D4.3

Integrated architectures for LR-PON supporting wireless and wireline services

Dissemination Level: PU

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Abstract:

A variety of LR-PON architectures are discussed from the perspective of wireless backhauling and fronthauling requirements (latency and bandwidth) as well as regarding achievable power budgets when using cascaded in-line semiconductor optical amplifiers (SOA) for signal amplification both in downstream and upstream direction.

For the wireless x-hauling applications different constraints as given by the respective radio system standards are provided and their impact on the optical network solution is discussed: e.g. maximum propagation delays on the radio links (cell size), Synchronous HARQ processes in LTE, Intersite propagation delays tolerable in coordinated scheduling and CoMP scenarios. Suitable optical system architectures are shown and discussed.

In previous studies on LR-PON architectures EDFAs have been used for compensating fiber and splitter losses. Since their use restricts the useable optical spectrum on the fiber, we investigate the system performance when using linear SOAs instead. Various ODN (Optical Distribution Network) architectures, including cascaded trees and combined bus/tree architectures, with in-line SOAs are analyzed by numerical simulations and feasible variants are identified.

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1 Introduction

Passive Optical Networks have been devised as a fibre access system able to decrease the installation cost per customer by allowing sharing of fibre infrastructure and network electronic terminations among multiple users. Indeed one of the main aims of DISCUS LR-PON access architecture is to further capitalize on the PON sharing potential by increasing the number of users per PON by well over an order of magnitude, compared to current GPON values.

Besides increasing the number of users, another important approach to further increases the PON profitability is to increase the number of supported services, beyond provisioning of broadband access to residential and small business. Services that are currently delivered over different (sometimes dedicated) networks could migrate on PON access systems, which are able to deliver high capacity and will be ubiquitous.

One of the main applications we consider is that of providing backhaul or fronthaul interconnection for mobile networks, in a converged wireless-optical access architecture. Especially as mobile network operators start deploying larger numbers of smaller cells in order to offer higher capacity per user, the idea of a shared, low-cost backhaul fibre network based on existing PON systems becomes very attractive. It becomes of paramount importance however to investigate the requirements that mobile backhauling and fronthauling pose on the PON architecture and address any outstanding issue at design phase.

The main issues that will be discussed in this document are the latency and capacity requirements for backhaul and fronthaul of mobile systems.

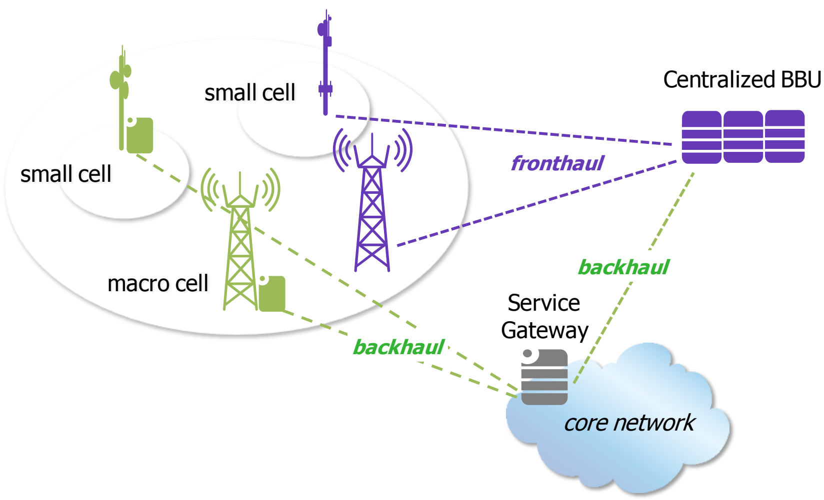
Latency issues can originate from the potentially long feeder fibre in LR-PON (which can introduce propagation round-trip delays of up to 1 ms), and from the dynamic Bandwidth Assignment algorithm required to schedule upstream bandwidth among the PON users. DBA, which is also affected by the feeder length, can create delays of many milliseconds. Although in this document we do not provide final solutions to this problem, initial studies suggest that mitigation of such latency constraints might require a separation of back/fronthauling traffic from residential traffic. For example dedicated PON wavelengths could be used, as well as architecture modifications that allow to shortcut fibre links between access points, i.e., bypassing the long feeder fibre. Other solutions that will be considered are also improvements to DBA algorithms to reduce latency for specific applications.

Capacity can also become a problem in the long term, as PON users will require higher peak and sustained rates, while more and more business users will require dedicated wavelength services. In particular fronthauling represents a problem as its required transmission rates can be over an order of magnitude larger than the capacity provided by the base station to the users, and can easily go beyond 10 Gb/s per cell. While optical fibre has large usable spectrum, in LR-PON this will be limited to the C/L-band if Erbium-Doped Fibre Amplifiers (EDFAs) are used to boost the signal at the first-stage splitter. In this document we discuss how Semiconductor Optical Amplifiers (SOAs) can be adopted to remove such spectral range constraints and thus will pave the way not only to higher network capacities, but also to utilization of LR-PON infrastructures with multiple independent systems operating in different spectral regions.

2 Optical networks for wireless back- and fronthauling

2.1 Basic configurations

The main links and interfaces involved in wireless backhauling and fronthauling are generically shown in Figure 1 (only the data interfaces are considered here) [1]. In present networks the basestations together with the antennas are directly connected to the core network via the Service Gateway. User data are transmitted via backhauling links (logical S1 interface in LTE) to either macro cells (typically 1 km in diameter) or to small cells (typically 200 m in diameter). In an alternate, more distributed architecture under discussion for LTE networks the antennas are separated from the base station (remote radio head concept, RRH). The base station functions for a group of RRHs are combined into a centralized BBU (Baseband Unit) that is attached to the core network via a backhauling link (S1) as before. The individual RRHs only contain a reduced functionality. They are connected to the Centralized BBU via fronthauling links. There are a number of different possible ways how to split the processing chain in a basestation for accomplishing this architecture. The optimum choice of split is still under discussion, as there is a trade-off between potential cost benefits from BBU pooling ("pooling gain") and from simplified antenna hardware on the one hand and increased bandwidth and latency requirements on the fronthaul links on the other hand [2]. In an extreme case, opposite to the fully integrated base station architecture of today, the RRH only contains RF related hardware and the RF signals are transmitted to and from the BBU as digitized RF samples employing the CPRI protocol (Common Public Radio Interface).



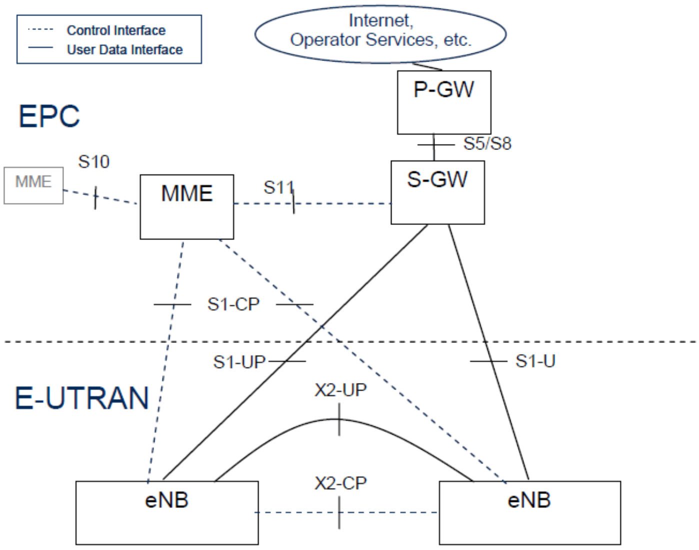


Figure 1: Generic backhauling and fronthauling links in wireless networks (top); LTE nodes (eNB or eNodeB) and Service Gateway (S-GW) with their corresponding interfaces (bottom)

In LTE networks there also is an option to let neighbouring base stations cooperate in order to improve the capacity of the radio network by employing coordinated scheduling, interference cancellation and more (CoMP: Cooperative Multipoint Processing). The communication between them is established using the logical X2 interface over which radio channel coordination and/or user data can be exchanged. The efficiency of such approaches is critically dependent on the time it takes to exchange data between sites, i.e. on transmission system induced latencies.

2.2 Critical design parameters given by radio requirements

Both backhauling and fronthauling links must meet certain requirements that are directly given by the respective radio standards or can be derived therefrom. In the following sections both bandwidth and latency requirements are discussed as they are the most critical parameters for designing an optical back-/fronthauling network using LR-PON technologies.

2.2.1 Bandwidth

A legacy TDM-PON technology such as GPON is a good candidate for mobile backhauling because a time shared point to-multipoint topology suits perfectly the bursty traffic scenario that is typical in small-cells deployments, thus taking advantage of statistical gain for traffic throughput. With higher optical system capacities also macro cells can be served using PON technologies (XGPON).

A critical parameter for backhauling is the provisioning capacity required for each small cell or macro cell. Calculations must be made depending on the number of sectors per cell, the bandwidth of the carriers and the number of carriers in a radio access network.

In the white paper “NGMN optimized backhaul requirements” ([3], section 4.3), it is stated that:

- The NGMN Backhaul service bandwidth profiles, consisting of peak and committed information rates, should be configurable in increments of 2 Mbps between rates of 2-30 Mbps, increments of 10 Mbps up to 100 Mbps, and increments of 100 Mbps beyond 100 Mbps, in a pay as you grow model
- The NGMN Backhaul solution MAY provide up to 450/150 Mbps Downstream/Upstream (up to 3 sectors, each with one 20 MHz BW carrier assuming that all three sectors can simultaneously support the highest peak rate of 150/50Mbps, one Radio Access Technology) Peak Access Bandwidth where required (in those e-NB's specified by the operator). Peak Access Bandwidth relates to the instantaneous bursting of traffic in all sectors of the e-NB. This figure refers to the effective Bandwidth and does not include the transport protocol overhead or signaling overhead. In case of the support of multiple carriers per sector (multi-band base station for instance), higher rates may be necessary.
- The NGMN Backhaul solution MUST provide at least 150/50 Mbps Downstream/Upstream Minimum Access Bandwidth (99%-tile) where required (in those e-NB's specified by the operator). This figure assumes a 20 MHz BW carrier and refers to the effective Bandwidth and does not include the transport protocol overhead or signaling overhead.

Figure 2.a and 2.b show the recommendations from the Next Generation Mobile Networks (NGMN) Alliance for backhaul dimensioning for the specific cases of 3G and LTE small cells. The rows on the left-hand side show the different possible transmission modes for a 3G or LTE cell, together with their peak capacity, both in uplink and downlink. The graphs show the capacity backhaul requirement for each cell, for different configuration of HSPA and LTE transmission. These requirements are divided into: busy hours requirements (solid green line) and quiet times (shaded green line). The former present lower values because the average cell capacity is reduced due to interference among users (and the limited processing capabilities when considering small cells). The latter instead is close to the peak cell rate, since if only one or few users are served by the cell, the interference is minimal.

