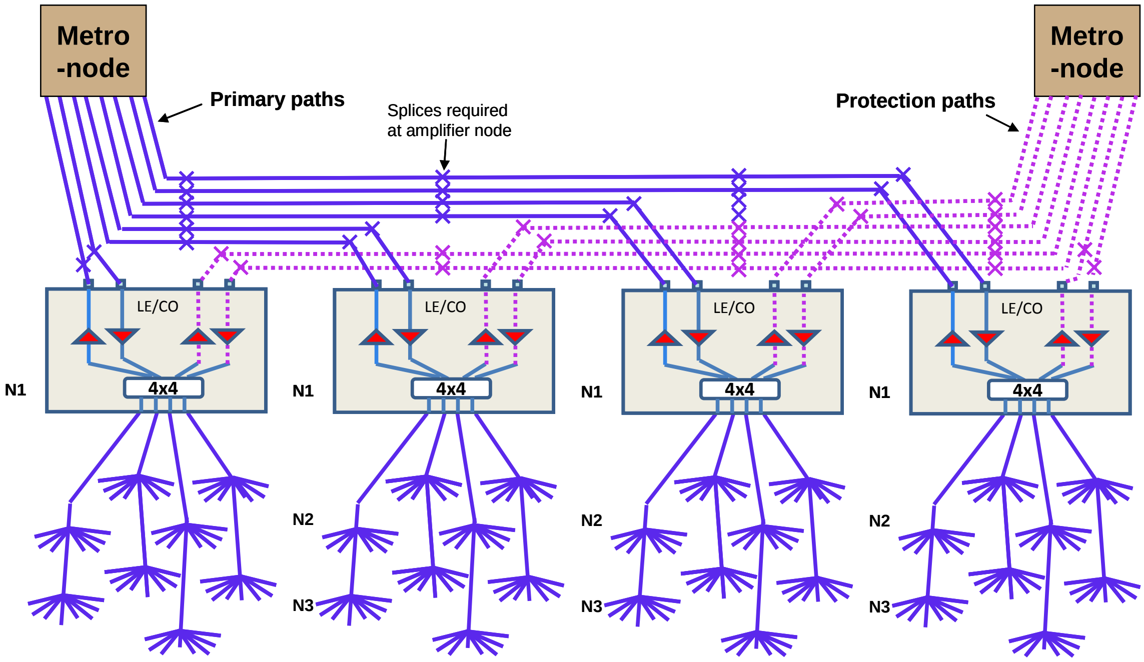


Figure 4 Chain cable model applied to LR-PON "lollipop" model for urban areas.

exchange site /central office would contain amplifiers for several LR-PONs in order to serve the customer base served by the site. A cable chain is configured between a pair of adjacent metro-nodes, the number of LE/CO sites in the chain would depend on local customer densities and LE/CO site densities. The number of fibres in the cable serving the chain is equal to the two times the total number LR-PONs in all the LE/CO sites connected via the chain cable plus any spare fibre planned for future growth. This makes very efficient use of the feeder cable fibre network and minimises cost per customer

An alternative LR-PON chain model for rural areas is shown in Figure 5. The node design is a little more complex than chain model of Figure 3 but has the advantage that the protection fibres can be monitored while the system is in the normal working state. This is an interesting option and builds directly on more conventional ring topologies. There are additional components in the amplifier node which will add cost and it needs to be compared from a cost perspective with the previous chain model for rural areas but the advantage that the protection fibre paths are used by the working paths means that full fault coverage is possible.

The operation is more complex than the conventional LR-PON configurations and will therefore be described in more detail. There is a mix of single fibre and two fibre working in the feeder fibre sections with single fibre working in the ODN part after the amplifier nodes. Referring to Figure 5, which also shows the up and downstream wavelength bands in various parts of the network to aid clarity (the downstream band is arbitrarily shown as green and the upstream band as red), it can be seen that the fibres from the metro nodes (both working and protection nodes) to their nearest amplifier node are two fibre working with each fibre carrying only the upstream or downstream wavelength bands. The ODNs are all single fibre working carrying both up and down stream wavelength bands in all fibres. The intermediate feeder fibre between first and last nodes in the chain now also carry both up and down stream wavelength bands which is different from the configurations shown in figures 3 and 4. This is because the upstream wavelengths from the ODN are combined via the coupler with the

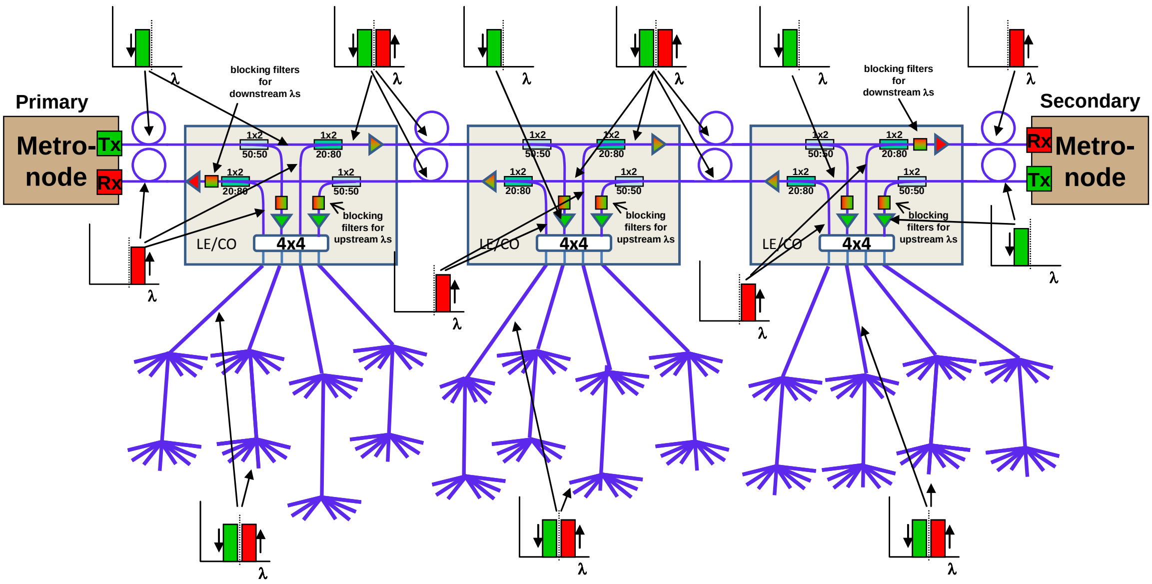


Figure 5 Alternative LR-PON chain model or "Open Ring" design for rural areas

downstream wavelengths from the metro-node. The intermediate amplifiers therefore have to support both upstream and downstream wavelength bands whereas the upstream amplifiers towards the metro-nodes only need to carry the upstream wavelength band and the downstream amplifiers into each ODN only need carry the downstream band but require band filters to block the upstream bands from the adjacent ODNs. Similarly the upstream amplifiers at the ends of the chain into the metro-core nodes may also need optical band pass filters to block the downstream wavelengths band from the distant metro-core node when the standby metro-core node is used for monitoring purposes (these filters could be left out and the upstream amplifier could be used to transit both up and downstream wavelengths to the standby metro-node for monitoring purposes. The relative merits of this option need further consideration).

Although there is a wavelength mixing between upstream wavelengths from the local ODN and the ODN of the previous amplifier node there will be no wavelength collisions for LR_PON wavelengths as they are avoided by the LR-PON protocol, in this configuration all the amplifier nodes in the chain form a single LR-PON. There will be constrains on the number of amplifier nodes and the total chain length. In general the number of amplifier nodes should be kept as small as required to serve the targeted rural area, the greater the number of amplifier nodes in the chain the greater will be the cost per customer due to less customers sharing amplifiers and other components, typically there would be no more than three or four amplifier nodes per chain. The ODN split and reach can be traded off as discussed in D2.1 where approximately each factor of two reduction in split can provide ~10km increase in ODN reach. The longest path length from a metro-node through the chain to the furthest ONU should be less than

125km. This is currently the design limit on the LR-PON protocol we are considering within the DISCUS project, increasing RTT of the LR-PON while at the same time meeting XGPON delay targets will add significantly to PON overheads and reduce payload efficiency. The total sum of split on all ODNs in the chain should be <=1024 (again this is a design limitation decision for the LR-PON protocol).

The structure of the remote node can be seen more in details in Figure 6. The PON ODN entry point is a 4x4 splitter combiner, which is the first splitter in the ODN the total split will be a trade-off of reach and distance with an overall constraint of a total split for all ODNs in the chain of 1024 as mentioned above. Typically each node could support 4x32=128 or possibly 4x64=256 users in a four node chain (a four node chain with 256 split at each amplifier node is technically challenging but is possible). Internally the 4x4 splitter would be used to connect the 2 downstream drop ports and the 2 upstream add ports. The open ring fibre entry points for the upstream channels are 1x2 combiners. Combiners with 80/20 split ratio can be used to reduce the add loss for the upstream (80% port introduces ~1dB). The exit points from the open ring fibres for the downstream channels are also 1x2 splitters which could also be asymmetric 80/20 to help the power budget. In this case the 20% port could be used for downstream channels drop and the lower loss 80% for the path forwarded to the next node. A filter might be required to remove upstream channels, added by previous nodes, in the path of the downstream channels dropped to the PON ODNs, as they might interfere with upstream traffic due to Rayleigh backscattering and reflections in the PON ODNs.

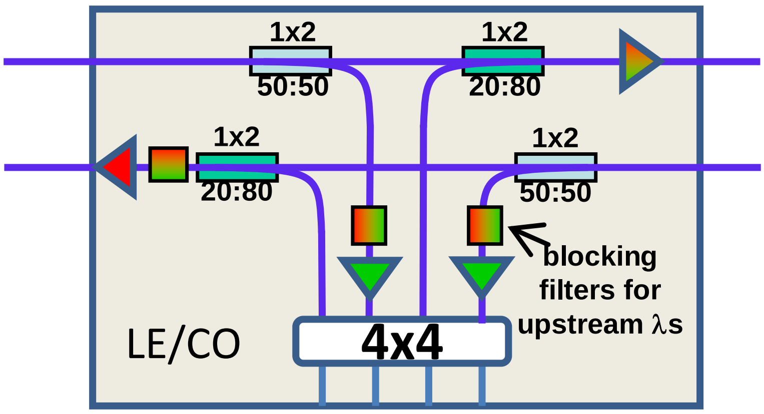


Figure 6 Amplifier node design for the alternative "Open Ring" LR-PON design for rural areas

The RN contains 4 optical amplifiers, which is the same number used in the remote node of the structures shown in Figure 3 and Figure 4. The total amplifier count for the LR-PON would of course be higher in this case since multiple RNs are chained, but, due to advantage of the distributed amplification, lower output power is required from the amplifiers (for details see the power budget). This could be advantageous if cheaper, lower power, optical amplifiers can be employed. Two optical amplifiers are located after the upstream add point and just before the output of the RN. These two in-line amplifiers compensate for the power loss to the next amplifier and the nominal input power of the channels to the next amplifier is kept constant. Another two optical amplifiers are located between the downstream drop and the 4x4 splitter to boost the power of the downstream channels before entering the high loss PON ODNs. Less launched power is required compared to the lollipop structure of Figure 4 due to the lower split targeted per PON ODN.

As an example the power and OSNR budget has been calculated for this architecture with 4 RNs each separated by 30km of fibre, with 4x32=128 users connected to each node giving a total of 512 users. In terms of upstream performance the estimated minimum OSNR is 19dB which has ~4dB margin over the performance expected from the BM receiver (ref. D2.1). This is also achieved with maximum per channel powers of +4dBm at the output of the EDFAs which means that relatively lower power EDFAs can be used compared to the lollipop (ref. D2.1). In terms of downstream performance the limiting factor is the power at the ONT receiver, which can be maintained to -26.6dBm using per channel EDFA launched power of +8.6dBm, also lower than the lollipop (it should be noted that an APD receiver and FEC are assumed for the downstream). The calculations for this architecture show margin, which could be used to add more RNs (increasing the total number of users supported) or to increase the number of users supported by a single RN (at the expense of requiring higher EDFA powers for the downstream).

3.2 General amplifier node design

The amplifier node is used to regenerate (1R = amplification) the downstream (DS) and the upstream (US) data signals. Optical amplifiers are employed within such nodes to increase the weak power levels of both the DS and the US signals. This way, the reach-extending amplifier node is an important feature of the LR-PON to enable the bypass of the local exchange (LE) equipment required for today's copper and short reach access networks. The amplifier node will be placed at the location of today's LE site where electrical power is available. However, a major objective of the DISCUS architecture is to enable closure of these buildings. Therefore arrangements would need to be made for access to electrical power at that site even when the building has been closed for telecommunications use. The amplifier node will therefore need to be placed outside of the equipment rooms of those buildings and either into the outside exchange manhole or the cable chamber, if external access is available or can be arranged. These issues are organisational and process oriented and beyond the scope of the DISCUS project. However a consequence of placing the amplifier node in a relatively small space such as the cable chamber or exchange manhole requires that the design be both small and low power consumption and probably environmentally sealed. Attention will need to be paid to thermal design and management.

Key features for the design of the amplifier node in addition to the optical design parameters are: management, power feed and battery pack up, maintainability, upgradability, reliability and cost.

The design of the amplifier node will be an iterative part of the LR-PON architecture and the overall design of the DISCUS network scenario. In this section, we update the work on amplifier node design presented in the DISCUS deliverable D2.1. First, we introduce important optical design parameters of the erbium-doped fibre amplifiers (EDFA) and also for the semiconductor optical amplifiers (SOA). Afterwards we describe some options for the design of the node for two different ODN and backhaul network approaches together with the analysis on the key node features. We also consider optical amplifier node solutions for bespoke network scenarios. Finally, we compare both amplifier node designs in terms of the key features.

3.2.1 Optical design parameters of the amplifier node

The optical parameters of the amplifiers employed in the node are discussed in detail in the DISCUS deliverable D4.3. In this section, a brief summary of these parameters is provided for better understanding of the subsequent discussions.

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 optical-signal-to-noise ratio (OSNR) of the upstream signal within acceptable levels. The amplifiers should also be able to provide a high gain and a high output power in order 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 in the downstream direction 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 networks which make them attractive for deployment in an access scenario. However, another important aspect of the EDFAs 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 in order not to impair the burst transmission in PONs have become commercially available. However, this does not come for free and requires additional components, which increase the overall costs of the amplifier node.

From modelling work performed for the DISCUS deliverables D2.1 and D4.2, desirable optical parameters for the EDFA have been obtained: a noise figure of 5.5 dB, a maximum gain of ~ 30 dB, a maximum aggregated output power of +28 dBm (depending on the number of channels supported and also on the particular configuration deployed).

Another mature technology for amplification in access networks is given by SOA. The requirements of a low noise figure as discussed above are achievable using this technology. However, typically SOA cannot provide high gain values and simultaneously high output power levels without introducing signal distortions. Thus, a higher number of SOAs (cascade of SOAs) is used to support the required loss budget of the DISCUS LR-PON architecture. The number of cascaded SOAs should be as low as possible to avoid significant OSNR degradations caused by noise funnelling (refer to the DISCUS deliverable D4.3 and D4.2).

From modelling work performed for the DISCUS deliverables D4.3 and D4.2, desirable optical parameters for the SOAs have been obtained: a noise figure of 8 dB is definitely achievable and it is also sufficient to support the different LR-PON scenarios. 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 to avoid signal impairments by non-linear effects such as cross-gain modulation or four-wave-mixing. The saturation input power (1-2 dB point) should be in the range of 0 dBm. This way, an acceptable output power per channel in the range of 0 dBm (~ 15 dBm if assuming 32 wavelength channels) can be obtained. 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 amplifier gain should be constant (high gain flatness) over the entire wavelength band.

3.2.2 Amplifier node for single fibre ODN and two fibre backhaul

The amplifier node for the basic LR-PON design introduced in Figure 1 has the conventional single fibre working in the ODN and two fibres working in the backhaul parts of the LR-PON. In this design the different outputs of the 4 x 4 splitter in backhaul direction are used to separate the up- and downstream paths, which would then be connected to separate fibres in the backhaul. The different outputs of the 4 x 4 splitter in ODN direction carry up- and downstream data signals simultaneously, but in opposite directions.

Figure 7 shows an example of an amplifier node configuration for this LR-PON architecture employing either EDFAs (a) or SOAs (b). The downstream signals are transported over a separate fibre and launched into the amplifier node. Here, either a single EDFA (a) or a single SOA is used to amplify the data signals. In (a), no further downstream data signal amplification is required, because of the use of the high gain EDFA. In (b), behind the 4 x 4 splitter 4 additional SOAs are employed for amplification. This SOA cascade is employed to achieve the required accumulated gain required. The upstream signals are transported over the ODN and launched into the amplifier node. Here, either a single EDFA (a) or a cascade of SOAs is used to amplify the signals.

Management/maintainability: in the case of using EDFAs as introduced in Figure 7(a), an optical tap is placed on the ODN side of the 4 x 4 splitter to access the optical

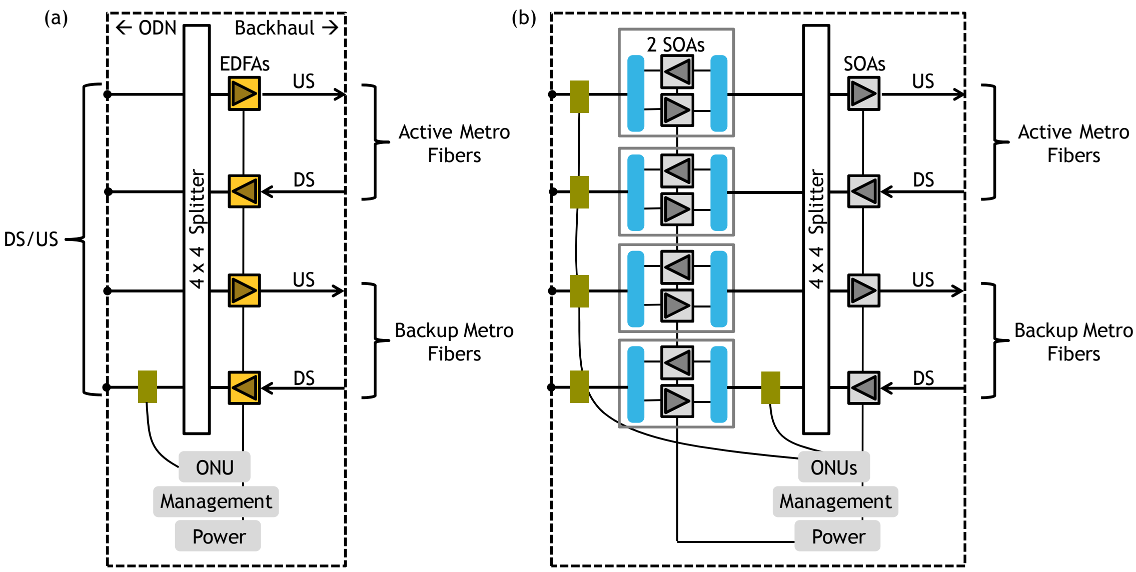


Figure 7 Amplifier node for conventional LR-PON with single fibre ODN and two fibre backhaul. In (a) the amplifier node comprises 4 EDFAs for upstream and downstream amplification and in (b) the amplifier node comprises 12 SOAs (parallel cascade of linear SOAs).

signals for operations and maintenance supervision. The tapped optical signals are fed to what is essentially an optical network unit (ONU) and enables management messages to be passed between the amplifier node and the optical line termination (OLT) at the metro-core node. The optical tap can be very low loss as the optical signal power level at this point will be high, in the order of +9 dBm, so an optical 99:1 tap could be used. In the case of using SOAs, Figure 7(b), 4 optical taps are placed on the ODN side of the 4 x 4 splitter to access the optical signals for operations and maintenance functions. The use of more than a single tap and a single ONU function is required to monitor the functionality of the amplifiers in upstream and downstream direction, respectively. The optical taps can be low loss as the optical signal power level at this point will be high, in the order of + 0 dBm/λ-channel, so an optical 99:1 optical tap (or a 95:5 tap) could be used.

Energy/power consumption: in general a LE site will support a number of LR-PON systems and it would be expected that the amplifier node will be modular and able to flexibly accommodate a number of amplifier modules to serve the LE site. This gives the opportunity of sharing some components such as power supplies and battery back-up systems and possibly the management ONUs on a shared protection basis to improve reliability of the node.

For the standard LR-PON "lollipop" solution there are four EDFAs per amplifier node. A typical high gain EDFA has a power consumption in the range of 15W. Of these four amplifiers the downstream amplifier in the standby path will be in an off state and consuming little power. The total power consumption is therefore expected to be in the range of 60W, including 10W for the management ONU. The SOA-solution for the LR-PON "lollipop" requires the use of 12 SOAs per amplifier node. A typical medium gain SOA has power consumption in the range of ~4-7 watts including drive electronics. Again the standby downstream amplifier in the feeder fibre is switched off so 11 amplifiers will be powered on, the expected total power consumption is therefore in the range of 54-87W including 10W for the management ONU. It can therefore be considered that the power consumption of both solutions will be in a similar range.

Cost/reliability/upgradability: the EDFA-solution requires 4 high gain EDFAs compared to the 12-medium gain SOAs required for the SOA-solution. It is anticipated that the cost of each of these specific EDFAs is significantly higher than that of discrete SOAs. Additionally, the SOA-solution requires a higher number of monitoring taps and monitoring ONUs. However, the SOA-amplified splitter has high potential to be integrated into a single chip containing the SOAs, the splitter as well as the taps for monitoring. This integration could make the SOA amplified integrated-splitter cost competitive to the EDFA option despite the greater number of amplifiers required.

The EDFA-approach makes use of less equipment units compared to the SOA-approach. This way the reliability at the EDFA-solution is increased by reducing the total probability of failure of all operated amplifiers. Additionally, the long-term performance of EDFAs is good and well known from their deployments in core networks. SOAs are widely used in the scientific community and also in some integrated transmitters. However, their long-term stability for use in LR-PONs, e.g. in manholes, is currently unknown and for further study.

The upgradability is given in both of the amplifier node solutions. The EDFA- and the SOA-solution can be operated with a single wavelength channel at the early stage of the deployment. An upgrade of the system to be operated with a higher number of wavelength channels seems to be possible for both solutions.

3.2.2.1 Possible realizations of the amplifier node depending on LR-PON wavelength plan

The optical amplifiers used in the amplifier node can be equipped with isolators, circulators or filters depending on the wavelength plan used for the DISCUS LR-PON realization. In the following, possible wavelength plans of the LR-PON are briefly described (see DISCUS deliverable D4.2 for more details) and the influence of the wavelength plan on the equipment required at the amplifier node is discussed.

The wavelength plan for the LR-PON strongly depends on the technology of choice, especially on the availability of optical amplifiers for the desired wavelength region, see also DISCUS deliverable D3.2. Operation in the C-band is preferred because of the availability of mature components, especially, the EDFA which provides a key technology in this wavelength region. For other wavelength regions of the fibre 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 briefly.

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 long wavelength side of the C-band to the downstream and the short wavelength to the upstream) see Figure 8(a) and with guard-band Figure 8(c)). alternatively interleaving of the up- and down-stream channels, see Figure 8(b), could be considered.

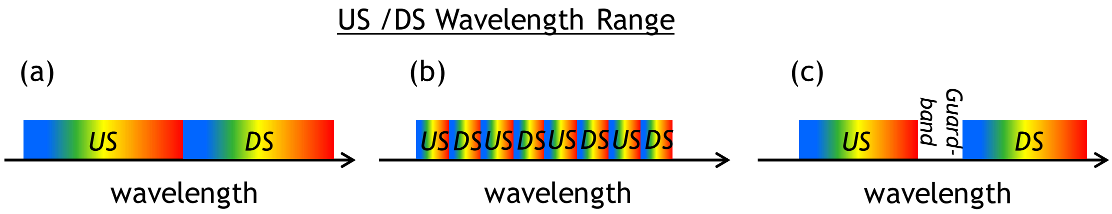


Figure 8 Possible wavelength plans for US / DS channels of the LR-PON.

By using SOAs the constraint to the C-band operation could be overcome. The use of wavelength regions other than the C-band can be used to expand capacity and add additional services and for very high bit rate services may also have advantages in terms of dispersion management if e.g. the O-band is used. Using either SOA or EDFA technology, the above mentioned scenarios of applying a band splitting or a band interleaving would apply equally.

In Figure 9, optical devices to block the transmission of data signals in the opposite directions of the PON are introduced, respectively, for the EDFA-amplified node solution. Isolators are standard components in EDFAs as shown in Figure 9a This way a protection of the US or DS transmitters from backward propagating amplified spontaneous emission (ASE) noise introduced by the EDFAs is achieved. Additionally, the US data signals are prevented from disturbing the DS amplifier.

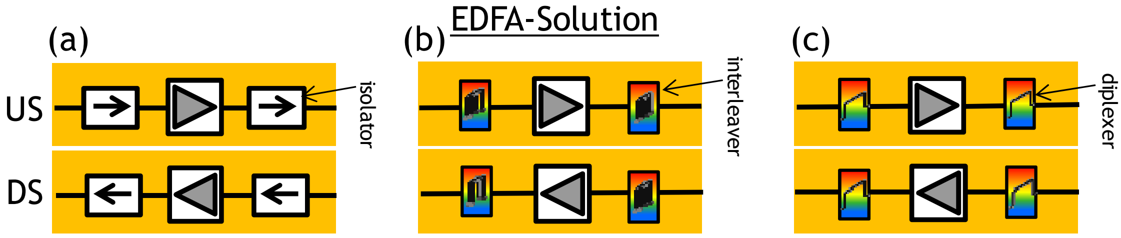


Figure 9 EDFA within the amplifier node equipped with isolators in (a), with interleavers in (b) and with diplexers in (c). The use of the different configurations depends on the wavelength plan of the LR-PON.

Consider the use of EDFAs with a wavelength plan according to Figure 8(b). Using interleavers, as shown in Figure 9(b), in front of and also behind each EDFA does not protect the US or DS transmitters from backward propagating amplified spontaneous emission (ASE) noise and therefor the standard isolators would still be required. However, the interleavers do prevent the US data signals from disturbing the amplification of the DS channels. This also holds true for the case of using a wavelength plan according to Figure 8(c), where an optical diplexer would be used rather than an interleaver see Figure 9(c).

Configurations for the use of SOAs are shown in Figure 10. Optical isolators to block the transmission of data signals in the opposite direction of the PON are shown. The use of a wavelength plan accordingly to Figure 8(a), requires the use of optical isolators, Figure 10(a), in front of and also behind each SOA. Again, this way a protection of the US or DS transmitters from backward propagating ASE noise is achieved. Additionally, the US data signals are prevented from disturbing the DS amplifier. Instead of using Isolators in the amplifiers on the ODN side of the 4 x 4 splitters optical circulators may be used as shown in Figure 10(b). Considering the use of a wavelength plan accordingly to Figure 8(b), requires the use of either optical isolators/circulators or interleavers, as shown in Figure 10(c) and a similar explanation holds true in case of using a wavelength plan accordingly to Figure 8(c) here an optical diplexer is used to prevent the US data signals being launched into the DS amplifier, see Figure 10(d).

The major advantage of SOA technology is the increased degree of freedom in terms of wavelength band allocation for DS and US channels. US and DS channels could either be allocated to all bands from O, S, C, L-band or even a separation of US and DS channels to different wavelength bands is possible.

At day 1 of the LR-PON deployment, the network could be operated with a single channel, or just a few channels in US and DS direction respectively, to facilitate lower start-up cost. This could be achieved by using specific filters, e.g. as introduced above, and also separate amplifiers. At a later stage a network upgrade to dense wavelength division multiplexing (WDM) network could be done. The specific filter arrangement could then easily enable the WDM upgrade of the network.

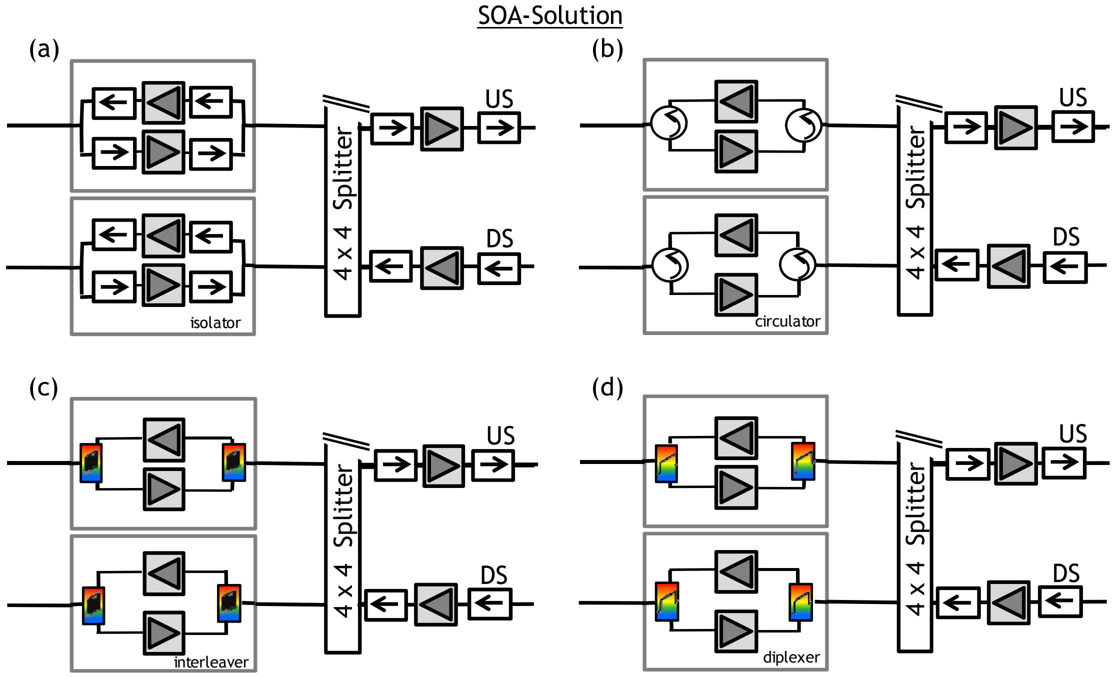


Figure 10 SOA within the amplifier node equipped with isolators in (a), with circulators and isolators in (b) with interleavers and isolators in (c) and with diplexers and isolators in (d). The use of the different configurations depends on the wavelength plan of

3.2.3 Amplifier node for two fibre ODN and two fibre backhaul

The amplifier node design for the LR-PON architecture working with two fibres in the ODN and two fibres working in the backhaul parts of the LR-PON, as introduced in Figure 1, is shown in Figure 11. In Figure 11(a) an amplifier node that makes use of solely EDFAs is shown and in Figure 11(b) an amplifier node in which solely SOAs are employed are presented. In these configurations of the amplifier node the 4 x 4 splitter is divided into two 2 x 4 splitters separating the upstream and downstream directions of propagation.

The configurations shown in Figure 7 and Figure 11 differ only slightly in the components used and will be of similar cost as the main cost elements will be the optical amplifiers and the management and control electronics.

Management/maintainability: the management ONU does not need a diplexer, as in the previous amplifier node design, but it needs to be connected to both the upstream and downstream 2 x 4 splitter ports via two (in a) or 10 (in b) optical taps.

Energy/power consumption: the power consumption of this amplifier node configuration seems to be comparable to the previously introduced node configuration. This is because of the use of an identical number of EDFAs/SOAs (dominant elements to the power consumption) in the configurations shown in Figure 7 and Figure 11.

Cost/reliability/upgradability: the costs and the reliability of the configurations introduced in Figure 11 seem to be comparable to the formerly introduced configurations from Figure 7. As already mentioned, an identical number of optical amplifiers are employed, but a higher number of taps is used in the configuration from Figure 11.

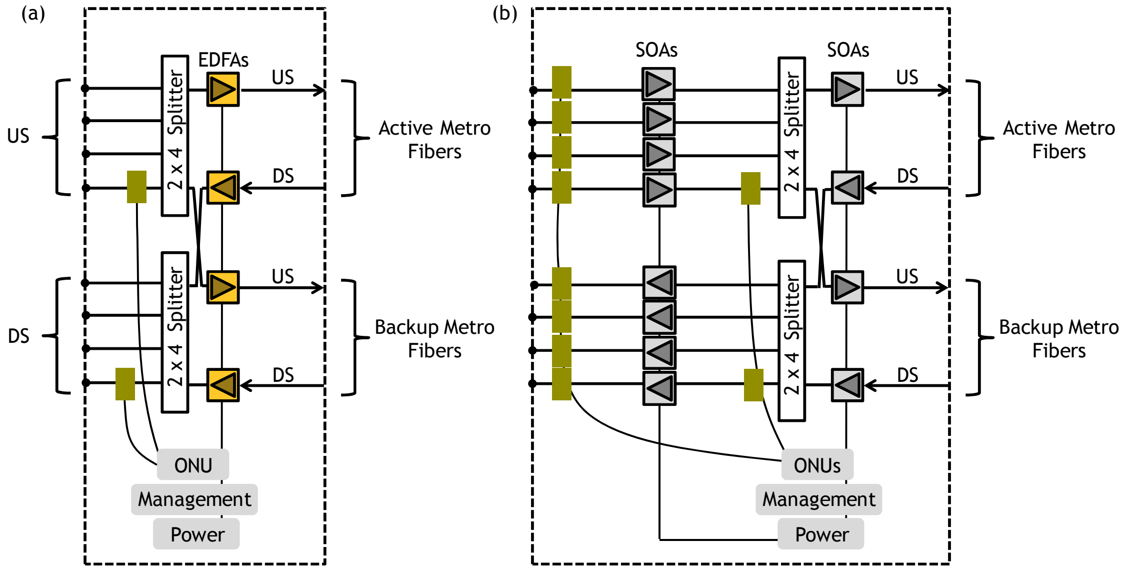


Figure 11 Amplifier node for LR-PON with two fibres ODN and two fibres backhaul. In (a) the amplifier node comprises 4 EDFAs for upstream and downstream amplification and in (b) the amplifier node comprises 12 SOAs (parallel cascade of linear SOAs).

The upgradability is given in both of the amplifier node solutions. There are no specific wavelength selective elements required in the above configurations and therefore they can all be used to support WDM operation, but as discussed previously there is a design decision to be made concerning the performance of the amplifiers for the initial deployment. To keep costs to an absolute minimum the first installed amplifiers may only be provided with sufficient performance for a single wavelength LR-PON system and would need to be upgraded when WDM is required. The upgrade can be carried out with minimal disturbance to the working customers by upgrading the standby path first and then switching the working path to this upgrade path. The working path can then be upgraded and when all work is completed the working path can be restored. A design choice for the early system deployment is therefore whether or not the first optical amplifiers installed should have sufficient performance to support WDM upgrade or whether simpler amplifiers designed only for single wavelength working of the initial LR-PON should be deployed.

3.2.3.1 Possible realizations of the amplifier node depending on LR-PON wavelength plan

The optical amplifiers used in the amplifier node can be equipped with combinations isolators, circulators or filters depending on the wavelength plan used for the DISCUS LR-PON realization. Identical solutions as already described above can be implemented for two fibre working in the ODN. Additionally, because of the fibre separation for the US and DS paths, the full wavelength band of the specific deployed amplifier technology can be used in both directions, as presented in Figure 12 (a).

In Figure 12, the standard optical isolators to block the transmission of data signals in the opposite directions of the PON are shown for both the EDFA-amplified node Figure 12 (b) and the SOA-amplified node Figure 12 (c). These are independent of the specific wavelength plan. This way a protection of the US or DS transmitters from backward propagating ASE noise introduced by the amplifiers is achieved. In this configuration,

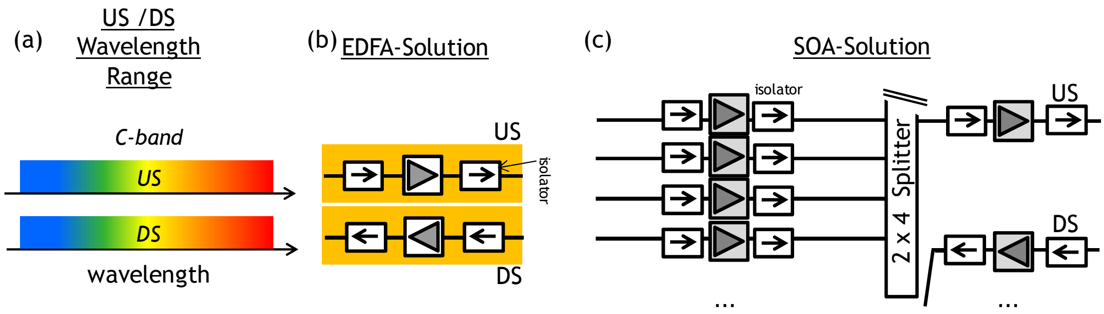


Figure 12 Specific wavelength plan for the US/DS direction (a) and possible amplifier node design realizations for EDFAs (b) and SOAs (c).

there is no need to prevent the US data signals from disturbing the DS amplifier.