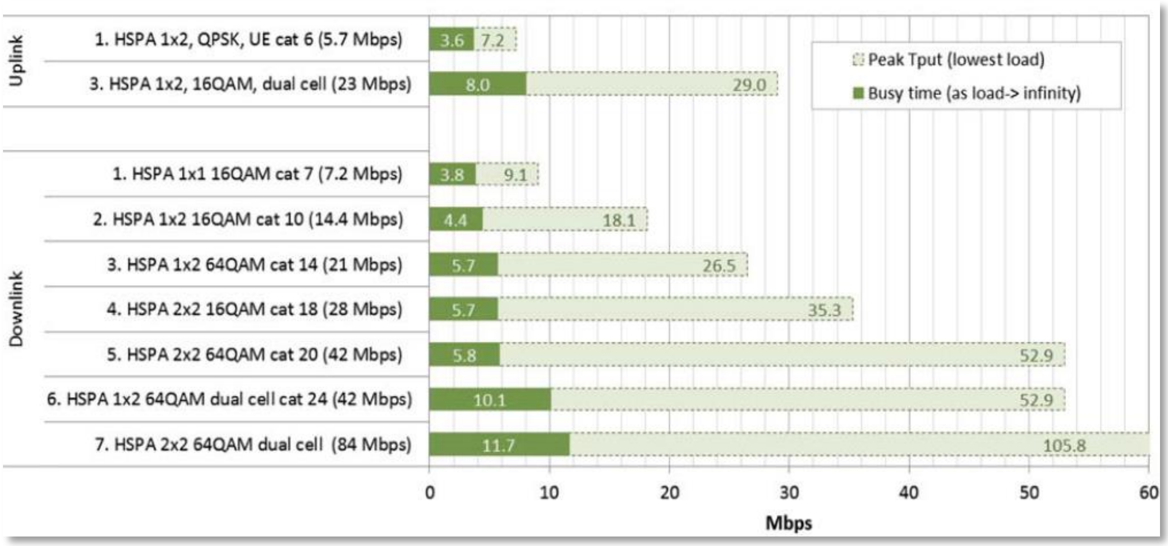


Figure 2a: Recommendations of backhaul dimensioning for 3G small-cells

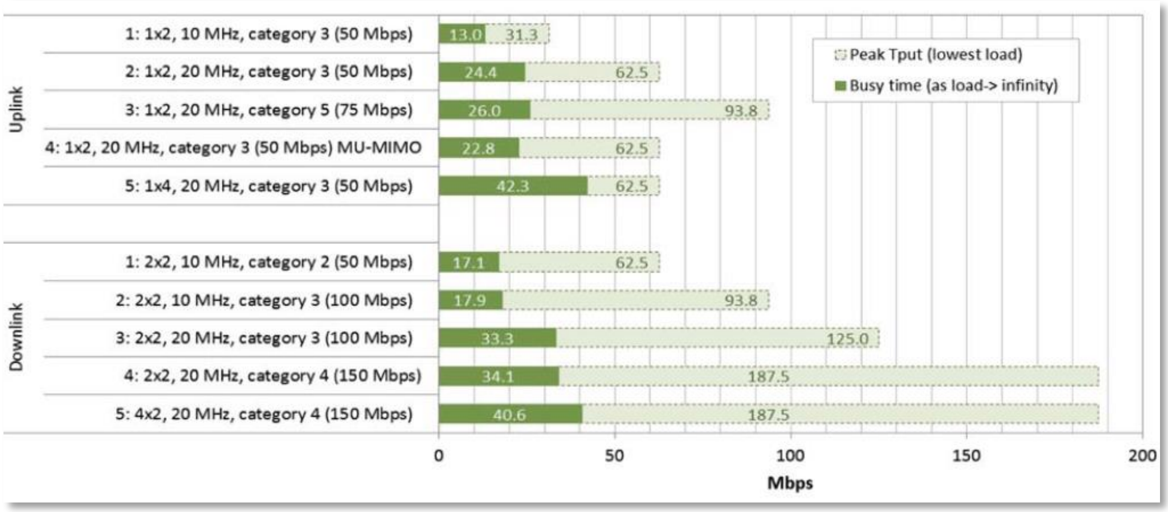


Figure 2b: Recommendations of backhaul dimensioning for LTE small-cells

Figure 3 (left) instead reports the physically achievable peak cell capacity, and hence the maximum required backhaul capacity, for LTE systems using between 1 and 8 antennas per sector. These antennas are either individual elements or may consist of multiple antennas to enable beam forming. In this latter case each group counts as one single antenna, since all its elementary antennas receive and transmit the same user data. Peak rates vary between about 100Mb/s (when the cell channel bandwidth is 10 MHz and only one antenna is used) and 10 Gb/s (when the cell channel bandwidth is 100MHz and 8 antennas are used).

Such values are important for determining the amount of assured capacity that each cell should require at different times from the PON both in the upstream (i.e., in the DBA algorithm) and downstream (i.e. at the access switch). Knowing such values in advance can in fact help optimize the PON capacity allocation, and reduce the backhauling cost for mobile operators. Finally, it should be noticed that the higher capacity cases will require an entire PON wavelength dedicated to an individual base station.

Figure 3 (right) reports the bandwidth requirements on CPRI links assuming no compression. Here each antenna element receives and transmits its own CPRI stream, even in case of beam forming set-ups. When compared to the backhaul bandwidths in the right figure it is seen that the CPRI fronthaul capacities are typically an order of magnitude higher. And since these are constant rate bitstreams that do not benefit from statistical multiplexing, these links are to be implemented using ptp transmission technologies, either via separate fibers or via WDM links over PON.

As discussed in the previous section there are also other fronthauling architectures under discussion (split processing) requiring lower bandwidths on the fronthaul links. So the bandwidth specifications in Figure 3 (right) can be considered an extreme case.

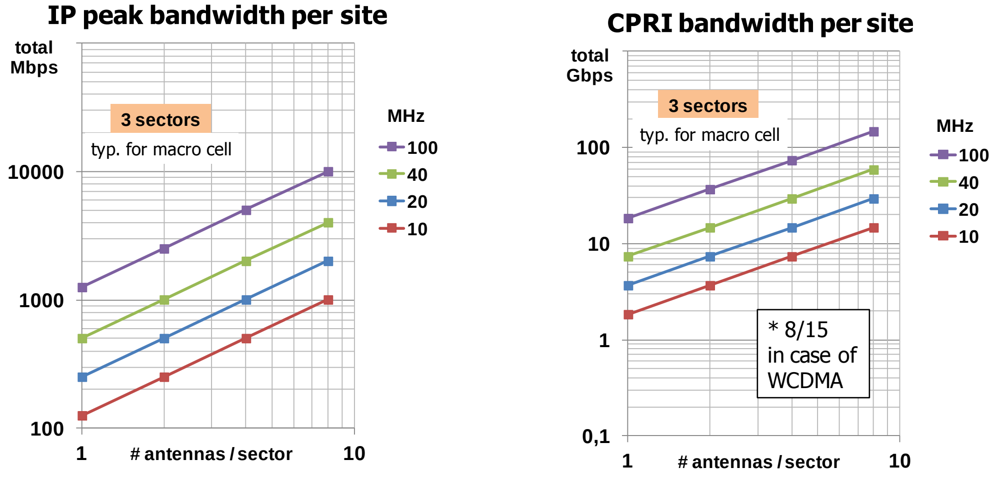


Figure 3: Backhauling bandwidth requirements in LTE assuming full capacity on the air interface, i.e. maximum physically achievable peak cell capacity (left); Fronthauling bandwidth requirements assuming uncompressed CPRI streams (right).

2.2.2 Latency

2.2.2.1 Backhauling

Table 1 (3GPP TS 23.107 R5) reports latency requirements and tolerable packet error rates for different class of services in 3G systems. Such delay values indicate the maximum delay for 95% percentile of the distribution of delay for all delivered Service Data Units (SDU) during the lifetime of a bearer service, where delay for an SDU is defined as the time from a request to transfer an SDU at one Service Access Point (SAP) to its delivery at the other SAP.

For LTE, the packet delay budgets are specified in 3GPP Technical Specification 23.203 (R8) for the different Quality Class Identifiers (QCIs).

QCI	RESOURCE TYPE	PRIORITY	PACKET DELAY BUDGET (MS)	PACKET ERROR LOSS RATE	EXAMPLE SERVICES
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational video (live streaming)
3	GBR	5	300	10^{-6}	Non-conversational video (buffered streaming)
4	GBR	3	50	10^{-3}	Real-time gaming
5	Non-GBR	1	100	10^{-6}	IMS signaling
6	Non-GBR	7	100	10^{-3}	Voice, video (live streaming), interactive gaming
7	Non-GBR	6	300	10^{-6}	Video (buffered streaming)
8	Non-GBR	8	300	10^{-6}	TCP-based (for example, WWW, e-mail), chat, FTP, p2p file sharing, progressive video and others
9	Non-GBR	9	300	10^{-6}	

Table 1: Packet delay budgets in LTE (R8)

According to the NGMN, the following additional recommendations are given for delay values in small cells [3]:

- Looking at figure 1 (bottom), for the S1 interface, i.e., that connecting the eNode BS to the Serving Gateway, it is recommended that the one-way delay from the small-cell to the core network equipment does not exceed 20ms for 98% of packets with high priority Class of Service or in uncongested conditions.
- For the X2 interface, i.e., that directly interconnecting two adjacent eNodeB's, the S2 application protocol (X2AP) is responsible for providing signaling transport between eNodeB's. NGMN recommends a maximum delay of 20 ms on the X2 interface. In Releases 8-9 some load management functionalities are supported, and Inter Cell Interference Cancellation are specified in Release 10. Network coordination techniques using X2 are known under the name of Coordinated Multi-Point Processing (CoMP), which covers specific scenarios such as joint processing and coordinated scheduling/beamforming between multiple sectors. It has been studied that the delay in the X2 with CoMP can limit the traffic throughput, and a one way latency between 1-5 ms is recommended for guaranteeing maximum throughput values [4].

Table 2 summarises the maximum tolerable delays for the S1 and X2 interfaces (with and without CoMP).

	S1	X2	X2 with CoMP
Maximum delay (one-way)	10-20 ms	20 ms	1-5 ms

Table 2: Summary of latency requirements in LTE small cells backhauling

2.2.2.2 Fronthauling

2.2.2.2.1 Timing advance

Timing advance is a technique used in TDM-based mobile systems, where the base stations shifts the timing of the mobile set (user equipment, UE) to account for propagation delays on the radio link. The maximum allowable timing advance is a function of the time slot duration, and it is limited by the maximum cell size of 120 km in 2G systems (3GPP TR 43.030). Alternately, the maximum fiber length allowed in an optical fronthaul architecture is about 80 km.

For LTE systems, the timing advance is limited to 667,71 μs (TS 36.213), which allows a maximum cell range of about 100 km or correspondingly to a maximum fronthauling fibre distance of 67 km.

2.2.2.2.2 Synchronous Uplink HARQ

The most stringent latency requirement in LTE originates from Synchronous HARQ (Hybrid Automatic Repeat Request) which is used in the uplink to correct for errored data received at the basestation by retransmission of the data from the UE after 8 ms. The request for retransmission has to be sent to the UE 3 ms after that the original data have been received. As there are certain processing steps involved on the PHY and on the MAC layer in the eNB which are aligned with the 1 ms frame duration of the data, there is only little time left for transmission over a fiber link in a fronthauling architecture. Depending on the specific node implementation one usually considers allowable transmission latencies between BBU and RRH in the range 200 – 500 µs. Since this is a round trip delay, the maximum fiber distance is limited to 20 – 50 km. However, these figures do not take into account delays induced by the switching, encapsulation and other MAC processes in the optical system hardware. So the maximum fiber link length in real system implementations is accordingly reduced with respect to the above figures.

The above discussion and the resulting tight latency and fiber length limits relate to the CPRI fronthauling architecture. For other split processing architectures the timing as well as bandwidth limitations may be more relaxed, depending on where in the processing chain the split is made [2].

2.3 Potential issues with PON back-/fronthauling solutions

When a PON is used as a backhaul for a mobile network, the latency associated to potentially longer fibre distance and scheduling delays of the PON protocol need to be taken into account. For GPON, if we assume a maximum fibre distance of 20 km we obtain a maximum propagation delay of 100 µs for the S1 interface and 200 µs for X2. (Traffic between two eNB's needs to cross the PON twice, if it has to go through the OLT. An alternate architecture with lower latencies is proposed below in a subsequent section of this report). While such propagation delays might be acceptable, the latency of the PON Dynamic Bandwidth Assignment scheduling algorithm can be quite significant, as it can be in the order of few ms. Simulations in a GPON backhauling scenario (Figure 4) show that a scheduling period lower than or equal to 0.75 ms is required for reducing the delay of the signaling process for a hard handover procedure to an acceptable level. The simulations were done for a mobile backhauling PON with 40% traffic load and where residential and backhauling ONUs are sharing an OLT. However, further decreasing the scheduling period would increase the overhead of the DBA mechanism, thus further reducing the available PON capacity.