3.2.4 Additional optical amplifier design for bespoke network solutions

To enable bespoke LR-PON architectures, for example to provide cross links between different parts of the LR-PON or adjacent LR-PONs specific configurations for the optical amplifier node design could be thought of. In DISCUS deliverable D2.1, different solutions to generate ONU-to-ONU communication is discussed for the EDFA amplifier technology only. Thus, beside the solutions comprising spare fibres to generate a point to point intra PON link or a point to point inter PON link as well as the solution of using WDM techniques, power splitters can be used in the configurations using the SOA amplifier technique.

Power taps can be added e.g. in front of the 4 x 4 splitters and behind the first SOA US amplifiers to enable ONU-to-ONU connection. Another possible approach is to add the power splitters behind the 4 x 4 power splitters. This way, the US data traffic from a specific ONU is looped back via the DS path (including amplifiers) to the remaining ONUs. A careful allocation of wavelength resources is required in this configuration. Additionally, the use of SOAs, which can amplify US and DS wavelength band simultaneously, is needed.

3.2.5 Comparison of approaches

The different amplifier node designs are already compared in the various sections. Following, a brief summary in

Table 2 is provided to conclude this section. For this summary, the use of a WDM LR-PON network employing isolators for the EDFA and also for the SOA solution is assumed.

Architecture	1 fibre ODN/ 2 fibres backhaul		2 fibres ODN/ 2 fibres backhaul	
Amp. technology	EDFA	SOA	EDFA	SOA

Number of units				
Amplifiers (total/on)	*4/3*	*12/11*	*4/3*	*12/11*
Number of Isolators	*8*	*24*	*8*	*24*
Monitoring Taps	*1*	*5*	*2*	*10*
Power Splitter(s)	*1*	*1*	*2*	*2*
Performance				
Bit rate upgradability	*yes*	*yes*	*yes*	*yes*
Format transparency	*yes*	*yes*	*yes*	*yes*
Number of supp. λ-ch.	*high*	*medium*	*high*	*medium*
Burst-mode capability	*not naturally*	*yes*	*not naturally*	*yes*
λ-range				
Availability	*C-/L-band*	*Entire-fibre window*	*C-/L-band*	*Entire-fibre window*
3 dB bandwidth	*30-35nm*	*60-100nm*	*30-35nm*	*60-100nm*
Power consumption.	60W	50W-90W	60W	50W-90W
Cost				
Individual. amplifier	*high*	*medium*	*high*	*medium*
Total amplifier module	*comparable/TBD*	*comparable/TBD*	*comparable/TBD*	*comparable/TBD*
Potential for cost reduction by integration	*Limited integration: e.g. pump arrays and integrated splitters*	*high*	*Limited integration: e.g. pump arrays and integrated splitters*	*high*
Reliability	mature	Long-term stability open	mature	Long-term stability open

Table 2 Summary of the two amplifier node architectures in terms of key features for the EDFA and SOA technologies

Note: in the table the cost comparisons are very preliminary at this stage a cost model which will compare options including the amplifier node costs in detail is under construction, TBD means To Be Determined.

3.3 LR-PON Resilience options

In this section, we focus on resilience for the rural deployment of LR-PON, where multiple stages of amplifier nodes are needed to support ultra-long reach as well as longer distances between the users that are spread over a large service area**.**

Rural cases for LR-PON: The initial simple design as describe in D2.1 and shown in Figure 13 has the ODN section with single fibre working and two fibre working between the working and standby metro-core nodes and the first amplifier node, with apparently single fibre working between successive amplifier nodes.

In this figure for the rural scenario, the total unprotected distribution fibre could have a length of up 70km plus several stages of amplifiers (active nodes) that are needed in the field, such a configuration would affect reliability performance significantly.

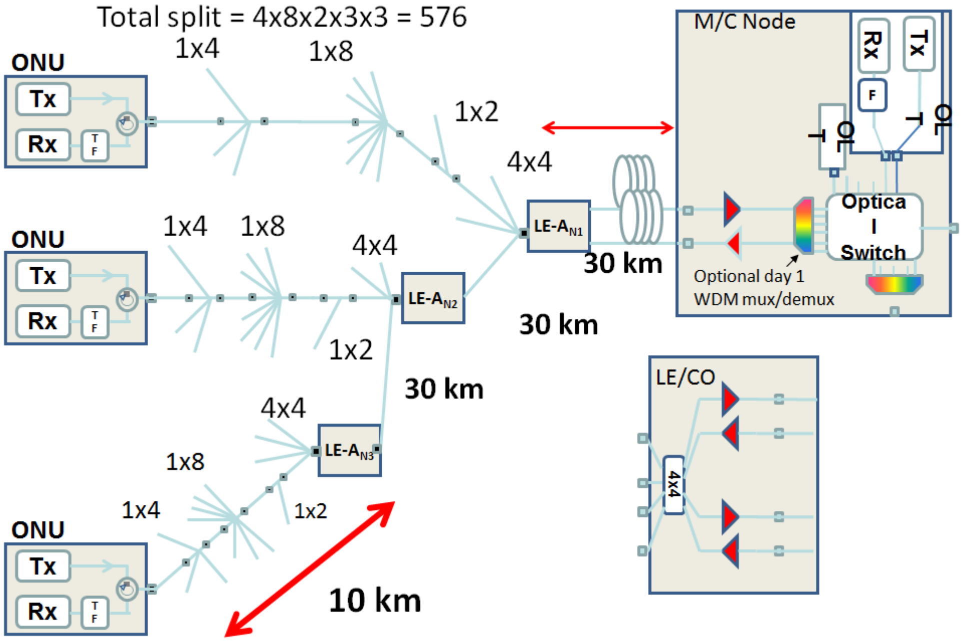


Figure 13 Distributed amplifier node solution for rural areas - basic concept

Figure 9: Distributed amplifier node solution for rural areas – basic concept

If a fibre cut occurs in the fibre sections between the amplifier nodes one third to two thirds of the customers on the LR-PON could lose service which can be considered to be a high failure impact. Besides previous studies [5] has shown that with long unprotected fibre it's hard to reach the connection availability of 99.99% (i.e., 4 nines). In order to offer adequate reliability for rural areas, it will be necessary to provide protection paths between the cascaded amplifier nodes and the M/C nodes. In section 3.1, Figure 2 we show Figure 13 redrawn with two fibre working between the amplifier nodes and also with the additional protection paths shown. The working fibres and the protection fibre should be in separate cables with geographically separate paths. Note: the physical separation could be quite small e.g. on each side of a road as the most common cause of fibre failure is third party dig-up which usually only occurs on one side of a road at a time.

In Figure 13 the 4x4 splitter configuration at the 2nd and 3rd amplifier nodes has no spare ports for the protection fibres. To overcome this limitation/problem we need to replace the amplifier node 4x4 splitters with 4x8 splitters as shown in Figure 2. This use of 4x8 splitters increases the split capability at each amplifier node (note that the last amplifier node can revert back to the 4x4 splitter). The problem with this solution is the protection paths for the cascaded amplifier nodes AN2 and AN3 cause a multipath propagation problem and to avoid this both the downstream and upstream amplifiers in the protection path will need to be turned off when the working amplifiers are operating normally.

This means that the standby M/C node cannot monitor the upstream transmissions of these LR-PON systems. This will have implications for the control of protection switching mechanisms and LR-PON management. However, the working M/C node still can supervise the working signals and inform the standby M/C node in case of fibre break/cable cut.

There may also be the problem from a resilience perspective that customers on the cascaded amplifier nodes could suffer lower connection availability than customers on the first amplifier node in the chain (AN1) due the possible failure of any cascaded nodes. On the other hand, as all the amplifiers are protected, the connection availability degradation for the customers connected to the cascaded remote nodes is only dependent on the reliability performance of the cascaded splitters/combiners which are generally very reliable, passive devices.

Another advantage of the configuration shown in Figure 2 is that the working and protection paths have the same configuration and can be interchanged, if required, to balance traffic loading of the metro-core node nodes. The longest fibre path between either working or standby metro-core node must of course meet the overall power budget requirements and also the differential path lengths between the working and protection paths of the cascaded amplifier nodes must now be part of the differential range of the LR-PON protocol.

A further configuration for protection fibre paths for rural deployments is shown in Figure 14. This is aimed at removing the reduction in connection availability of the customers connected to successive amplifier nodes down the chain as protection paths now bypass one or more stages of amplifier nodes. It also enables monitoring of the protection path as the upstream amplifier can now be on as multipath propagation and amplified loops are avoided. The splitters at the amplifier nodes can also revert back to the 4x4 as standard. However, the problem with this solution is the need for additional

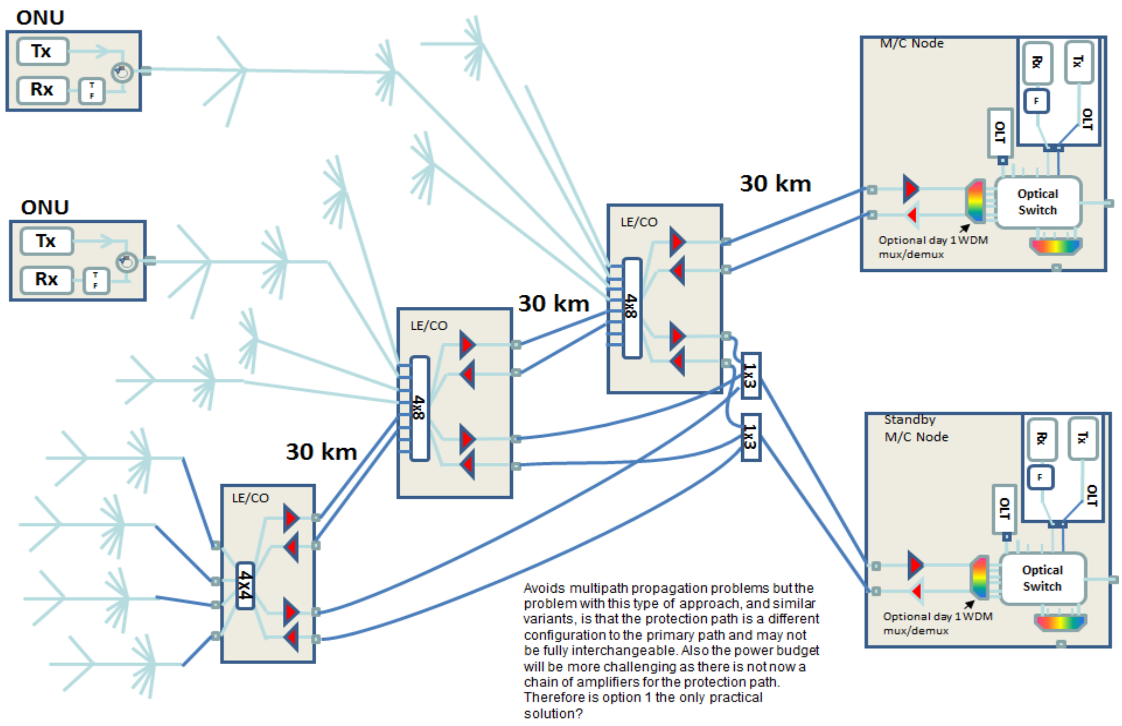


Figure 14 Distributed amplifiers for rural areas - protection option 2

splitters in the backhaul path and hence will have an impact on power budget.

Also, unlike the solution shown in Figure 2, the protection path and the working paths are now different configurations and will require more complex planning, and finally the protection fibre lengths could be long and possibly requiring separate cables making it less competitive from cost and transmission performance point of view.

Ring topology for cable layout: the deployment cost of fibre infrastructure is a significant part of the capital expenditures (CAPEX) and should be minimized by a proper fibre layout, taking advantage as much as possible of fibre infrastructure sharing, where trenching/ducts can be shared by different fibre links. In section 3.1 Figure 3 shows a "chain" cable layout design for LR-PON in DISCUS with dual-parenting which can enable sharing the fibre infrastructure and duct network as much as possible. As previously mention in section 3.1 a chain can be considered as part of a ring which would contain two metro nodes and a number of remote amplifier nodes placed at old local exchange/central office sites. Different backhaul fibres for different LR-PONS and/or amplifier nodes share the same backhaul cable which could form a cable ring as shown in Figure 15 while the distribution fibres associated with the same LR-PON goes through the distribution cable (DC) which in some cases could also form rings. Ring cable layouts also opens the possibility to have a dark fibre monitoring scheme, where a

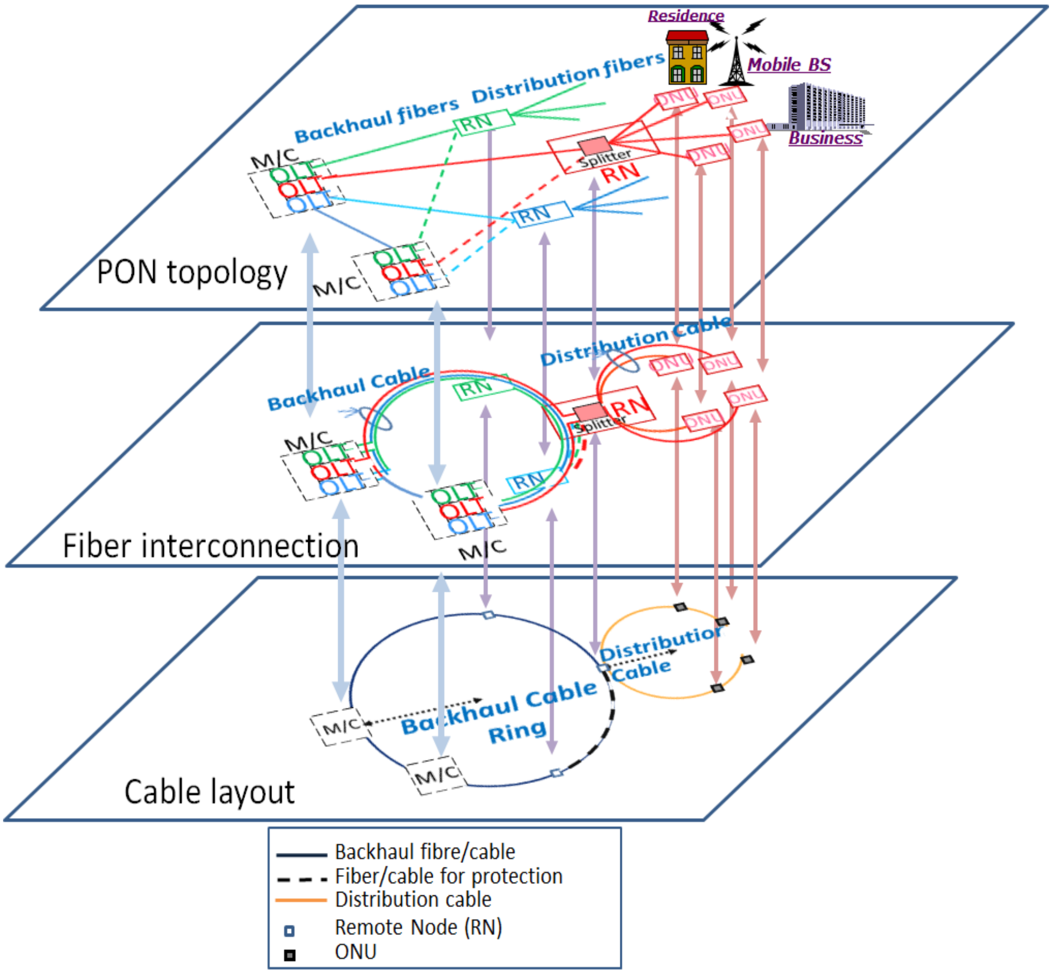


Figure 15 Cost-efficient reliable cable layout for dual parenting protection in DISCUS.

fibre deployed in the same cable but not used for any working LR-PONs or other systems can carry out the supervision signals for fault monitoring (see more details in

D4.4). We will further explore the possibility of chain as ring arcs to get the optimal solutions for distribution fibre sections.

4 Update on coherent upgrade for LR-PON

Coherent technology applied to LR-PON is a potential upgrade route for the DISCUS architecture. However there is not funded resource for development of coherent technology within the DISCUS project. Such developments are carried out in other projects or by individual partners for DICUS that partner is Coriant. The objective for DISCUS in this area is to keep a watching brief and where possible influence future work on coherent systems for access applications such that more efficient use of the technology can be made within the DISCUS architecture and also so that DISCUS can adopt coherent options in the future.

Most coherent access projects are effectively investigating point to point overlay using ultra dense WDM via coherent technology. Although DISCUS will enable upgrade to such systems a more graceful update strategy would be to also consider point to multipoint (e.g. PON protocols) transmission over the coherent wavelength channels this would mean increasing the bit rate per channel from the ~1Gb/s, which is the predominant technology being investigated today, to ~10Gb/s so that LR-PON protocol developments can be directly applied to coherent systems and wavelength sharing of the coherent channels can be also be exploited by mass market users in addition to point to point systems for high end /business users.

However for this deliverable the following is a report of work by our partner Coriant on coherent access network developments and field trials in conjunction with Deutsche Telekom in Berlin. This is part of the ongoing watching brief activity within the DISCUS project.

4.1 Recent developments in coherent access technology and systems

The upcoming NG-PON2 standard series G.989 [6] describes the next generation optical access systems. Within this standard, a point-to-point WDM PON overlay is foreseen to provide connectivity for demanding applications such as mobile backhaul, mobile fronthaul and business applications while the home users are connected with a TDM-WDM hybrid system (TWDM). Coherent Ultra Dense WDM PON (UDWDM PON), as for example described in [7, 8], offers a good match to the requirements for the point-to-point overlay, as described in G.989.1 [6]. This section describes the first real-time transmission of a coherent UDWDM system over field deployed fibre. An UDWDM prototype implementation and the demonstration of its LTE backhauling capabilities over 75 km of deployed fibre in the Deutsche Telekom testbed in Berlin, Germany, are described. Furthermore, its capability to coexist with GPON and 100G WDM transmission systems on the same optical fibre has been shown. In a subsequent field trial in another Deutsche Telekom testbed in Darmstadt, Germany, the system was modified in order to use a Silicon Photonics (SiP) integrated CMOS laser [9] for the downstream transmission. Successful coexistence measurements with a legacy GPON system, an analogue RF video overlay and an OTDR system simultaneously on the same fibre were performed. No degradation in transmission performance was measured due to either the use of the SiP laser or due to the presence of the coexisting systems.

4.2 Real Time UDWDM System setup

The setup of the coherent UDWDM system is shown in Figure 16. The OLT consists of 3 Optical Transceiver Groups (OTGs) each of which transmits up to 10 wavelengths and receives one wavelength. The central frequencies of the OTGs are separated by 50 GHz while the wavelengths generated by the OTGs are separated by 2.799 GHz. Each wavelength transports 1.244 Gbit/s. The modulation format is pulse shaped (α=0.5) DQPSK, resulting in a baud rate of 622 Mbaud, and the framing structure is OTU 0.

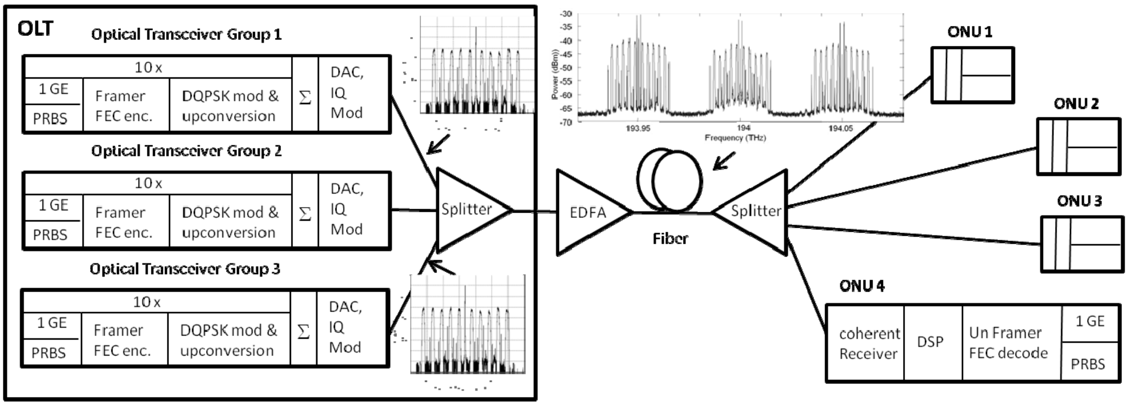


Figure 16 Real time UDWDM system setup. The insets show transmit spectra at the output of the optical transceiver groups and the spectrum in the fibre. Up to 30 wavelengths were transmitted

The payload is either a 1 Gbit/s Ethernet signal or a PRBS15 sequence. For each of the 10 wavelengths, the OTGs contain a framer unit, an FEC encoder and a digital up-conversion stage, which converts the digital baseband signals to digital RF carriers. The output signals of all 10 digital up-conversion stages are then added and sent to a pair of 60 GSamples/s DACs. The pair of DACs drives an IQ modulator that generates the 10 wavelengths out of a single continuous-wave laser source.

The signals of the OTGs are combined by a passive splitter and amplified by an EDFA. After transmission of various fibre distances, the signals are split by another passive splitter and received by four ONUs. Each ONU contains a polarization diversity coherent receiver, a DSP unit that generates a bit stream, a de-framing unit and an FEC decoder. The use of FEC is configurable: the BER curves in this paper were performed without FEC, while the high-definition (HD) video transmission and the LTE backhauling were with FEC.

The system has been described in more detail e.g. in [7] and [8].

4.3 Field trial Testbed setup

The generic field trial test set-up is shown in Figure 17. Two field trials were performed over two different testbeds of Deutsche Telekom in Berlin and Darmstadt, Germany. The Berlin testbed offered several SSMF fibre links from Berlin Centre to Berlin Wannsee. The fibre at the remote Wannsee site was patched in order to form fibre loops with a loop length of 37.5 km. The fibre links differed in age and properties, one link had a very high PMD of 80 ps and a high attenuation of about 20 dB while the other link had negligible PMD and an attenuation of about 15 dB. The Darmstadt site offered a field deployed SSMF fibre link of 14.8 km length. The UDWDM system transmitted either PRBS test data for BER measurements, real time HD Video payload or real time LTE backhauling data.

Many FTTx deployments use a RF Video overlay in order to provide non-IPTV video services to their customers. Therefore, coexistence with those RF Video systems is essential and UDWDM and RF-Video were sent over the same fibre. The RF Video system was a mixed analogue and digital system, occupying channels from 86 MHz to 866 MHz.

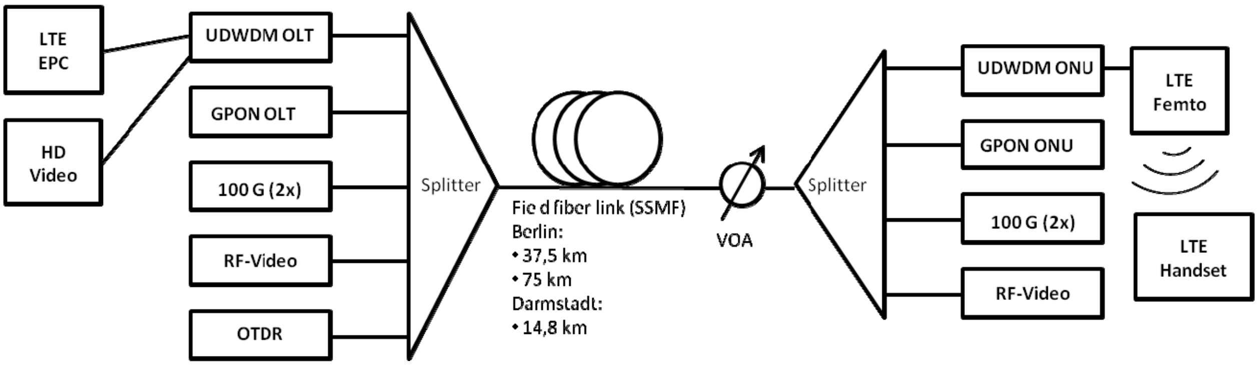


Figure 17 Generic field trial setup. Not all legacy services were always present at the same time due to limited availability at the test sites.

The field trials had three purposes: to show the transmission of UDWDM signals over field deployed fibre for the first time, to demonstrate the coexistence of UDWDM with legacy systems on the same fibre and to show the suitability of SiP CMOS lasers for such a system. For the coexistence measurements, GPON, 100G and LTE were available at the Berlin site, while the Darmstadt site offered GPON, RF-Video and OTDR. In the Darmstadt trial, a Silicon Photonics CMOS laser [9] was used for downstream transmission. The laser is tuneable over the full C band and shows a linewidth of less than 200 kHz over the band.

4.4 Results

As an example for the performance of real time transmission of UDWDM over a field fibre, an ONU receiver BER curve from Darmstadt is shown in Figure 20; the sensitivity at the FEC threshold of BER=10-3 is about -49 dBm. The measurement has been taken with deactivated FEC.

Further measurements concentrated on coexistence verifications. Figure 19 shows the spectrum of an UDWDM system, operating over the same field deployed fibre (Berlin) as two wavelengths of a commercial 100G WDM transport system. No impact could be observed, neither from the 100 G onto UDWDM or vice versa.

In the Darmstadt test site, coexistence measurements were performed with GPON, RF-Video and an OTDR system, all running over the same field fibre. The spectrum in the fibre is shown in Figure 18 (OTDR at 1640 nm not shown). Again, no impact of any system onto UDWDM could be observed, as well as any impact from UDWDM onto other systems. As the receive filters of the RF Video systems are quite broadband, a degradation of the RF Video BER was observed when the UDWDM wavelength was moved into the RF Video Receive window. When the UDWDM wavelength was outside the RF Receive window, no deteriorating effect, e.g. Raman nonlinearity, could be observed.

At the Berlin site, the UDWDM system was used to backhaul a LTE femto base station to its Evolved Packet Core (EPC) over the Ethernet link that the UDWDM system provided. The fibre distance was 75 km. No impact of the transmission link could be observed, any potential delay and jitter addition was below the resolution threshold of the measurement equipment.

A Silicon Photonic CMOS tuneable laser was used at the Darmstadt site for the transmission experiments. When comparing the test results with using a commercial tunable laser, no difference on the transmission performance could be observed.

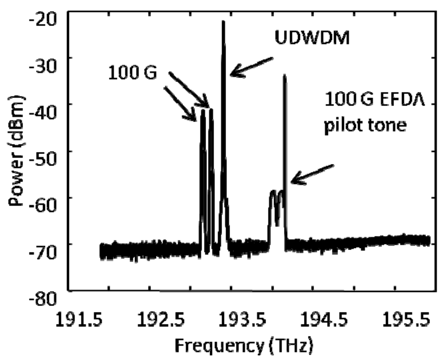


Figure 19 100 G coexistence spectrum

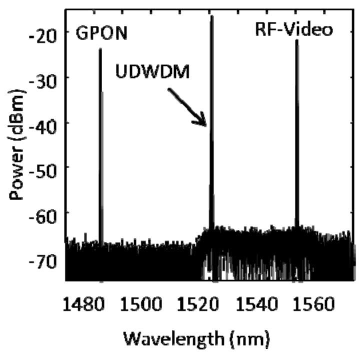


Figure 18 GPON and RF Video coexistence

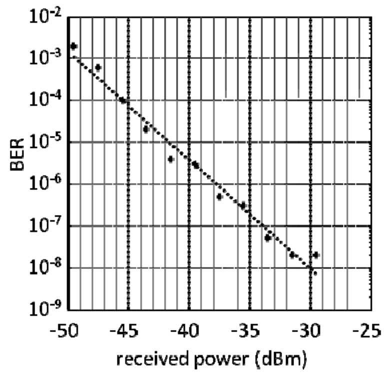


Figure 20 ONU RX BER curve

4.5 Coherent UDWDM PON Summary

A prototype of a coherent UDWDM PON system was tested for the first time over field deployed fibre in two different testbeds of Deutsche Telekom in Germany. The receiver sensitivity back-to-back and over fibre was identical. A Silicon Photonics CMOS laser was used in parts of the experiments and no performance degradations in comparison with a best in class InP tuneable laser could be observed.

The suitability of a coherent UDWDM system for LTE backhauling has been proven. Any potential increase of jitter or delay was below the resolution of the LTE measurement equipment; therefore, no additional delay or jitter could be measured.

Coexistence with legacy systems such as GPON, RF-Video, 100 G and OTDR measurement equipment has been demonstrated. Neither was the UDWDM transmission influenced by any legacy system nor did UDWDM influence any of the legacy systems when the UDWDM wavelengths were outside the respective legacy filter bands. Tuneable lasers and the potential to use a filter less architecture provides full spectral flexibility.

The demonstrated system operates in the C-Band, which is compliant with the expanded spectrum case of the emerging G.989 standard [6]. This technology can also operate in the L band in order to coexist with TWDM in the shared spectrum case. Coherent UDWDM therefore supports the NG-PON2 point-to-point overlay requirements for pure power-splitter based optical distribution networks.

5 Update on 40Gb/s upgrade

In Deliverable D4.1, we have proposed an electrical 3-level duobinary modulation scheme with bit-interleaving PON (BiPON) protocol to upgrade to a single carrier 40Gbit/s downstream for LR-PONs. The 3-level duobinary relaxes the component bandwidth requirement at ONU and shows better tolerance for chromatic dispersion. The BiPON protocol would further reduce the power consumption and enable cost-effective implementation of advanced FEC codes because the FEC decoder only needs to operate at the user rate. The required optical signal to noise ratio (OSNR) and optical power budget were investigated and summarised in D4.1 based on analytic calculation of OSNR requirements and analysis of the “Lollipop” LR-PON optical link model. In this section, we will re-visit the 40Gbit/s downstream scheme for the proposed distributed amplifier node rural solution described in section 3.

5.1 Case 1: 40Gbit/s downstream using 3-level duobinary modulation and APD-Rx

Figure 21shows the 40Gbit/s downstream path with 3-level duobinary modulation applied to rural areas, it shows the 40Gbit/s downstream topology with the 3-level duobinary modulation scheme applied to the distributed amplifier scheme for sparse

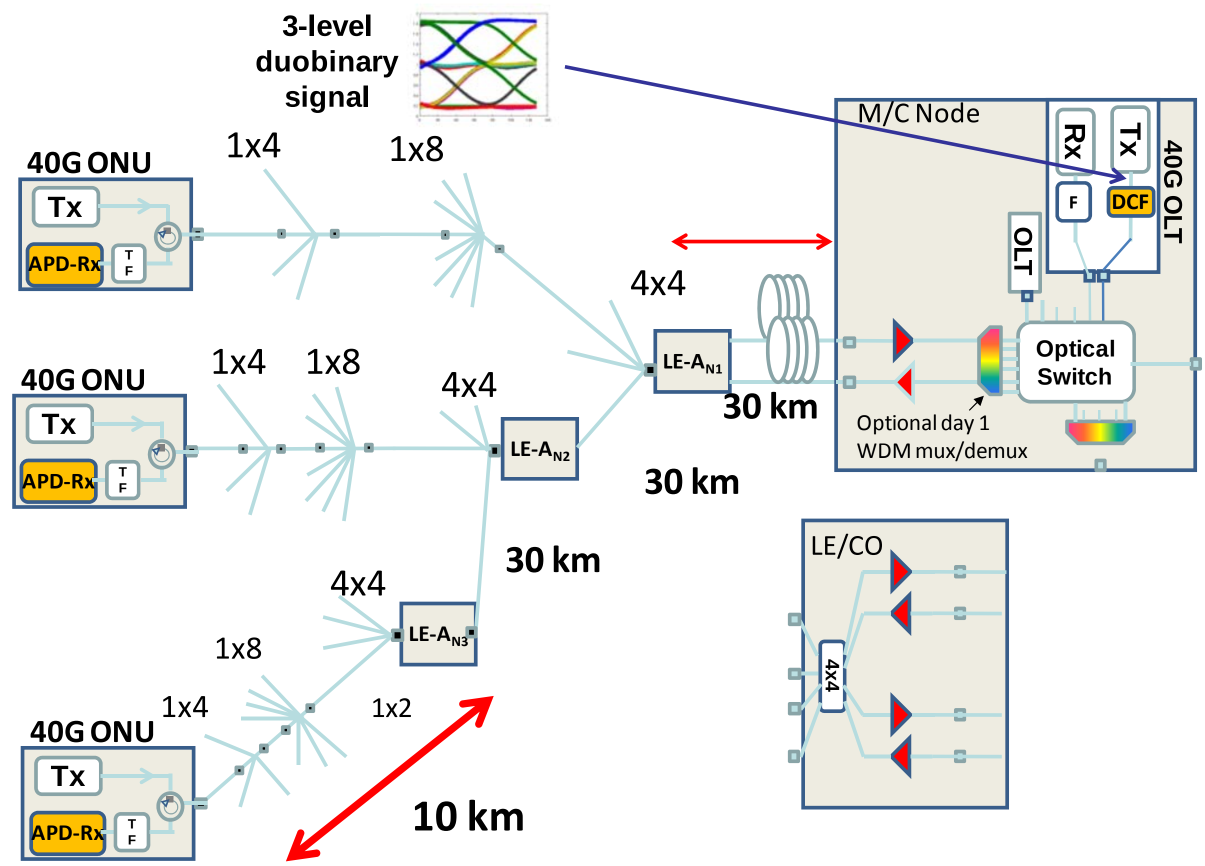


Figure 21 40Gbit/s downstream path with 3-level duobinary modulation in rural areas.

rural areas as described in D2.1. The proposed rural solution employs distributed amplifiers, namely, LE-A$_{N1}$, LE-A$_{N2}$, and LE-A$_{N3}$, in this configuration. With the additional

EDFAs and similar last drop distance (<10km), one should expect that the OSNR and power budget will be improved. The losses of various components used in the modelling have been summarised in Table 3.

Given the optical power requirement of 40Gbit/s downstream, we assume high power metro/core (MC) node EDFA and distributed local exchange (LE) downstream EDFAs with +17dBm output power. All EDFAs have a noise figure of 5.5dB.