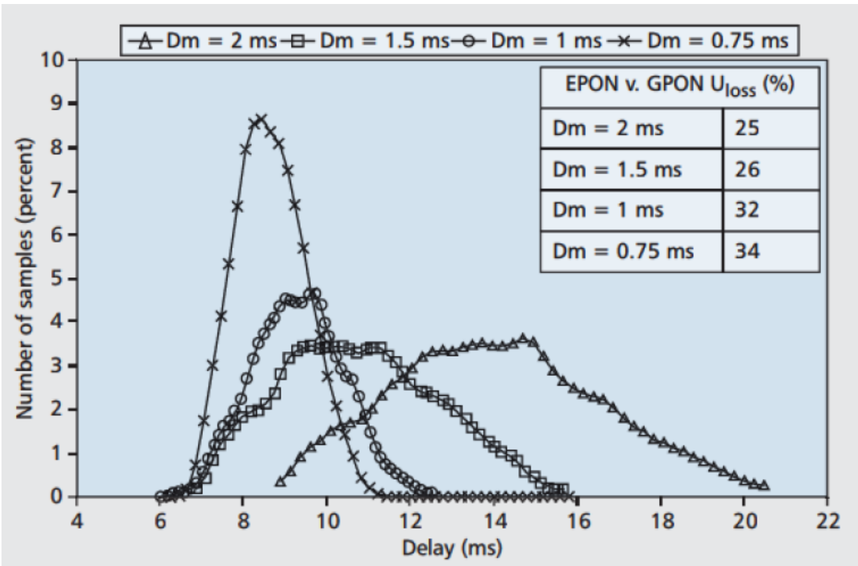


Figure 4: Probability distribution function of the signaling delay in a hard handover procedure using PON backhaul, and inset showing throughput loss of EPON vs GPON [5].

When considering LR-PON, this issue becomes even more significant. The additional latency due to transmission over the long LR-PON feeder is up to 500 µs in one direction (for 100 km distance). While such delay might be acceptable when considering conventional operation of the wireless network (no CoMP), it does constitute a significant percentage of the maximum delay tolerable for CoMP techniques. Even more relevant is the delay due to DBA scheduling. For a LR-PON this could vary between hundreds of µs and 5-10 ms, depending on the feeder length as well as on the overhead we are willing to tolerate. In addition, typically the scheduling mechanisms of the LTE system and the PON are not coordinated, which further increases the overall latency. Such high delays can heavily affect the performance of both the S1 and X2 interfaces, and are critical for CoMP applications. Techniques for reducing DBA scheduling delays for LTE backhaul application, as well as mechanism for coordinated scheduling of PON and LTE bandwidth have to be considered in LR-PON.

Finally, when considering fronthauling, the maximum tolerable delay over a CPRI interface is of the order of 200-500 µs. It seems clear that PON protocols are not able to satisfy such requirement, due to the relatively high scheduling time of DBA. However, since the bandwidth requirement for CPRI is also very high, point-to-point wavelength over PON infrastructure might be considered as an alternative solution, as this does not incur any scheduling delays. The only limitation then becomes the propagation delay over fibre and switching delays in the nodes, which will limit the maximum length of the PON.

2.4 PON architectures for backhauling

2.4.1 Mixed macro & small cells network

In Figure 5a PON based backhauling network is proposed serving macro cells and small cells in the serving area around a traditional Central Office of a fixed line network [1]. According to the bandwidth considerations in the previous chapters the macro cells should be attached by a symmetrical 10G-PON system, whereas the small cells can be served by using a GPON system. The underlying assumptions for the network design were:

- Serving area (SA) around CO has 6 km diameter
- 32 macro cells (1 km diameter) per SA with 3 sectors, 8 antennas/sector, 100 MHz bandwidth
- 16 small cells (200 m diameter) per macro cell with 1 sector, 4 antennas, 100 MHz bandwidth

The optical solution comprises a symmetrical 10G-PON with a 1:32 split factor and 8 GPON systems with 1:64 split factor. As shown in Figure 5 there are 8 feeder fibers carrying both 10G-PON and GPON traffic to the different site clusters in the SA. Depending on the availability of fibers the external 1:4 splitter can also be integrated into the CO site. So in case of the 10G-PON system, the architecture primarily serves for reducing the number of optical ports in the CO. Outside of the CO the fiber plant essentially comprises ptp links to the different macro cells. This design acknowledges the fact that the macro cells are too far apart from each other to be served by a common ptmp ODN (Optical Distribution Network). For the GPON subsystem the situation is different as seen from the network layout in Figure 5. The small cells (metro cells) are concentrated in smaller areas (typ. 200 m diameter) such that they can be served via a common ptmp ODN.

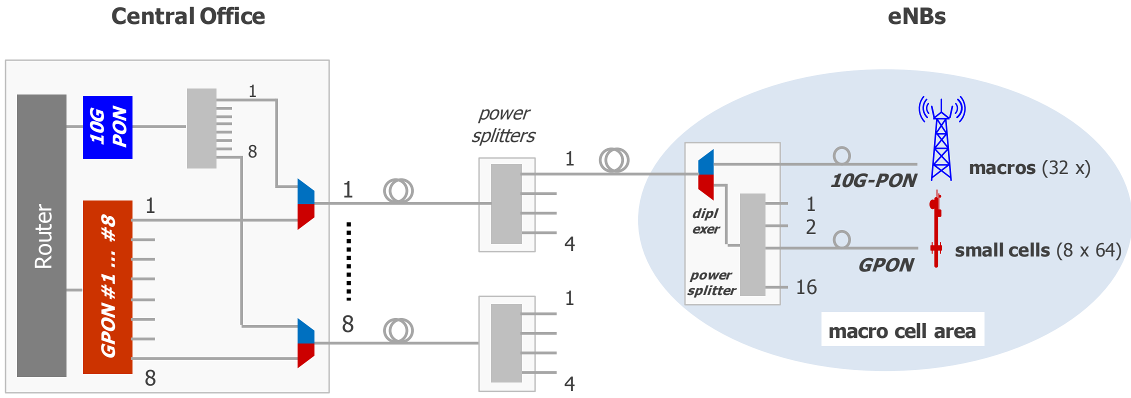


Figure 5: TDM-PON based backhauling architecture for mixed macro and small cells (metro cells)

The above scenario assumes existing GPON and 10G-PON system definitions as given by the ITU-T Recommendations G.984, G.987 or G.989. The latter (NGPON2) is particularly useful as it will provide for symmetrical 2.5G- and 10G-PONs per wavelength channel (in contrast to the asymmetrical variants specified in the other two Recommendations). However, the WDM capability is not necessary here, as the signals will be transmitted over separate feeder fibers, i.e. over different ODNs. Hence all OLTs can operate on the same wavelength channel. The architecture in Figure 5 can in principle be transposed also into a LR-PON architecture, since it only includes backhauling links that are not severely affected by latency constraints. However, the considerations in the previous chapter still apply.

2.4.2 Drop section architectures for small cell backhauling

With increasing number of small cells being served by a single PON system there is a demand for a) limiting the amount of fibers in the drop section and b) providing for protection on the feeder side (e.g. by dual homing) as well as in the drop section. Figure 6 shows 4 different layouts of the drop section, assuming it is being served from the CO by feeder fibers over two disjoint routes (on the left side in the figures, feeder details not shown). It is further assumed that the PON system is designed for a split factor of 1:N in the drop section. The fiber lengths in the drop section are short, so their loss can be neglected. The feeder section is identical in all cases shown, so the split factor of 1:N represents the available common loss budget for the different drop architectures.

The layouts in the upper row do not provide for protection of the drop section. But the right architecture allows for a reduction in number of fibers by a factor of two as compared to the conventional architecture on the left.

In the lower row two examples for a protected drop section are shown. The one on the left requires multiple fibers, the number being identical to the number of areas (M) and dependent on the number of sites per area (K) with N=M*K. The one on the right employs a daisy chain architecture, requiring only 2 fibers in the drop section. However, since in this architecture the links to the different cells experience different optical losses, the allowed differential loss of the PON system (presently 15 dB max) sets an upper limit to the total number of sites that can be connected (N/2 to about N/6 for M=2 to 5 areas). It is lower than in the architecture on the left (N).

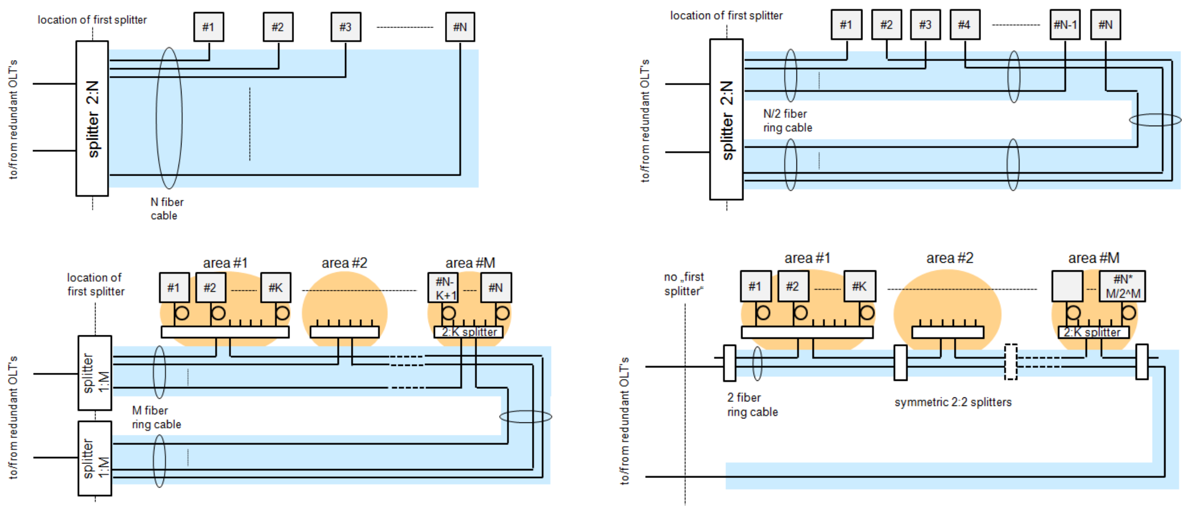


Figure 6: PON drop section architectures for small cell backhauling (with feeder protection): no drop protection (top left); ring for fiber savings, no drop protection (top right); multiple serving areas for reducing fiber count on ring, ring protection for drop (bottom left); daisy chain serving multiple areas, 2 fibres on ring, ring protection for drop section (bottom right)

2.4.3 Local optical mesh network for CoMP in LTE-Advanced

Implementing an optical backhauling network for CoMP in LTE-Advanced networks faces two major challenges: latency constraints and bandwidth requirements. In TDM-PON systems the communication between neighbouring nodes usually has to be via the central OLT. In an LR-PON architecture with total fiber length up to 100 km the latency constraints could hence become a blocking argument. Also the bandwidth requirements (which depend on the details of the CoMP approach taken) can become severe, since in LR-PONs with high number of nodes the X2 interface will request a large fraction of the upstream bandwidth, in addition to the user data via the S1 interface.

The architecture shown in Figure 7 allows for circumventing these restrictions [6] and is particularly useful with LR-PON applications. It realizes a bespoke network, here a local mesh, on a conventional PON ODN.

On the LTE layer the desired backhauling topology is shown: red links for S1 between eNB's and S-GW, blue links for X2 between neighbouring eNB's. The S1 interface can readily be realized by employing a TDM-PON system as shown on the PON layer in Figure 7 (the feeder link is kept short in the picture in order to focus the attention on the drop section). Since deploying additional fibers between eNB's is usually no option, an additional "splitter box" (yellow) is attached to the PON power splitter. It serves for redirecting optical signals from one eNB to its nearest neighbours. These signals are transmitted by additional dedicated transceivers in the eNB's operating in a wavelength band different from the (e.g. 10G-PON) bands for the S1 links. Depending on the PON technology used for the S1 interface the new band can be located in the optical E- or C-band (GPON or XGPON for S1) or in the L-band (NGPON2 for both S1 via TWDM and X2 via ptp DWDM).