Table 3 Set of assumptions used for 40Gbit/s downstream power and OSNR modelling

	Min. Loss (dB)	Max. Loss (dB)	Noise Figure (dB)
DCF	5	5	0
Circulator	0.2	0.6	0
Connector	0	0.5	0
Fibre (per km)	0.2	0.3	0
Splice	0	0.3	0
1:2 Splitter	2.6	3.8	0
1:4 Splitter	5.4	7.1	0
1:8 Splitter	7.95	10.5	0
Mux/DeMUX	4	6	0
Optical Switch	1.8	2	0
Tuneable Filter	4	4	0
EDFA (N1, N2, N3)			5.5

Table 4 40Gbit/s downstream power and OSNR modelling with ONU APD-Rx for rural solution and totally 320-way split

Components	Singal Power (Max) [dBm]	Noise Power (Max) [dBm]	OSNR (Max) [dB]	Singal Power (Min) [dBm]	Noise Power (Min) [dBm]	OSNR (Min) [dB]
40G Tx	5	-35	40	5	-35	40
DCF/TDC	-1.0000	-41.0000	40.0000	-1.0000	-41.0000	40.0000
Connector	-1.5000	-41.5000	40.0000	-1.5000	-41.5000	40.0000
Optical Switch	-3.5000	-43.5000	40.0000	-3.5000	-43.5000	40.0000
Mux/Demux	-9.5000	-49.5000	40.0000	-9.5000	-49.5000	40.0000
EDFA	**17.0000**	-21.2201	38.2201	17.0000	-21.2201	38.2201
Connector	16.5000	-21.7201	38.2201	16.5000	-21.7201	38.2201
Fibre (30km)	7.5000	-30.7201	38.2201	7.5000	-30.7201	38.2201
Connector	7.0000	-31.2201	38.2201	7.0000	-31.2201	38.2201
EDFA	**17.0000**	-21.1875	38.1875	17.0000	-21.1875	38.1875
splice	16.7000	-21.4875	38.1875	16.7000	-21.4875	38.1875
splitter1to4	9.6000	-28.5875	38.1875	9.6000	-28.5875	38.1875
Connector	9.1000	-29.0875	38.1875	9.1000	-29.0875	38.1875
Fibre (30km)	0.1000	-38.0875	38.1875	0.1000	-38.0875	38.1875
Connector	-0.4000	-38.5875	38.1875	-0.4000	-38.5875	38.1875
EDFA	**17.0000**	-21.0127	38.0127	17.0000	-21.0127	38.0127
splice	16.7000	-21.3127	38.0127	16.7000	-21.3127	38.0127
splitter1to4	9.6000	-28.4127	38.0127	9.6000	-28.4127	38.0127
Connector	9.1000	-28.9127	38.0127	9.1000	-28.9127	38.0127
Fibre (30km)	0.1000	-37.9127	38.0127	0.1000	-37.9127	38.0127
Connector	-0.4000	-38.4127	38.0127	-0.4000	-38.4127	38.0127
EDFA	**17.0000**	-20.8447	37.8447	17.0000	-20.8447	37.8447
splice	17.0000	-20.8447	37.8447	16.7000	-21.1447	37.8447
splitter1to4	11.6000	-26.2447	37.8447	9.6000	-28.2447	37.8447
Connector	11.6000	-26.2447	37.8447	9.1000	-28.7447	37.8447
splice	11.6000	-26.2447	37.8447	8.8000	-29.0447	37.8447
splitter1to8	3.6500	-34.1947	37.8447	-1.7000	-39.5447	37.8447
splice	3.6500	-34.1947	37.8447	-2.0000	-39.8447	37.8447
splice	3.6500	-34.1947	37.8447	-2.3000	-40.1447	37.8447
splitter1to4	-1.7500	-39.5947	37.8447	-9.4000	-47.2447	37.8447
splice	-1.7500	-39.5947	37.8447	-9.7000	-47.5447	37.8447
Connector	-1.7500	-39.5947	37.8447	-10.2000	-48.0447	37.8447
Fibre (0/10km)	-1.7500	-39.5947	37.8447	-13.2000	-51.0447	37.8447
Circulator	-1.9500	-39.7947	37.8447	-13.8000	-51.6447	37.8447
Tunable Filter	-5.9500	-43.7947	37.8447	-17.8000	-55.6447	37.8447

For the first analysis we assume a 20-GHz APD receiver is used in a 40Gbit/s ONU and a high power optical transmitter with +9dBm output power is used at the 40Gbit/s OLT.

Table 4 shows the 40Gbit/s downstream analysis in terms of power and OSNR budget for a rural solution which achieves a 320-way total split. Given the TX output power, the derived optical gains for the downstream MC node EDFA and the distributed LE EDFAs are summarised in Table 5. As we do not have an optical pre-amplifier in the front of the downstream Rx the architecture will not be limited by the OSNR. This assumption is confirmed by the estimated OSNR (~37.8dB), which is sufficiently high for 40Gbit/s 3-level duobinary operation. Therefore, the relevant limiting parameter is the input optical power at the ONU receiver. The minimum received signal power at the APD input is -17.8dBm. The receiver needs a dynamic range of more than 11.9dB to avoid overloading.

Table 5 Required optical gains for downstream MC node EDFA and distributed LE EDFAs for ONU APD Rx

	Required Optical Gain (dB)
MC EDFA	26.5
LE EDFA N1	10
LE EDFA N2	17.4
LE EDFA N3	17.4

Since FEC is commonly employed in 10G-class PON systems to improve the optical link budget, we assumed a similar pre-FEC BER threshold of 10E-3 for the sensitivity estimation. We assume the APD receiver sensitivity for 40Gbit/s duobinary signal is -19.5dBm for BER=1E-3. Because of the bit-interleaving protocol, the downstream FEC decoder will work at much lower user rate, making more complex FEC codes feasible for use in the ONUs. Therefore, if a strong FEC, such as low-density parity-check (LDPC) codes, would be used, it would give us some extra margin due to a higher pre-FEC BER tolerance.

This leads to the optical power margin shown in Table 6, assuming ~2dB sensitivity improvement by using a strong FEC.

Table 6 Optical power margin for 40G downstream with APD receiver in rural areas

	Standard FEC (pre-FEC BER=1E-3)	Strong FEC (2dB improvement)
320 split	1.7	3.7
640 split	Negative margin	0.3

5.2 Case 2: 40Gbit/s rural downstream using pre-amplifier SOA in ONU

In order to further improve the optical budget and exploit the good OSNR results from the previous analysis, a semiconductor optical amplifier (SOA)-preamplifier with a PIN ONU receiver can be employed, as shown in Figure 22. The compact size and ability for integration of the SOA makes it a suitable candidate for the use as an optical preamplifier in ONUs. SOAs usually have higher inherent noise figures than EDFAs and in the following power and OSNR analysis, an SOA with a noise figure of 7.5dB and maximum power gain of 12dB is assumed. As the gain of the SOA can be controlled by changing the bias current, the maximum gain assumption is applied here to lower the power consumption of ONUs. In the analysis, the real power gain of the SOA is derived on condition that the PIN-Rx is not overloaded (i.e., +3dBm maximum power at the input of the PIN-Rx). Other loss and noise figure assumptions are the same as those shown in Table 3.

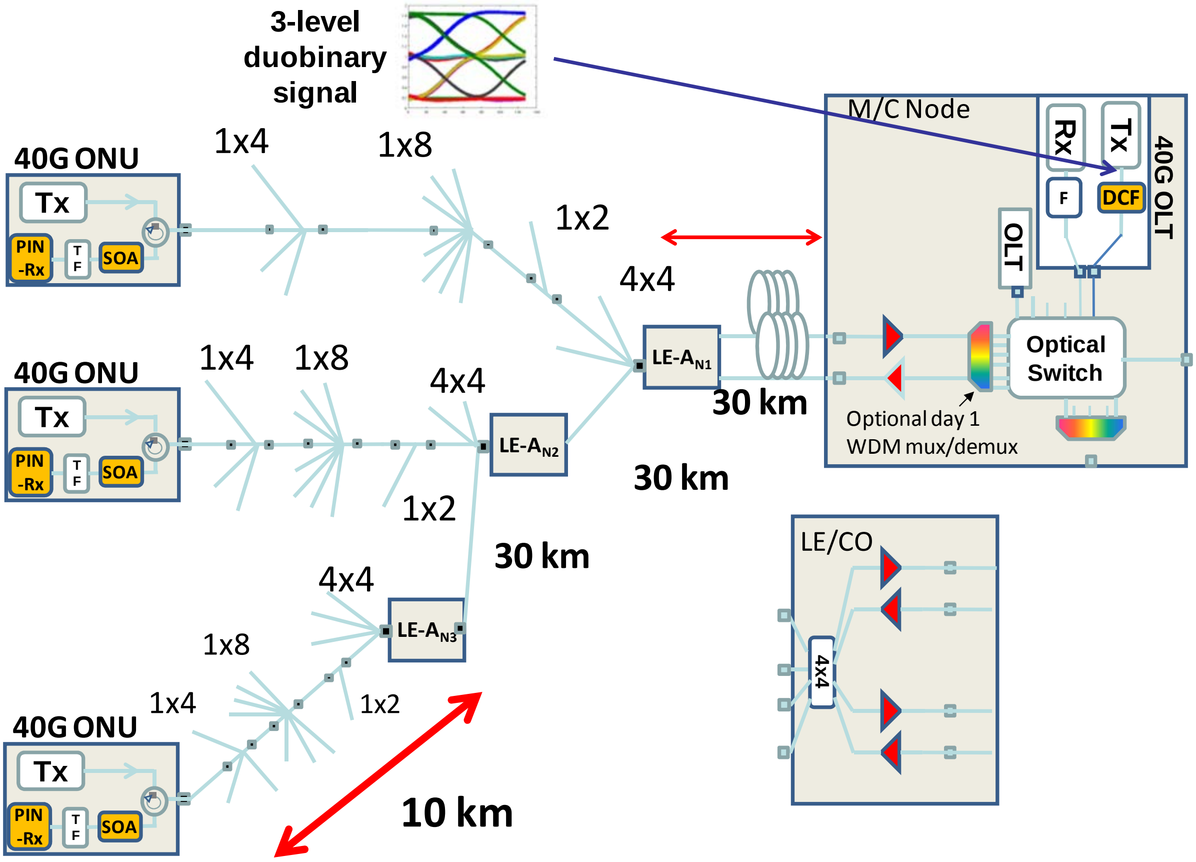


Figure 22 40Gbit/s downstream path with SOA-PIN Rx in rural areas.

Table 8 shows the 40Gbit/s downstream analysis using a combination of an SOA and a PIN-Rx for a rural solution with a total 640-way split. Given the TX output power of +9dBm, the derived optical gains for the downstream MC node EDFA, the distributed LE DEFAs and the ONU SOA is summarised in Table 7. The power and OSNR results suggest that the downstream is still not limited by the OSNR (minimum 31.4dB) and the limitation comes from the receiver input optical power. In this case, the minimum received signal power at PIN-Rx input is -10.4dBm. The receiver needs a dynamic range of more than 13.4dB to avoid Rx overload.

Table 7 Required optical gains for downstream MC node EDFA and distributed LE EDFAs for ONU SOA-PIN Rx

	Required Optical Gain (dB)
MC EDFA	26.5
LE EDFA N1	10
LE EDFA N2	17.4
LE EDFA N3	17.4
ONU SOA	11.5

Table 8 40G downstream power and OSNR modelling with ONU SOA-PIN Rx for rural solution and totally 640-way split

Components	Singal Power (Max) [dBm]	Noise Power (Max) [dBm]	OSNR (Max) [dB]	Singal Power (Min) [dBm]	Noise Power (Min) [dBm]	OSNR (Min) [dB]
40G Tx	5	-35	40	5	-35	40
DCF/TDC	-1.0000	-41.0000	40.0000	-1.0000	-41.0000	40.0000
Connector	-1.5000	-41.5000	40.0000	-1.5000	-41.5000	40.0000
Optical Switch	-3.5000	-43.5000	40.0000	-3.5000	-43.5000	40.0000
Mux/Demux	-9.5000	-49.5000	40.0000	-9.5000	-49.5000	40.0000
EDFA	**17.0000**	-21.2201	38.2201	17.0000	-21.2201	38.2201
Connector	16.5000	-21.7201	38.2201	16.5000	-21.7201	38.2201
Fibre (30km)	7.5000	-30.7201	38.2201	7.5000	-30.7201	38.2201
Connector	7.0000	-31.2201	38.2201	7.0000	-31.2201	38.2201
EDFA	**17.0000**	-21.1875	38.1875	17.0000	-21.1875	38.1875
splice	16.7000	-21.4875	38.1875	16.7000	-21.4875	38.1875
splitter1to4	9.6000	-28.5875	38.1875	9.6000	-28.5875	38.1875
Connector	9.1000	-29.0875	38.1875	9.1000	-29.0875	38.1875
Fibre (30km)	0.1000	-38.0875	38.1875	0.1000	-38.0875	38.1875
Connector	-0.4000	-38.5875	38.1875	-0.4000	-38.5875	38.1875
EDFA	**17.0000**	-21.0127	38.0127	17.0000	-21.0127	38.0127
splice	16.7000	-21.3127	38.0127	16.7000	-21.3127	38.0127
splitter1to4	9.6000	-28.4127	38.0127	9.6000	-28.4127	38.0127
Connector	9.1000	-28.9127	38.0127	9.1000	-28.9127	38.0127
Fibre (30km)	0.1000	-37.9127	38.0127	0.1000	-37.9127	38.0127
Connector	-0.4000	-38.4127	38.0127	-0.4000	-38.4127	38.0127
EDFA	**17.0000**	-20.8447	37.8447	17.0000	-20.8447	37.8447
splice	17.0000	-20.8447	37.8447	16.7000	-21.1447	37.8447
splitter1to2	14.4000	-23.4447	37.8447	12.9000	-24.9447	37.8447
splice	14.4000	-23.4447	37.8447	12.6000	-25.2447	37.8447
splitter1to4	9.0000	-28.8447	37.8447	5.5000	-32.3447	37.8447
Connector	9.0000	-28.8447	37.8447	5.0000	-32.8447	37.8447
splice	9.0000	-28.8447	37.8447	4.7000	-33.1447	37.8447
splitter1to8	1.0500	-36.7947	37.8447	-5.8000	-43.6447	37.8447
splice	1.0500	-36.7947	37.8447	-6.1000	-43.9447	37.8447
splice	1.0500	-36.7947	37.8447	-6.4000	-44.2447	37.8447
splitter1to4	-4.3500	-42.1947	37.8447	-13.5000	-51.3447	37.8447
splice	-4.3500	-42.1947	37.8447	-13.8000	-51.6447	37.8447
Connector	-4.3500	-42.1947	37.8447	-14.3000	-52.1447	37.8447
Fibre (0/10km)	-4.3500	-42.1947	37.8447	-17.3000	-55.1447	37.8447
Circulator	-4.5500	-42.3947	37.8447	-17.9000	-55.7447	37.8447
SOA	**7.0000**	-30.2138	37.2138	-6.3500	-37.7784	31.4284
Tunable Filter	3.0000	-34.2138	37.2138	-10.3500	-41.7784	31.4284

We assume the PIN receiver sensitivity for 40G duobinary signal is -12.5dBm for BER=1E-3. The resulting optical power margins are shown in Table 9, again assuming 2dB sensitivity improvement by using a strong FEC.

Table 9 Optical power margin for 40G downstream with SOA + PIN receiver in rural areas

	Standard FEC (pre-FEC BER=1E-3)	Strong FEC (2dB improvement)
320 split	3	5
640 split	2.1	4.1

5.3 Conclusion

By employing distributed optical amplifiers in the downstream path, the OSNR and power budget analysis has resulted in a better performance with an increased split ratio in rural areas this can be a useful benefit for reaching a greater number of sparsely populated rural communities from the same LR-PON system and reducing the cost per customer. The dispersion penalty simulated in deliverable D4.1 should be also subtracted to evaluate the final system margin for the proposed rural upgrade solutions. When this is included the calculation result shows that a 40-Gbit/s APD receiver using 3-level duobinary can support ~320 way total split in rural areas assuming a strong FEC. Alternatively if the SOA-PIN receiver is used in the ONU a split ratio >512 ways, having a margin of 1.1 dB with a standard FEC and 3.1 dB with a strong FEC can be achieved.

6 100G-DP-QPSK transmission over LR-PON infrastructure

Dual-polarization of quaternary phase-shift keying QPSK (DP-QPSK) at 25-GBaud symbol rate is a good candidate for the implementation of next generation high-speed transmission systems [10], [11]. It helps reduce the requirements on electrical and opto-electronic components because it requires a symbol-rate of only ¼ of the bit-rate and is now adopted for use in commercially available 100Gb/s systems. Adopting this modulation scheme for use over LR-PON means we can directly benefit from ongoing developments for long haul system.

Digital signal processing (DSP) combined with coherent detection has the potential to mitigate the impact of transmission impairments. Coherent DP-QPSK uses DSP which is able to mitigate the impact of phase noise (phase and frequency mismatch between laser transmitter and local oscillator (LO), chromatic dispersion (CD) and polarization-induced distortions, i.e. polarization mode dispersion (PMD) and polarization cross-talk (cross-talk between orthogonally polarized channels resulting from the misalignment between the states of polarization (SOP) of the LO and the detected signal using polarisation beam splitters (PBSs) in the signal and LO paths) as shown in Figure 23 [12].

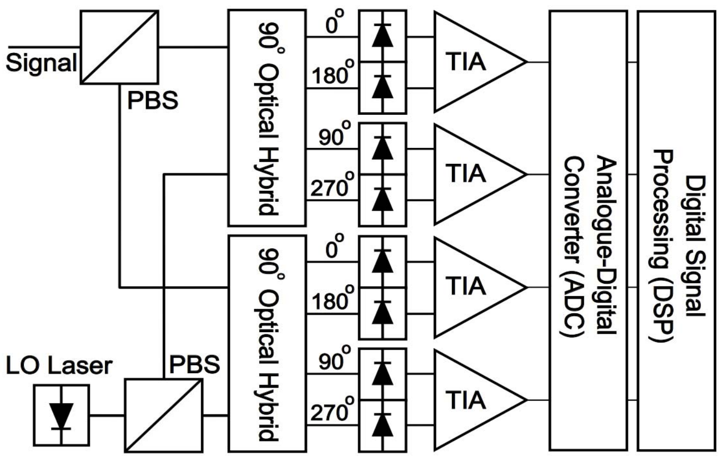


Figure 23 A phase- and polarisation-diverse digital coherent receiver using balanced trans-impedance amplifiers (TIA) for common mode rejection. The LO laser provides a continuous wave (CW) reference signal which produces an intermediate beat frequency when combined with the signal. Using this method of signal detection, all four dimensions of the optical field can be recovered.

Our simulation setup, as depicted in Figure 24, consists of a single-channel using a combination of two 50-Gb/s DP-QPSK transmitters resulting in total 100-Gb/s (25 GBaud), a transmission line and polarization-diversity receivers that include two 90° hybrids and a DSP unit (downstream PON). The noise figure of the optical amplifier (Erbium-doped fibre amplifier (EDFA) was set at 5.5 dB. Positive-intrinsic-negative (PIN) photodiodes have been used for the coherent homodyne receiver and the source laser and LO line widths have been set to 1 MHz. For this simulation we have also assumed an ideal polarization multiplexer (MUX) in the transmitter with zero insertion loss (effectively any losses are compensated by the laser output power).