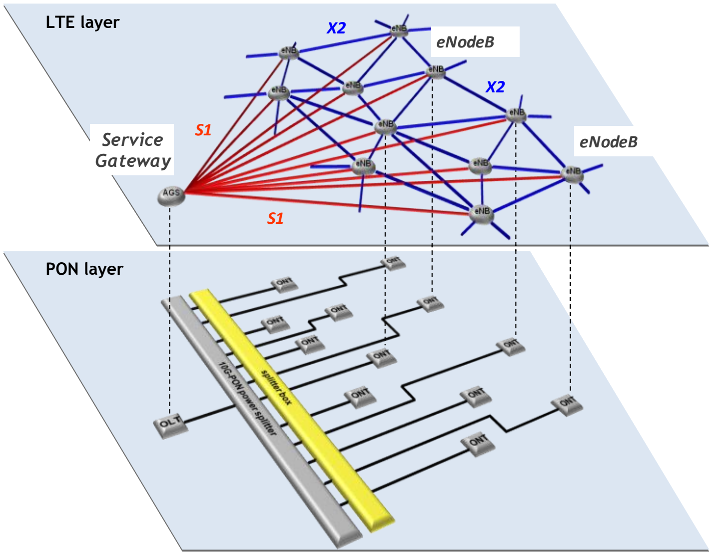


Figure 7: Mapping of LTE-Advanced with next-neighbour communication for CoMP to underlying PON fiber infrastructure. Nearest neighbour connections are established by yellow splitter-box next to the PON power splitter.

The internal architecture of the splitter box is shown in Figure 8. The required topology for X2 is exemplified for nodes on a square grid on the left in the picture. The trapezoidal elements attached to each node are 1:4 power splitters. Each ONT (eNodeB) is connected only to its nearest 4 neighbours. The structure can arbitrarily be extended into either direction without challenging or modifying the optical power budget on each cluster of interconnected nodes. In reality a number of splitters (here 15) are collected in a common box (yellow) and the S1 interfaces are implemented by a 10G-PON system being attached via diplexers as shown in the figure. The loss budget of the links for the X2 interface can be bridged without requiring optical amplifiers for split factors up to 1:8 per ONT, i.e. for up to 8 neighbours attached to each eNodeB.

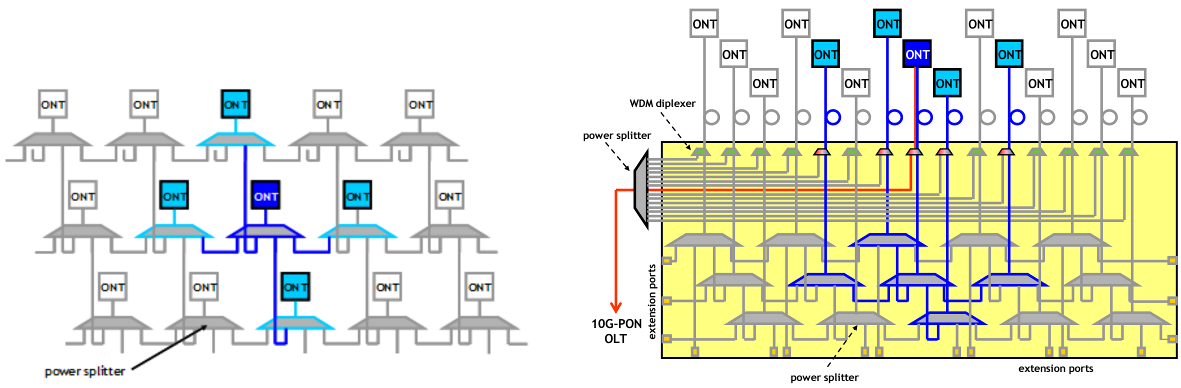


Figure 8: Example architecture of yellow splitter box in Figure 7. Target topology for square grid of eNodeB's (left); implementation of power splitters along with waveband diplexers in a common box (right). The 10G-PON system for the S1 connections (cf. Figure 7) is attached via the power splitter on the

left side of the box. (coloured links and splitters highlight the elements and connections needed for connecting the dark blue ONT. The ONTs are the optical frontends in the respective eNodeB's).**

Multiple such splitter boxes can be connected to form a virtually infinite "X2 cloud" around the last splitter stage in a TDM-PON network. As shown in Figure 9 the boxes can also be used across multiple ODNs and can be applied in a mixed architecture in which the PON serves both residential and business customers as well as eNodeB's in a wireless network.

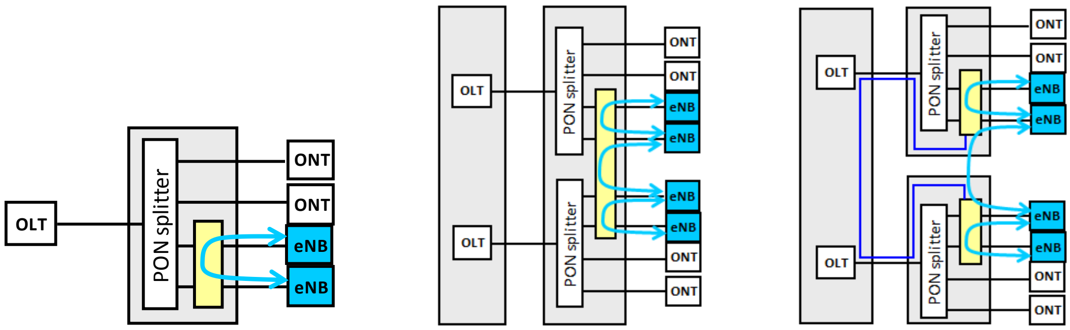


Figure 9: Inserting the splitter box (yellow) into a mixed FTTx/backhaul ODN (left); splitter box interconnects multiple ODNs (middle); interconnecting two different PONs via the PON feeders (right)

3 LR-PON architectures

3.1 LR-PON budget extension by in-line optical amplifiers

This section covers the concept of increasing reach and / or split of a passive optical network (PON) via intermediate optical amplifiers. Optical amplifiers have been of research interest for access networks since the 1990s [7]. The use of erbium-doped fiber amplifiers (EDFA) are intended in the *DISCUS* project. This is because of the low noise figure of EDFAs, their capability to be operated with a high number of wavelength channels by simultaneously offering a large gain (>30 dB). However, the recent development trends of semiconductor optical amplifiers (SOA) show that these devices can also offer a low noise figure [8], a high input power dynamic range, even for multiple channels [9], and the possibility to be cascaded for various modulation formats [10]. A major advantage of the SOA technology compared to the EDFA technology is the availability of the gain over the entire wavelength region of the fiber [11] and their capability to be integrated with, e.g. power splitters.

At the beginning of the 21st century, first attempts to use SOA as reach extenders have been performed successfully by demonstrating so-called SuperPON [12]. A severe issue of using optical amplifiers in the PON becomes evident in the upstream (US) path of the long reach (LR)-PON. When several optical amplifiers are placed in parallel, the effect of amplified-spontaneous emission (ASE) becomes more severe. Each optical amplifier produces ASE that then is combined with the ASE contributions from the other amplifiers at the splitter, which acts as a combiner in the upstream direction. This effect is known as noise funneling and increases the amount of ASE present at the receiver. Thus, the designers of the SuperPON were forced to implement a complex gating mechanism that reduced noise funneling by only switching on an optical amplifier when it was required to amplify a signal. Using this method, SuperPON achieved a 2048-way split [13].

This noise funneling issue can be counteracted if high gain and low noise figure optical amplifiers are deployed in front of the power splitter only. This way, a low number of amplifiers can be used to support a high number of customers. These requirements have been fulfilled for high-split DWDM PON demonstrations [14] by using EDFAs. The use of EDFAs is attractive here due to their high gain values and their large input dynamic range which was unavailable for SOAs at that time. It should be mentioned that the experiments using an EDFA are always limited to C-band operation.

Recently, so-called linear SOAs [15, 16], which offer a constant gain over a large range of input power levels as well as a low noise figure are evolving. Therefore, an interesting and open question is if by using the new generation of SOA devices as well as narrow-band filtering in the PON receivers, a long-reach and high-split PON can be realized without the need of complex gating-techniques. Thus, in this section, we focus on the use of SOAs in LR-PONs. This work is done within the *DISCUS* project to extend the knowledge of possible LR-PON solutions with state-of-the-art amplifier technologies.

The section is organized as follows:

In subsection 3.1.1, the general LR-PON scenario and the requirements are introduced. In subsection 3.1.2, different architectures are discussed and in the subsection 3.1.3, simulation as well as the calculation results for the downstream and upstream path are presented. Subsection 3.1.4 provides a discussion and comparison of the different architectures using the obtained results. Optimization of promising architectures will be discussed in the following *DISCUS* deliverable D4.2.

3.1.1 Introduction to long-reach passive optical networks

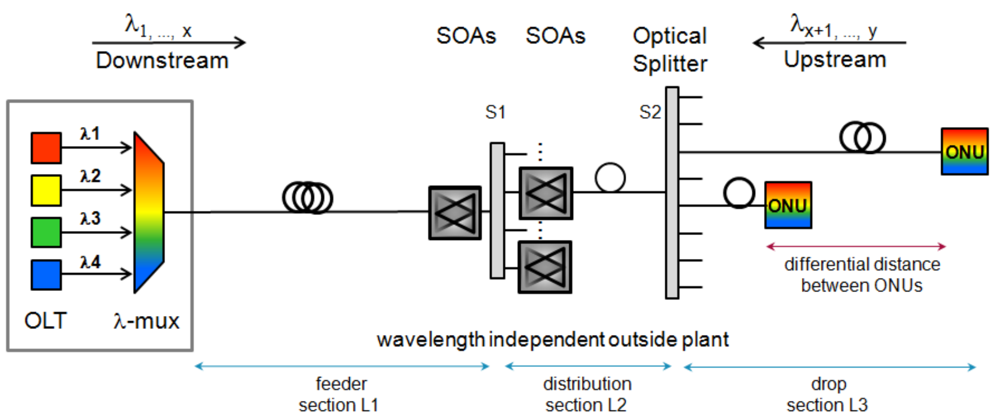


Figure 10: Typical configuration of a long-reach PON deploying optical amplifiers. Several downstream wavelength carrying, e.g. 10 Gbit/s data signals are transmitted over a feeder fiber section L1, optical amplifier stages, split stages S1, S2, … and a distribution fiber section L2 as well as a drop fiber section L3 before the signals are detected at the ONU receiver. The upstream direction makes use of the identical fiber infrastructure, but of different optical amplifiers. No wavelength dependent equipment should be deployed in the optical distribution network.

Today's PON, e.g. gigabit PON (GPON) or 10 Gbit/s-capable PON (XG-PON) typically offers a reach of 20 km by a split of 1:32, always depending on budget classes and operator's deployment scenarios. For future PON evolution, the potential of deploying LR-PONs is strongly discussed. In [7], it is discussed that operators value greatly the passive nature of access network enabled by the PON architecture, and it is not the intention of the PON reach extension to move away from this. Nevertheless, having the option of active mid-span reach extenders can provide several benefits, as e.g. a reduced number of required OLT sites (major central offices), higher deployment flexibility for operators, and an efficient sharing of fiber infrastructure and OLT equipment.

In Figure 10, the basic architecture for the following discussion is shown and the important parameters are defined. The starting point for the basic scenario is a reach-extended version of the next-generation of passive optical networks (NG-PON2). Here, time-and-wavelength-division multiplexing (TWDM) has been selected as primary solution which will provide an aggregated bit rate of at least 40 Gbit/s OOK (e.g. 4 λs on 100 GHz grid with 10 Gbit/s each) in the downstream (DS) path and an aggregated bit rate of 10 (40) Gbit/s OOK (e.g. 4 λs with 2.5 (10) Gbit/s each) in the US path. Thus, it should be mentioned that in this study, we focus on intensity-modulated and direct detected systems only in which the data signals are amplified by in-line amplifiers.

In our first approach for the LR-PON using SOA, we target a total fiber reach of 100 km with a total split ratio of at least 1:512 by using 4 US and 4 DS wavelength at a symmetric aggregated bit rate of 40/40 Gbit/s. Afterwards, by optimizing LR-PON architectures, a higher number of wavelength, e.g. up to 32 DS and 32 US channels will be studied together with the maximization of the split ratio.