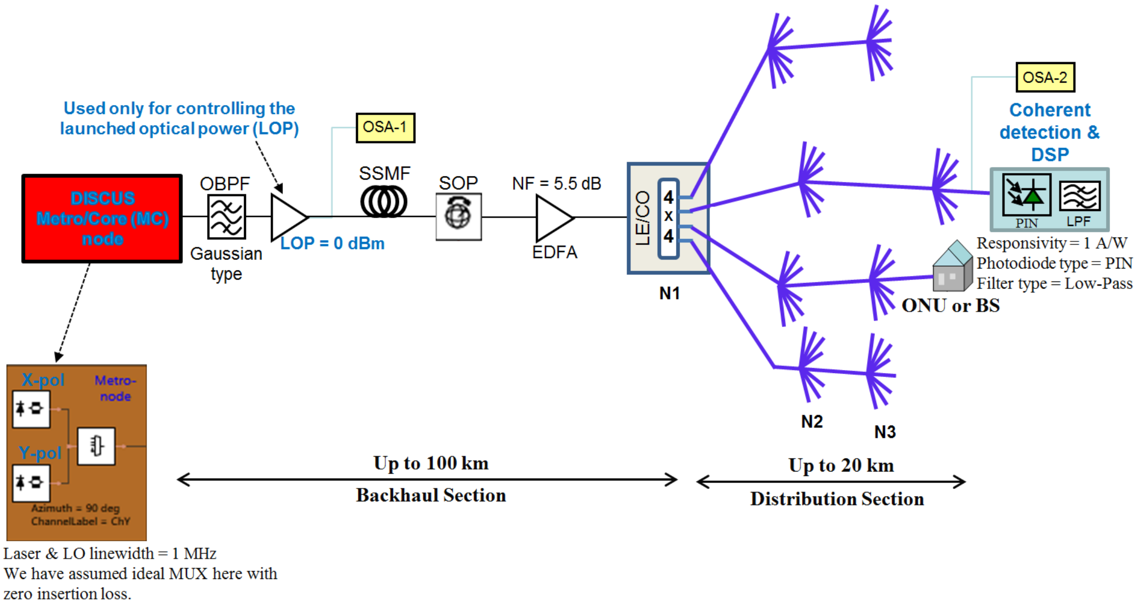


Figure 24 Transmission-link diagram of 100G-DP-QPSK with 25 GBaud symbol rate for the configuration of Section 2.1

The transmission line is composed of a standard single-mode fibre (SSMF) and a polarization tracker (to control the alignment between the signal SOP and the polarization beam splitter at the receiver). Residual CD is compensated using a finite impulse response (FIR) filter with a variable number of taps, up to 60 depending on the optical distribution network (ODN) and transmission losses (see Figure 31). Polarization effects (PMD and Pol-X-talk) are mitigated using a multiple-input multiple-output (MIMO) structure consisting of up to 8 tap FIR filters which are similarly dependent on the network losses (see Figure 32). The coefficients of the MIMO structure are optimized using the constant-modulus algorithm (CMA) [13]. The phase noise is corrected using a multi-symbol phase estimation (MSPE) technique based on the Viterbi & Viterbi algorithm [13].

An example of the DP-QPSK modular approach to digital compensation of channel impairments in the LR-PON system we are simulating and the subsequent carrier and data recovery is depicted in Figure 25:

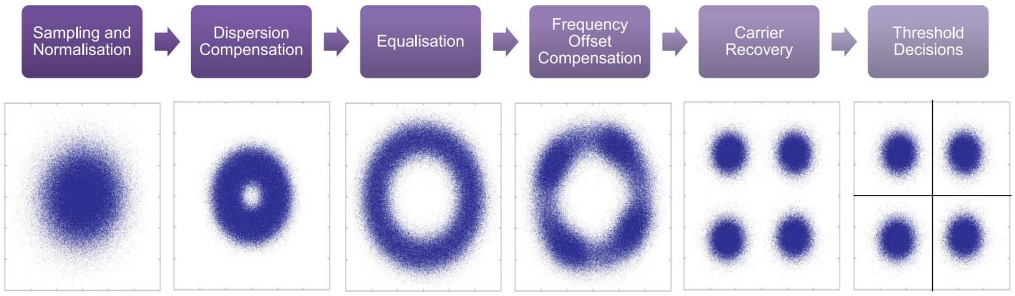
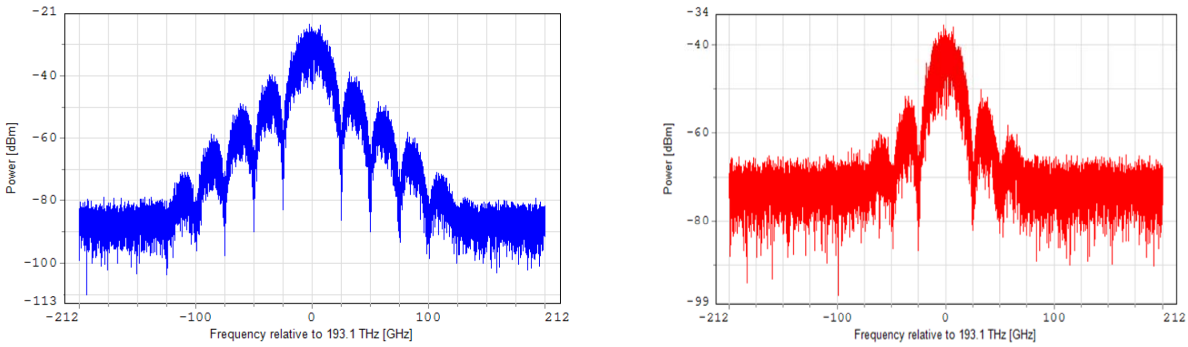


Figure 25 Example of a DP-QPSK modular approach to digital compensation of channel impairments and subsequent carrier and data recovery (x-polarization shown here).

In Figure 26, the optical spectrums from (a) OSA-1 transmitted, and (b) OSA-2 received, of the 100G-DP-QPSK downstream PON are shown:



(a) OSA-1 at transmitter (b) OSA-2 at receiver before the ONU

Figure 26 Optical spectrums from (a) OSA-1 transmitted, (b) OSA-2 received, of 100G-DP-QPSK for PON design of Figure 6 (x-polarization shown)

In Figure 27, the maximum achievable transmission distances for upstream and downstream PON directions against the ODN losses is plotted for the 100G-DP-QPSK modulation at a targeted average (x- and y- polarization) BER_{av} of 10^{-3}. It is shown that

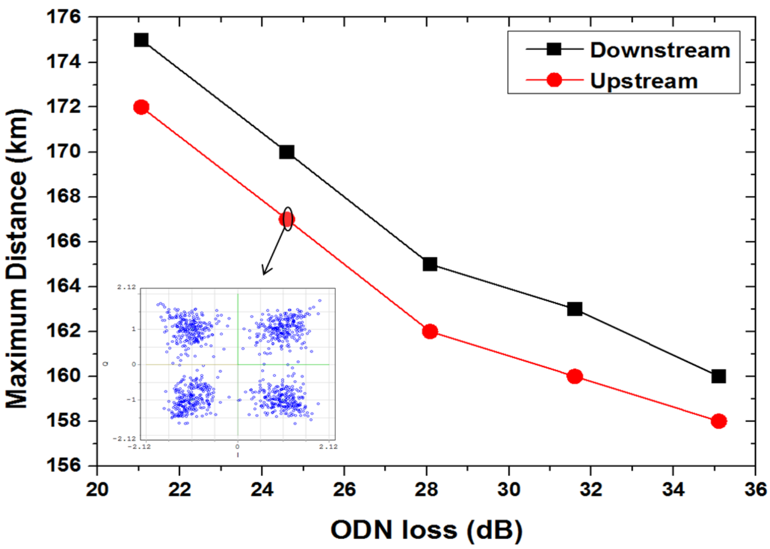


Figure 27 Maximum achievable transmission distances for upstream and downstream directions vs. ODN losses of 100G-DP-QPSK at a targeted average BERav of 10-3. The LOP for both directions is assumed identical and equal to 0 dBm. Inset: Received constellation diagram for x-polarization at 167 km of transmission with a BER of 10^{-3}

the upstream PON performance is very close to the downstream PON when considering identical launched optical power (LOP) of 0 dBm for both directions, This result shows that 100GB/s could be supported over for 1024 split LR-PONs with distances up to 125km the maximum distance supported by the design of the DISCUS LR-PON protocol.

In Fig. 10, the transmission-link diagram of a distributed amplifier LR-PON for rural applications with up to 1:1024 total splitting ratio is depicted.

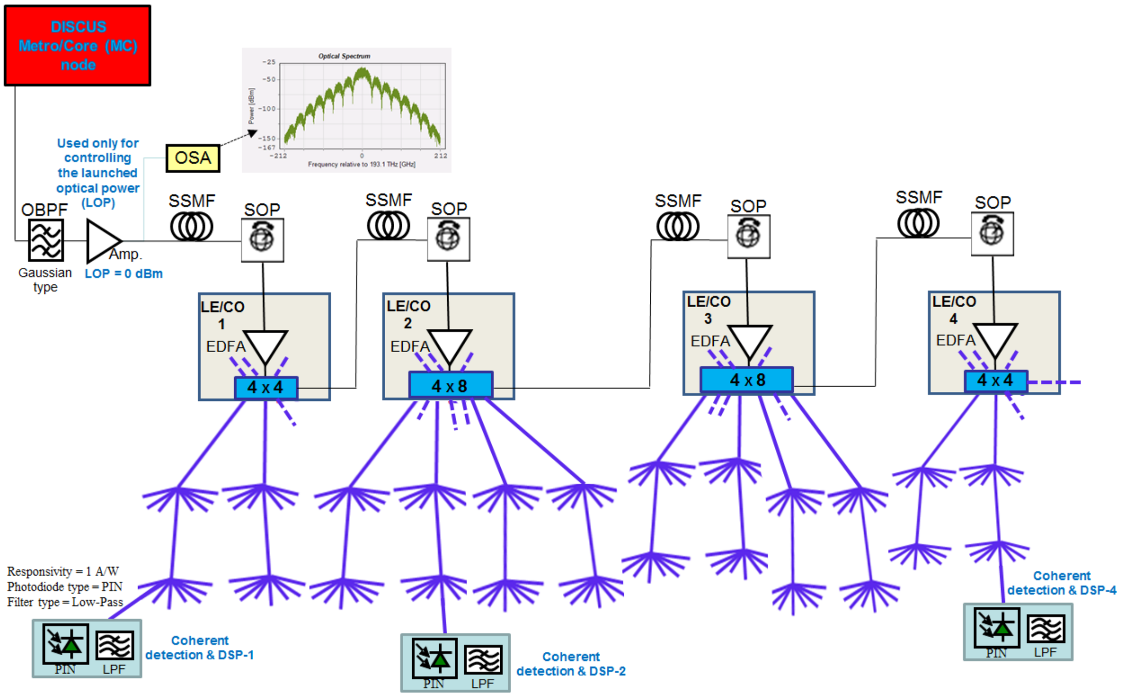


Figure 28 Transmission-link diagram of a “lollipop” rural downstream LR-PON system for up to 1:1024 splitting ratio

The results shown in Figure 29, are the corresponding received constellation diagrams for the receivers 1, 2, and 4 in the diagram with the longest distance over 110 km at receiver 4 (total transmission distance ~25 km × 4 + 10km for the ODN). These results give an acceptable transmission performance of BER < 10^{-3} before the LR-PON receiver DSP.

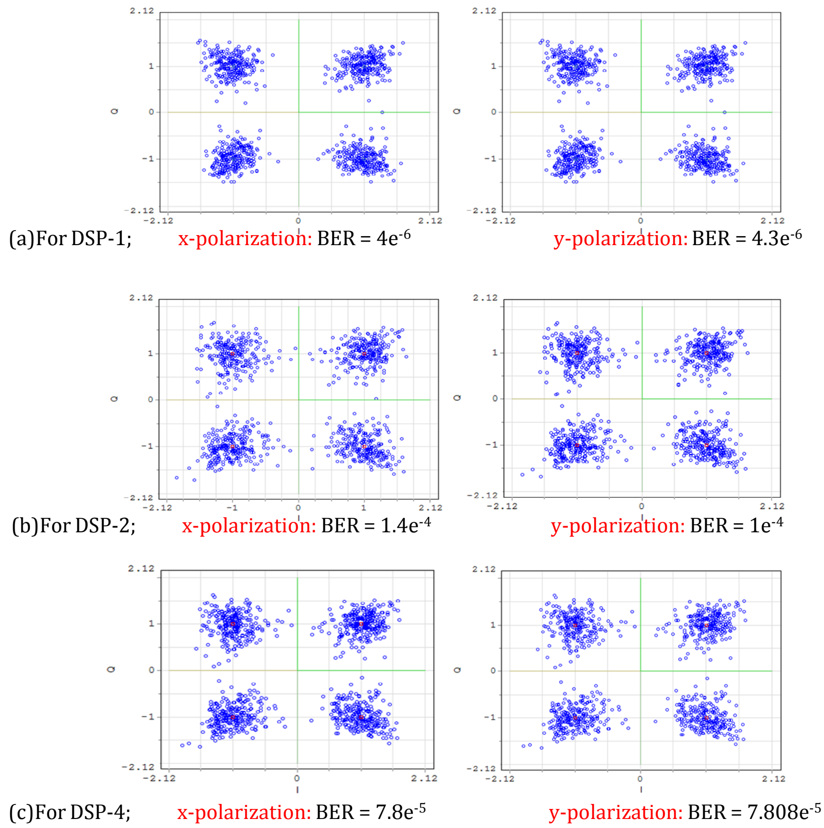


Figure 29 (a)-(f) Received 100G DP-QPSK constellation diagrams for PON DSP receivers (1), (2), and (4) at total maximum transmission distance of 100 km (25 km × 4)

The results shown in this section are for a fibre loss of 0.2db/km at 1500nm. This can be optimistic for the installed fibre base where cable and splice losses could increase this figure to closer to 0.3db/km. In Figure 30 the effects of increasing fibre loss on achievable LR-PON reach is shown keeping all other parameters constant. They show a

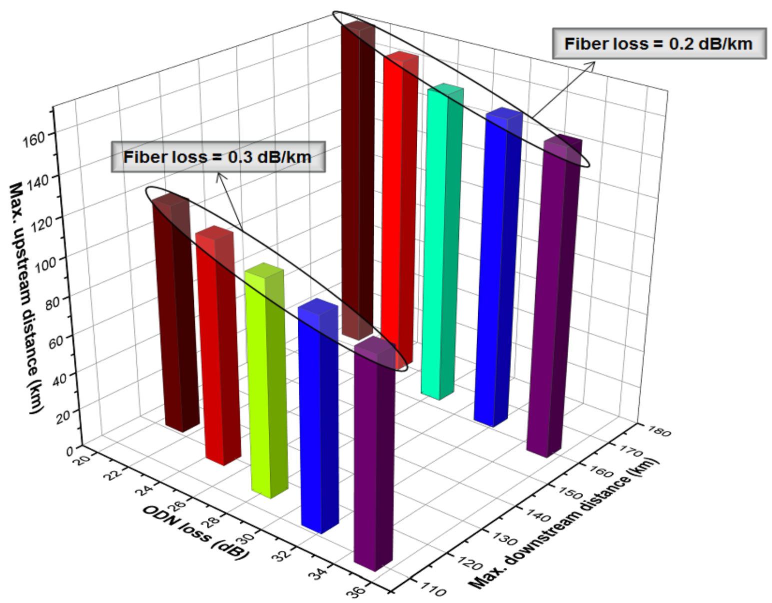


Figure 30 comparison of the effect of increasing fibre loss

reduction in maximum achievable transmission distances for upstream and downstream directions vs. ODN losses of 100G-DP-QPSK at a targeted average BERav of 10-3. The LOP for both directions is assumed identical and equal to 0 dBm.

The performance of DP-OPSK coherent systems depends heavily on the level on the digital signal processing employed mainly in the complexity (i.e. number of taps) of the FIR filters. By increasing the number of taps used, increased performance can be achieved but at the expense of greater DSP processing and power consumption. In Figure 31, the number of FIR filter taps required for CD compensation is plotted versus the maximum achievable transmission distance when considering a fixed average (x- & y- pol) BER_{av} of 10^{-3} for different amount of ODN losses (colour bars) and number of users. The LOP is also fixed at 0 dBm. It is shown that for higher ODN losses and therefore number of users, the maximum achievable transmission PON distance is reduced (down to <160 km for 1024 users), whilst the required number of FIR taps increases up to 60.

Also shown in figure 13 is a comparison of the number of taps for MIMO and CD compensation for the 100G DP-QPSK downstream PON system (corresponding to the LR-PON design in Figure 24). The LOP is also fixed here at 0 dBm. It is shown from Fig. 13 that in comparison to the MIMO taps used for mitigating polarisation impairment effects(maximum number is 9 at ~35 dB of ODN loss), the requirement for CD taps is much higher as the ODN loss is increased (up to a number of 60 at ~35 dB of ODN loss – corresponding to a split of 1024 ways).

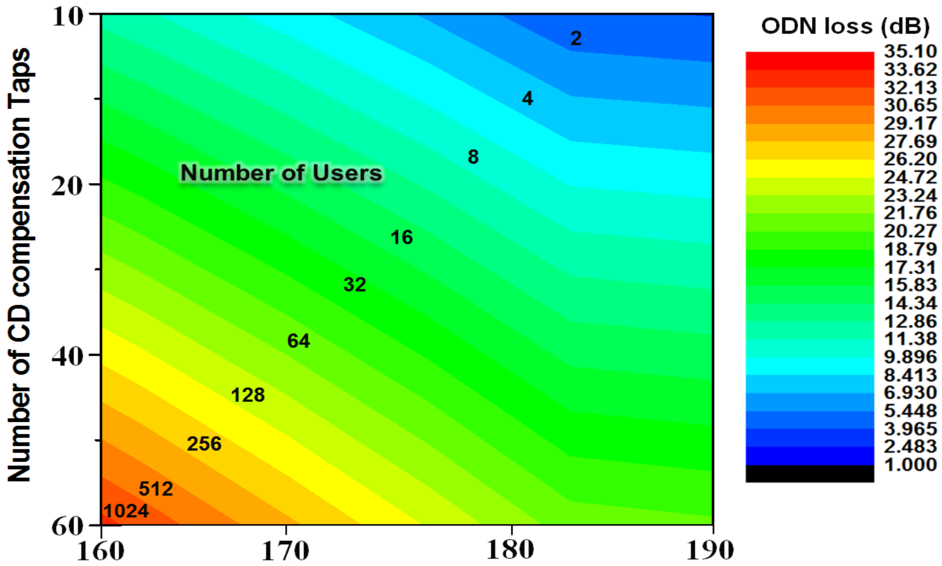


Figure 31 Contour plot of optimum number of FIR filters for CD compensation vs. maximum achievable transmission distance when considering a fixed average (x- & y- pol) BERav of 10-3 for different amount of ODN losses (colour bars) and number of users. The LOP is fixed at 0dBm.