Figure 10 shows an OLT which comprises 4 wavelength channels with 10 Gbit/s NRZ-OOK signals each for the downstream direction. The wavelength channels are multiplexed using e.g. an arrayed waveguide grating (AWG) and the signals are sent to the direction of the optical network units (ONU) over the feeder section with length L1, amplifying SOA stages, split-stage S1, S2, … and the distribution fiber section of length L2 as well as the drop fiber section of length L3. No wavelength selective devices in the optical distribution network (ODN) are deployed, as e.g. an optical filter. The ONU receiver comprises an optical filter to select the desired wavelength channel. The upstream direction makes use of the identical fiber infrastructure, but using separate optical amplifiers.

3.1.2 LR-PON architectures with in-line semiconductor optical amplifiers

In this section, different LR-PON architectures are introduced. The study contains a simple LR-PON architecture using a star–topology, a tree as well as bus–topologies. The architectures are according to the *DISCUS* deliverable D2.1 [17]. Different amounts of SOAs are deployed in the architectures.

3.1.2.1 Simple star architecture using single amplifier extender

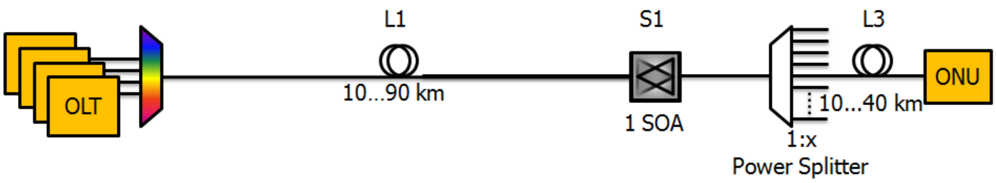


Figure 11: LR-PON architecture using a single SOA for DS and a single SOA for US amplification, respectively

The first LR-PON architecture uses a single SOA as reach extender in the DS direction and a single SOA as reach extender in the US direction, see Figure 11. The length of the feeder section is between 10…90 km, the distribution fiber section L2 is zero and the drop fiber section L3 is between 10…40 km. In general the split ratio 1:x strongly depends on the SOA gain values. According to Figure 10 and the discussions in the previous subsection, 4 DS and 4 US wavelength channels with a bit rate of 10 Gbit/s each is assumed.

3.1.2.2 Cascaded amplifier splitters-tree architecture

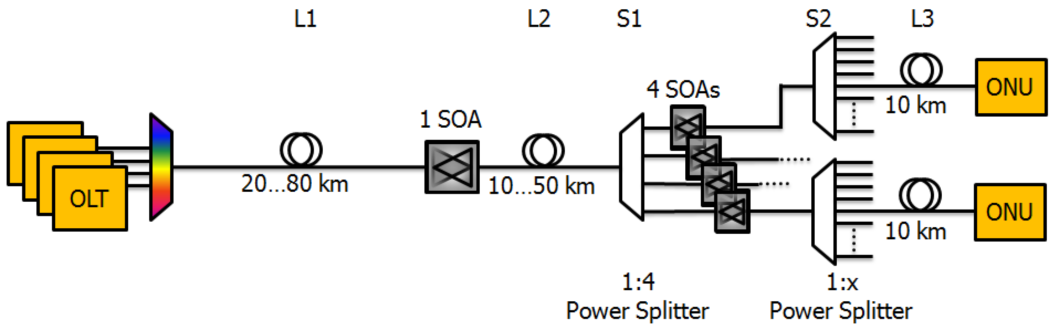


Figure 12: Tree-based LR-PON architecture deploying 5 SOAs for the DS and 5 SOAs for the US

The second LR-PON architecture uses a single SOA as reach extender in the DS direction and a single SOA as reach extender in the US direction to amplify all wavelength channels between section L1 and L2, see Figure 12. The length of the feeder section L1 is 20…80 km. Behind L1, the distribution fiber section with length L2 of 10…50 km is used. Then, a fixed 1:4 power splitter (S1), an individual SOA for each branch (amplifying all wavelength channels) and following a 1:x power(S2) splitter is tested. Finally, the drop fiber section L3 has a fixed length of 10 km. The overall structure of the LR-PON scenario is based on cascaded amplifier splitters. This topology can be related to a tree architecture. In general, the split ratio 1:x strongly depends on the SOAs gain values. It should be mentioned here that the configuration of the splitter S1-SOAs-S2 has the potential to be integrated on a single chip.

3.1.2.3 Bus-feeder and combined bus-feeder / tree-distribution architecture

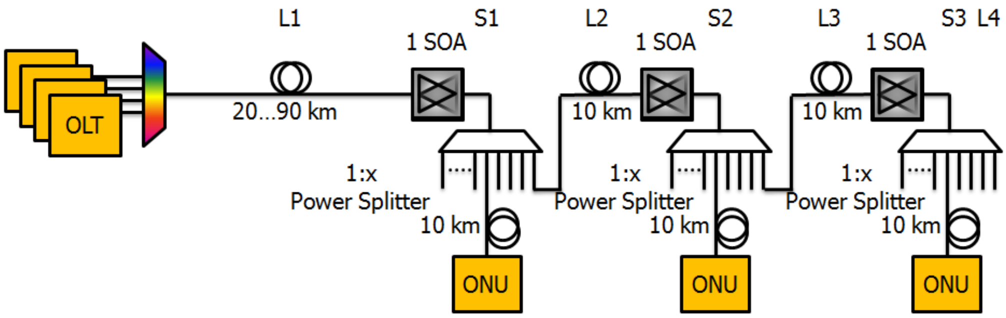


Figure 13: Bus-based LR-PON architecture deploying 3 SOAs for the DS and 3 SOAs for the US

The third LR-PON architecture uses a single SOA as reach extender in the DS direction and a single SOA as reach extender in the US direction to amplify all wavelength channels after the feeder fiber section L1, see Figure 13. The length of the feeder section is 20…90 km. Behind L1 and the SOA, a 1:x splitter (S1) is deployed. (x-1) of the splitter branches are used to drop the signals over a fixed drop fiber length L4 of 10 km to the customer premises. A single arm of the splitter S1 is connected to the distribution fiber L2 which has a fixed length of 10 km. Then, the signals in this main arm of the bus architecture are amplified by another SOA. Behind L2 and the second SOA, a 1:x splitter

(S2) is deployed. Again, (x-1) of the splitter branches are used to drop the signals over a fixed drop fiber length L4 of 10 km to the customer premises. A single arm of the splitter S2 is connected to the distribution fiber L3 which has a fixed length of 10 km. Then, the signals in this main arm of the bus architecture are amplified by a third SOA and afterwards, the signals are finally dropped by a 1:x (S3) splitter to the direction of the customer premises. Again, a drop fiber length (S3) of 10 km is used.

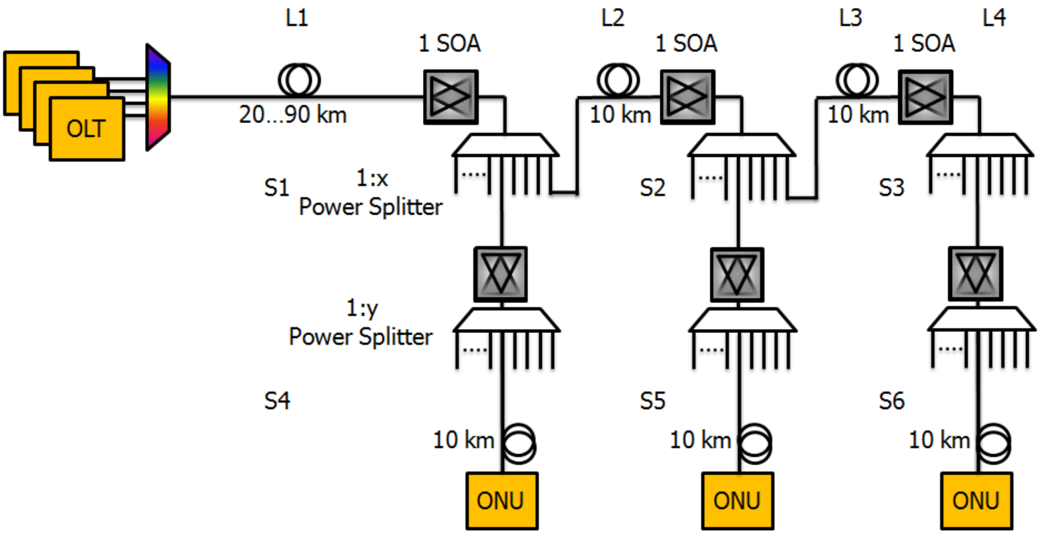


Figure 14: Extended version of the bus-feeder based LR-PON architecture using (3x+1) SOAs for the DS and US, respectively

An extended version of the third LR-PON architecture is shown in Figure 14. Here, each of the x-1 drop arms (S1, S2, S3) comprise an SOA and following a 1:y splitter (S4, S5, S6) to drop the signals to the customer premises over a fixed drop fiber section of 10 km (L4, fixed).

3.1.3 Simulation and calculation results for different LR-PON architectures

In this subsection, the introduced LR-PON architectures are investigated in simulations using a system simulator software tool. Additional signal power and noise power calculations using Excel sheets and receiver sensitivity calculations using Matlab codes are performed. First, the simulation and calculation environment is introduced and afterwards the results are presented, discussed and analyzed.

3.1.3.1 Simulation and calculation environment

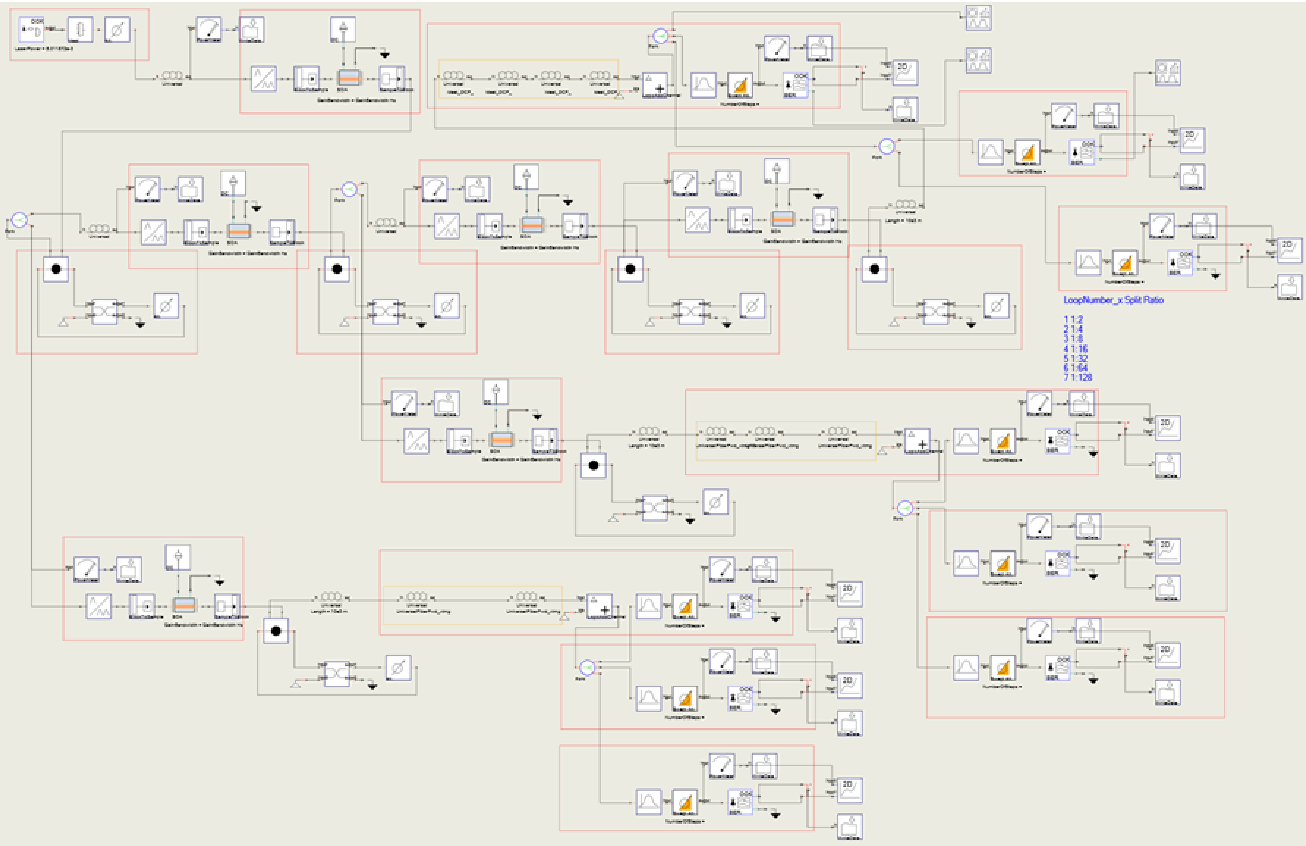


Figure 15: Generic setup scheme of simulation environment using a system simulator. Here, the extended version of the third setup according to Fig. 5 is shown exemplarily.

The simulation environment to investigate the different LR-PON architectures in the downstream direction is generated based on the system simulator VPI, see Figure 15. According to the intended E1 budget class of the NG-PON2 standard, the components such as OLT/ONU transceivers, max. splitter losses, max. fiber loss and dispersion parameters are implemented. Table 3 provides an overview of the important device and system parameters.

Table 3: Important system and simulation parameter overview

Parameter	Value
Number of DS/US wavelength channels	4/4
WDM Channel Spacing in DS around 193.1THz	100 GHz
Modulation format	NRZ-OOK
Bit rate per channel with PRBS of 2^{15}-1	10 Gbit/s
OLT transmitter extinction ratio of externally modulated source	10 dB
OLT transmitter output power per λ-channel	+7 dBm
ONU transmitter output power	+2 dBm

Fiber losses assumed for DS and US path	0.375 dB/km
Fiber chromatic dispersion assumed for DS path	20 ps/km nm
Splitter losses per 1:2 stage	3.5 dB
ONU receiver sensitivity (direct detection using avalanche photodiode (APD)) @ bit-error-ratio (BER) of 10^{-3} and 10 Gbit/s including a 50 GHz filter	– 28 dBm
OLT receiver sensitivity (pre-amplifier direct detection using avalanche photodiode (APD)) @ bit-error-ratio (BER) of 10^{-3} and 10 Gbit/s	– 33 dBm
Simulation bandwidth	10 THz
Number of simulated bits	2048

The OLT transmitters are based on a continuous-wave black-box laser model (100 MHz linewidth) followed by an external modulator and an AWG. The fiber model describes a single mode fiber (SMF) including loss, dispersion and non-linear effect such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave-mixing (FWM). The SMF is modeled using the split-step method. The SOA is based on a longitudinal segmented (about 30 segments) physical rate-equation model based on bulk material. ASE noise is included in the model via the inversion parameter. The SOA parameters, shown in Table 4, are chosen to approximately achieve the gain and noise figure values of a typical commercial-available-SOA. The SOA fiber-to-fiber gain (coupling losses of 3 dB / facet) versus the in-fiber input power is shown in Figure 16(a) as well as the ASE in-fiber output power versus the frequency is shown in Figure 16(b). Thus, a power and wavelength depend SOA gain model is used including also effect such as cross-gain modulation (XGM) between the wavelength channels. The ONU receiver (Rx) comprises a 50 GHz bandpass filter followed by an APD with 10 GHz bandwidth. Additionally, the ONU-Rx is equipped with an ideal dispersion compensation using lossless and linear dispersion compensation fiber (DCF) with dispersion values always adapted to the downstream fiber length. At the Rx, the simulated bits are superimposed, and a Gaussian probability density function of the bit 1 and the bit 0 is used for BER estimation.

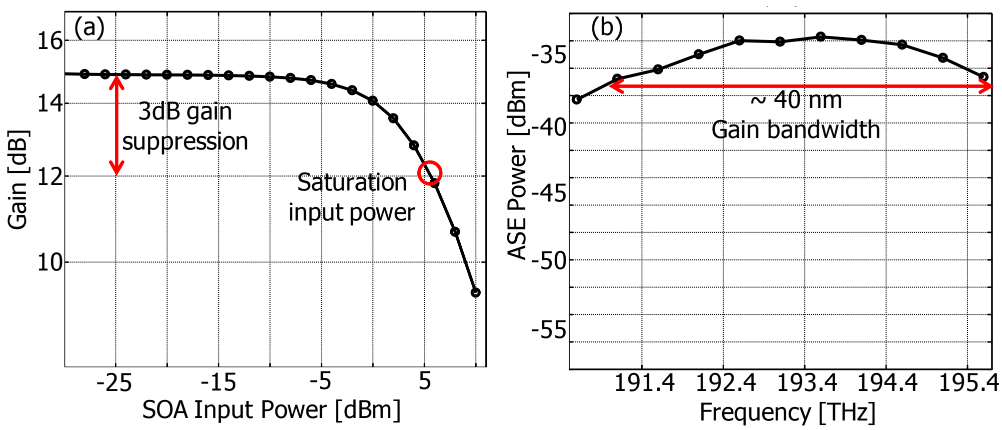


Figure 16: Characterization results of the SOA model. (a) The gain versus the input power is shown, and the 3 dB saturation input power is indicated by the circle. (b) The ASE output power versus the signal carrier frequency. The 3 dB gain (ASE) bandwidth is indicated, and it is about 40 nm.

Table 4: Important parameter overview of the bulk-SOA

SOA Parameter	Value
Device length	500 µm
Active region width	3 µm
Active region thickness	200 nm
Confinement factor	0.2
Operating current	350 mA
Gain and ASE bandwidth (> 0 dB)	10 THz
3 dB-Gain and ASE bandwidth	~ 40 nm
Small-signal gain	15 dB
Noise figure	9 dB
Saturation input power (at 3 dB gain reduction point)	+5 dBm

The upstream path of the different architectures is studied in terms of power budget and ASE power accumulation, e.g. in case of noise funneling. Therefore, Excel calculations are generated applying the parameters presented in Table 3 and Table 4. By knowing the total accumulated ASE power level at the OLT-Rx, the influence of this noise on the receiver sensitivity for the pre-amplified OLT receiver is studied using Matlab. Here, the delivered signal-to-noise-ratio (SNR) at the receiver after the US path including important noise contributions such as signal-ASE noise beating, ASE-ASE noise beating, shot noise, thermal noise and relative-intensity-noise is calculated.

In the following subsections, results for the DS and the US path for the different architectures are presented in terms of max. achievable split ratio for a given max. feeder, distribution and drop fiber length.

3.1.3.2 Downstream simulation results for the various architectures

In Figure 17 the simulation results for the first architecture presented in Figure 11 are shown. Figure 17(a) shows the BER versus the ONU receiver input power for different feeder fiber length from 10 km…60 km and a fixed drop fiber length of 10 km. The possible split ratios are indicated for two cases (10 km, 50 km feeder fiber length). Obviously, for very short feeder fiber length a very high split ratio can be obtained. Further, here the input power to the SOA reach extender is exceeding the saturation input power causing bit patterning effects as well as XGM. This becomes obvious in the error-floor at BER of 10^{-9} for the 10 km curve. However, the target BER of 10^{-3} can still be reached with a small power penalty compared to the back-to-back (BtB) case. For long feeder fiber length, no noise issue induced by the SOA can be seen. Here, the system is power limited because the receiver input power is below the BtB receiver sensitivity. In Figure 17(b) the max. feeder fiber length versus the split ratio (1:x) for different drop fiber length is shown. Using this configuration, the target values for the LR-PON cannot be achieved, because the feeder fiber length and the split ratio cannot be maximized simultaneously.

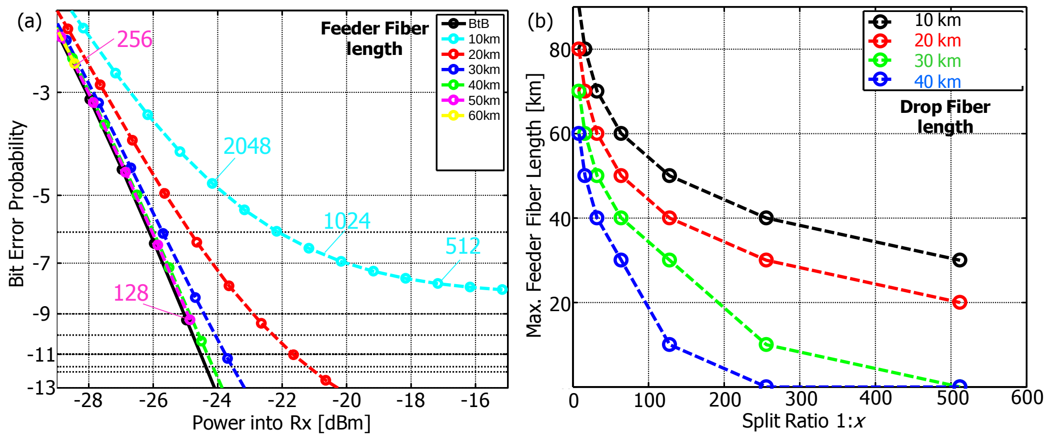


Figure 17: Simulation results for the first architecture according to Figure 11. In (a), the BER versus the ONU receiver input power is shown. In (b), the max. feeder fiber length versus the total split ratio for different drop fiber length is presented.

In Figure 18 the simulation results for the second architecture presented in Figure 12 are shown. Figure 18(a) shows the BER versus the ONU receiver input power for different feeder fiber length from 20 km…80 km and a fixed distribution and drop fiber length of 10 km, respectively. The possible split ratios are indicated for two cases (20 km and 60 km feeder fiber length). For very short feeder fiber length, a very high split ratio can be obtained. Further, here the input power to the SOA reach extender is exceeding the saturation input power causing bit patterning effects as well as XGM as it is the case for the previously discussed architecture. For long feeder fiber length, a small power penalty induced by the SOA can be seen at a BER of 10^{-11}. At the target BER of 10^{-3}, no power penalty is obtained. Thus in this regime, the system is power limited. In Figure 18(b) the max. feeder fiber length versus the split ratio (1:4 and 1:x) for different distribution fiber length of 10…50 km and a fixed drop fiber length of 10 km is shown. Using this configuration, the target values for the LR-PON can be (almost) achieved, e.g. using a 60 km feeder fiber length, a 10 km distribution fiber length as well as a 10 km drop fiber length and a 512 split ratio.

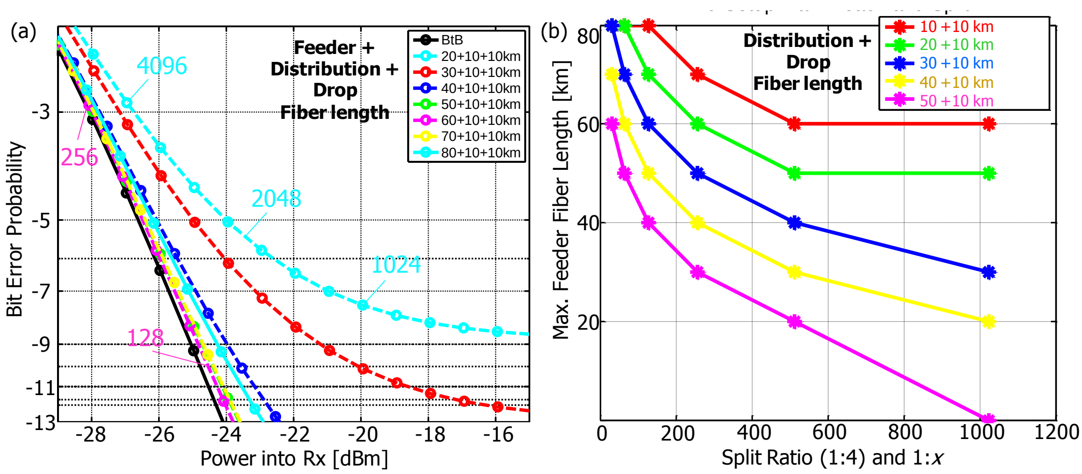


Figure 18: Simulation results for the second architecture according to Figure 12. In (a), the BER versus the ONU receiver input power is shown. In (b), the max. feeder fiber length versus the total split ratio for different distribution and a fixed drop fiber length is presented.