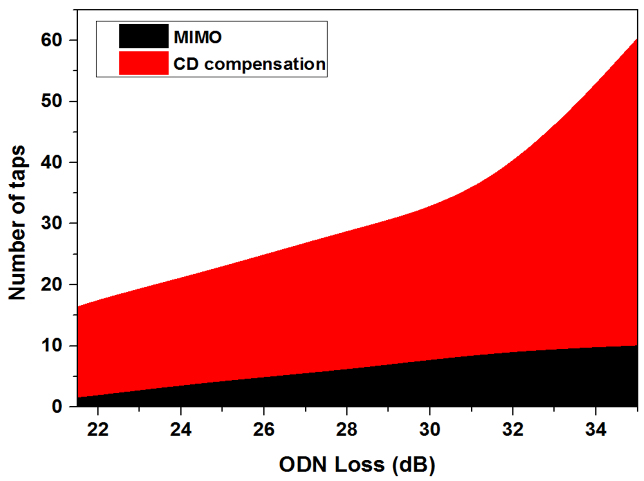


Figure 32 Plot of optimum number of required MIMO and CD compensation FIR taps for a targeted BERav of 10-3 at fixed 125 km of transmission for different amount of ODN losses

7 Metro-node design

In order to derive the functions required at the DISCUS metro-core node (MC), we first identified basic network services, covering the applications that are expected to be carried out through both long-reach passive optical network (LR-PON) and the flat optical core within the DISCUS architecture. Our considered overall DISCUS MC node architecture described in D6.1 contains the functions for different layers supporting the specified DISCUS network services, such as optical switching, optical transport, optical line terminal towards LR-PON dealing with time and wavelength division multiplexing, Layer2/3 switching as well as the corresponding control plane interfaces. Furthermore, we elaborated the structure for flex-grid reconfigurable optical add/drop multiplexer

ROADM (see details in D7.1), offering contentionless, connectionless and/or directionless features, along with control plane, which will be fully reported in D6.3.

DISCUS supported network services: The DISCUS infrastructure is envisaged to serve two different types of customers, the service "consumers" (the end users) and the service providers, which take leverage of the high performance and flexible DISCUS infrastructure to reach their customer base. Taking that into account, network services are divided into two main categories (the detailed description and QoS requirement can be found in Deliverable D6.1):

- End user-oriented network services:
  - Residential (triple play)
  - Business and Cloud Computing
  - Mobile backhauling (2G, 3G, 4G and beyond)
- Core-oriented network services:
  - Photonic layer (associated to the classes of homogenous clients that share the same transport requirements)
  - Packet transport layer (The MPLS/MPLS-TP transport switch is required to provide packet based transport services on the core network)

DISCUS metro-core node architecture: In Figure 33 we show an abstract view of functions as well as the associated interfaces to the control plane that should be included in the metro-core node architecture in order to accommodate the DISCUS supported network services. The mandatory functions in L1, L2 and L3 cover the optical switching, optical transport, optical line terminal (OLT) dealing with time and wavelength division multiplexing towards LR-PON and the Layer2/3 MPLS/MPLS-TP based switching.

It should be noted that the optical space switch used in DISCUS Metro-core node offers a transparent optical layer that can provide fibre connection paths between both access and core segments as well as the electronic layers (e.g. L2/L3 switches) and can flexibly interconnect all those segments. Both two-sided and single-sided optical switch structures based on beam steering technology are being considered to realize this optical transparent layer. The two-sided switch has less flexibility than the single side switch, but can have a maximum size, when configured as a three stage Clos switch, for a given maximum matrix size, that is twice that of the single-side switch. Beam steering switch matrices are limited in size by the number of resolvable ports that can be scanned by the beam steering technology while still producing the required performance. As the technology develops, and demand requires it, the matrix size can be increased. The current matrix size of the Polatis beam steering switch is 192 ports irrespective of whether it is a single sided configuration or a two sided configuration. There is no fundamental cost difference between the two approaches as the number of beam steering elements in the matrix scales directly with the switch size. The decision between the two approaches is therefore one of maximum required switch size versus the greater operational flexibility of the single sided switch.

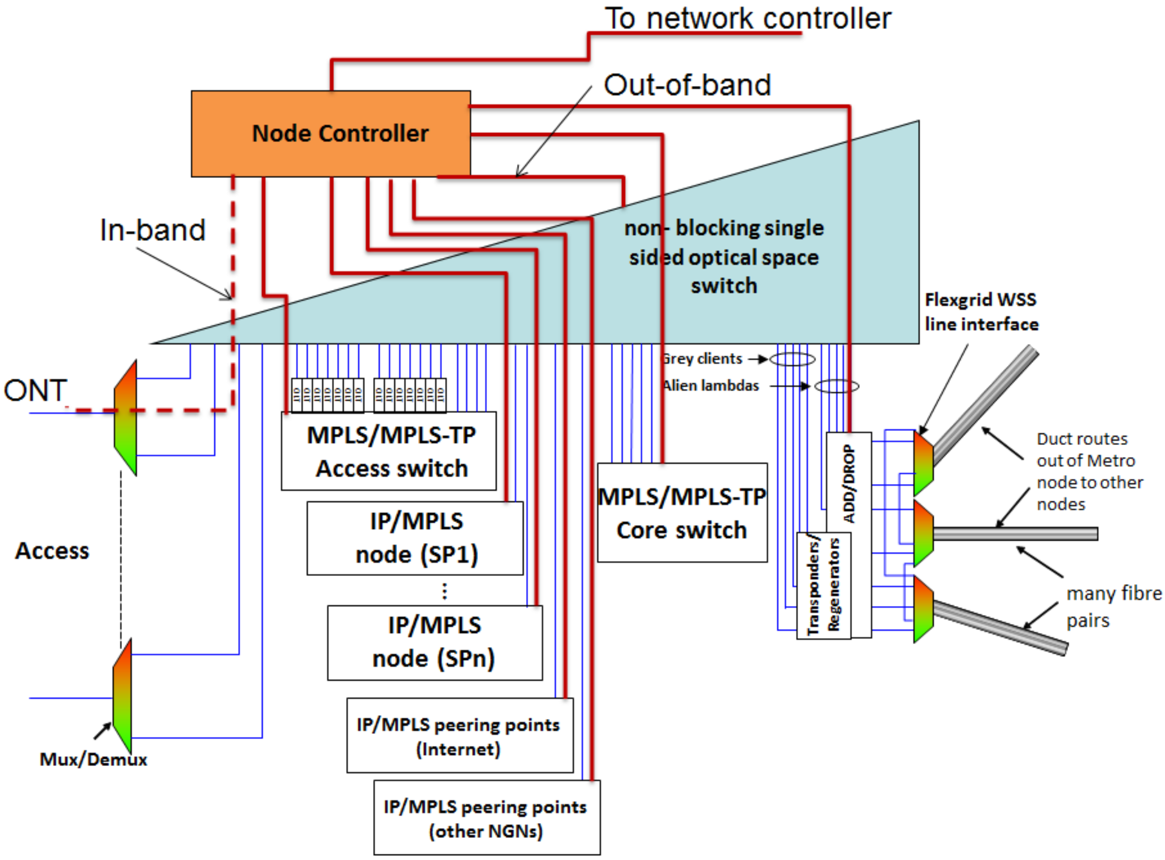


Figure 33 Abstract view of overall DISCUS Metro-core node architecture

The preliminary MC node dimensioning model covers the two-sided optical switch and is being extended to accommodate the other switch configurations. According to the results based on UK scenario, by using the current beam steering technology largest two-sided switch matrix size (i.e. 192x192 optical ports) with customers having a sustained bandwidth up to 50Mb/s per ONU (burst speed or PIR can in principle be 10Gb/s if the access and ONU port technology can support it) then a MC node coverage of 300,000 premises can be served for fully flexible wavelength assignment to the LR-PON networks. To go beyond this bandwidth per user and/or greater node coverage, larger switch matrices are required. This is completely possible with the beam steering technology but requires further development with matrix size up to possibly 500x500, which could proportionally increase MC sizes to greater than 1.5 million ONUs with customer sustained rates of 100Mb/s.

In addition the background bases have been presented for the different architectural aspects with respect to resiliency, QoS, open access, optical power budget, energy efficiency, and cost. Some preliminary performance assessment has been carried out, based on which several challenges and issues (in particular in resiliency and open access) have been identified and need to be further investigated over the remainder of the project to improve the DISCUS Metro-core node design.

Flex-grid ROADM: Both fixed-grid and flex-gird transmission technologies are expected and required to co-exist in the DISCUS core network for many year to come and therefore the DISCUS MC node must be able to support both technologies. This requirement is also considered in our proposed ROADM architecture (described in D7.1). In general, ROADM functions can be divided into WSS Line Interfaces and Add/Drop (A/D) functions (see Figure 34). To support flex-gird, it is important that the WSSs used in ROADM should have flex-gird feature. Each line interface encompasses two flex-grid WSSs. This architecture is mandatory when high port count WSS components (e.g., 1x20) are used because of the prohibitive insertion loss of the alternative architecture, the so called broadcast-and-select, where a passive power splitter and a WSS are used instead of a couple of WSSs. Line interfaces also include two Erbium Doped Fibre Amplifiers (EDFAs) used as booster amplifier and pre-amplifier for the line optical signal. Finally, Optical Performance Monitoring (OPM) functions are included to provide real-time measurement of the line signal optical spectrum. Three kinds of add/drop multiplexer can be used in DISCUS MC node, namely colourless only, colourless and directionless, and colourless directionless and contentionless. Obviously, the third type, i.e., colourless directionless and contentionless has the best, most flexible

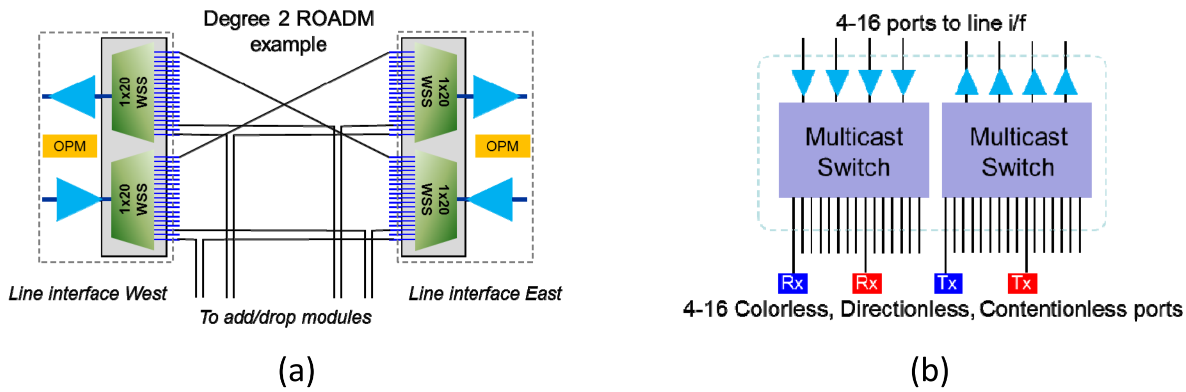


Figure 34 ROADM architecture (a) WSS line interfaces (an example with degree 2) and (b) Add/Drop (an example with colourless directionless and contentionless features)

features, but is realized at the expense of more complicated devices and structure. These will be compared in more detail as will flex-grid and fixed grid in the cost modelling work to be reported in later deliverables.

Control plane: Work on the control plane has progressed to define the general architecture and the interfaces among the control plane components, the SPs and the network elements. The architecture was developed in agreement with concepts defined by the Open Networking Foundation (ONF) Software Defined Network (SDN) Architecture document [14]. The DISCUS control plane architecture is based on a two-their hierarchical structure, presented in deliverable D6.3. The SP, applications, Network Management System (NMS), and Operation support System (OSS) can make path requests to the northbound interface (or Application-Controller Plane Interface – A-CPI in ONF terminology) of the network orchestrator. The orchestrator coordinates the actions of the lower tier control system, composed of the access network controllers (controlling the access elements of each MC node) and the core network controller (controlling the core transmission network as well as the core elements of the MC nodes). Thus a request from an SP is broken down by the orchestrator into sub-path requests and forwarded to the appropriate access and core controllers, through an

Intermediate Controller Plane Interface (I-CPI). The access and core controller then communicate with the network element using appropriate southbound interfaces (or Data Controller Plane Interface - D-CPI in ONF terminology). The D-CPI to the access elements is mainly based on OpenFlow, while the interfaces to the core elements on GMPLS. The DISCUS control plane architecture is described in detail in Deliverable D6.3. The deliverable also describes the main target scenarios for the DISCUS architecture and the interfaces between SP, control plane and network elements.

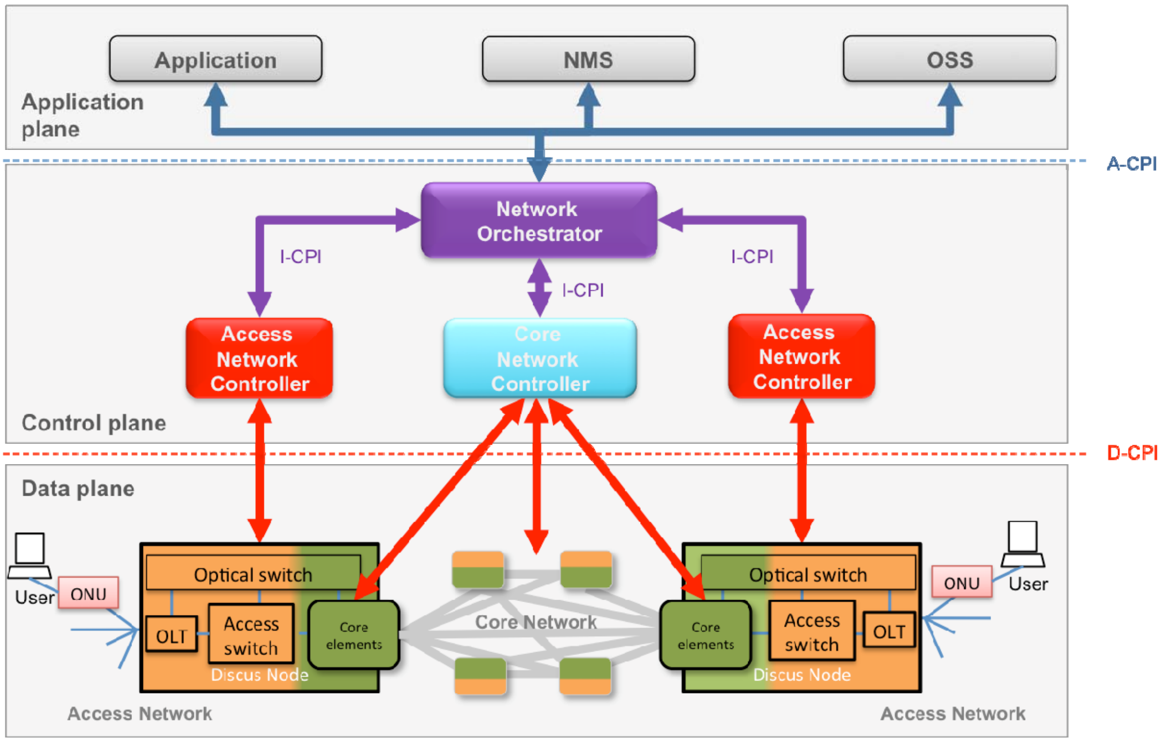


Figure 35 DISCUS two-tiered control plane architectural design

8 Update of core network design

In this section the architectural vision of the DISCUS core network is updated based on the performance of the transmission technology of choice (32 Gbaud Nyquist DWDM) and the reach requirements of the largest European national backbones.

After a short review of the well-known approaches to the design of photonic backbones, the new concept of transparent network with sparse Raman amplified links is presented as a viable solution for the DISCUS core network.

8.1 Translucent networks

In core networks, based on ultra-long-haul optical transmission systems and flexgrid ROADM, the concept of optical transparency reach is fundamental. The *optical transparency reach* is the distance an optical signal can travel before the signal quality degrades to a level that the information transported by the optical signal cannot be correctly revealed [15]. Optical noise, chromatic dispersion, nonlinear effects, polarization mode dispersion and cross-talk are the main causes of the degradation of the quality of an optical signal propagating through the fibers in photonic backbones as described in D7.2 [27].

When the lightpaths' maximum length exceeds the optical transmission reach, a 3R regenerator is necessary to reshape, re-time and re-amplify the signal [16]. Optical networks where regenerators are present are called *translucent networks*.

In more details, in an Operator's core network it is important to consider that:

- the optical reach of a given transmission technology should be compared with the maximum connection length including the second shortest path, required for some classes of traffic, disjoint from the first one, in order to add resiliency. The maximum of the set of shortest paths between all couples of nodes (including the second shortest path) is defined as *network diameter*.
- when a photonic backbone has a network diameter shorter than the optical transmission reach, it can be considered as a single transparency island
- if the photonic backbone diameter is larger than the optical transmission reach, some 3R regenerators are necessary and, as consequence, the network is translucent
- for the sake of completeness there is the case of opaque networks (i.e. all traffic is regenerated in all intermediate nodes). This case is considered too expensive and energy hungry and for these reasons it will be not considered.

Translucent networks are broadly classified into three categories, namely [17]

1. Translucent networks made up of transparent islands [18,19]
2. Translucent networks with sparsely placed opaque nodes [20,21]
3. Translucent networks made up of translucent nodes [19]

The case 1 consists in a translucent network made up of several subdomains (transparent islands) of optical transparency [18,19]. The optical transparency in a given island means that the network diameter (as defined in previous section) of each transparent island is shorter than the optical transparency reach and, as consequence, all nodes are transparent and no node has regeneration capacity (inside the island). The Digital Cross-Connects are located on the island borders [17]. Figure 36 illustrates a translucent network made up of three transparent islands and red spots represent the borders nodes. Lightpaths crossing the border between neighbouring transparent islands are 3R regenerated, via an Optical-Electrical-Optical (OEO) conversion provided by translucent nodes.

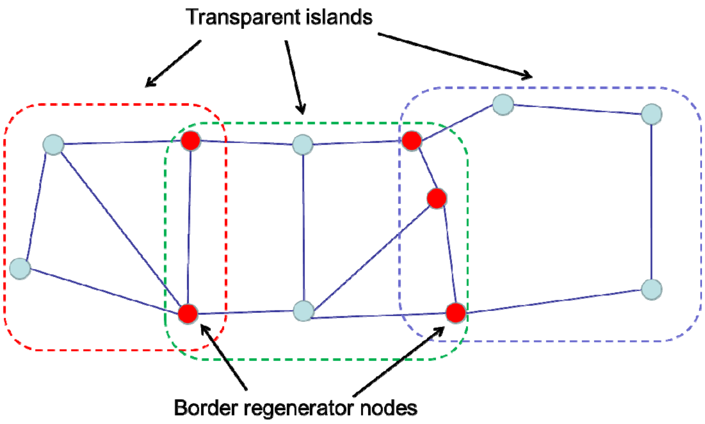


Figure 36 - Example of a translucent network made up of multiple transparent optical Islands

The case 2 represents a model where some switches are equipped with regeneration function that can be shared by all lightpaths in the network as a whole. One such type of implementation is based on sparse placement of opaque switches [18,19]. Thus the network can have small number of electronic (opaque) nodes, where 3R regeneration is performed. All other nodes are low-cost optically transparent OXCs [17]. Figure 37 shows an example of a translucent network with sparsely placed opaque nodes, where red spots are opaque nodes, and as the rest of the nodes are transparent.

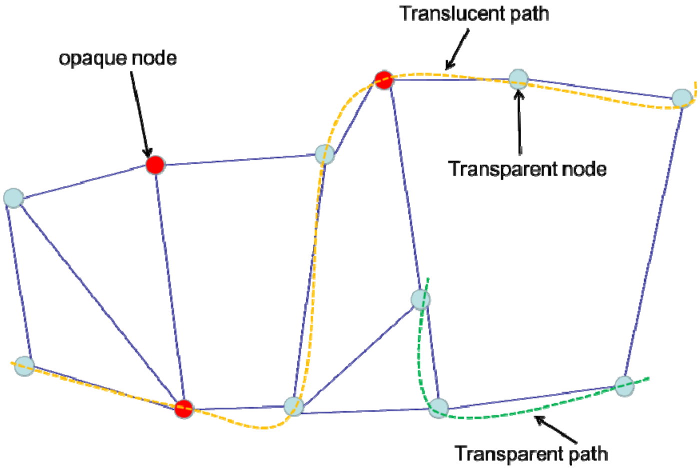


Figure 37 - Example of a translucent network with sparsely placed opaque nodes

The approach 3 consists in hybrid (translucent) switches at some or all of the nodes in an optical network [22]. Each switch (Figure 38) can act as Digital Cross Connect providing 3R regeneration only for signals needing it, the remaining part of signals cross the node transparently.

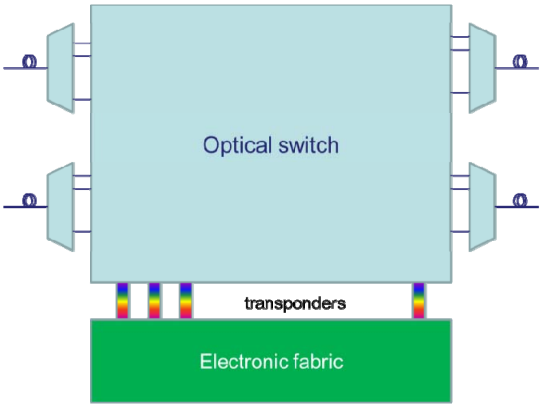


Figure 38 - Architecture of a translucent OXC node.

This latter option (translucent networks made up of translucent nodes) presents the following advantages, in particular compared to the transparency islands:

- lightpath routing is not constrained by transparency island boundaries but only by the optical transparency reach. In fact, no regeneration is needed for lightpaths that cross transparency islands border if they are shorter than optical transparency reach, overpassing one of the main drawbacks of transparent islands, where a lightpath crossing the borders between two islands is regenerated, independently with the distance and, consequently, the quality of the signal.

- the number of regenerators in translucent nodes and the size of electronic fabric are dimensioned according to the traffic pattern and not to the rigid boundaries of transparency islands, improving the scalability and, on the other hand, minimizing the cost.

- no need of architecture change when technology improves. The evolution of baud rate and modulation formats can modify the optical transparency range. Just add or remove some regenerators from the translucent nodes is sufficient to transport the traffic adopting new technology and It is not necessary to change the translucent nodes location or substitute the nodes at all. Analogously, a change of traffic pattern has no dramatic effect on the network architecture, often it can be solved via software (GMPLS or SDN governing the translucent network) that can address lightpaths towards a regenerator or not.

In order to minimize the cost of the network it is important to state some assumptions:

- electrical switching is more expensive than optical switching (particularly at high bit rates).

- the greatest share of CapEx and OpEx of a transport network lies in electrical components (3R regenerators, transponders, electrical fabrics). So, the minimization of electrical parts corresponds to a minimization of the total cost of ownership of the network.

It is fundamental to minimize the number of 3R regenerators, task that can be performed in two ways:

- Intelligent placement of regenerators
- Increase the optical transparency range.

Abundant literature can be found on the translucent network optimization [23 - 26], leveraging on the best placement of regenerators or traffic engineering devoted to the minimization of electrical treatment of the signal. In these papers, the idea is to provide a global planning procedure for translucent OTNs that should be able to choose regenerator sites, place translucent nodes, and assign DWDM systems to links to satisfy a given static traffic matrix. The case studies reported in 23 show the appropriate algorithms based on linear programming for the regenerators placements make possible the achievement of benefits by decreasing the quantity of resources even though it can increase the number of regenerating nodes, due to the sharing of regenerators in dynamic traffic behaviour.

As shown in deliverable D7.2 , the network diameter of the larger European backbones are shorter that the optical transparency reach of the technology selected for the DISCUS core network. However, this holds only for 40G services while 100G and 400G services may require regeneration, and even protected 40G services can sometimes require regeneration on the protection path when it's longer than the reach.

In other words, the larger European backbones are to be considered translucent networks with respect to the 32 Gbaud Nyquist DWDM, but they are indeed very close to full transparency. So the second alternative reported above is to increase the optical transparency reach (40% to 80% increase should be sufficient). A cheaper solution than regeneration it to increase the optical transparency reach is by insertion of sparse Raman links, as reported in next section.

8.2 Transparent network with sparse Raman amplified links

Raman amplification is a well-established technology suitable for increasing system reach in a much cheaper way compared to regeneration.

The main characteristics of Raman amplification are:

- the transmission fibre is used as the active medium;
- pump power is injected at the receiver side (counter-propagating) or at the transmitter side (co-propagating) of the transmission fibre;
- like EDFAs, a Raman amplifier works on the whole DWDM aggregate and its cost is of the order of an EDFA;
- Raman amplification is typically used in combination with EDFAs with a remarkable reduction of the equivalent noise figure of EDFAs and therefore of the link OSNR.

In terrestrial systems, counter propagating Raman amplifiers with pump power of the order of 500 mW, typically give a 3 dB reduction of the equivalent noise figure of the EDFAs and, if used in all links, they allow doubling the transparent transmission reach with respect to a transmission technology based solely on EDFAs.

In DISCUS core network, it is unlikely that transmission reach doubling is needed on all lightpaths (see deliverable D7.2 results), and therefore an architecture with a limited number of sparse Raman amplified links is proposed as shown in Figure 39.

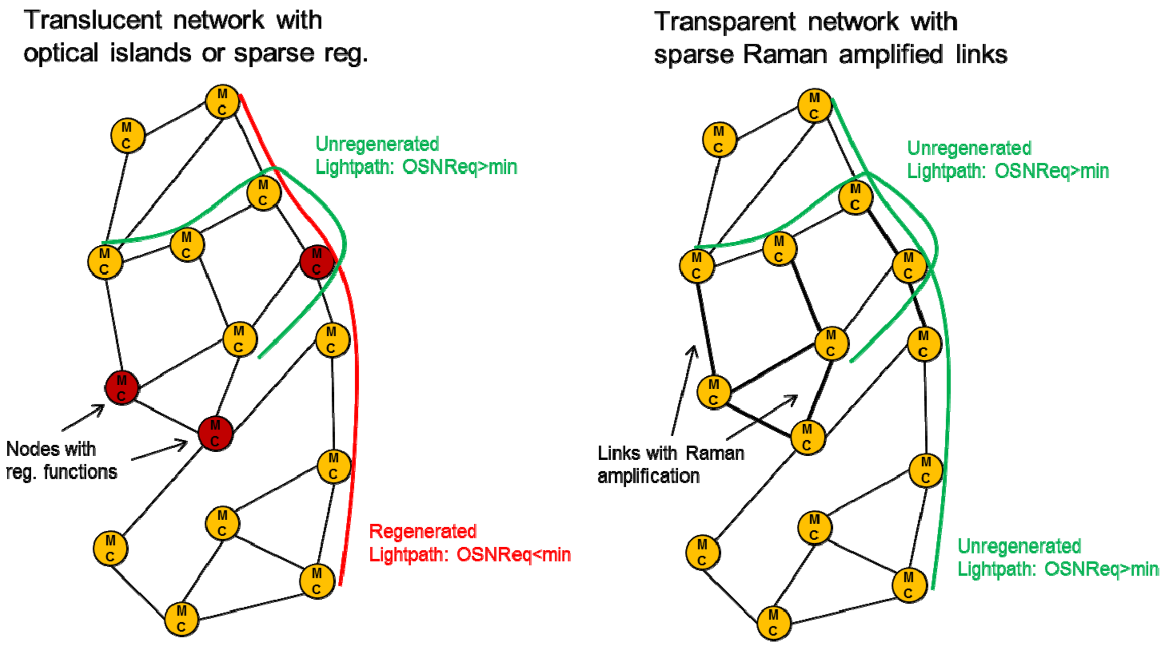


Figure 39 - Translucent network with sparse regeneration nodes (on the left), and transparent network with sparse Raman amplified links (on the right). In the latter network regenerators are replaced by Raman amplified links thus obtaining a fully transparent network

The development of this network concept require two basic tools: a transmission degradation model which includes Raman amplification and a network optimization strategy to minimize the number of Raman amplified links in the network.

As far as it regards the transmission degradation model, the one already described in deliverable D7.2 and suitable for EDFAs only, will be updated with Raman amplification formulas.

The problem of optimizing the transparent network with Raman amplified links is briefly outlined here and will be addressed in deliverable D7.6.

The Raman amplified links can be allocated heuristically considering that typically all the longest lightpaths pass through a limited number of common links located in the central part of the network. Rigorous design criteria can be envisaged as well as described below.

Using the concepts introduced in deliverable D7.2, the problem of minimizing the number of Raman amplified links can be stated as follows: minimise the number of Raman amplified links that makes the network transparent for a given modulation format on all shortest paths (i.e. the OSNReq of all shortest paths is higher than OSNReq, min characteristic of that modulation format). The optimization procedure can be outlined as follows:

1. OSNReq of all shortest lightpaths is calculated using the formulas of D7.2 (updated to include Raman amplification);
2. The set of shortest lightpaths whose OSNReq is lower than a given modulation format threshold OSNReq,min are considered (non-transparent lightpaths);

3. Raman amplifiers are progressively introduced in the links that are shared among the maximum number of non-transparent lightpaths unless their OSNReq becomes higher than OSNReq,min;
4. If some non-transparent lightpaths remains after the previous step, further Raman amplified links are heuristically introduced in the network.

This procedure can be repeated for the second shortest paths to guarantee protection and possibly to the third one for enhanced resilience.

The procedure can be repeated also for other modulation formats (i.e. setting other values of OSNReq,min).

9 Summary and conclusions

This deliverable is an update of the DISCUS architecture and should be read in conjunction with D2.1 for a complete description of the current thinking concerning the end to end design of the DISCUS architecture.

A focus of this deliverable has been to give greater consideration to the deployment of FTTH using LR-PON into rural areas. Although this was considered in D2.1 the thinking has been considerably expanded since then. We see finding rural solution that minimise the level of government subsidies required as a critical component of the actions necessary to tackle the DISCUS objective of removing the digital divide between customers in dense urban areas and those living in remote and sparse rural areas. The solutions therefore have to be both technically feasible and economically viable. Design options originally conceived and reported in D2.1 have been expanded in the options considered, detail design and analysis and are describe in section 3.1. An important part of the LR-PON design both for rural and urban solutions is the design and choice of technology for the amplifier node and this topic has been examined and reported in some detail in section 3.2. Resilience consideration for the rural design options are described in section 3.3. the main updates on the rural designs is a mapping of the designs to cable rings which should minimise cost per customer for the long feeder cables and also allows re-use of today's legacy ring technology deployed during the SDH/SONET era.

DISCUS is keeping a watching brief on coherent access technologies as a future upgrade strategy for the WDM /TDM hybrid LR-PON by providing a description from our partner Coriant of results from recent experiments and field trials, this is reported in section 4. Developments of the 40Gb/s upgrade of the downstream direction of the rural design of the LR-PON are given in section 5 and show that by using an SOA pre-amplifier at the ONU 512 way total split can be supported making it compatible with the infrastructure of the 10Gb/s TDM OOK channels.

100GB/s point to point transmission over the LR-PON infrastructure using DP-QPSK modulation scheme is described in section 6. The analysis shows that with appropriate FIR filter designs 100GB/s transmission can be achieved with at least 512 way split and up to 160km total distance which is sufficient for many of the optical paths in a practical situation (e.g. private circuits across London) for point to point link from one LR-PON to another LR-PN through the optical switch at the metro nodes and across a core light path through the core network without regeneration.

In section 7 updates for the metro-core nodes design are described; the functional packet processing switches, the optical switch and the need for the co-existence of fixed and flex grid in the same network, which we believe will be a requirement for a number of years into the future, are discussed. Also described is a summary of the progress on the work on the control plane for the metro-core node.

The work on core network design is described in section 8 and focuses for this deliverable on the design of the so called "translucent" network and in particular the Translucent network which allows a sparse population of possible light paths through the core network to have regenerators when the more extreme links distances are encountered. The general objective of the DISCUS architecture is still to have transparent light paths throughout the optical island if possible but it is recognised that in some country geographies there may be particularly long light paths between some node pairs, particularly under fault (protection switched conditions where the occasional regenerator may be needed. This section also considers the use of sparse Raman amplification which can further reduce the need for the sparse regenerators. In the remain small subset of cases where regeneration may still be required we believe occasional use of regenerators is better than sticking to a rigorous definition of the optical island having only transparent light paths (with no regeneration), which could force the core to be unnecessarily split into smaller, less optimal optical islands. Such a network would have lower overall transparency across the core compared to the single island with spares regeneration also a multi-island island network has the added complexity and cost of optical island interconnect.

10 References

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27. DISCUS D7.2 "Optical islands description", October 2013

Abbreviations

ACCORDANCE	FP7 project "A convereged copper optical radio OFDMA – based access network with high capacity and flexibility"
ADSL	Asymmetric Digital Subscriber Line
AN	Active Node
ASE	Amplified Spontaneous Emission
APD	Avalanche Photo Diode
APD-RX	Avalanche Photo Diode Receiver
BAU	Business As Usual
BC	Backhaul Cable
BER	Bit Error Rate
BiPON	Bit-interleaving Passive Optical Network
BM	Burst Mode
CAPEX	Capital Expenditures
CD	Chromatic Dispersion
CMA	Constant Modulus Algorithm
CMOS	Complementary Metal Oxide Semiconductor
CO	Confidential
CPE	Customer Premises Equipment
DAC	Digital To Analogue Conversion
DC	Distribution Cable
DCF	Dispersion Compensating Fibre
DF	Distribution Fibres
DQPSK	Dual Polarization Quaternary Phase Shift Keying
DS	Downstream
DSL	Digital Subscriber Line
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexer
EDFA	Erbium-Doped Fibre Amplifiers
EPC	Evolved Packet Core
FEC	Forward Error Correcting

FIR	Finite Impulse Response
FTTH	Fibre To The Home
FTTx	Fibre To The x (x is an arbitrary point in the access network usually not the home as FTTH is used for that case)
GHz	Giga-Hertz
GMPLS	Generalised Multi-Protocol Label Switching
GPON	Gigabit Passive Optical Network
HD	High Definition
IP/TCP	Internet Protocol/Transmission Control Protocol
IPTV	Internet Protocol Television
IQ	In-Phase Quadrature-Phase
ITU-T	International Telecommunications Union - Telecommunication Standardization Sector
LDPC	Low Density Parity Check
LE	Local Exchange
LE/CO	Local Exchange/ Central Office
LO	Local Oscillator
LOP	Launched Optical Power
LR-PON	Long Reach Passive Optical Network
LTE	Long Term Evolution
MC	Metro/Core
MHz	Mega-Hertz
MIMO	Multiple Input Multiple Output
MPLS	Multi-Protocol Label Switching
MPLS-TP	Multi-Protocol Label Switching – Transport Profile
MSPE	Multi Symbol Phase Estimation
MUX	Multiplexer
NGPON	Next Generation Passive Optical Network
OASE	FP7 project "Optical access seamless evolution"
ODN	Optical Distribution Network
OEO	Optical Electrical Optical
OLT	Optical Line Termination
ONT	Optical Network Termination
ONU	Optical Network Unit

OpEX	Operational Expenditure
OPM	Optical Performance Monitoring
OSI	Open Systems Interconnect
OSNR	Optical Signal To Noise Ratio
OSNReq	Optical Signal To Noise Ratio Required
OTDR	Optical Time Domain Reflectometer
OTG	Optical Transceiver Groups
OTN	Optical Channel Transport Network
OTU	Optical Channel Transport Unit
OXCs	Optical Cross Connect
PIEMAN	FP7 project "Photonics integrated extended metro & access network"
PIN	Positive Intrinsic Negative
PIR	Peak Information Rate
PMD	Polarisation Mode Dispersion
PON	Passive Optical Network
PP	Restricted to other programme participants
PRBS	Pseudo-Random Binary Sequence
PtMP	Point To Multipoint
PU	Public
RE	Restricted to a group specified by the consortium
RF	Radio Frequency
RN	Remote Node
ROADM	Re-Configurable Optical Add Drop Multiplexer
RTT	Round Trip Time
RX	Receiver
SDN	Software Defined Network
SiP	Silicon Photonics
SOA	Semiconductor Optical Amplifier
SOP	States Of Polarization
SSMF	Standard Single Node Fibre
TBD	To Be Determined
TDM	Time Division Multiplexing
TWDM	Time & Wavelength Division Multiplexing

TX	Transmitter
UDWDM	Ultra Dense Wavelength Division Multiplexing
US	Upstream
WDM	Wavelength Division Multiplexing
WSS	Wavelength Selective Switch
XGPON	10G Passive Optical Network