In Figure 19 the simulation results for the third architecture presented in Figure 13 are shown. Figure 19(a) shows the BER versus the ONU receiver input power for different feeder fiber length from 20 km...90 km and a fixed distribution fiber section 1 and 2 of 10 km, respectively, and a fixed drop fiber length of 10 km. The split is 22 in this case. For long feeder fiber length, a large power penalty induced by the noise accumulation of the SOA chain can be seen at a BER of 10^{-3}. Figure 19(b) shows the BER versus the ONU receiver input power for different feeder fiber length from 20 km...40 km and a fixed distribution fiber section 1 and 2 of 10 km, respectively, and a fixed drop fiber length of 10 km. The split is 94 in this case. For feeder fiber length of 40 km, no power penalty induced by the noise accumulation of the SOA chain can be seen at a BER of 10^{-3}. Using this configuration, the target values for the LR-PON cannot be achieved, because of the very low split.

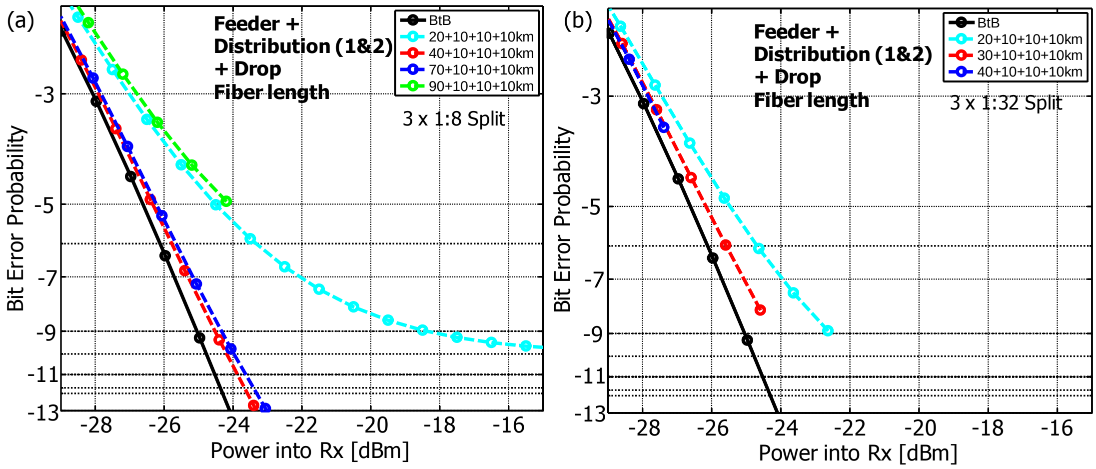


Figure 19: Simulation results for the third architecture according to Figure 13. In (a), the BER versus the ONU receiver input power is shown for a split ratio of the three 1:x splitters of 1:8. In (b), the BER versus the ONU receiver input power is shown for a split ratio of the three 1:x splitters of 1:32.

Finally, Table 5 shows the results obtained for the extended version of the third architecture according to Figure 14. Using this configuration, the target values for the LR-PON can be achieved, with the drawback of a high number of SOAs.

Table 5: Simulation results of the extended version of the third setup according to Fig.13.

Main Split Ratio 1:x	Max. number of customer (1:x,y) @ total fiber length	Total number of SOA(US and DS)
1:2	2816 @ 100 km	14
1:4	4352 @ 90 km	26
1:8	11264 @ 70 km	50

3.1.3.3 Upstream calculation results for the various architectures

In this subsection, the upstream path of the different architectures is investigated in terms of power budget and noise accumulation (noise funneling) along the SOA chain. Figure 20 provides the OLT receiver sensitivity (of the pre-amplifier receiver comprising an SOA with a gain of 15 dB and a noise figure of 7 dB, a 50 GHz ideal filter and an APD, see inset) versus the noise power density in the 50 GHz filter bandwidth. The BtB-performance of the OLT receiver is – 33 dBm including an additional 2 dB power margin. Starting with the undisturbed case of the receiver sensitivity (ASE power density of – 50 dBm/50 GHz), an increase of the noise power density by 10 dB causes a power penalty of about 5 dB.

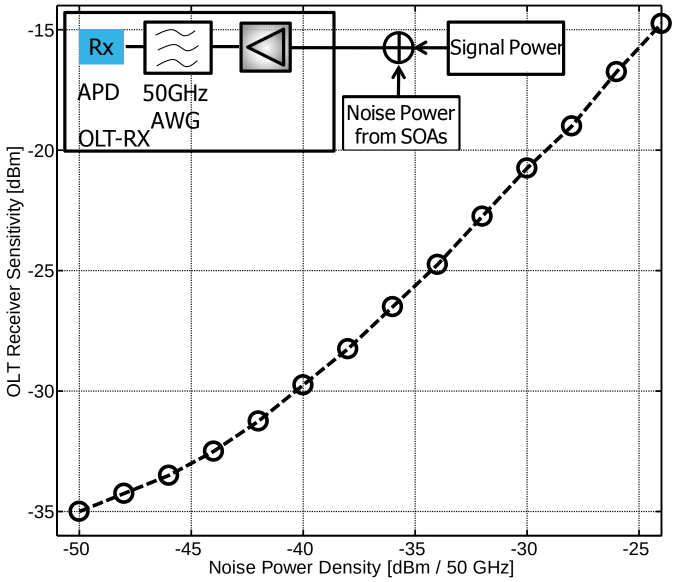


Figure 20: OLT receiver sensitivity at a BER of 10^{-3} versus the noise power density in the 50 GHz receiver bandwidth. The inset provides insight into the pre-amplifier receiver structure.

In the following, the max. achievable fiber length and the max. split ratio in the upstream path for the different architectures are analyzed. The power penalties in the OLT receiver due to the additional noise contributions according to Figure 20 are taken into account. A total ASE output power of – 7.5 dBm over the entire gain bandwidth of the SOA which is about 100 nm is taken into account. This number is according to the simulated device parameters. Additionally for the calculation, it is assumed that as long as the SOA is operated in its linear regime the ASE output power is constant and the SOA operating point is not changed by the accumulated ASE power. This assumption seems to be reasonable for the state-of-the-art linear SOA devices which offer a large input saturation power.

In Figure 21 the calculation results for the first architecture presented in Figure 11 are shown. The figure shows the max. feeder fiber length versus the total split ratio (1:x) for different drop fiber length. Noise funneling does not exist in this architecture, because all the upstream signals are amplified with an identical SOA. Using high split ratios, the signal power level from the ONU-Tx is too low to obtain the required optical-signal-to-noise ratio (OSNR) at the OLT-Rx. Using this architecture, the target values for the LR-PON cannot be achieved because the feeder fiber length and the split ratio cannot be maximized simultaneously.

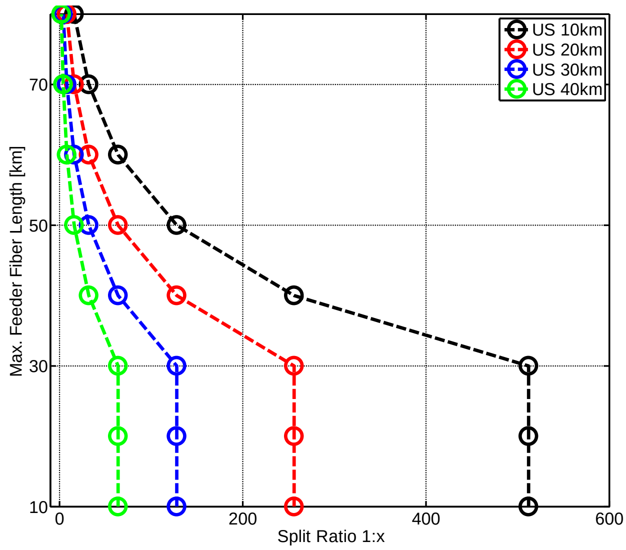


Figure 21: Calculation results for the first architecture according to Figure 11. The max. feeder fiber length versus the split ratio for different drop fiber length is presented.

In Figure 22 the calculation results for the second architecture presented in Figure 12 are shown. The figure shows the max. feeder fiber length versus the total split ratio (1:4, 1:x) for different drop fiber length. Noise funneling has a small influence in this architecture, because of the use of individual SOAs in the split arms which are combined in front of the feeder fiber. Using this configuration, the target values for the LR-PON can almost be achieved, e.g. using a 60 km feeder fiber length, a 10 km distribution fiber length as well as a 10 km drop fiber length and a 512 split ratio. It should be mentioned that the presented upstream values for split and reach are identical to the downstream values.

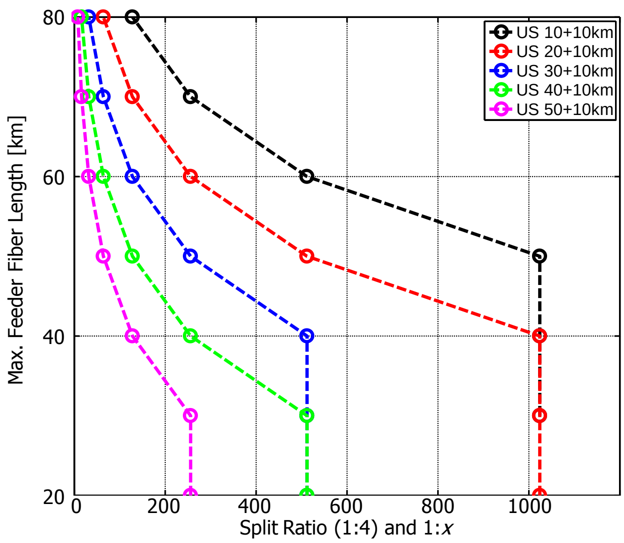


Figure 22: Calculation results for the second architecture according to Figure 12. The max. feeder fiber length versus the split ratio for different distribution fiber length and a fixed drop fiber length is presented.

In Figure 23 the calculation results for the third architecture presented in Figure 13 are shown. The figure shows the max. feeder fiber length versus the total split ratio (3 times 1:x) for a fixed distribution fiber length 1 and 2 of 10 km, respectively, and a fixed drop fiber length of 10 km. Noise funneling has no influence in this architecture, because of the use of SOAs along the main path of the bus topology only. Using this configuration, the target values for the LR-PON cannot be achieved due to the low amount of supported customers, e.g. using a 40 km feeder fiber length, a 10 km distribution fibers length as well as a 10 km drop fiber length and a 94 split ratio. However, the presented upstream values for split and reach are identical to the downstream values.

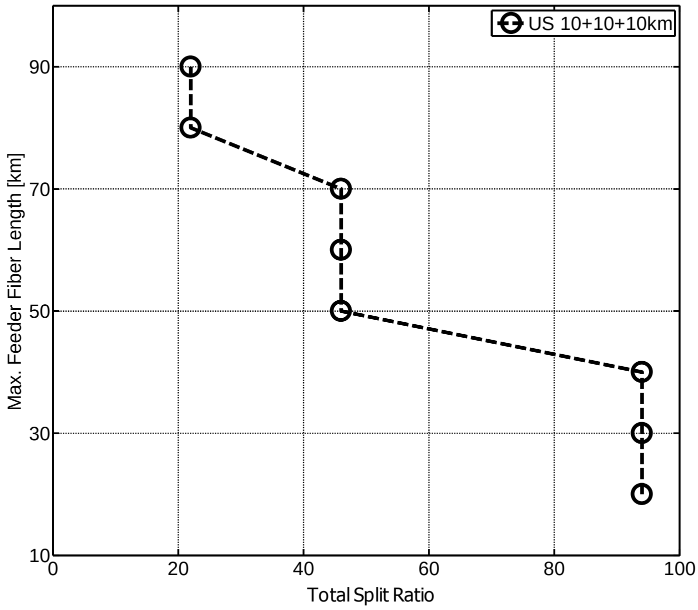


Figure 23: Calculation results for the third architecture according to Figure 3. The max. feeder fiber length versus the total split ratio for fixed distribution fibers length and a fixed drop fiber length is presented.

In Figure 24 the calculation results for the extended version of the third architecture presented in Figure 14 are shown. The figure shows the max. feeder fiber length versus the total split ratio (1:x, and 1:y) for a fixed distribution fiber length 1 and 2 of 10 km, respectively, and a fixed drop fiber length of 10 km for three cases of the 1:x splitter (x = 2,4,8). Noise funneling has a severe influence in this architecture, because of the use of SOAs in each of the arms of the 1:x splitter. However, using this configuration, the target values for the LR-PON can be achieved (x = 4,8), even in case of a massive reduction of supported customer if comparing to the DS results.

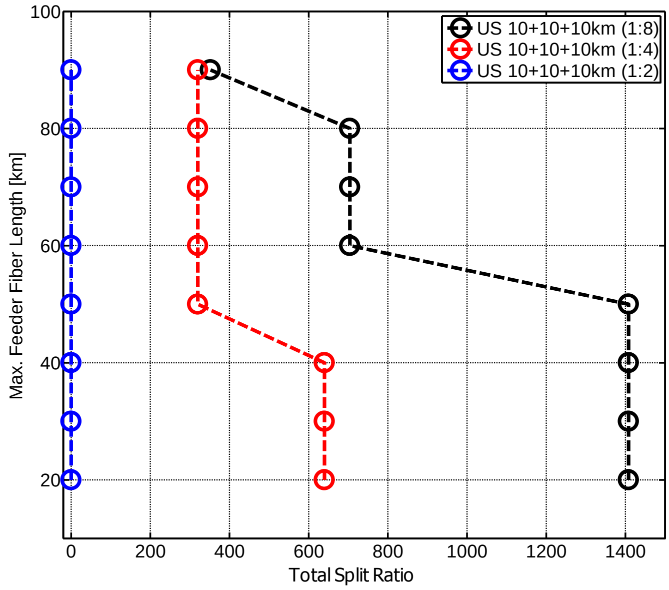


Figure 24: Calculation results for the extended version of the third architecture according to Figure 14. The max. feeder fiber length versus the total split ratio (1:2, 1:4, 1:8 and 1:y) for a fixed distribution fiber length 1 and 2 and a fixed drop fiber length is presented.

3.1.4 Comparison of pros / cons for different architectures

Table 6 is used to compare the max. achievable fiber reach and the max. achievable split ratios for the different LR-PON architectures in the US and the DS path.

Table 6: Comparison of the results for the different architectures in DS and US direction.

Archi.	Max. number of customer @ total fiber length in DS	Max. number of customer @ total fiber length in US	# SOA	Sustained bit rate per customer	Limitations	Flexibility	Remarks
1 (Fig.11)	512 @ 60 km	128 @ 60 km	2	312 Mbit/s	Power	low	Short reach
2 (Fig.12)	1024 @ 80 km	512 @ 80 km	10	78 Mbit/s	OSNR	medium	target values reached
3 (Fig.13)	94 @ 70 km	94 @ 70 km	6	425 Mbit/s	Power	low	very low number of customers
3E (1:2) (Fig.14)	2816 @ 100 km	Very low number	14	Power penalty > 20dB	Noise funneling	medium	US not working
3E (1:4) (Fig.14)	4352 @ 90 km	320 @ 90 km	26	125 Mbit/s	Power, ASE noise	high	target values reached
3E (1:8) (Fig.14)	11264 @ 70 km	1408 @ 70 km 704 @ 100 km	50	57 Mbit/s	Power, ASE noise	high	target values reached

Recapitulating the target values for the LR-PON in the *DISCUS* project, a total reach of 100 km with a total split ratio of at least 1:512 is intended. Comparing the target values to the simulated and calculated values from Table 6, we can conclude the following for the different architectures:

- Architecture 1: The performance of this architecture is limited mainly by the power budget. The target values for the split and the reach are not achievable simultaneously with the used gain of the linear SOA.
- Architecture 2: The performance of this architecture is limited mainly by the OSNR in the US path. If a high split of the 1:x splitter is used, a low signal power enters the amplified splitter stage. Here, noise funneling causes a high ASE noise which reduces the delivered OSNR. However, the target values for the split and the reach are almost achievable simultaneously with the used gain of the linear SOAs. The flexibility of this architecture is medium which comes from the use of a tree structure only.
- Architecture 3: The performance of this architecture is limited mainly by the power budget. The target values for the split are not achievable with the used gain of the linear SOAs.
- Architecture 3E (1:2): The performance of this architecture is limited mainly by noise funneling in the US path. If a high split of the 1:y splitters is used, a low signal power enters the amplified splitter stage. Here, noise funneling causes a high ASE noise power which significantly reduces the delivered OSNR. The power penalty in the US path is almost always > 20 dB which is unacceptable. Thus, this architecture does not support the target LR-PON numbers.
- Architecture 3E (1:4): The performance of this architecture is limited mainly by the power budget in the DS path and by noise accumulation in the US path. However, a large split ratio and a long reach are supported. Additionally, this architecture provides a high flexibility due to the combination of a bus feeder path and a tree distribution paths.
- Architecture 3E (1:8): The performance of this architecture is limited mainly by the power budget in the DS path and by noise accumulation in the US path. However, a large split ratio and a long reach are supported. Additionally, this architecture provides a high flexibility due to the combination of a bus feeder path and tree distribution paths. A reach of 100 km with a split ratio of about 700 are supported. The high number of required SOAs can become feasible with integrated SOA-splitter chips.

3.2 Dispersion mitigation in LR-PONs

Chromatic Dispersion (CD) is one of the characteristics of an optical fiber that limits the distance a signal can travel with a certain quality. It is of special interest for high bit rate transmission systems. Other kinds of dispersion as e.g. polarization mode dispersion are not considered here. The speed of light in a fiber is inversely proportional to the refractive index and the refractive index depends on the wavelength. By this, signals of different wavelength, as e.g. resulting from the modulation induced spectral broadening, travel through the fiber with different speed. In addition optical transmitters under direct modulation exhibit a chirp, meaning that e.g. for OOK modulation the optical "0" is emitted at a slightly different wavelength than the optical "1". The result of both effects is that at the end of an optical fiber link the signal shape is degraded which for pulse transmission results in an undesired pulse broadening.

CD can be compensated in the optical or electrical domain. Commonly used in optical core networks is a dispersion compensation fiber (DCF). The length of the DCF is selected to achieve the same magnitude but opposite sign of the link fibers dispersion. In this way, a relative broad compensation of S, C and L-band is possible with commercially available DCF. For access networks it would be also of interest to compensate the O-band. A possible solution would be special engineered fibers e.g. of photonic crystals. Compensation down to zero CD is possible only for a relative small wavelength range and only for a specific link length. For the rest of the wavelength (typically the edges of the range) a low residual CD remains, that has to be tolerated.

Another possible compensation scheme is an Optical Dispersion Compensator (ODC), typically implemented as tunable Bragg gratings or other cascaded filter structures. The basic idea is that for a filter, a small tuning around the center of the pass band will cause a certain phase shift at small amplitude variation. An ODC is typically used to ideally compensate CD for one channel. It is of special interest for very high bit rate transmission systems or for compensation at the edges of the usable spectrum of DCF.

Electronic Dispersion Compensation (EDC) compensates on a per channel base like an ODC, but in the electrical domain. By the transfer of the signal from the optical domain to the electrical domain, the optical phase information is lost and therefore a complete compensation of CD is not possible, but only a mitigation of the effect with a certain residual penalty. The characteristics of the optical transmitter (alpha factor) with the fiber dispersion define the fiber transfer function [18]. The goal of EDC is to compensate this complex filter function by an inverse transfer function. A good approximation is possible by a linear equalizer (multiple tap transversal filter structure) that tries to create the inverse filter function in the linear domain. Another possible solution is to modify the decision threshold in a decision feedback equalizer. In this way the information on previous bits is taken into account for the decision of the actual bit. The described techniques are applied in the DISCUS Task T5.1 by the 10Gbit/s burst mode receiver with EDC.

4 Summary and conclusions

The most critical parameters in designing optical networks for backhauling and fronthauling in wireless networks are latency and link capacity.

In backhauling applications both parameter specifications can be met in many cases using low cost TDM/TDMA based PON solutions like GPON and their 10G variants or their respective symmetric versions specified in NGPON2. The transport bandwidth offered by these systems is sufficient for macro and small cell backhauling and the statistical multiplexing of TDM/TDMA based PONs is particularly beneficial. Latency constraints are moderate in backhaul applications and get a bit more stringent only when it comes to coordinated operation among multiple base stations. Still, they are generally no principal block in optical backhaul architectures. However, optimisation of the applied DBA algorithms will help improve the performance on the radio link. Related considerations also suggest to keep wireless backhaul and residential/business access separate on different PONs. Further studies will be needed to provide more specific recommendations. These arguments also hold true for LR-PON architectures, unless cooperative multipoint processing is required. In these scenarios the small latencies allowed are generally inconsistent with the long fiber links. But this can be circumvented by employing a dedicated optical overlay on the feeding PON allowing for an optical short cut between neighbouring basestations ("bespoke network").

In fronthaul architectures the allowed latencies are much smaller and the required bandwidths are much higher when CPRI fronthauling is considered. TDM/TDMA-based PONs are generally no good choice for this application. Instead ptp-links either via dedicated fibers or via DWDM channels are preferred. However, it must be acknowleged that in this respect CPRI fronthauling is an extreme case of an architecture. Other variants, employing a different version of split processing in the base station architecture are under study in the wireless research community and will probably allow for more relaxed specifications of the latency and bandwidth budgets on the optical links.

For bridging the loss budget of LR-PON architectures optical repeaters are used that are generally located at one or multiple splitter sites in the ODN. Usually the optical signals are assumed to be amplified using EDFAs. But as this technology limits the optical spectral range that can be used, we numerically analyzed the performance of SOAs replacing the EDFAs in different LR-PON architectures. Their gain spectrum for linear operation is almost flat over more than 20 nm wide ranges and can be tailored to be centered at virtually any wavelength between O- and U- bands on transmission fibers. Commercially available SOAs now allow for linear operation over a wide range of input powers being compatible with power levels encountered in LR-PONs and making them suitable for use with DWDM as well as with burstmode transmission.

Simulations and calculations were performed for the DS and the US path of the architectures using SOAs for budget extension in either direction. It has been found that certain variants of tree and combined bus/tree architectures employing cascaded amplifiers can meet the requirements of the DISCUS network regarding total link length and split ratio. They will be investigated in more detail within the *DISCUS* deliverable D4.2. Subsequently the LR-PON architectures will be further optimized by assuming a higher number of wavelength channels, e.g. up to 32 DS and 32 US channels as well as higher total split ratios. The split ratios of the combined bus-feeder and tree-distribution paths will be varied allowing for different split ratios in different paths.

Several tools are available for mitigating chromatic dispersion induced signal distortions after transmission over long fiber distances, operating both in the optical and in the electrical domain. Within the DISCUS project an electronic mitigation technique will be employed that acts on the received signals after a linear receiver. This will also be useable with burstmode signals up to 10G. Details will be provided in Task T5.1.

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Abbreviations

ASE	Amplified Spontaneous Emission
APD	Avalanche Photo Diode
AWG	Arrayed Waveguide Grating
BBU	Baseband Unit
BER	Bit Error Ratio
btb	Back-to-back
CD	Chromatic Dispersion
CoMP	Cooperative Multipoint Processing
DCF	Dispersion Compensating Fiber
DS	Downstream
EDC	Electronic Dispersion Compensation
EDFA	Erbium Doped Fiber Amplifier
FWM	Four Wave Mixing
LTE	Long Term Evolution
NGMN	Next Generation Mobile Networks
ODC	Optical Dispersion Compensator
ODN	Optical Distribution Network
OLT	Optical Line Termination
ONT, ONU	Optical Network Termination, Unit
OOK	On-off-keying
OSNR	Optical Signal-to-Noise-Ratio
(LR) PON	(Long Reach) Passive Optical Network
ptp	Point-to-point
Ptmp	Point-to-multipoint
RRH	Remote Radio Head
Rx	Receiver
S-GW	Service Gateway
SMF	Singlemode Fiber
SNR	Signal-to-Noise-Ratio
SOA	Semiconductor Optical Amplifier

SPM	Self Phase Modulation
Tx	Transmitter
US	Upstream
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation