Upgrade paths from existing copper-based access solutions to advanced agile wavelength-routed passive optical networks

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Title

Upgrade paths from existing copper-based access solutions to advanced agile wavelength-routed passive optical networks

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To Sílvia, Marina and my parents

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List of acronyms

ADSL	Asymmetric Digital Subscriber Line
AN	Access Network
APON	Asynchronous Passive Optical Network
ASE	Amplified Spontaneous Emission
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BPON	Broadband Passive Optical Network
CATV	Cable Television
CDM	Code Division Multiplexing
CWDM	Coarse Wavelength Division Multiplexing
CO	Central Office
DBA	Dynamic Bandwidth Allocation
DEMUX	Demultiplexer
DOCSIS	Data Over Cable Service Interface Specification
DSLAM	Digital Subscriber Loop Access Multiplexer
DWDM	Dense Wavelength Division Multiplexing
EAM	Electro Absorption Modulator

EDFA	Erbium Doped Fiber Amplifier
EPON	Ethernet Passive Optical Network
FBG	Fiber Bragg Grating
FDM	Frequency Division Multiplexing
FM	Frequency Modulation
FSK	Frequency Shift Keying Modulation
FSR	Free Spectral Range
FTTC	Fiber-To-The-Curb
FTTCab	Fiber-To-The-Cabinet
FTTB	Fiber-To-The-Building
FTTD	Fiber-To-The-Desktop
FTTH	Fiber-To-The-Home
GBA	Geographical Bandwidth Allocation
GCSR	Grating assisted co-directional Coupler with rear Sampled Reflector
GEPON	Gigabit Ethernet Passive Optical Network
GPON	Gigabit Passive Optical Network
HDTV	High-Definition Television
IEEE	Institute of Electrical and Electronics Engineers
IM	Intensity Modulation
ITU	International Telecommunications Union
LRPON	Long-Reach Passive Optical Network
MAC	Medium Access Protocol
MAN	Metropolitan Area Network
OADM	Optical Add and Drop Multiplexers
OBS	Optical Burst Switching
OLT	Optical Line Terminal
ONU	Optical Network Unit
ONT	Optical Network Terminal
P2P	Point-to-Point
PON	Passive Optical Network

P2MP	Point-to-Multipoint
RN	Remote Node
RSOA	Reflective Semiconductor Optical Amplifier
SCM	Subcarrier Multiplexing
SOA	Semiconductor Optical Amplifier
TDM	Time Division Multiplexing
UTP	Unshielded Twisted Pair
VCSEL	Vertical Cavity Surface Emitting Laser
VDSL	Very high datarate Digital Subscriber Line
VoD	Video on Demand
VR	Virtual Reality
WWW	World Wide Web
xDSL	Digital Subscriber Line

1 Introduction

Data communications are developing very quickly and new applications demand a redesign of the access network infrastructures in order to fulfill new bandwidth and latency requirements. At present, there is an important bottleneck in the communication between local area networks and core networks due to the low data rate transmission capabilities of access networks.

xDSL technologies present a temporary solution, as xDSL transmission capabilities rely on the copper infrastructure, deployed several decades ago, set up to carry voice services. Copper wires do not have enough bandwidth for high data bit services and therefore xDSL technologies require advanced signal processing and modulation techniques to exploit the available bandwidth to the limit. Also, xDSL compromise between distance and data rate is very limiting, so when data rate is increased to the tenths of Mbps the distance of the data link needs to be reduced to less than 500m to be able to establish a reliable transmission.

Wireless communications is another competitor of fiber in access. The main advantage of wireless networks is its quick deployment and low cost implementation. However, the main problem of wireless data transmission is robustness, added to the fact that the available bandwidth is limited and many times regulated by national government bodies. Also, applications with high demanding bandwidth or low latency requirements are difficult to deploy on wireless networks due to the variability of the transmission media together with limited bandwidth availability.

Access optical networks overcome all the problems of both xDSL and wireless technologies by offering immense bandwidths over long distance links solving all present and future bandwidth requirements for present and future applications. The main difficulty of optical networks to become the chosen technology for access relies on their higher deployment costs. xDSL technologies use an infrastructure which has already been deployed and wireless communications do not require any infrastructure at all. Nevertheless, once the optical network infrastructure is deployed there is no other transmission media that can compete against fiber in terms of bandwidth or distance. Also, optical access solutions are the best economic model for green field deployments.

There are of special interest optical network architectures based on passive devices. These networks are called Passive Optical Networks (PONs) and constitute the most advanced access topology so far. As PONs do not use any powering in field, PONs are very reliable. Also, network maintenance costs are low as PONs do not require any environmentally-controlled location in field to install active equipment.

The objective of this thesis is to evaluate different network topologies for passive optical networks in access focusing on efficiency and cost effectiveness in order to find a realistic approach that can compete against other access technologies in terms of costs. Also, a realistic upgrade path from a copper-based infrastructure to a completely optical access solution will be described. Transmission distance is another parameter that is considered together with the ability to serve as many subscribers as possible from a unique Exchange Center. The limit of this is the Long-reach PON concept, which merges the Metropolitan Area Network (MAN) and the access network into one.

All these concepts will be explored and analyzed in the present document, which has been classified as follows:

Chapter 2, State of the art, will describe the present developments in access networks and will help the reader to get focus into the work. After a brief description of different FTTx scenarios, the long-reach PON concept will be presented and described. Then, different media access control (MAC) protocols and multiplexing techniques will be described and the commercial standards that are being deployed at present will be presented.

Chapter 3 will describe the components that are required to deploy an advanced network infrastructure, from optical routers based on arrayed-waveguide gratings (AWG) to tunable sources for agile wavelength tuning and reflective receivers and modulators based on reflective semiconductor optical amplifiers (RSOA).

Chapter 4 analyses the commercial viability of a gradual upgrade path, from the existing copper-based infrastructure to a totally optical outside plant, by incorporating two intermediate stages, the first one based on VDSL and the second one based on switched Ethernet.

Chapter 5 will dive us into advanced topologies for FTTx, where different outside plants and multiplexing techniques will be described, analyzed and experimentally demonstrated.

Chapter 6 will develop advanced MAC protocols for FTTx to optimize available bandwidth on high-density access networks.

Finally, the conclusions section will summarize the work and present future research lines to continue developing this topic.

2 State of the art

The concept of optical access networks is very wide and has many different approaches. Fiber-To-The-x (FTTx) includes all the possible cases of deploying optical fiber from the Central Office (CO), also known as Optical Line Terminal (OLT) to the end user subscribers. “x” is a variable that could be “H” for home (FTTH), “B” for business/building (FTTB) and “C/Cab” for curb/cabinet (FTTC/Cab). These terms pertain to several “last mile” network access applications, involving typically single fiber telemetries between a remote terminal (at the OLT / CO) and the subscriber premises (ONT: Optical Network Terminal or ONU: Optical Network Unit).

Advances in single fiber, full duplex, transceiver technology has enabled several important “last mile” network access applications including FTTB, FTTC, and FTTH. Typically, FTTB networks transport bi-directional, high data rate voice and data signals to businesses, whereas FTTC and FTTH support bidirectional high data rate voice, data and broadcast video signals for bundled residential subscriber services.

Fiber To The Home (FTTH) is the most advanced of these applications, typically using a single optical fiber to directly connect the subscriber’s home to the network. This provides a truly “future proof” network with no electrically active components, since passive, single mode fiber optic telemetry supports virtually unlimited signal bandwidth. No changes to the outside cable plant would then be required as new services, which require increasingly higher digital data rate and analog bandwidth, are developed. Telephony, voice over IP, very high data rate internet access, CATV, Direct Broadcast Satellite, HDTV are among the most popular services being offered today.

However, there is a further evolution stage to FTTH which is Fiber To The Desktop (FTTD). This would be the final evolution of the fiber deployment, deploying fiber inside the house to interconnect all the equipment of the home by means of optical fiber.

Another classification in today's FTTx network architectures is the type of connection between the CO and the ONUs.

This can be PTP (Point to Point) in which a direct fiber link connects each end user to the local network node, and PTMP (Point to MultiPoint) in which the signal is divided between several end users (the number of users depends on the characteristics of the application: distance, optical loss budget, wavelength...). When PTMP networks have a passive outside plant are named PONs (Passive Optical Networks) and are the ideal solution to deliver advanced services to end users, due to its multicast nature and high sharing factors of the optical equipment located at the CO, together with relatively low deployment costs [Green05].

2.1 Passive and Active Access Networks

A Passive Optical Network (PON) consists of an optical line terminator (OLT) located at the Central Office (CO) and a set of associated optical network terminals (ONT), also known as optical network units (ONU) to terminate the fiber. In at FTTH deployment, ONUs are located at the customer's premise but in the other FTTx approaches, ONUs are located in an intermediate point between the CO and the end user. Both of these devices require power.

PON gets its name because instead of using powered electronics in the outside plant, it instead uses passive splitters and couplers to divide up the bandwidth among the end users – typically 16/32 or 64 over a maximum distance of 10-20 km.

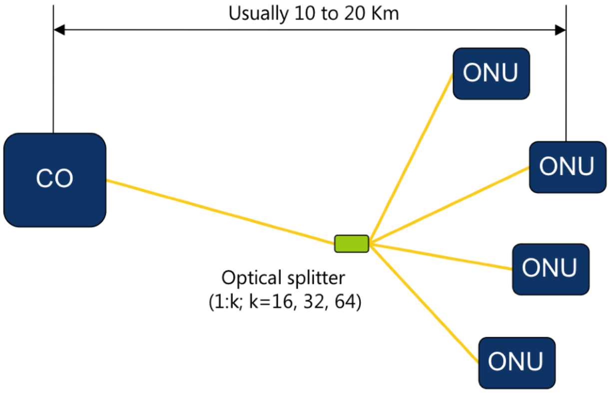


Fig 2.1 PON architecture

Active networks look very similar to PONs; however, there are several important differences. The most relevant one is that instead of having passive splitters in the field, it uses electronics to provide fiber access aggregation. At the RN, there is then a dedicated connection between the OLT and each of the ONTs by means of an active electric switch. Because of this, this type of architecture is sometimes referred to as Point-to-Point (P2P). Distances in active networks are greater than in PONs because all the links are P2P and just limited by power budget constraints. Active networks can then reach 50 km in the feeder fiber link and up to 10-20 km in the distribution links. The number of ports is limited by the switch employed and not by the infrastructure itself. However, the price to pay to have this distance extension and added number of connection ports is the use of active equipment in the field. This is a very limiting factor due to the requirement of an environmentally controlled location to place the switching equipment. Also, at the remote node there is a mirror optical interface for each ONU so the total number of optical interfaces is higher than in the PON approach.

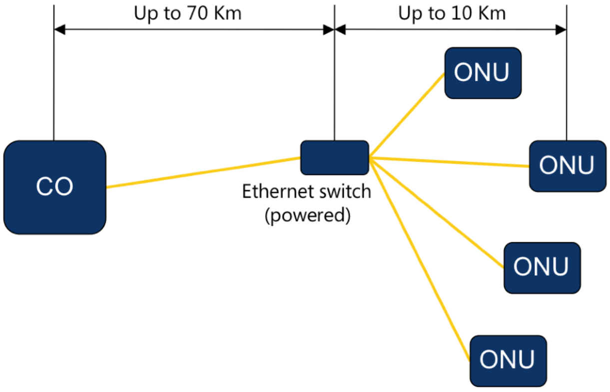


Fig 2.2 Active architecture

The main advantage of active networks is that the link between the remote node and the ONUs is dedicated and, therefore, it is possible to use simple electrical/optical devices at the ONU. In the passive networks, all the devices transmit at of the optical channel data rate in burst mode, so electronics are more complex.

Although active networks have some advantages, the limitations make them less attractive than PONs. Outdoor power supplying, the requirement of environmentally controlled locations for the equipment, higher maintenance costs of the network, less reliability due to the use of electronics at the remote node and higher number of optical interfaces make active networks not attractive for a future proof deployment.

Network scalability is also more complicated and costly for active networks, since it is generally necessary to change RN electronics to adequate new capacities and modulation formats. A passive network is completely transparent to these changes and only the ONUs and the OLT need the new capacity features to be modified. In addition, passive networks can be extended to all available optical bands.

Network	Advantages	Disadvantages
Active access networks	Optics/electronics at end user data rate Dedicated link between RN and ONU P2P links Simple network standards	Low interface utilization no burst-mode available Bit rate-dependent infrastructure Active equipment in field Not future proof
Passive access networks (PONs)	Efficient for burst traffic Reliable Passive outside plant (not powered) Transparent bit rates & modulation Easy to upgrade	shared transmission media MAC required burst mode equipment

Table 2.1 Comparison between active and passive access networks

Another interesting solution is a hybrid extended topology, where passive optical splitters and an active remote node are used on the same network. This approach is very flexible and allows high density and, at the same time, cost effectiveness.

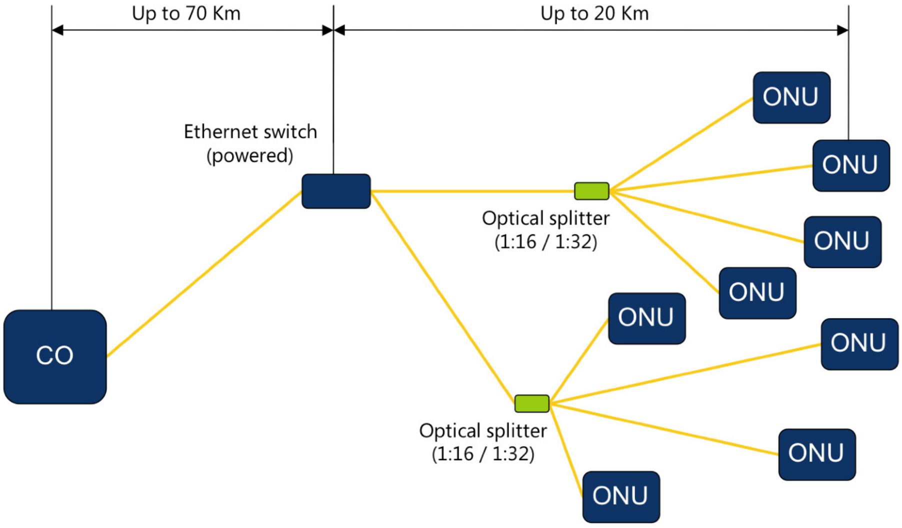


Fig 2.3 Hybrid architecture

The idea is to deploy an outside part based on two stages: the first stage an active point-to-point link between the CO and the first remote node, offering a high bandwidth connection. The second stage is *n* passive networks to interconnect the remote node with the end users. This approach is a good solution for long reach access networks as it allocates simple powered equipment in field but provides high number of connections and long distances.

2.2 FTTx

Having presented passive and active access networks, this section will describe different approaches to interconnect the CO with the end users under the FTTx concept. FTTx was coined to describe the progressive progress of migration from a copper-based access network to a fiber-based one, to deploy fiber from the CO to the users gradually, by adapting the outside plant in stages so the required investment to totally exchange the copper infrastructure by fiber is spread in time.

There are mainly four different FTTx approaches.

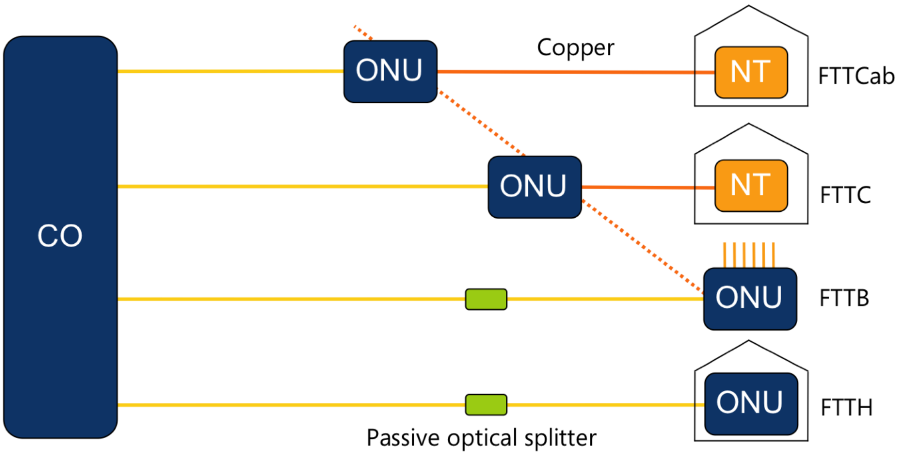


Fig 2.4 FTTx approaches

2.2.1 FTTCab

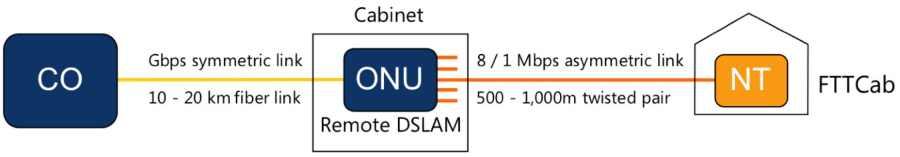


Fig 2.5 FTTCab block diagram

FTTCab architecture runs an optical fiber from the CO to the neighborhood cabinet, where the signal is converted to feed the subscriber over a twisted copper pair. Typically, the neighborhood cabinet is about 1 km from the subscriber's home or business. In the cabinet, a Digital Subscriber Line Access Multiplexer (DSLAM) distributes and aggregates traffic to / from the end users

[ITUTG995.1]. From that point to the end subscriber, the twisted pair transmits data to the end subscriber normally using ADSL technology [ITUTG992.x, x=1..5]. Data rates are mainly limited by the product bandwidth per distance of the copper cable. HFC networks also use this approach, but in this case, the copper media is a coaxial cable and the transmission protocol is based on DOCSIS standards [DOCSIS].

2.2.2 FTTC

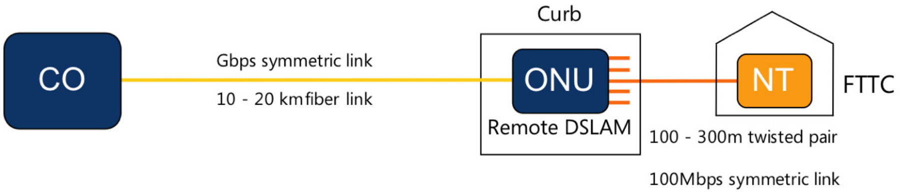


Fig 2.6 FTTC block diagram

FTTC architecture runs an optical fiber from the CO to a small curb-located cabinet, which is nearer (typically within 150 – 200 m) to the subscriber than in FTTCab approached. It is then converted to twisted copper pair. As the DSLAM is now located nearer the end users datarates can be higher and thus, VDSL [ITUTG993.1] solutions at higher data rate can be deployed. Using this approach, bidirectional 100Mbps per user can be transmitted using VDSL2+ [ITUTG993.2] standards on some links. However, data rates depend on the copper link characteristics.

2.2.3 FTTH/B

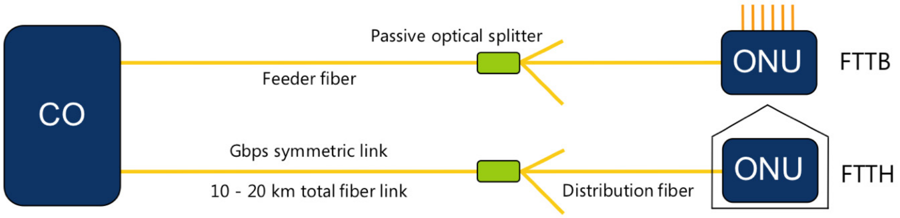


Fig 2.7 FTTH block diagram

The PON, when included in FTTH/B architecture, runs an optical fiber from a CO to an optical splitter and on into the subscriber's home or building. The optical splitter may be located in the outside plant or in a building. This is the last stage of the evolution as optical fiber runs all the way between the CO and the end subscribers. In this scenario, the network infrastructure has unlimited transmission capabilities, which are just limited by the technology used for the data transmission and the electronics used for its implementation.

A PON deployment can be common to all of these architectures. However, it is only in the FTTH/B configurations that all active electronics are eliminated from the outside plant. The FTTCab and FTTC architectures require active outside-plant electronics in a neighborhood cabinet or curb, which increases maintenance and operational costs. Also, those electronics are complex, especially for VDSL transmission due to the complex data modulation formats required to exploit the available electrical bandwidth. Power dissipation becomes also an issue in this case.

When fiber is used in a passive point-to-multipoint (PON) fashion, the ability to eliminate outside plant network electronics is realized, and the need for excessive signal processing and coding is eliminated. This signal processing was required in the xDSL scenarios in order to exploit all the available bandwidth of the twisted pair in an effective way because it was a very limited resource.

The PON, when deployed in a FTTH/B architecture, eliminates outside plant components and relies instead on the system endpoints for active electronics. These endpoints are located at the CO, at the local exchange, and the ONU, at the end subscriber premises.

Fiber-optic networks are simple, more reliable, and less costly to maintain than copper-based systems. When these components are ordered in volume for potentially millions of fiber-based access lines, the costs of deploying technologies such as FTTH/B, FTTCab and FTTC become economically viable. This is especially true on green field deployments, where several economic studies show that fiber is the most cost effective solution when a new network is deployed [Lin06, Park01, Vetter00].

2.3 Long reach PONs

The concept of long reach PONs define an access network of at least 100 km, with data rates starting at 2.5Gbps and giving connectivity to +1,000 users. This design parameters require the development of advanced transmission techniques to fulfill all the specifications at a reasonable cost.

A possible architecture of a long reach PON (LR-PON) is shown in Fig. 8. The headend of the LR-PON is located in the metro node instead of in the CO and the idea is to cover a complete metropolitan area from a single headend. Amplification in field is almost mandatory so transmitters should work in the 1550 nm window, where erbium doped fiber amplifiers (EDFAs) can be are used at the headend and at intermediate local exchange locations to extend the reach to at least 100 km. The 100 km reach is required to allow dual parenting of local exchanges onto metro nodes.

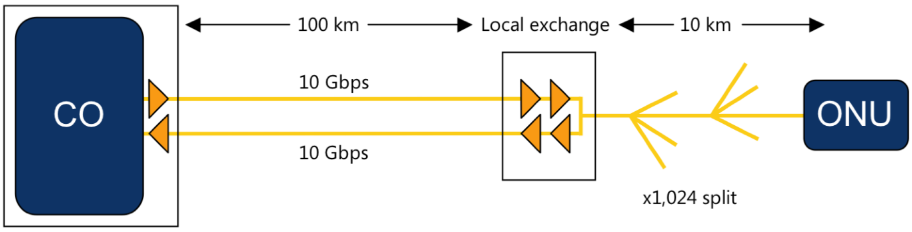


Fig 2.8 Long reach PON system architecture

LR-PONs are primary targeted for FTTH applications. However, they could equally be used to feed VDSL cabinets or radio base-stations and as such provide a flexible, future-proof solution.

As mentioned above one of the objectives of LR-PONs is to reduce the amount of equipment in nodes. Related to this, power consumption is another characteristic to minimize in future access solutions. Therefore, LR-PONs also targets the development of low-power equipment

2.3.1 Long reach PON – technical challenges

LR-PONs are not commercially available and are as yet a research concept. Nevertheless the potential benefits they offer are such that they are a very worthy research topic.

Given the large span losses involved, the first issue is whether adequate signal to noise performance can be achieved. Amplification in field will be required but this reduces signal to noise ratio, so amplification can not be infinite. Another issue is compatibility with commercial standards and whether the various PON protocols will scale to long lengths and high split. Long lengths in themselves are not an issue for existing GPON systems, as ranging protocol logically adjust distances between two consecutive ONUs by means of guard bands. A question which remains to be answered is the impact on system performance of bursty upstream data passing through erbium doped fiber amplifiers. Further work is also needed to develop a suitable 10 Gbit/s burst-mode receiver for the LR-PON headend. Cost reduction of the ONU transmitter is clearly another key area.

In order to further improve fiber efficiency, wavelength division multiplexing (WDM) could increase transmission capabilities of the LR-PON between the metro node and local exchange.

In conclusion, in order to economically support significant bandwidth growth, it is necessary to simplify networks. This can be accomplished by deploying LR-PONs. The concept is very wide and in the longer term, LR-PONs will provide further network simplification and so cost reduction [Talli06, Nessett04].

2.4 Multiplexing strategies

The Passive Optical Network concept, which has already been introduced in previous sections, define an access network without active devices between the Central Office and the end user. In any case, this definition is very wide and allows different technologies and access methods to be developed.

As in PONs there is a shared resource (the fiber), which is used for all the users to connect to the CO, a Media Access Control (MAC) needs to be established in order to guarantee the integrity of the information that is exchanged between the CO and each of the ONUs connected to the network.

There are many ways to multiplex different users on a common transmission channel. Sub-Carrier Multiplexing (SCM), Code Division Multiplexing (CDM), Time Division Multiplexing (TDM) and finally Wavelength Division Multiplexing (WDM) are the classical multiplexing techniques. There are many variants of each technology and also hybrid solutions combining two or more techniques are possible.

From the optical domain perspective, the two protocols that are more interesting are TDM and WDM. CDM is also becoming more attractive in the research field but with no commercial implementation yet. In this section we will mainly discuss TDM and WDM PONs and hybrid solutions combining both techniques.

2.4.1 Time Division Multiplexing

The principle of TDM PONs is to share a single laser source among the users connected to the network on time basis, assigning to each used a time slot, which can be dynamic or fixed. The information on a TDM PONs is broadcasted which means that all ONUs have access to the information sent from the CO. ONUs receive all the data streams and reject the ones which are not addressed to them. This feature is interesting for multicast transmission (like video broadcasting) but turns into a drawback when transmitting unicast traffic due to security inconsistencies.

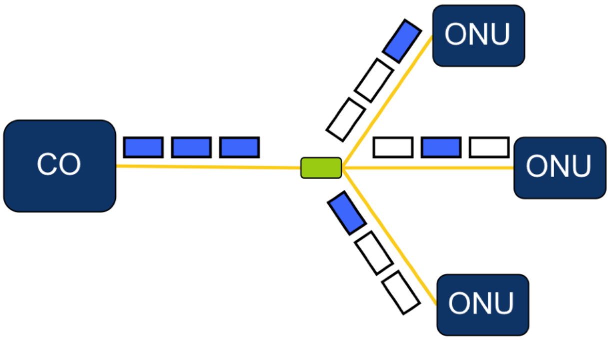


Fig 2.9 TDM PON

The most critical aspect of TDM PONs is however upstream transmission. Downstream transmission has just one emitter and several receivers so collisions of packets are not possible as they are just sent from a single source. However, the upstream transmission has several emitters (each ONU) and just one receiver (the CO) so in this case, collisions may occur if two emitters transmit at the same time. Therefore, synchronization of the upstream channel is critical on TDM PONs. Commercial standards and research groups have developed optimized upstream synchronization protocols, which can be easily implemented on the firmware of ONUs.

Another important consideration of TDM PONs is that the available bandwidth is shared among the ONUs connected to the network. The ability to share this bandwidth to the ONUs in an effective way is another important specification of TDMA PONs, which is currently under study and has different approaches.

The main advantages of TDM PONs arise when analyzing the economics of the implementation. The optical transmission is carried by a single laser at the CO shared among the ONUs connected to the network. Also, the power splitter located at the outside plant is relatively inexpensive when compared to wavelength-selective devices and furthermore, ONU laser equipment is simple and optical transmission requirements are not strict. This leads to a configuration that can be deployed at present and is commercially available. However, pure TDM PONs do not exploit the full potential of optical fiber, as just a very small portion of the available bandwidth is used.

2.4.2 Wavelength Division Multiplexing

To exploit more of the fibers THz bandwidth there are solutions that complement or even replace TDM as multiplexing technique. One obvious choice is WDM (wavelength division multiplexing), in which several baseband-modulated channels are transmitted along a single fiber but with each channel located at a different wavelength. Each of n different wavelength lasers is operating at the slower Gbps speeds, but the aggregate system is transmitting at n times the individual laser speed, providing a significant capacity enhancement [Park04].

The WDM channels are separated in wavelength to avoid cross-talk when they are demultiplexed by an optical fiber. The wavelengths can be individually routed through a network or individually recovered by wavelength-selective components. WDM allows using more of the fiber bandwidth than in a TDM PON. Note that each WDM channel may contain a set of even slower time-multiplexed channels.

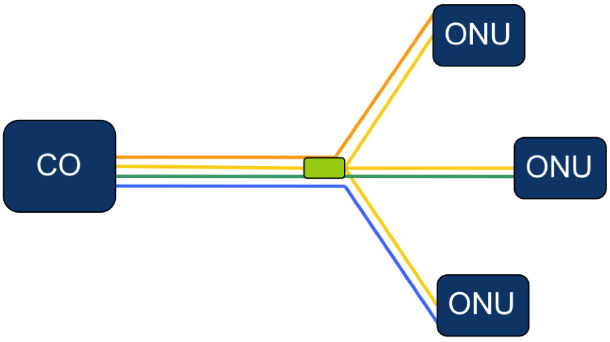


Fig 2.10 WDM PON

Pure WDM PONs are based on multiplexing users using a specific wavelength for each ONU. This technique creates a virtual point-to-point connection that allows full duplex transmission independently from the traffic of the rest of the users. As each ONU is connected on a specific channel, there is no need for any MAC protocol to assure correct transmission.

The main advantage of WDM is the very high transmission capabilities that the network can offer, together with the flexibility to use different data rates and network interfaces on each transmission channel.

However, the advantages of TDM PONs turn into disadvantages for WDM PONs. The main drawback of WDM PONs is the higher cost of implementation. First of all, at the CO there is the need to install one optical transceiver for each ONU, increasing the number of optical devices at the CO side. Also, in the outside plant, a wavelength router is required to route each wavelength to each of the ONUs connected to the network and finally, each ONU needs to transmit its upstream channel on a specific and unique wavelength. For that last purpose, if we want all ONUs to be the same, wavelength agnostic sources are needed.

Transmission requirements of WDM devices are very strict and require thermal stabilization to avoid crosstalk between adjacent channels (each dense-WDM channel is normally separated 0.8nm and defined on ITU-T G.984.1 grid). A more cost effective approach is to use Coarse-WDM, which relaxes the requirements of the devices by separating the channels to 20nm. However, this limits the number of channels that a single fiber can accommodate to 18, as per ITU-T G984.2 grid, and thus reduces the number of ONUs per fiber.

2.4.3 Combined WDM / TDM PONs

To overcome the problems of WDM PONs, in the last years some research has been develop in the field of combined WDM / TDM solutions. The idea is to mix both concepts to try to offer the best of both. The most accepted approach is to concatenate a WDM PON with a TDM PON, leading to a very dense network capable of offer connectivity to a very large number of users.

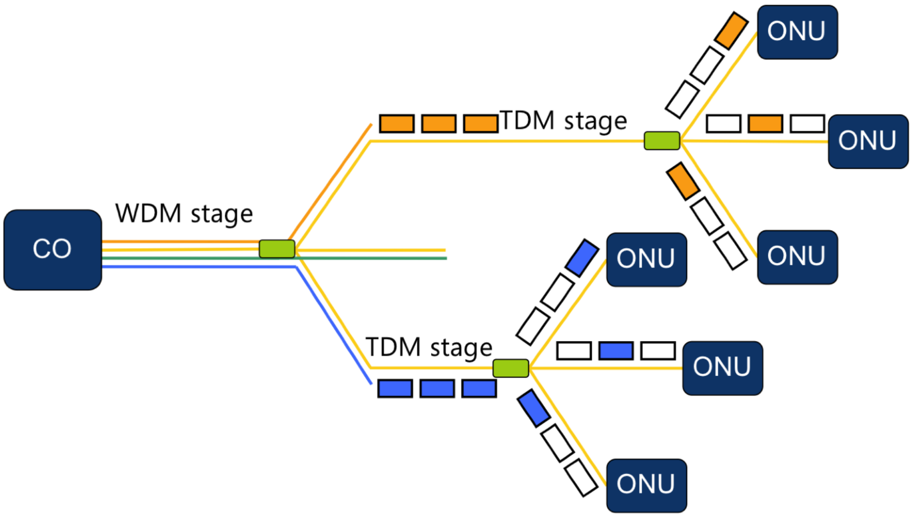


Fig 2.11 Combined WDM / TDM topology

The characteristics of the WDM stage allow low losses as thus the possibility to transmit long distances on the fiber feeder extension. Then, the WDM router at an intermediate remote node routes each wavelength to a outside port which interconnects the end user in a TDM PON. The principle is identical to the LR-PON but without using active equipment and any amplification. However, distances are not as high as in the LR-PON case. A very interesting approach is to combine C-WDM in the WDM and TDM to achieve so good compromise between cost and performance is achieved.

Another interesting approach that uses a combined WDM / TDM access method consists of sharing a laser stack at the CO among the ONUs connected to the network. In that case, each tunable laser located at the CO switches to different wavelengths sending data on TDM basis to the different ONUs. This alternative also reduces costs because there is no need to allocate one laser for each ONU at the CO. As ONUs are not transmitting all the time, network performance is not severely affected.

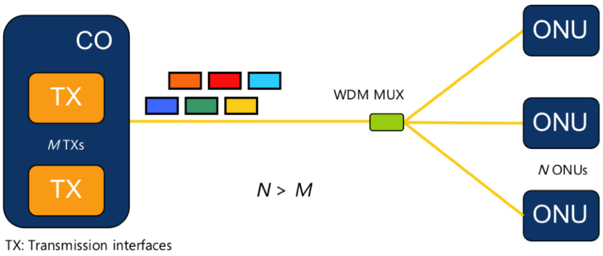


Fig 2.12 WDM / TDMA topology with a laser stack at the CO

The concept of this approach is to create a pure WDM-PON and reduce the equipment at the CO and do not use one transmitter per ONU. This reduces the cost of the equipment located at the CO but increments the complexity of the laser control and management.

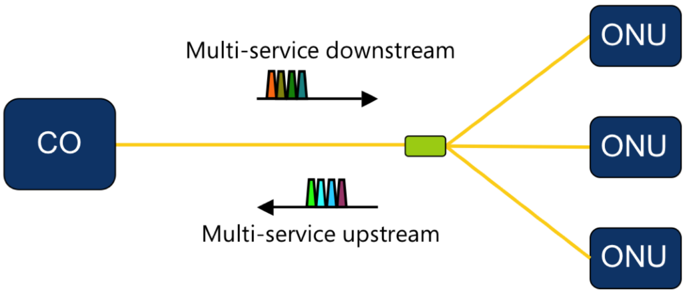


Fig 2.13 Open-access network solution

Finally, there is another approach based on offering different services on different wavelengths. This is sometimes called open-access networks and is an interesting model for municipalities, which deploy their own fiber and then give access to different operators. Open-access networks are based on a classical TDM-PON outside plant with a power splitter but transmitting several wavelengths on the fiber (tentatively a wavelength per operator). Then, at the end user side, by means of an optical filter, the end user selects the service that they want to receive (see Fig. 2.13)

2.4.4 SubCarrier Multiplexing

Another method conceptually related to WDM is subcarrier multiplexing (SCM). Instead of directly modulating a ~terahertz optical carrier wave with ~100s Mbps baseband data, the baseband data are impressed on a ~gigahertz subcarrier wave that is subsequently impressed on the THz optical carrier. Figure 2.14 illustrates the situation in which each channel is located at a different subcarrier frequency, thereby occupying a different portion of the spectrum surrounding the optical carrier. SCM is similar to commercial radio, in which many stations are placed at different RF (Radio Frequency) such that a radio receiver can tune its filter to the appropriate subcarrier RF. The multiplexing and demultiplexing of the SCM channels is accomplished electronically, not optically.

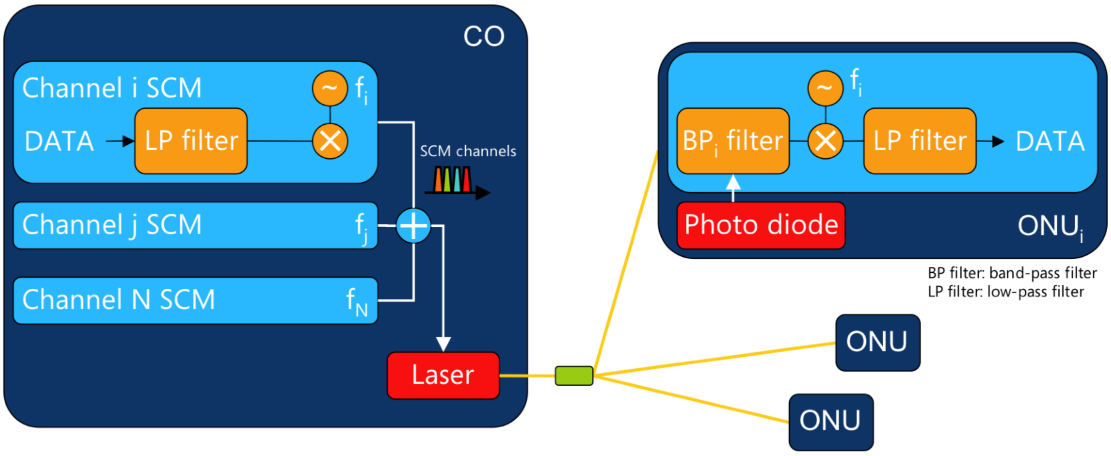


Fig 2.14 SCM principle, multiplexing and demultiplexing

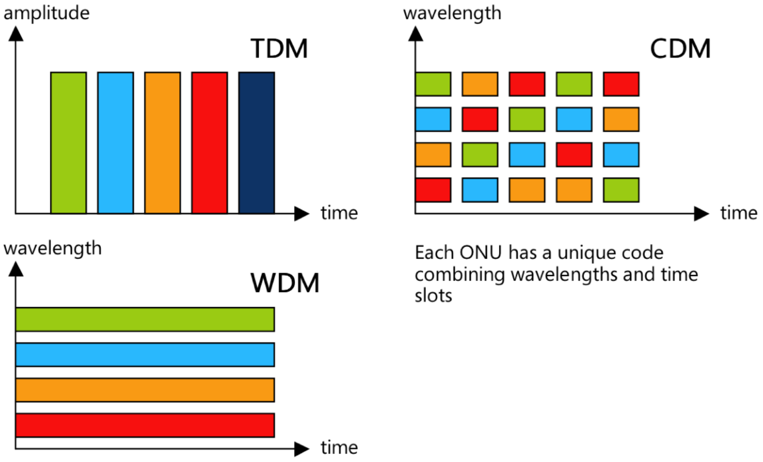
The obvious advantage of cost-conscious users is that several channels can share the same expensive optical components; electrical components are typically less expensive than optical ones. Just as with TDM, SCM is limited in maximum subcarrier frequencies and data rates by the available bandwidth of the electrical and optical components. Therefore, SCM must be used in conjunction with WDM if any significant fraction of the fiber bandwidth wants to be utilized, but it can be used effectively for lower-speed, lower-cost multiuser systems [Ho98].

2.4.5 Code Division Multiplexing

Another method is the code-division multiplexing (CDM). Instead of each channel occupying a given wavelength, frequency or time slot, each channel transmits its bits as a coded channel-specific sequence of pulses.

This coded transmission typically is accomplished by transmitting a unique time-dependent series of short pulses. These short pulses are placed within chip times within the larger bit time. All channels, each with a different code, can be transmitted on the same fiber and asynchronously demultiplexed. One effect of coding is that the frequency bandwidth of each channel is broadened, or spread.

If ultra-short (<100 fs) optical pulses can be successfully generated and modulated, then a significant fraction of the fiber bandwidth can be used. Unfortunately, it is difficult for the entire system to operate at these speeds without incurring enormous cost and complexity, at least at present [Kitayama06].



Each ONU has a unique code combining wavelengths and time slots

Fig 2.15 CDM transmission concept

2.5 Commercial solutions

The two commercial solutions for PONs that are offered at present work on TDM basis. Ethernet passive optical networking (EPON) [IEEE802.3ah] and Gigabit passive optical networking (GPON) [ITUTG984.x] are the solutions presented by IEEE and ITU-T under IEEE802.3ah and ITU-T G.984 respectively to provide connectivity for last mile access using optical fiber and a passive outside infrastructure. GPON defines also a completely new protocol designed to support multiple services in their native formats.

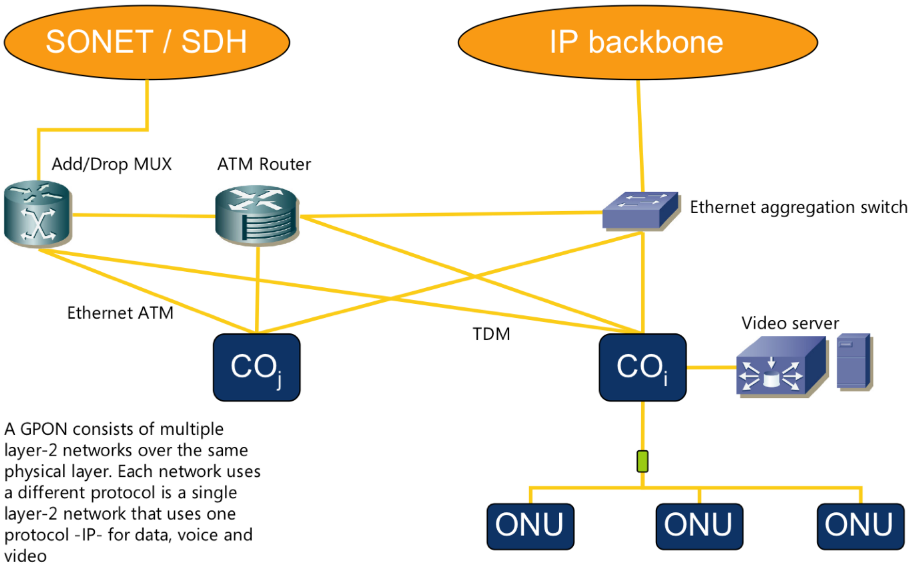
The development of both standards has been parallel. The starting point for GPON was ATM-based passive optical networking (APON), and subsequently BPON, both included on the ITU-T G.983 standard. In January 2003, ITU ratified GPON, but in 2006 was modified to define new classes of optical equipment transmitters and receivers.

Meanwhile, in June 2004, the IEEE ratified EPON as the IEEE802.3ah standard. Since then, it has been rapidly adopted in Japan. EPON is also gaining momentum with carriers in China, Korea, and Taiwan.

While GPON promoters argue that the ITU standard is approaching maturity faster than the IEEE EPON standard, EPON advocates cite the recent emergence of the IEEE standard, deployments of EPON underway, and announced deployment plans by carriers as strong evidence of EPON's acceptance. Additionally, EPON partisans note that most data begins and ends its life as IP/Ethernet traffic, and they ask the question of why to interpose still another protocol encapsulation.

2.5.1 GPON and EPON

Perhaps the most dramatic distinction between the two protocols is a marked difference in architectural approach. GPON provides three Layer 2 networks: ATM for voice, Ethernet for data, and proprietary encapsulation for other services. EPON, on the other hand, employs a single Layer 2 network that uses IP to carry data, voice, and video.



A GPON consists of multiple layer-2 networks over the same physical layer. Each network uses a different protocol is a single layer-2 network that uses one protocol -IP- for data, voice and video

Fig 2.16 Diagram showing a typical GPON network

A multiprotocol transport solution supports the GPON structure. Using ATM technology, virtual circuits are provisioned for different types of services sent from a central office location primarily to business end users. This type of transport provides high-quality service, but involves significant overhead because virtual circuits need to be provisioned for each type of service. Additionally, GPON equipment requires multiple protocol conversions, segmentation and reassembly (SAR), virtual channel (VC) termination and point-to-point protocol (PPP).

EPON provides seamless connectivity for any type of IP-based or other "packetized" communication. Since Ethernet devices are ubiquitous from the home network all the way through to regional, national and worldwide backbone networks, implementation of EPONs can be highly cost-effective. Furthermore, based on continuing advances in the transfer rate of Ethernet-based transport — now up to 10 Gigabit Ethernet — EPON service levels for customers are scalable from T1 (1.5 Mbit/s) up through 1 Gbit/s.

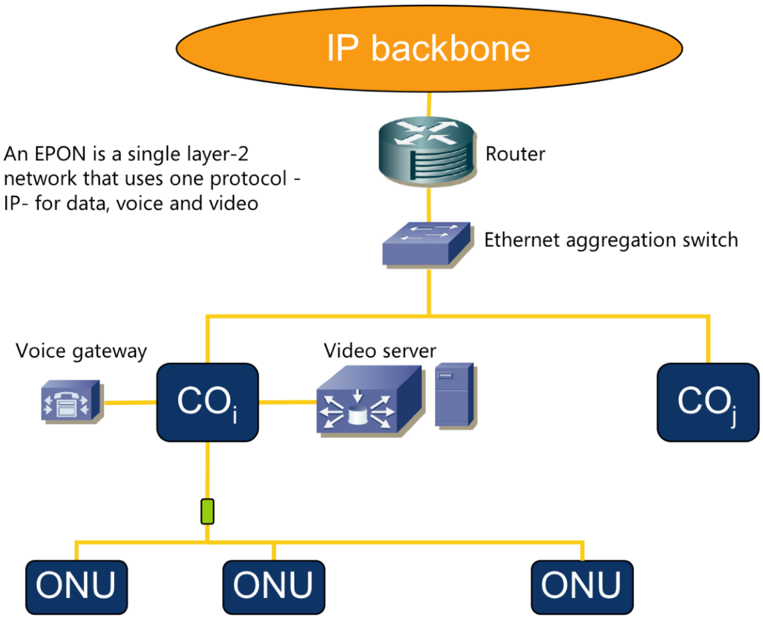


Fig 2.17 Diagram showing a typical EPON network

2.5.1.1 Comparisons and Contrasts

There are some distinct differences between EPON and GPON at Layer 2. However, these are not the only differences between the technologies. Designers will also find differences in terms of bandwidth, reach, efficiency, per-subscriber costs and management.

2.5.1.2 Usable Bandwidth

Bandwidth guarantees vary between the two protocols: GPON promises 1.25-Gbit/s or 2.5-Gbit/s downstream, and upstream bandwidths scalable from 155 Mbit/s to 2.5 Gbit/s. EPON delivers 1-Gbit/s symmetrical bandwidth. EPON's Gigabit Ethernet service actually constitutes 1 Gbit/s of bandwidth for data and 250 Mbit/s of bandwidth for encoding. The approach of EPON, as part of the Gigabit Ethernet standard, parallels that of Fast Ethernet, which also uses 25 percent for encoding.

GPON's 1.25-Gbit service specifies a usable bandwidth of 1.25 Gbit/s, with no requirement for encoding. Will the additional 250 Mbit/s promised by GPON promoters stand as a clear advantage for GPON? The answer may lie not in the sheer bandwidth comparisons, but in the practicality of 1.25-Gbit uplinks.

Gigabit Ethernet interfaces to the aggregation switch, central office, and metro are currently the cost-effective way to aggregate 1-Gbit ports for transport. With no cost-effective switches for 1.25 Gbit available, the added bandwidth promised by GPON, although measurable, could come at a significant premium over the price of EPON equipment. In other words, the low-cost uplink for the foreseeable future is likely to be Gigabit Ethernet, which is the exact bit rate of EPON. In that light, GPON's "added" bandwidth may not prove advantageous for carriers.

2.5.1.3 Reach

With either protocol, the practical limitation to reach comes from the optical-link budget. With the reach of both protocols currently specified at approximately 20 kilometers, the difference in split rates — the number of optical network units (ONUs) supported by one optical line terminal (OLT) — is a point of differentiation.

GPON promises to support up to 128 ONUs. With the EPON standard, there is no limit on the number of ONUs. Depending on the laser diode amplitude, when using low-cost optics, EPON can typically deliver 32 ONUs per OLT, or 64 with forward error correction (FEC).

In any case, power losses are the limiting factor to increase reach and splitting ratios.

2.5.1.4 Per-subscriber costs

The use of EPON allows carriers to eliminate complex and expensive ATM and SONET/SDH elements and to simplify their networks, thereby lowering costs to subscribers. Currently, EPON equipment costs are approximately 10 percent of the costs of GPON equipment, and EPON equipment is rapidly becoming cost-competitive with VDSL.

2.5.1.5 Efficiencies of Each Standard

With both PON protocols, a fixed overhead is added to convey user data in the form of a packet. In EPONs, data transmission occurs in variable-length packets of up to 1518 bytes according to the IEEE 802.3 protocol for Ethernet. In ATM-based PONs, including GPONs, data transmission occurs in fixed-length 53-byte cells (with 48-byte payload and 5-byte overhead) as specified by the ATM protocol. This format makes it inefficient for GPONs to carry traffic formatted according to IP, which calls for data to be segmented into variable-length packets of up to 65,535 bytes.

For GPONs to carry IP traffic encapsulated into ATM frames, the packets must be broken into the requisite 48-byte segments with a 5-byte header for each. This process is time-consuming and complicated and adds cost to the central-office OLTs as well as the customer premise-based ONUs. Moreover, 5 bytes of bandwidth are wasted for every 48-byte segment, creating an onerous overhead that is commonly referred to as the "ATM cell tax". This is the case with GPON's ATM encapsulation mode. In its other encapsulation mode, called GEM (Generic Encapsulation Method), the ATM cell tax does not apply and packets are transmitted in the “Ethernet way” so the excess bandwidth lost to control ATM cells is avoided.

By contrast, using variable-length packets, Ethernet was made for carrying IP traffic and can significantly reduce the overhead relative to ATM. One study shows that when considering trimode packet size distribution, Ethernet packet encapsulation overhead was 7.42 percent, while ATM packet encapsulation overhead was 13.22 percent.

In addition, since Ethernet frames contain a vastly higher ratio of data to overhead than GPON, that high utilization can be reached while using low-cost optics. The more precise timing required with GPON results in more expensive optics. High-precision optics are mandatory as part of the GPON standard.

2.5.1.6 Management systems

EPON requires a single management system, versus three management systems for the three Layer 2 protocols in GPON, which means EPON results in a significantly lower total cost of ownership. EPON also does not require multiprotocol conversions, and the result is a lower cost of silicon.

GPON does not support multicast services, which makes support for IP video more bandwidth-consuming.

2.5.1.7 Support for CATV Overlay

Both protocols support a cable television (CATV) overlay, which meets requirements for a high-speed downstream video service. EPON wavelengths are 1490 nanometers downstream and 1310 nanometers upstream, leaving the 1550-nanometer wavelength for a CATV overlay — similar to the specified wavelengths for BPON and GPON.

In this matter, there is a consensus to develop similar specifications so development costs of optical equipment and reduced and thus implementation becomes more cost effective.

2.5.1.8 Encryption

With GPON, encryption is part of the ITU standard. However, GPON encryption is downstream only.

EPON, on the other hand, uses an AES-based mechanism, which is supported by multiple silicon vendors and deployed in the field. Furthermore, EPON encryption is both downstream and upstream.

2.5.1.9 Network Protection

Both protocols provide vendor-specific and carrier-specific protection. This includes support for vendor-specific and carrier-specific operations, administration and maintenance (OAM).

	EPON	GPON
Standard	IEEE 802.3ah	ITU-T G.984
Data rate	1Gbps bidirectional	2.5Gbps down / 1.25Gbps up
Distance	< 20km	< 60km
Splitting ratio	16 / 32	64
Encapsulation	Ethernet frames	Ethernet over GEM or ATM
Layer	Layer 2	Layer 2 + extra functionality
Comments	Lower cost	Higher cost Stricter specifications

Table 2.2 GPON/EPON comparison

From the summary above, it can be clearly seen, that GPON and EPON will compete to establish as the prevalent solution for PONs. Each of them has its advantages and drawbacks, mainly determined by the protocol from which they have evolved. GPON, coming from ATM standards is more focused on services and specifically tailored for carrier while EPON, an evolution of Ethernet for PONs, implements the same functionalities from the network operator perspective.

2.6 Worldwide deployments

Present evolution of FTTH in the world is mainly focused in Asia, where Korea and Japan are leading the evolution of FTTH in both, numbers of subscribers and bandwidth per user. Competition is encouraging the increase in data rates together with a reduction in price fees. This positive cycle in increasing the number of connections thus the access network requires more transmission capabilities and therefore new topologies and technologies are being implemented. The following list summarizes the situation in countries where remarkable FTTH deployments have been reported (in alphabetic order):

2.6.1 China

Since 2002, several field trials have been implemented in China. The first one was the Wuhan Changfei FTTH project in 2002 which wanted to demonstrate the feasibility of deploying FTTH, with a tested of 87 users in three buildings.

The first commercial FTTH network was the Zisong FTTH project in Wuhan by Wuhan Telecom, which consisted of 420 subscribers, connected by GE-PON with video overlay features.

In Aug. 2005, Wuhan South Lake FTTH network deployed. This commercial FTTH network was commercially operated by China Netcom for new buildings in Wuhan. This project had about 700 subscribers, and the services that were offered where the same as in Zisong project.

Beijing FTTH network deployed in July 2005 and commercially operated by China Netcom in Beijing provided triple-play with GEPON. In addition to this, a bigger FTTH project has been planned. It is an FTTH network for combined residential and business users. The district occupies about 7 square kilometers with a population of 160,000 inhabitants.

2.6.2 Denmark

In Denmark, the northern parts of Zealand north and west of Copenhagen, the Power Company DONG Energy is providing FTTH to areas where they are laying airborne power cables in the ground, with 100 Mbit/s connection. The services on the FTTH will be provided by external providers. The plan is to have all of these areas provided with FTTH by 2010 and then follow up on those areas that haven't been giving the opportunity during that time.

Prices are approximately 30$/month for the fiber installation itself (charged by DONG Energy) and approximately 30$/month additionally for a 2/2 Mbit/s link provided by an external provider. 10/10 Mbit/s can be had for a price of approx. 50$ per month. 20/20 and 25/25 is also available for higher prices. 100/100 is available from Jay.net (for approx. 33$/month), but is not flat-rate priced, as all data above 10 Gigabytes per month is charged 16 cents pr. Gigabyte transferred.

2.6.3 France

A residential fibre service has been deployed in the 15th Arrondissement (borough) of Paris by Cité Fibre. Bandwidth allocated to each user is 100 Mbit/s with 30 Mbit/s reserved for internet traffic. The package includes Digital Television and VoIP Telephone services along with the above-mentioned unlimited internet starting at 49€ per month. The 15th arrondissement was probably selected for its comparatively high residential population.

The Cité Fibre website also contains an excellent comparison of residential fibre technology with existing cable and DSL/ADSL.

In June 2006, France Telecom/Orange SA launched a test program for FTTH in some arrondissements of Paris. It proposes up to 2,5 Gbit/s upstream and 1,2 Gbit/s downstream per 30 users using PON for 70€ a month.

In September 2006, Free announced a €30 a month quadruple play offer including 50 Mbit/s Internet connection, free phone calls to 28 countries and high-definition television.

2.6.4 Iceland

In Iceland, FTTH deployment has begun by Orkuveita Reykjavikur (Reykjavik Power Company), they have already begun connecting the towns of

Seltjarnarnes, Akranes and parts of Reykjavík, with estimated 50% of Reykjavik connected by 2008 and all of Reykjavík, Seltjarnes, Akranes, Mosfellsbær, Þorlákshöfn and Hveragerði connected by 2012, other areas are pending an agreement by the city officials. OR only owns the FTTH network; ISP services is provided by HIVE, Skýrr, Vortex and VoIP service is now available from HIVE and video will be provided by other third party providers. As time passes, it is expected that other companies will also take part of OR FTTH network. The monthly cost of having the FTTH in house is 1.990 ISK (approx $26 US dollars) which is a little more then having a phone line in the house which costs 1.340 ISK (approx $18 US dollars); this does not include any services. All FTTH connections are 100 Mbit/s but today ISP services offer speeds of 10Mbit/s, 20 Mbit/s and 30 Mbit/s.

2.6.5 Italy

The Italian environment for broadband is oriented around DSL and FTTH. With regards to fibre, Italy is one of the most advanced countries in Europe in developing fibre-to-the-building technology and services.

The country had 7.4 million broadband connections at the end of March 2006 and it increased from 5.20 million connections at the end of 2005. This was in line with the government's expectations to reach 7.1 million connections by mid 2006.

The broadband penetration reached 26.76 percent of the households, 37 percent of the companies and 61 percent of the government in June 2005.

With no major cable operators or cable infrastructure, the Italian broadband market is dominated by DSL and FTTH services. Especially in highly dense areas where a large number of apartment blocks were built with direct fibre access to the building, FTTH service becomes highly desirable and results in the significant growth in the Italian market and also an upcoming trend in Europe. .

Fixed-line penetration in the country stands at around 48 percent and a subscriber base of around 26.59 million at the end of March 2006.

2.6.6 Japan

FTTH, often called FTTP in Japan, was first introduced in 1999, and did not become a large player until 2001. In 2003-2004, FTTH grew at a remarkable rate, and DSL's growth slowed. 4.63 million FTTH connections (includes 1.99 million FTTX for multifamily housing) are reported in March, 2006 in Japan.

FTTH first started with 10Mbit/s (at end-user rate) passive optical network (PON) by Nippon Telegraph and Telephone (NTT), and 100Mbit/s (at end-user rate) with GEPON (Gigabit Ethernet-PON) or broadband PON is major one in 2006. PON is major system for FTTH by NTT, but some competitive services present 1Gbit/s (at end-user rate) with SS (Single Star).

Major application services on fibers are voice over IP, video-IP telephony, IPTV (IP television), IPv6 services and so on [Shinohara05].

2.6.7 Kuwait

South Surra, in four cities, Alsalam, Hutteen, Alshuhada, and future Seddeek. The project started on 2003, and hasn't finished yet as of September 2006. The equipment is from Alcatel.

2.6.8 Netherlands

In The Netherlands in the city Eindhoven and a nearby village called Nuenen, there is a large network with 15 000 connections. triple play is offered. Houses and companies are connected with single-mode fibre. The network is owned by the members itself, who did form a corporation. The first European FTTH project was also in Eindhoven in a neighborhood known as the "Vlinderflats". This was a multi-mode fibre but was in 2005 changed to single-mode fibre. FTTH resulted in new broadband services; the inhabitants started their own broadband TV station called VlinderTV.

2.6.9 New Zealand

Telecom New Zealand (dominant telco) is starting a FTTP trial in a new subdivision (Flat Bush) in Manukau city in May 2006. Pricing isn't yet set. Vector Communications provides fiber to premises in very limited Auckland CBD and Wellington CBD for around NZ$329 unlimited per month. You can also get fiber to premises services from Citylink in Wellington - price suggests this is for businesses only.

2.6.10 South Korea

Korea is one of the most wired nations in the world, with over 85% of the population having access to broadband with speeds of 10 Mbps to 1000 Mbps.

In 2001, the government of Korea and telecom providers became actively involved in bringing fiber to the home as a result of an initiative to improve the lives and circumstances of their people. With a national broadband policy to guide them, Korea sought partners to underwrite the cost of deployment. AIG Consortium, an American insurance company, contributed $1 billion toward the deployment project for one telecom provider, Hanaro Telecom.

The first installations of 100 Mbps fiber to the home began in Gunpo City, Korea in 2001. Installation of fiber to the home meant that Korean entrepreneurs could begin to develop online businesses at lower costs.

Fiber to the Home is also affecting economy in Korea with new and inexpensive telephone, television, internet and video on demand services and products. With FTTH, content is produced at an accelerated rate for millions of digital hungry consumers. Forrester Research, a highly regarded research company, recently projected that by 2007, video on demand will attract 7.5 million users spending approximately $700 million annually with the total market for on-demand television weighing in at about $6 billion. The Korean VOD market has already achieved this goal in 2004.

New businesses are also emerging in the biomedical and technical fields. Fueled by the ability to work with other scientists, researchers and technicians across the country and the world, new products are being developed rapidly.

Korea has become the world's most enthusiastic adopter of broadband. There are no 56K phone modem users left in Korea. Korean Photonic R&D centers are now investing billion dollar budgets to develop FTTH parts cheaply for the world market. They are now going towards 10 Gbps FTTH.

By 2007, all the households across the country will be able to access between 100~1,000 Mbps broadband Internet. Korean condos and home buildings are being designated as Super class who have 1,000 Mbps wiring, 1st class who have 100 Mbps wiring and 2nd class who have 10 Mbps wiring.

2.6.11 Sweden

Sweden is often classified as one of the most developed nations in the world. When it comes to broadband in particular, Sweden has a quite unique history. In the year of 1999, several Swedish FTTH projects were initiated. One of them was Svenska Bredbandsbolaget, B2, the largest project of its kind in the world. B2 today has over 270.000 homes passed and over 100.000 paying customers.

2.6.12 United Arab Emirates

Dubai Internet City, formally Sahm Technologies offer triple play services to properties within the Emaar properties, Dubai Marina, Emirates Lakes, Hills development.

2.6.13 United States

In the United States, the largest FTTP deployment to date is Verizon's FiOS. Verizon is the only Regional Bell Operating Company thus far to deploy FTTP on a large scale.

With its U-Verse product, AT&T (formerly SBC) has pursued a strategy of Fiber to the Neighborhood (FTTN) and is now delivering Fiber to the Premises (FTTP) to select areas. AT&T has deployed FTTN in the Dallas, Texas area, including Richardson, Texas. The company is now upgrading the telephone and broadband Internet network to deliver FTTP in this area.

Broadweave Networks has multiple FTTP installations in new or greenfield communities in the west, including a contract with the Utah State Trust Lands Administration for up to 21,000 units in Washington County, Utah.

EATEL offers FTTP in the Ascension Parish, Louisiana area. Services currently available via their fiber-optic network include telephone, broadband Internet and television, which includes video on demand and regular broadcasts.

T^2 Communications of Holland, MI has deployed Fiber to the Home in order to deliver phone, television (IPTV) and Internet services, and is actively building its own fiber network.

Several carriers, municipalities, and planned communities across America are deploying their own fiber networks [Batson04], [Whitman04], [Jianli05], [Montagne05].

3 Optical devices for advanced network topologies

Requirements of advanced network topologies in terms of optical equipment encourage the development and redesign of optical devices that are able to perform advanced routing and modulation features. At present, optical devices of TDM-PONs are just emitters and receivers that directly modulate data streams on a single wavelength and transmit it along the fiber in a very basic approach. However, future access networks will optically implement features that are now implemented in the electrical domain on the optical domain, so the development and refinement of advanced optical devices will be a requirement.

This section will describe in detail the specifications and characteristics of future access network optical devices. Tunable laser sources to provide bandwidth on demand in an agile and flexible way, wavelength routers to route data streams depending on their wavelength and wavelength-agnostic receivers and modulators for WDM PONs will be described, together with their requirements and future viability.

3.1 Tunable lasers

Tunable lasers are not used at present in access networks because of its cost but are a key component in future access networks, as they can offer many advantages to advanced topologies in terms of optimization of resources and transparency [Lee03].

The definition of a tunable laser is a laser the output wavelength of which can be tuned. This tuning can be on a wide range of accessible wavelengths, while in other cases it is sufficient that the laser wavelength can be tuned to a certain value. Some single-frequency lasers can be continuously tuned over a certain range, while others can access only discrete wavelengths or at least exhibit mode hopping when being tuned over a larger range.

Tunable lasers are usually operating in a continuous fashion with a small emission bandwidth, although a Q-switched or mode-locked laser can also be wavelength-tuned. In the latter case, one may either spectrally shift the envelope of the frequency comb or the lines in the spectrum.

3.1.1 Wavelength tuning

The wavelength of the output of a laser can be tuned by inserting an element with tunable wavelength-dependent losses in the laser cavity. The laser will then usually operate on the wavelength where the inversion level of the gain medium required for lasing (i.e., for generating a gain which equals the cavity losses) is at its minimum. In the steady state, the light at the laser wavelength has zero round trip net gain, and all other wavelengths experience a negative net gain.

A wide wavelength tuning range of a laser requires a wide gain bandwidth of the gain medium. Some broadband gain media such as Ti:sapphire or Cr:ZnSe allow tuning over hundreds of nanometers. The obtained tuning range is usually the wavelength range in which sufficient net gain can be achieved. Its limits are often set by the points where the emission cross sections get too low or the cavity losses get too high. In some cases, the tuning range may be smaller because there is excited state absorption, or because emission at wavelengths with maximum laser gain can not be fully suppressed. In some fiber lasers, for example, the inversion level (and thus the gain at extreme wavelengths) is limited by amplified spontaneous emission near the wavelength of maximum gain.

Frequently used tuning elements in laser cavities are:

- ✓ a prism pair in combination with a movable aperture
- ✓ a single prism in combination with and end mirror which can be tilted to adjust the wavelength for which the cavity alignment is good
- ✓ a holographic grating as an end mirror (→ Littrow configuration), which is rotated for tuning, or a fixed grating within the cavity combined with a movable end mirror (→ Littman configuration)

- ✓ an etalon (Fabry-Perot interferometer) or a birefringent tuner (Lyot filter) which can be rotated to adjust the wavelength of maximum transmission
- ✓ a movable output coupler for fine tuning of the output of a single-frequency laser within the free spectral range of the laser cavity

A single-frequency laser can often be wavelength-tuned over some fraction of the free spectral range of the laser cavity simply by tuning the cavity length. If one tries tuning beyond this (typically rather small) range, one obtains mode hops. Relatively wideband mode-hop-free tunability can be obtained with very short laser cavities. This is used e.g. with MEMS VCSELs, having a separate output coupling mirror the position of which can be tuned via thermal expansion, electrostatic forces, or a piezoelectric element.

Wavelength-tunable radiation can also be obtained with alternative techniques:

- ✓ with tunable gain, achieved by changing the temperature of the gain medium (via the drive current of a laser diode)
- ✓ with synchrotron radiation sources (wigglers and undulators, free electron lasers)
- ✓ with an optical parametric oscillator (also having tunable gain, although not from stimulated emission)
- ✓ with an optical parametric amplifier, which amplifies a selectable part of a very broad spectrum (a supercontinuum)
- ✓ by Raman self-frequency shift in an optical fiber, where the amount of shift is controlled via the launched power of the pulses

[Buus06]

3.1.2 Applications in access networks

The applications of tunable lasers are wide in access networks and their specifications are completely different depending on the case. Mainly, a tunable laser source can have two functionalities: it can be used for routing purposes in a WDM-routed access network or it can be used as a wavelength agnostic device to simplify stocks and reduce the complexity of the wavelength assignation.

The requirements for both solutions are different. If the tunable laser is just used as a wavelength-agnostic device, tuning speed is not a crucial factor. This is the main application of tunable lasers in ONUs at present. However, if the tunable laser source is used to route packets on a WDM network, then tuning speed becomes a crucial parameter. Therefore, depending on the application, the tunable laser technology will be completely different.

This is also applicable at the CO side. There, tunable laser sources can be used to reduce the number of transmission interfaces and to provide advanced bandwidth on demand functionalities [Bock05] or to perform as a simple backup device for a WDM system. In the first case, tuning time is critical, while in the second one it is not a design criterion at all. At present, the main application of tunable lasers at the CO is as back-up wavelength-agnostic transceivers but this will change in the future with the development and deployment of routed-WDM PONs.

To have an order of magnitude of required tuning ranges and tuning times in advanced WDM applications, tuning time should be in the range of 30nm in case we use a single D-WDM transmission band and tuning speed below 1µs to achieve a good compromise between network throughput and network delay [Bock05b].

3.1.3 Laser characterization

This section presents the experiments that were carried out to characterize a Grating Assisted Coupler with Sampled rear-Reflector (GCSR) laser. A GCSR laser consists of four sections, i.e. a gain block, a phase module, a coupler and a Bragg grating. The coupler acts as a coarse tuner, transferring power vertically between the two waveguides, one that runs forward to the gain block, and another one, above it, that runs backward into the phase and Bragg grating sections. Increasing Coupler current the filter shifts to shorter λ, this is a kind of coarse tuning. As reflector current increases, the comb filter shifts to shorter wavelengths. Fine-tuning is done by current injection on Phase section (see Fig. 3.1), what tunes all cavity modes simultaneously.

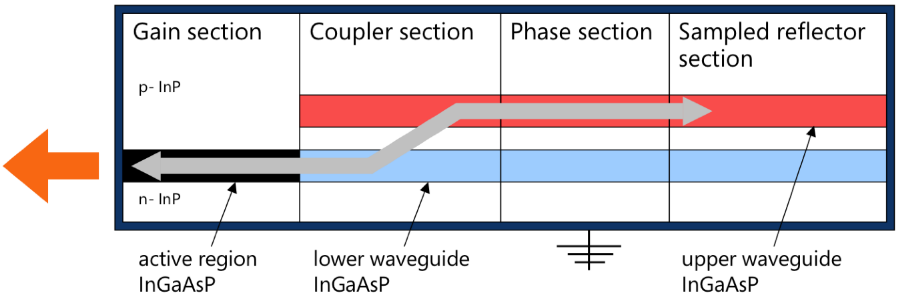


Fig 3.1 Detail of the 4-sections of a GCSR

The 4-sections Grating assisted Coupler with Sampled rear-Reflector (GCSR) laser source, makes possible fine and stable wavelength tuning with a tuning range of about 40 nm, covering the whole C-Band required for optical communications and allowing efficient use of spectral bandwidth [Fukashiro00]. Its low tuning currents requirements and fast tuning properties make the GCSR a good candidate for switching applications [Rigole97]. Also its relative fabrication simplicity, its good Side Mode Suppression Ratio (SMSR) and its potential low cost make possible its application in future WDM environments. Channel selection for continuous wavelength transmission is done by biasing the three tuning electrodes of the GCSR laser to a steady-state current.

A map of the static tuning currents of one GCSR unit is shown in Table 3.1, showing output frequency, output power and Side Mode Suppression Ratio (SMSR) versus gain, coupler, reflector and phase currents. The maximum deviation of the measured output wavelength des-alignment from the standard ITU channel wavelength is of about ±0.005 nm.

ITU Channel	Freq.	Wavelength channel (nm)	Tuned wavelength (nm)	Iactive (mA)	Icoupler (mA)	Ireflect (mA)	Iphase (mA)
58	195.8	1531.12	1531.15	100	14.2	18	2.7
57	195.7	1531.9	1531.91	100	13.9	14.1	1.5
56	195.6	1532.68	1532.66	100	13.6	11.1	2.6
55	195.5	1533.47	1533.49	100	13.3	8.4	1.1
54	195.4	1534.25	1534.27	100	12.7	6.6	1.8
53	195.3	1535.04	1535.09	100	12.7	4.8	2.9
52	195.2	1535.82	1535.85	100	12.1	18.3	2.8
51	195.1	1536.61	1536.62	100	11.8	14.4	1.5
50	195	1537.4	1537.39	100	11.5	11.1	3
49	194.9	1538.19	1538.13	100	11.2	8.7	2.6
48	194.8	1538.98	1539.00	100	10.9	6.6	1.8
47	194.7	1539.77	1539.76	100	10.9	5.1	3
46	194.6	1540.56	1540.57	100	10.6	3.6	1.6
45	194.5	1541.35	1541.35	100	10	14.4	1.8
44	194.4	1542.14	1542.15	100	9.7	11.4	2.6
43	194.3	1542.94	1542.94	100	9.7	8.7	1.2
42	194.2	1543.73	1543.75	100	9.4	6.6	2
41	194.1	1544.53	1544.50	100	9.1	5.1	1.1
40	194	1545.32	1545.35	100	8.8	18.9	2.6
39	193.9	1546.12	1546.18	100	8.5	14.7	4.2
38	193.8	1546.92	1546.85	100	8.5	11.7	3.6
37	193.7	1547.72	1547.72	100	7.9	8.7	1.4
36	193.6	1548.51	1548.56	100	7.9	6.6	1.7
35	193.5	1549.32	1549.31	100	7.9	5.1	3.4
34	193.4	1550.12	1550.16	100	7.6	3.6	1.5
33	193.3	1550.92	1550.92	100	7.3	15.3	1.3
32	193.2	1551.72	1551.75	100	7	11.7	2.1
31	193.1	1552.52	1552.51	100	6.7	9	1.3
30	193	1553.33	1553.33	100	6.7	6.9	1.6
29	192.9	1554.13	1554.18	100	6.4	5.1	2.5
28	192.8	1554.94	1554.98	100	6.1	20.1	2.1
27	192.7	1555.75	1555.82	100	6.4	2.4	2.1
26	192.6	1556.55	1556.62	100	6.1	1.2	1.15
25	192.5	1557.36	1557.31	100	5.5	9.3	1.4
24	192.4	1558.17	1558.21	100	5.5	6.9	1.4
23	192.3	1558.98	1559.04	100	5.5	5.1	2.2
22	192.2	1559.79	1559.77	100	5.2	3.9	1.5
21	192.1	1560.61	1560.63	100	4.9	16.2	3
20	192	1561.42	1561.41	100	4.9	12.6	1.6
19	191.9	1562.23	1562.26	100	4.9	9.3	2.4
18	191.8	1563.05	1563.06	100	4.6	7.2	1.2
17	191.7	1563.86	1563.84	100	4.6	5.4	2.4

Table 3.1 Static tuning currents of a GCSR sample

3.2 Arrayed Waveguide Gratings

Wavelength routers are another key component of future access networks. Wavelength routers can be divided into three categories depending on their application:

- Multiplexers
- Demultiplexers
- NxN router

Multiplexers are used to combine different wavelengths from different fibers into a single fiber, demultiplexers perform the opposite task: they separate incoming wavelengths from the input fiber to different fibers. Finally, NxN routers perform both actions simultaneously and act as optical cross-connects.

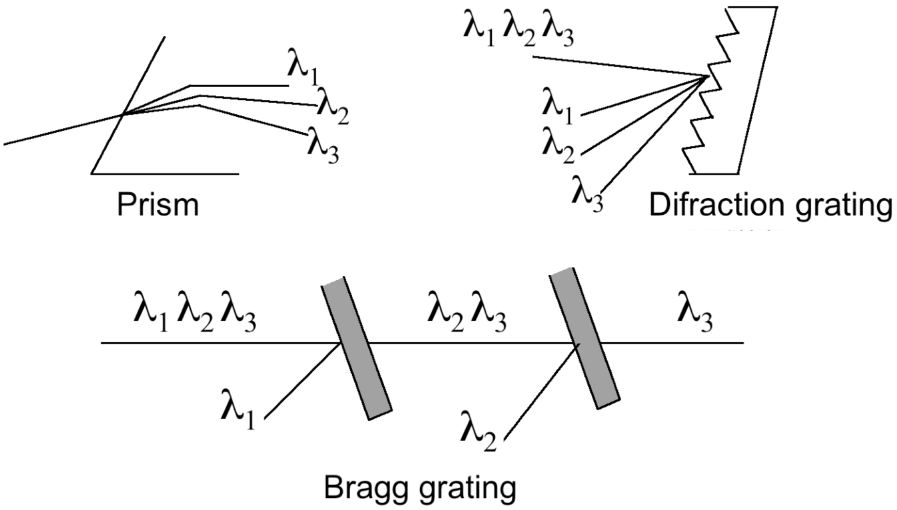


Fig 3.2 Different wavelength routers

To implement multiplexers, demultiplexers and routers one can use different techniques.

- angular dispersion using prisms
- concatenation of optical filters
- arrayed-waveguide gratings
- Angular dispersion MUX
- Concatenation of filters MUX

We will focus in this section on arrayed-waveguide gratings (AWGs) because it is the technology which offers more benefits, as AWG can be integrated thus its potential cost is low.

Fig. 3.3 shows the schematic layout of a AWG. The operation is understood as follows. When the beam propagating through the transmitter waveguide enters the free propagation region (FPR) it is no longer laterally confined and becomes divergent. On arriving at the input aperture the beam is coupled into the waveguide array and propagates through the individual array waveguides to the output aperture. The length of the array waveguides is chosen such that the optical path length difference between adjacent waveguides equals an integer multiple of the central wavelength of the demultiplexer. For this wavelength the fields in the individual waveguides will arrive at the output aperture with equal phase (apart from an integer multiple of 2π), and the field distribution at the input aperture will be reproduced at the output aperture. The divergent beam at the input aperture is thus transformed into a convergent one with equal amplitude and phase distribution, and an image of the input field at the object plane will be formed at the center of the image plane. The dispersion of the AWG is due to the linearly increasing length of the array waveguides, which will cause the phase change induced by a change in the wavelength to vary linearly along the output aperture. As a consequence, the outgoing beam will be tilted and the focal point will shift along the image plane. By placing receiver waveguides at proper positions along the image plane, spatial separation of the different wavelength channels is obtained.

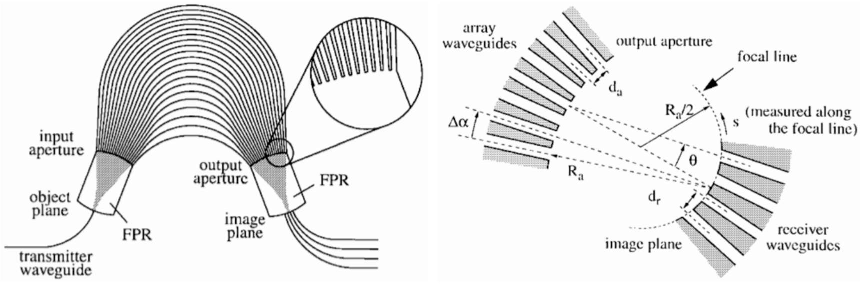


Fig 3.3 Structure of an arrayed waveguide grating

The design of AWGs allow them to perform as multiplexers, demultiplexers and wavelength routers.

3.2.1 Wavelength router functionality

Wavelength routers were first reported by Dragone [Dragone91], [Dragone91a]. They provide an important additional functionality as compared to multiplexers and demultiplexers and play a key role in more complex devices as add-drop multiplexers and wavelength switches. Fig. 3.4 illustrates their functionality. Wavelength routers have *N* input and *N* output ports. Each of the *N* input ports can carry *N* different frequencies. The *N* frequencies carried by input channel 1 are distributed among output channels 1 to *N*, in such a way that output channel 1 carries frequency N and channel *N* frequency 1. The *N* frequencies carried by input 2 are distributed in the same way, but cyclically rotated by 1 channel in such a way that frequencies 1–3 are coupled to ports 3 – 1 and frequency 4 to port 4. In this way each output channel receives *N* different frequencies, one from each input channel. To realize such an interconnectivity scheme in a strictly nonblocking way using a single frequency a huge number of switches would be required. Using a wavelength router, this functionality can be achieved using only one single component.

A wavelength router is obtained by designing the input and the output side of a AWG symmetrically, i.e., with *N* input and *N* output ports. For the cyclical rotation of the input frequencies along the output ports, as described above, it is essential that the frequency response is periodical as shown in Fig. 3.4(b), which implies that the FSR should equal N times the channel spacing.

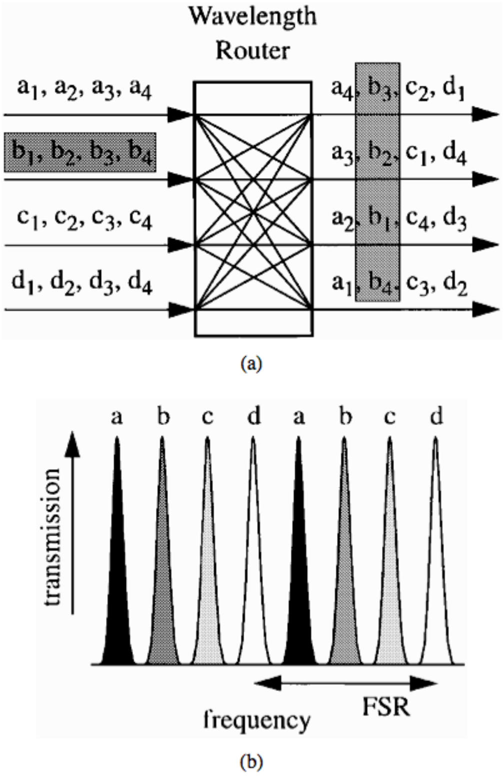


Fig 3.4 Schematic diagram of the wavelength router operation: (a) Interconnectivity scheme and (b) frequency response

3.2.2 Applications in access networks

The typical application of AWGs in access is to deploy a combined WDM / TDM PON, having a feeder fiber on which several WDM channels are transmitted and then an AWG to separate each channel and distribute it on a classical TDM-PON topology.

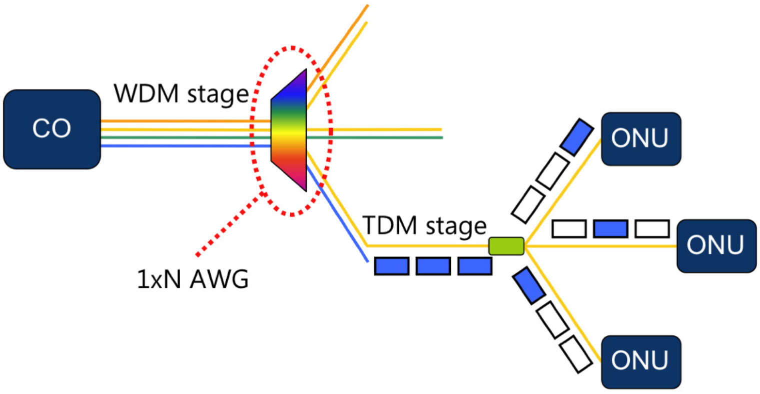


Fig 3.5 AWG in a WDM / TDM PON approach

However, NxN AWGs have many applications in access due to the cyclical periodicity of their routing profile. In [Bock06f] we present an advanced dynamic bandwidth allocation algorithm that uses an NxN AWG to avoid correlatation among traffic sources. Further explanation about applications of NxN AWGs in access are described in [Bock04],[Bock05a], [Tsalamanis04].

3.2.3 AWG characterization

Several AWG characterizations have been carried out during this thesis project. 1x8, 1x32 and 1x40 AWGs have been parameterized together with 8x8, 16x16 and 18x18 AWG-based routers. The main parameters to be measured on AWGs are:

- ✓ Insertion losses
- ✓ The H(f) response type (Gaussian or flatted)
- ✓ The wavelength plan of each output port
- ✓ Number of free spectral ranges (FSR)
- ✓ Thermal stability

Fig 3.6 presents the response of a 1x40 AWG that was parameterized in our labs.

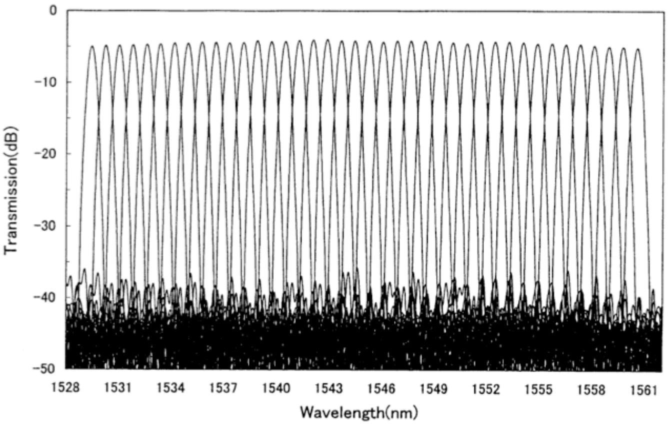


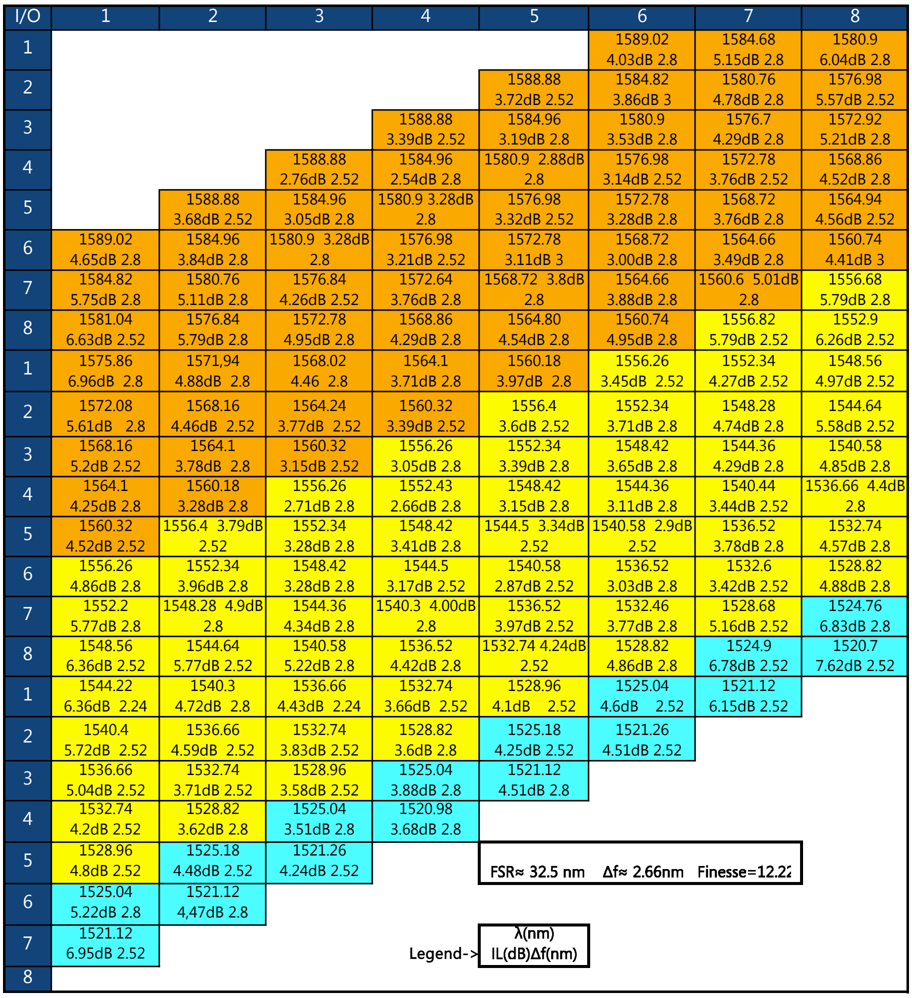
Fig 3.6 1x40 AWG channels

Channels were chosen to be ITU-T grid compliant [ITUTG694.1] and the maximum drifts were measured to be 0.02nm. The response was Gaussian and insertion losses were between 7.67 and 6.41dB. No FSR were recorded as the AWG encapsulation had a pre-filtering stage that suppressed any wavelength out of the AWG main FSR range. Further parameters are detailed in the following table 3.2:

Parameter	Spec	Units
Channels	40	Ch
Channel Spacing	100	GHz
ITU Frequency	196.0 to 192.1	THz
Center Wavelength Accuracy	-0.035 +0.035 nm	
Reference Passband	-12.5 +12.5	GHz
Insertion Loss	≤ 7.0	dB
Insertion Loss Uniformity	1	dB
Ripple	0.4	dB
PDL	≤ 0.3	dB
0.5 dB Bandwidth*	≥ 0.25	nm
1dB Bandwidth	≥ 0.4	nm
3dB Bandwidth*	≥ 0.55	nm
Adjacent Channel Isolation	≥ 26	dB
Non-Adjacent Channel Isolation	≥ 33	dB
Total Crosstalk	≥ 23	dB
Return Loss	≥ 45	dB
Chromatic Dispersion	-10 .. 10	ps/nm
Polarization Mode Dispersion	0.5	ps

Table 3.2 1x40 AWG specifications

Further to the parameters described above, NxN AWGs require the specification of the routing matrix. Table. 3.3 presents the routing matrix of a 8x8 AWG. NxN AWGs are very rare devices, which are not commercially distributed but just produced as custom designs. Typically, they do not have any pre-filter so FSRs can be clearly measured. This is presented in Fig. 3.7

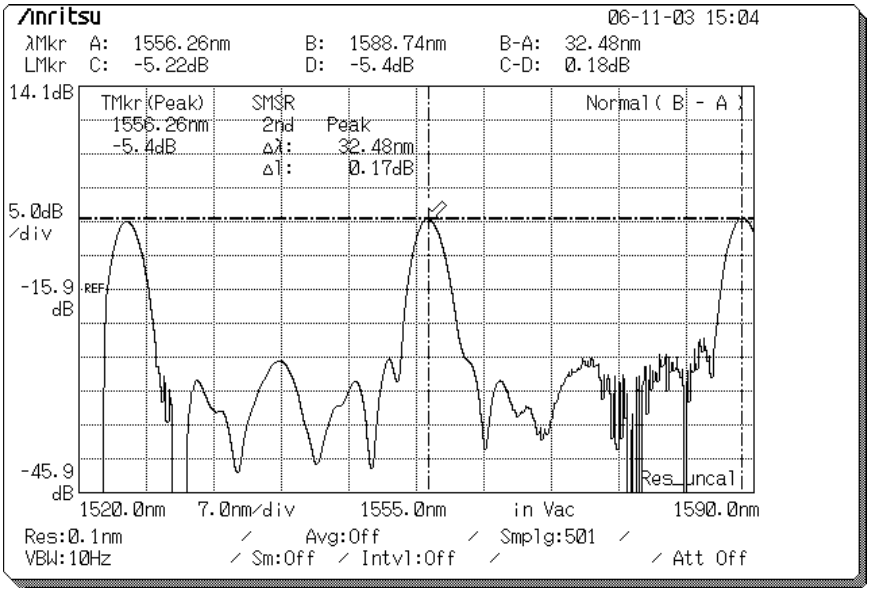


I/O	1	2	3	4	5	6	7	8
1						1589.02 4.03dB 2.8	1584.68 5.15dB 2.8	1580.9 6.04dB 2.8
2					1588.88 3.72dB 2.52	1584.82 3.86dB 3	1580.76 4.78dB 2.8	1576.98 5.57dB 2.52
3				1588.88 3.39dB 2.52	1584.96 3.19dB 2.8	1580.9 3.53dB 2.8	1576.7 4.29dB 2.8	1572.92 5.21dB 2.8
4			1588.88 2.76dB 2.52	1584.96 2.54dB 2.8	1580.9 2.88dB 2.8	1576.98 3.14dB 2.52	1572.78 3.76dB 2.52	1568.86 4.52dB 2.8
5		1588.88 3.68dB 2.52	1584.96 3.05dB 2.8	1580.9 3.28dB 2.8	1576.98 3.32dB 2.52	1572.78 3.28dB 2.8	1568.72 3.76dB 2.8	1564.94 4.56dB 2.52
6	1589.02 4.65dB 2.8	1584.96 3.84dB 2.8	1580.9 3.28dB 2.8	1576.98 3.21dB 2.52	1572.78 3.11dB 3	1568.72 3.00dB 2.8	1564.66 3.49dB 2.8	1560.74 4.41dB 3
7	1584.82 5.75dB 2.8	1580.76 5.11dB 2.8	1576.84 4.26dB 2.52	1572.64 3.76dB 2.8	1568.72 3.8dB 2.8	1564.66 3.88dB 2.8	1560.6 5.01dB 2.8	1556.68 5.79dB 2.8
8	1581.04 6.63dB 2.52	1576.84 5.79dB 2.8	1572.78 4.95dB 2.8	1568.86 4.29dB 2.8	1564.80 4.54dB 2.8	1560.74 4.95dB 2.8	1556.82 5.79dB 2.52	1552.9 6.26dB 2.52
1	1575.86 6.96dB 2.8	1571,94 4.88dB 2.8	1568.02 4.46 2.8	1564.1 3.71dB 2.8	1560.18 3.97dB 2.8	1556.26 3.45dB 2.52	1552.34 4.27dB 2.52	1548.56 4.97dB 2.52
2	1572.08 5.61dB 2.8	1568.16 4.46dB 2.52	1564.24 3.77dB 2.52	1560.32 3.39dB 2.52	1556.4 3.6dB 2.52	1552.34 3.71dB 2.8	1548.28 4.74dB 2.8	1544.64 5.58dB 2.52
3	1568.16 5.2dB 2.52	1564.1 3.78dB 2.8	1560.32 3.15dB 2.52	1556.26 3.05dB 2.8	1552.34 3.39dB 2.8	1548.42 3.65dB 2.8	1544.36 4.29dB 2.8	1540.58 4.85dB 2.8
4	1564.1 4.25dB 2.8	1560.18 3.28dB 2.8	1556.26 2.71dB 2.8	1552.43 2.66dB 2.8	1548.42 3.15dB 2.8	1544.36 3.11dB 2.8	1540.44 3.44dB 2.52	1536.66 4.4dB 2.8
5	1560.32 4.52dB 2.52	1556.4 3.79dB 2.52	1552.34 3.28dB 2.8	1548.42 3.41dB 2.8	1544.5 3.34dB 2.52	1540.58 2.9dB 2.52	1536.52 3.78dB 2.8	1532.74 4.57dB 2.8
6	1556.26 4.86dB 2.8	1552.34 3.96dB 2.8	1548.42 3.28dB 2.8	1544.5 3.17dB 2.52	1540.58 2.87dB 2.52	1536.52 3.03dB 2.8	1532.6 3.42dB 2.52	1528.82 4.88dB 2.8
7	1552.2 5.77dB 2.8	1548.28 4.9dB 2.8	1544.36 4.34dB 2.8	1540.3 4.00dB 2.8	1536.52 3.97dB 2.52	1532.46 3.77dB 2.8	1528.68 5.16dB 2.52	1524.76 6.83dB 2.8
8	1548.56 6.36dB 2.52	1544.64 5.77dB 2.52	1540.58 5.22dB 2.8	1536.52 4.42dB 2.8	1532.74 4.24dB 2.52	1528.82 4.86dB 2.8	1524.9 6.78dB 2.52	1520.7 7.62dB 2.52
1	1544.22 6.36dB 2.24	1540.3 4.72dB 2.8	1536.66 4.43dB 2.24	1532.74 3.66dB 2.52	1528.96 4.1dB 2.52	1525.04 4.6dB 2.52	1521.12 6.15dB 2.52	
2	1540.4 5.72dB 2.52	1536.66 4.59dB 2.52	1532.74 3.83dB 2.52	1528.82 3.6dB 2.8	1525.18 4.25dB 2.52	1521.26 4.51dB 2.52		
3	1536.66 5.04dB 2.52	1532.74 3.71dB 2.52	1528.96 3.58dB 2.52	1525.04 3.88dB 2.8	1521.12 4.51dB 2.8			
4	1532.74 4.2dB 2.52	1528.82 3.62dB 2.8	1525.04 3.51dB 2.8	1520.98 3.68dB 2.8				
5	1528.96 4.8dB 2.52	1525.18 4.48dB 2.52	1521.26 4.24dB 2.52					
6	1525.04 5.22dB 2.8	1521.12 4,47dB 2.8						
7	1521.12 6.95dB 2.52							
8								

FSR≈ 32.5 nm Δf≈ 2.66nm Finesse=12.22

Legend-> λ(nm)
IL(dB)Δf(nm)

Table 3.3 8x8 AWG routing matrix



```
/inritsu                                              06-11-03 15:04
 λMkr  A:  1556.26nm        B:  1588.74nm      B-A:  32.48nm
 LMkr  C:  -5.22dB          D:  -5.4dB         C-D:  0.18dB
   TMkr (Peak)      SMSR                        Normal( B - A )
    1556.26nm        2nd    Peak
    -5.4dB           Δλ:      32.48nm
                     Δl:      0.17dB
 Res:0.1nm            /      Avg:Off        /  Smplg:501  /
 VBW:10Hz            / Sm:Off  / Intvl:Off   /              / Att Off
```

Fig 3.7 8x8 AWG free spectral range

This 8x8 AWG had insertion losses between 5.16 and 2.71 dBs in a Gaussian profile, with a 3-dB passband of between 2.52 and 2.8 nm depending on the channel. FSR was measured to be 32.5nm.

3.3 Reflective receivers and modulators

At present, in commercial implementations there is always a laser diode at the ONU side that sends upstream data. This is a good approach for single wavelength PONs there is just one wavelength used for upstream transmission and VCSELs can be used, which are very cheap. However, when WDM PONs are deployed a wavelength-specific emitter is then needed. The use of wavelength-specific lasers for each ONU is not manageable because it generates huge stock problems, as each ONU of the WDM PON would need different equipment.

To solve this, there are two approaches:

- ✓ To use a tunable source: this is an option, which is under study at present, because the cost of tunable sources is high now, however, it is a future option if cost-effective tunable lasers can be designed.
- ✓ To use an optical modulator or a reflective device at the ONU and send the optical carrier from the CO. This option is very interesting from the research point of view because it opens a wide range of possibilities. However, there is no commercial product with these features as it is not cost-effective at present.

Tunable sources have already been described in this chapter.

An optical modulator is a device that allows manipulating a property of light (typically a laser beam). Depending on which property of light is controlled, one talks about intensity modulators, phase modulators, polarization modulators, etc.

Optical modulators can be divided in the following categories:

- ✓ acousto-optic modulators, used for switching or continuously adjusting the amplitude of a laser beam, for shifting its optical frequency, or its spatial direction
- ✓ electro-optic modulators, used for modifying the polarization, phase or power of a beam, or for pulse picking in the context of ultrashort pulse amplifiers

- ✓ electroabsorption modulators, used for transmitters in optical fiber communications
- ✓ interferometric modulators, e.g. Mach-Zehnder modulators, often realized in integrated optical circuits and used in optical data transmission
- ✓ liquid crystal modulators, used e.g. in optical displays and in pulse shapers; often used as spatial light modulators, i.e., with a spatially varying modulation
- ✓ chopper wheels for periodically switching or modulating the power of a light beam
- ✓ fiber-optic modulators, often being fiber pig-tailed bulk components
- ✓ micromechanical modulators (which are MEMS = microelectromechanical systems), e.g. silicon-based light valves and two-dimensional mirror arrays

This section will analyse electroabsorption modulators (EAM) and semiconductor optical amplifiers (SOA) [Simon83], [Saitoh87] and reflective SOAs (RSOAs) [Shin04] as they offer very good specifications to be used in wavelength-agnostic ONUs.

SOAs and RSOAs are not formal modulators, but can be used as modulators by controlling their bias current and thus, their amplification. All of them are integrable, which means that their potential cost is low. Furthermore, EAMs can be modulated at high data rates. SOAs and RSOAs cannot go so high in datarate but offer amplification capabilities.

3.3.1 ElectroAbsorption Modulator (EAM)

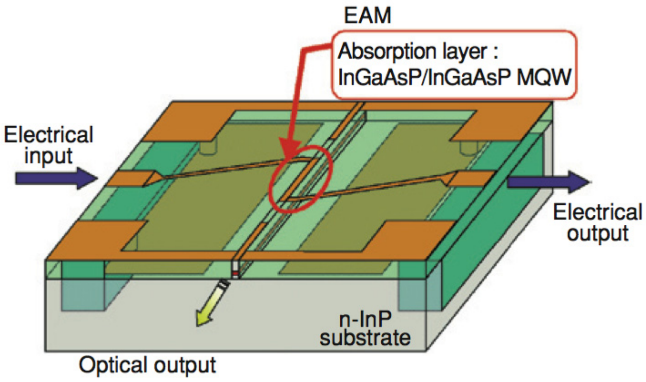


Fig 3.8 Electroabsorption modulator schematic

An electroabsorption modulator is a semiconductor device that allows controlling the intensity of a laser beam via an electric voltage. Its operation principle is based on the Franz-Keldysh effect, a change of the absorption spectrum caused by an applied electric field, which usually does not involve the excitation of carriers by the electric field.

Most electroabsorption modulators are made in the form of a waveguide with electrodes for applying an electric field in a direction perpendicular to the modulated light beam. For achieving a high extinction ratio, one usually exploits the quantum confined Stark effect in a quantum well structure.

Compared with electro-optic modulators, electroabsorption modulators can operate with much lower voltages (a few volts instead of hundreds of thousands of volts). They can be operated at very high speed; a modulation bandwidth of tens of gigahertz can be achieved, which makes these devices useful for optical fiber communications. A convenient feature is that an electroabsorption modulator can be integrated with a distributed feedback laser diode on a single chip to form a data transmitter in the form of an photonic integrated circuit. Compared with directly modulating the laser diode, one can in this way obtain a higher bandwidth and reduced chirp.

3.3.2 Semiconductor Optical Amplifiers

Semiconductor optical amplifiers (SOAs) have a similar structure to Fabry-Perot laser diodes but with anti-reflection design elements at the endfaces. Recent designs include anti-reflective coatings and tilted waveguide and window regions to eliminate endface reflection almost perfectly. This effectively prevents the amplifier from acting as a laser.

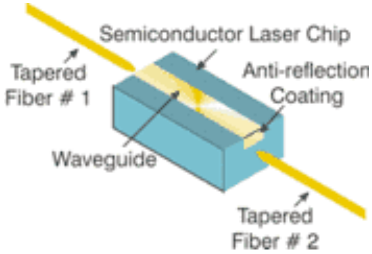


Fig 3.9 Semiconductor Optical Amplifier

The semiconductor optical amplifier is of small size and electrically pumped. It can be potentially less expensive than the EDFA and can be integrated with semiconductor lasers, modulators, etc. However, the performance is still not comparable with the EDFA. The SOA has higher noise, lower gain, moderate polarization dependence and high nonlinearity with fast transient time. This nonlinearity presents the most severe problem for optical communication applications.

High optical nonlinearity makes semiconductor amplifiers attractive for all optical signal processing like all-optical switching and wavelength conversion. There has been much research on semiconductor optical amplifiers as optical computing components.

3.3.3 RSOA

The Reflective Semiconductor Optical Amplifier (RSOA) [Prat05] consists of a conventional SOA in combination with a rear facet mirror such that the amplified lightwave is retro-reflected. This characteristic provides an increased gain from the device due to the double pass of the light through the gain region; an additional characteristic is their ability to modulate the incoming signal, removing the need for a local light source.

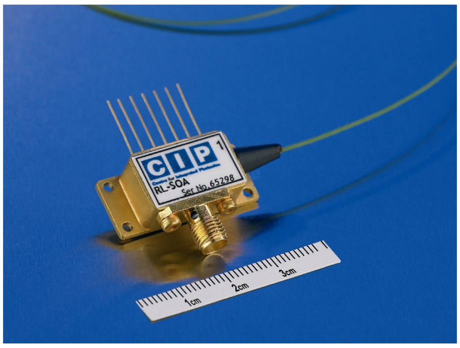


Fig 3.10 Reflective Semiconductor Optical Amplifier

3.3.3.1 RSOA characterization

RSOA response depends on the incoming signal power and the bias current that is injected to the device. Figure 3.11 presents the output power of an RSOA that has been characterized in our labs.

From the figure below it can be seen that the RSOA has different performance regions, which are the linear and the saturation response regions. The linear region is preferred to use the RSOA as a modulator, as offers the highest extinction ratio. On the other hand, the saturation region is preferred when RSOA performs as a photo receiver. This means that if the RSOA needs to be used as both, modulator and photo received [Prat05a], a compromise should be met to achieve correct performance on both tasks.

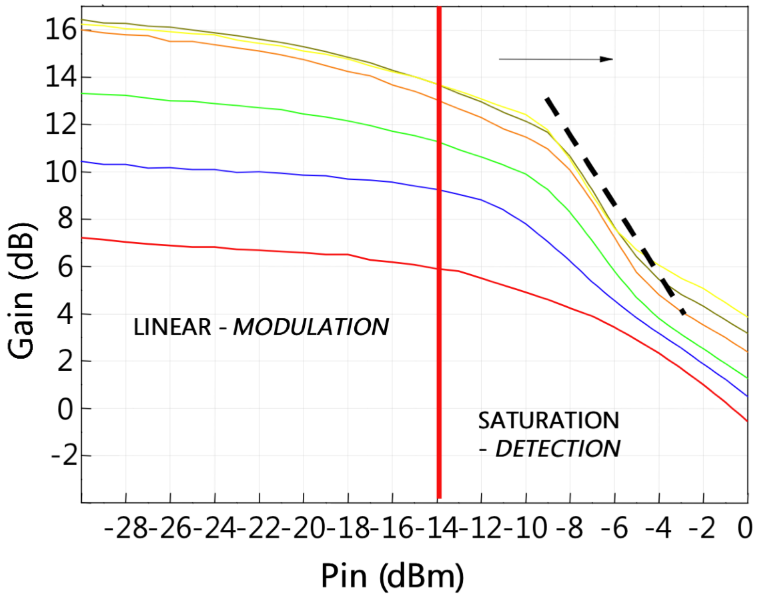


Fig 3.11 RSOA response

3.3.3.2 Applications in access networks

The use of reflective modulation techniques, RSOAs and EAMs is gaining attention in access due to the evolution of WDM PONs. As said in the introduction, in WDM PON systems each ONU requires a specific wavelength for upstream transmission and the use of wavelength-specific sources is not viable due to stock problems.

The use of an RSOA, or a combination of SOA+EAM or the use of a modulator to transmit upstream by modulating an optical carrier sent from the CO [Kang06], [Prat05], [Prat05a], [Takesue06] allows the design of wavelength agnostic ONUs, which is now the most relevant application of SOAs and EAMs in access at present.

4 Upgrade paths to FTTH

In previous chapters we have presented the state of the art of FTTx and the optical device requirements that are need to deploy advanced access networks. However, if there is no justification for the change, this will not take place as access networks are a very competitive market, which is mainly driven by deployment costs and end users requirements.

End user requirements and new applications are the main justification for investment in access networks. New applications with higher transmission requirements are encouraging operators to increase the bandwidth that they offer to the end users and this is causing the fiber infrastructure and xDSL technologies to reach their limit. This is what justifies the progressive upgrade path from the existing copper-based infrastructure to a totally optical one.

This chapter will focus on this. First, we will introduce new applicatons and their bandwidth and latency requirements and afterwards we will present an upgrade path that is based on two steps: a first FTTC VDSL stage and a second FTTB Ethernet stage. The evolution will conclude with a totally optical deployment, which will be described in the next chapter.

4.1 Justification: new applications and more bandwidth requirements

The justification for an upgrade path from the existing copper based infrastructure to an optical FTTH outside plant is one main driver, which is the possibility to deploy new applications that require more bandwidth.

The following list present advanced broadband applications and their transmission requirements, in terms of bandwidth, latency and transmission paths [Ransom92].

Table: New applications for future access networks

Video broadcasting and Video-on-Demand (VoD): video streaming is becoming the killer application that is encouraging the development of FTTH at present. MPEG standards are used to stream video on access networks, using MPEG-2 and MPEG-4/h.264 technologies. MPEG-2 has as main advantage the wide deployment of MPEG-2-capable equipment, as this is the standard used on DVDs and DVB. HDTV videos codified on MPEG-2 have bitrates around 20Mbps. On the other hand, MPEG-4 and h.264 standards offer more compression than MPEG-2 but require new equipment to decode the streams. MPEG-4 standards are used at present on peer-to-peer (P2P) networks thus devices capable of decode those streams and display them on TVs are becoming more popular now. An HDTV video on h.264 is about 7-8Mbps.

When one talks about video streaming, there is however a clear distinction between the offered service that influences on the network requirements to support it. This is whether multicast streaming or video-on-demand services are offered. If the network just multicasts several video channels, the required transmission capacity is *n* times the data bit rate. In this case, the network is dimensioned depending on the video channels. On the other hand, if the network offers VoD videos, the dimensioning will be done depending on the concurrent video streams, as one stream is required for each user that wants to watch a movie [Chan01].

Requirements in video streaming are mainly high and sustained data rate, together with constant latency. Network delay is relatively important, as the communications is just one way.

Videoconference: high-quality videoconference is an application that is very difficult to deploy on present access networks because of its tight transmission requirements. The characteristics of videoconference are that it is a bidirectional communication that requires high bandwidth (in case of high-quality video), low latency and very low network delay (under 80ms). High-quality video requires sustained video flows of 1-2 Mbps, which are difficult to transmit on present xDSL infrastructures especially on the upstream channel [Kim05].

Audio streaming: due to the proliferation of the digital world and P2P networks, audio streaming and online purchasing of multimedia content are becoming a very profitable business. Apple is leading the market with iTunes (www.itunes.com) but now many other players want also to enter into the business. Transmission requirements are not huge so present access networks can already offer this service with guarantees. The improvement on data rate would just reduce the time to download songs, which is now not a dramatic delay at present anyway. 1Mbps would allow reception of songs in a few minutes.

Online gaming: this is a huge market, especially in Asia, where online gaming is one of the main drivers of broadband, on both, fixed and mobile access [Xiang05]. Transmission requirements of online gaming applications depend on the middleware design [Hsiao05], [Bauer02]. However, the mores available bandwidth, the more interactivity and reality can be achieved, specially in the recreation of virtual worlds, were the transmission requirements can be as high as the required for virtual reality (VR) applications.

Teleworking: teleworking is a business model that is gaining popularity lately due to the economic and personal advantages that it offers to both, employers and employees. Employers can reduce their offices size while employees have a more user-friendly work environment, which increases productivity and also improves quality lifestyle, as no time I required to commute from home to work [Grozdanovic01]. Transmission requirements vary depending on the application but in general, to achieve total teleworking, data rates should be comparable to those of LANs, at least in peak mode. Anyway, 10Mbps are enough for present teleworking requirements and allows similar network experience as if the teleworker would be physically in the company's premises.

eLearning: eLearning an the recreation of educational environments is another interesting application on future access networks [Zahariadis02]. To recreate such an environment, the transmission requirements are similar to videoconference together with teleworking, as the learner needs a way to interact with the teacher and also a way to exchange information in a flexible way. There are also approaches that try to virtually recreate auditoriums to offer a more realistic approach, the requirements of which are similar to VR applications [Dong05]

Peer-to-peer: P2P traffic is at present the higher load of the Internet. The increase of broadband datarates and 24h connectivity has dramatically changed the traffic patterns of the Internet. In terms of bandwidth per user, network utilization follows a 80/20 Pareto law, and 20% of the network users allocate 80% of the bandwidth, mainly because P2P applications. Without entering in legal issues, the more bandwidth the network offers, the more P2P applications use it so there is no point in giving a figure to P2P traffic requirements, as all available bandwidth on future access networks could be used to P2P traffic. However, what one should guarantee is that traffic priorities do not allow P2P to cannibalize all the bandwidth.

Telemedicine: under telemedicine, one can identify two main applications: remote doctor practice and medical collaborative work [Kohli89]. Their transmission requirements are very different, as the first one is a virtual presence application, where the objective is to give a framework of interaction between the patient and the doctor. Requirements are similar than videoconference applications. On the other hand medical collaborative work has higher transmission requirements. In diagnostics, the network should support transmission of high quality images in order to diagnose with the highest resolution. Additionally, in remote surgery applications, further to high quality video streaming to watch the operation, in case of remote tool usage, then resilience and security should be 100% guaranteed. In terms of available bandwidths, one can think on 10 to 100Mbps depending on the video quality.

Virtual Reality: This application has the highest transmission requirements but at the same time is the most difficult to predict when trying to present any figures in terms of transmission requirements. Those requirements depend on the quality of the virtual world that one wants to recreate and the interaction between the VR environment and the user. In VR applications, network delay, latency and jitter are critical parameters to provide a correct interaction between the virtual world and the user while bandwidth determines the quality of the recreated world. Bandwidths can go up to +Gbps while jitter, network delay and latency should be kept under 3.5ms to offer correct interaction experience. [Nishino06].

High-speed Internet: The higher the datarate, the better the surfing experience on the Internet. Traditional services, like email, news browsing and WWW do not have excessive bandwidth requirements. However, attachments in emails and complex WWW pages are quicker transferred when datarate is high. Anyway, constant data rates are not required unless file transfer. Except for this last case and the transmission of large emails, high-speed Internet do not require more than 10Mbps per user.

From the list, above one can see that present xDSL solution will not be able to cope with the required transmission bandwidths, especially when applications are used simultaneously. However, they are a viable solution now and can be seen as a transition to a fully optical infrastructure.

Video applications and virtual reality (VR) are the hungriest players in terms of network requirements. Although advanced compression protocols are under development to increase resolution while keeping data rates low, fiber becomes almost a requirement in VR environments. The recreation of virtual worlds require 3-D renderings and high-quality audio which are also difficult to transmit on present PONs due to the huge transmission requirements of VR [Ishida05].

4.2 FTTC: Combined WDM / SCM network to deliver VDSL signals

This section describes two possible schemes developed to carry very high data rate DSL signals over a fibre to the cabinet architecture for the upgrade of legacy copper networks.

The first technique has been developed to exploit the sub-carrier bandwidth of un-cooled semiconductor lasers for the transmission of multiple VDSL signals using inexpensive interfacing hardware in the optical networking unit (ONU).

Using a hybrid fibre/copper link comprising >100m of twisted pair copper cable and up to 45 km of SMF, data transmission comparable to FTTH is achieved. In an extension to this design, we further demonstrate a system using a reflective semiconductor optical amplifier (RSOA) in a carrier-less remote ONU configuration [Prat05a]. Such a design might enable wavelength agility in the fibre access network for the purpose of signal routing or active bandwidth allocation.

4.2.1 Introduction

Fibre-to-the-home (FTTH) provides the ultimate wireline access medium due to its effectively unlimited bandwidth. However, without significant opportunity for new revenue generation, for example through high uptake rates of triple play services, the economic model for wide-scale FTTH deployment remains weak at present [Frigo04, Monath03]. The business case for fibre-to-the-curb or cabinet (FTTC) deployments is however much stronger now as copper-based infrastructure is still able to cope with the transmissions requirements of present applications. Here the fiber cable replaces much of the existing copper link but leaves the final copper drop-link untouched. The cost advantages are therefore drawn from increased sharing of the fibre plant, greater reuse of existing infrastructure and lower installation and purchase costs of the end user (CPE) equipment. Moreover, data rates of very high rate digital subscriber line (VDSL) and the spectrally enhanced VDSL2 technologies can now exceed 100MBps symmetric transmission over relatively short distances (up to ~300m), making it an ideal transmission format for FTTC deployments.

One considerable expense in deploying DSL over FTTC architectures is the requirement for the installation of a remote digital subscriber loop access multiplexer (DSLAM), often deployed in the optical networking unit (ONU). The heavy power requirement and increased footprint of such systems places a significant burden on both the CAPEX and OPEX of this architecture, and alternatives are sought [Silverman04].

This section presents a network topology together with the results of experiments on a scheme to provide fiber optic extended DSL signals over an FTTC architecture with inexpensive low power (<600mW) ONU interfacing equipment whilst retaining the DSLAMs at the CO. Furthermore, provision for multi-dwellings or multiple CPEs is afforded through the use of sub-carrier multiplexing in the ONU/OLT interfacing equipment [Penty02]. A noteworthy advantage of this system is that it provides a readily deployable upgrade path for fiber penetration into legacy copper-based access networks. This could form part of a staged upgrade solution that, with sufficient uptake of triple play services, could culminate in an FTTH network.

We study two ONU hardware architectures; the first uses a conventional optoelectronic interface comprising a laser and photo receiver. This could, for example, consist of a BiDi optical transceiver or of a photo receiver and laser pair. A particularly suitable choice of laser for this application would be the VCSEL as it is inherently inexpensive and suited to integrated circuit design. For the purpose of demonstration we use a DFB laser operating at ~1544nm.

In a further implementation of the ONU hardware, we describe an optical interface consisting of a photo receiver and a reflective semiconductor optical amplifier (RSOA), which has already been described in the previous chapter.

4.2.2 DSL over FTTC architecture

Figure 4.1 presents the link structure used to carry multiple DSL signals over a fibre to the curb (FTTC) network. The network contains some key features, amongst which are the compatibility with PON architectures and retention of the Central Office DSLAM equipment. OLT/ONU hardware has been designed to operate at low power with a small footprint, offering compatibility with the legacy cabinet and distribution point infrastructures. An ONU multiplexes each of the DSL signals from the customer premises equipment (CPE), with a maximum of 24 VDSL bandwidth signals expected to be contained within a 1 GHz modulation bandwidth optical carrier using the current implementation. Future designs may encompass single/vestigial sideband techniques to improve the spectral efficiency of the subcarrier signals.

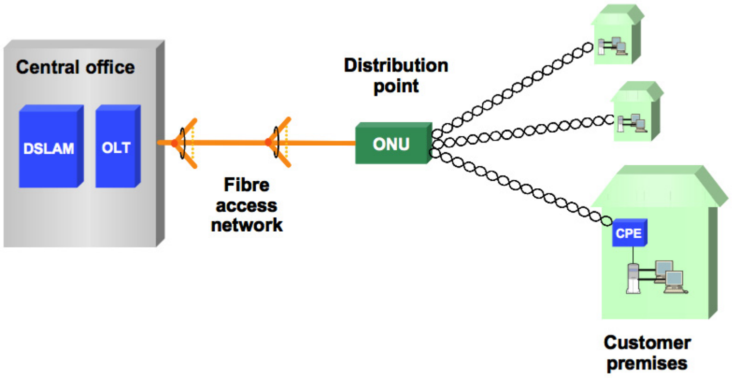


Fig 4.1 Network architecture used for DSL over optics solution

4.2.3 Local carrier ONU design

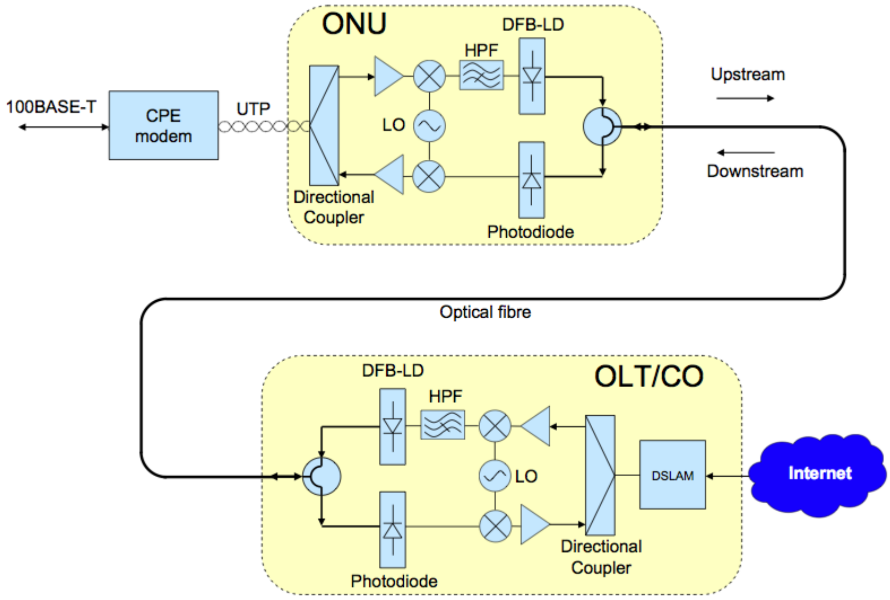


Fig 4.2 VDSL over FTTC experimental setup

Fig. 4.2 shows a schematic of the experimental setup. The system comprises a DSL modem at the CPE carrying 100BASE-T fast Ethernet traffic over a VDSL band 998 compliant channel. This is connected by 106m of UTP (unshielded twisted-pair) cable with a loss of ~8dB at 10MHz to the ONU equipment. Such a distance would be representative of a final drop UTP cable from a cabinet/distribution point. The UTP from each CPE terminates in the hardware represented by the ONU in Fig. 4.2. The line initially terminates into an electronic directional coupler to split the upstream and downstream signals. The design of the directional coupler consists of a lossless differential balanced op-amp pair with a measured isolation of 23dB in the forward direction and >80dB in the return direction. The directional coupler has been further designed to be frequency independent, thereby allowing for a band-plan agnostic ONU solution capable of carrying both QAM and DMT based signals. This design characteristic of both the OLT and ONU equipment makes the scheme capable of carrying true interoperable universal-DSL signals. Other designs for the directional coupler were considered; amongst which are the transformer based hybrids and directional couplers, however these suffer from limited up/downstream isolation and significantly higher losses.

The differential output of the directional coupler is converted to a common-mode signal before being upconverted to a channel within the sub-carrier multiplexed (SCM) spectrum. A passive high-pass filter is used after the mixer to remove the residual baseband signal that results from imperfect conversion. In the forward path, the upconverted signal is combined with the other SCM channels before being used to directly modulate a semiconductor laser. Frequency up-conversion of the DSL signals enables multiple signals to be combined within the ~1GHz modulation bandwidth of the optical components. In the current scheme, the VDSL signals have a baseband spectral width of 12 MHz (24 MHz including both sidebands). With the 998 spectral band plan this offers a maximum 67 Mbps upstream and 40 Mbps downstream data transmission rate. Given the spectral width of the up-converted signal, a 1 GHz modulation spectrum in the optical carrier would permit 40 VDSL channels, however with the inclusion of 16 MHz guard-bands the channel count would be reduced to ~25.

In the return path, the output of the circulator is connected to a photodiode before being passively split, down-converted and re-applied as the return signal to the directional coupler. The output of the laser is connected by a circulator to the fibre link, which consists of an unamplified section of NZDSF SM fibre with various lengths. The fibre carries the signal to the OLT terminal equipment, which comprises an identical circuit to the ONU, the output of which connects directly to the CO modem (or DSLAM). For experimental purposes both OLT and ONU transmitters operate within the 1550nm band.

Results obtained demonstrate two key experimental observations. Firstly, the transmission performance of the each VDSL signal over a range of subcarrier-multiplexed channels can be assessed. This was performed across the approximate frequency range 50 - 1000MHz, principally governed by the mixer bandwidth. Secondly, performance across increasing optical distance can be observed. Fig. 4.3 shows baseline performance of the modem transmission rate through the ONU/OLT equipment for a range of subcarrier frequencies implemented.

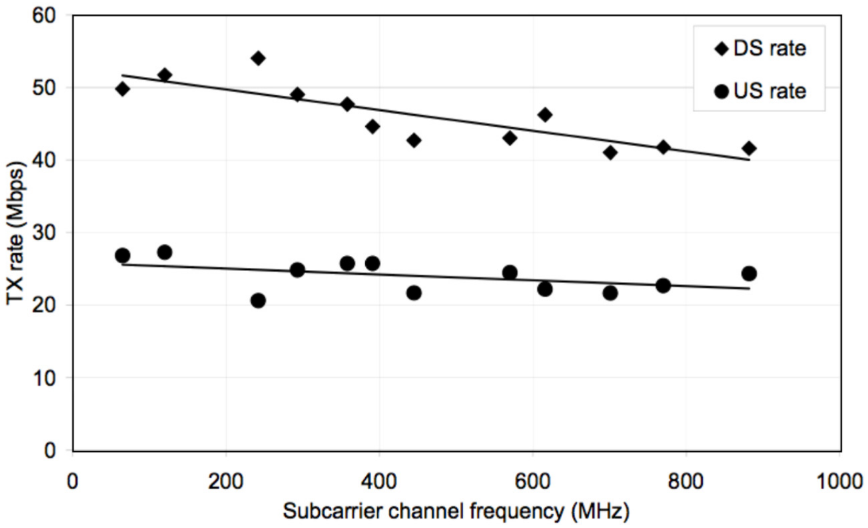


Fig 4.3 Baseline data rate versus subcarrier frequency though the OLT+ONU interface (DS: downstream; US: upstream)

The results of Fig. 4.3 indicate a mean downstream rate of 46.4 Mbps and an upstream rate of 24.1 Mbps, these compare to the 67 Mbps and 40 Mbps respectively available to the fast-998 band plan used, corresponding to transmission efficiencies of 69% and 60% respectively. The decreased efficiency results almost exclusively from the up- and down-conversion processes, namely the conversion loss of the mixers. It is expected that this efficiency could be improved with linearised mixers. As a measure of the unconverted efficiency, transmission of base band signals through the same circuit (i.e. bypassing the mixers) produced data transmission efficiencies of 91% and 97% for the down- and upstream signals respectively. This resulted in transmission rates of 96 Mbps and 48.5 Mbps over a 105/50 extended-998 band plan.

To measure transmission performance over the fibre optic extended link, the setup of Fig. 4.2 was used with increasing lengths of NZDSF fibre and again performance was measured as an average across the full subcarrier spectrum.

The results for baseline optical (i.e. a patchlead), 20 km and 45 km of the SM fibre are plotted in Fig. 4.4.

The results, as expected, show a gradual decrease in the data rate with distance reducing the mean downstream rates to 37 and 28 Mbps for 20 km and 45 km respectively whilst the upstream rates are reduced 24 and 12 Mbps for the same respective distances. In keeping with the expected access topologies, no optical amplification was used. The results therefore follow a predictable degradation due to the increased losses and their consequent reduced SNRs as received by the modems.

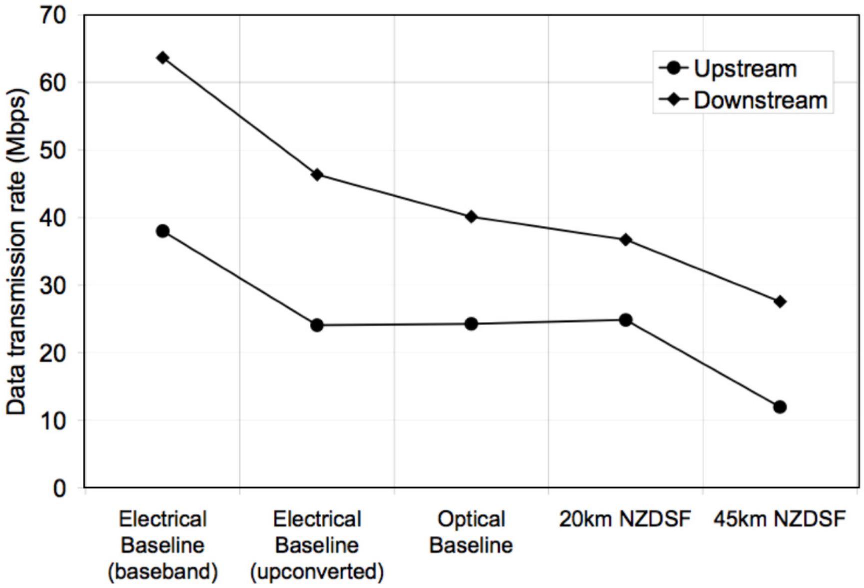


Fig 4.4 Mean data rate across subcarrier spectrum over increasing transmission distance

4.2.4 Carrierless ONU design

For the second part of this work, the design of the ONU equipment has been altered to include the RSOA device (as shown in Fig. 4.5).

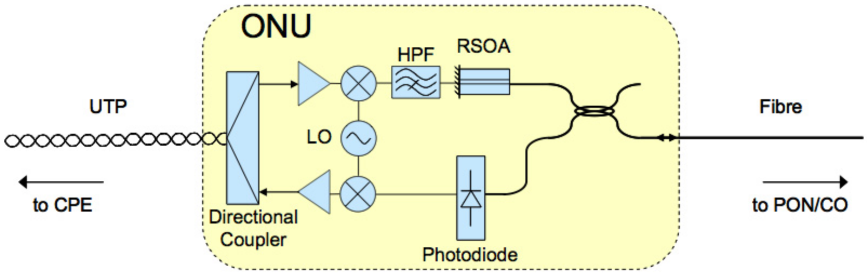


Fig 4.5 RSOA based ONU hardware

The OLT equipment remains the same as that shown in Fig. 4.2. In this ONU configuration, the RSOA is used as a carrierless transmitter, in that it amplifies and modulates the reflected light beam rather than generating a new light beam. This potentially extends the functionality of the RSOA-based ONU to wavelength assignment or routing architectures [Tsalamanis04a].

As the nature of the DSL signal is such that downstream and upstream data are frequency division multiplexed (FDM), the residual downstream signal that is amplified and reflected is effectively filtered by the DSLAM. A separate photodiode is used for detection of the downstream carrier signal. The up and downstream paths are power split using a 3dB coupler, with care taken to ensure that Fresnel reflections (which may lead to optical feedback in RSOA) are minimised. As with the previous setup, the DSL signal used is the 998 compliant VDSL standard with a 12 MHz spectral bandwidth and a maximum 67 Mbps downstream and 40 Mbps upstream data rate.

Both base band and SCM-based transmission tests were conducted to validate the operation of the RSOA-ONU architecture. The device had a threshold current of 50 mA and was biased at 80 mA; the upstream data modulated on it at 40 mA peak-to-peak. Under these conditions, the RSOA provided a gain of ~8dB, which is sufficient to ensure transparency of the ONU with ~1.5 dB of additional gain. The modulation bandwidth of the RSOA was ~1.5 GHz, although the end-to-end bandwidth of the optical system was restricted to ~1 GHz by the OLT components.

First, the ONU was operated in the subcarrier-multiplexing mode using an upconversion frequency of 260 MHz and the 998 67/40-band plan. With an unamplified 20 km section of SMF fibre separating the ONU and OLT, the data rates achieved were 38 Mbps downstream and 24 Mbps upstream, giving data transmission efficiencies of 57% and 60% respectively. Then, with the mixer circuit bypassed to transmit in base band mode, the data transmission rates were 48 Mbps downstream and 25 Mbps upstream, demonstrating data transmission efficiencies of 72% and 63% respectively.

4.2.5 Conclusions

The practical results of a novel subcarrier multiplexing scheme for transmission of multiple band-plan agnostic universal-DSL signals over a fibre optic extended network show good performance over the full subcarrier spectral range and distances of up to 45 km of single-mode fibre span, making this a possible solution for X-Large PON networks. By using these low power ONU/OLT interfaces in FTTC/FTTN architectures we propose an inexpensive upgrade solution for staged fibre penetration into legacy access networks. Fibre optic extended solutions such as this enable FTTH comparable data rates with maximal infrastructure reuse.

We have further extended the scheme by developing a carrierless ONU transceiver using an RSOA device. This provides a colourless ONU architecture with its potential flexibility in wavelength assignment and routing. Both solutions demonstrate triple-play capable bandwidth over X-Large PON distances and, through the incorporation of SCM, enable multi-user scalability from the distribution point.

4.3 FTTB: Switched Ethernet services over WDM /SCM access networks

In this section, a hybrid optical/copper access network designed for Fiber-To-The-Building (FTTB) implementing switched Ethernet (10/100/1000Base-T) services is presented and evaluated. The optical distribution is based on bidirectional WDM to establish virtual point-to-point connections between the Central Office (CO) and the Optical Network Units (ONUs) through Arrayed Waveguide Gratings (AWGs). Optical transmission is implemented with single fiber outside plant, using two different wavelengths to transmit upstream and downstream signals matching the cyclic free spectral range of the AWG. By means of Sub-Carrier Multiplexing (SCM), several switched Ethernet channels are multiplexed and transmitted on the same optical wavelength to the ONU. This acts as a multipoint transceiver from the optical link to the standard UTP infrastructure used to distribute the signal inside the building to the end users.

The advantages of this technique are simplicity, cost effectiveness and increased network security compared to PON standards. Switching of Ethernet signals is performed at the OLT and data from/to one user is isolated from the others. This establishes a transparent point-to-point connection from the OLT to the end user based on LAN Ethernet Services, via a bidirectional WDM+SCM path. The use of LAN Ethernet services makes the topology cost effective. Furthermore, the optical equipment is shared among all the users connected to the same ONU, with up to 96 possible depending on the Ethernet service that is deployed.

Bandwidth demands for new applications require an upgrade on existing copper access infrastructure to be able to accommodate these new services. Optical fiber and more specifically passive optical networks are an effective approach to deploy cost-effective networks [Prat02]. A/GPON and EPON are two alternatives that are currently on the market. GPON ITU-T G.984.3 offers asymmetrical bandwidth up to 2.5Gbps downstream / 1.25Gbps upstream while EPON IEEE 802.3ah offers symmetrical 1Gbps [ITUTG984.x, IEEE802.3ah], both having been analyzed in Chapter 2. The available bandwidth is shared on a TDM basis among the users connected to the network segment, which means that end user practical bandwidth depends on the network utilization. Also, the equipment required at the user premises requires packet processing to control OAM and from the transceiver point of view, a laser and photo receiver for each end user.

This section proposes an alternative broadband approach based on a hybrid fiber / copper topology to transmit switched Ethernet signals from the Central Office to the end users achieving high density and long reach. WDM transport technology is used for the optical links and SCM to multiplex several Ethernet connections on the same wavelength [Penty02]. In this approach, the WDM and SCM stages are transparent to the Ethernet protocol, so we can transmit standard electrical 10/100/1000Base-TX signals using inexpensive LAN cards at the end user side and position the switch and processing equipment at the CO. This approach is especially interesting for FTTB applications in highly populated areas such as condominium buildings. Here, the ONU would be located at the building basement and the copper infrastructure would run from there to each of the end-user Costumer Premises Equipment (CPE).

4.3.1 Network architecture

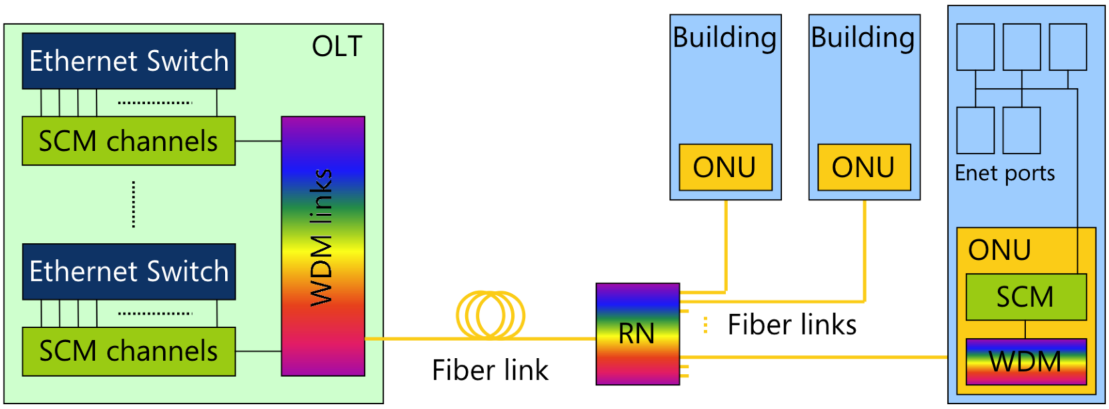


Fig 4.6 Network architecture

One of the features of the network is that the processing equipment is entirely located at the CO, while there is no active equipment in the outside plant except for the ONU. The use of passive components in the outside plant reduces mainly OPEX because no special environment-controlled spaces are required to place the equipment. Additionally, failure probability is much lower on passive than on active equipment. Figure 4.6 presents the proposed outside plant. As the optical, electrical and Ethernet domain are completely transparent, they will be described in separate subsections.

4.3.1.1 Optical layer access topology

In order to provide connectivity in the optical domain, we propose the use of a standard WDM-PON topology, based on an AWG at the remote node to route wavelengths to the appropriate ONU. Each ONU has a dedicated wavelength, connecting it to the OLT in a point-to-point configuration. To reduce outside plant size, we use a single fibre to transmit both, downstream and upstream. Although we could transmit both on the same wavelength [Prat04a], in order to reduce Rayleigh backscattering and reflections, we separate upstream and downstream on different wavelengths matching the free spectral range (FSR) of the AWG [Smit96] to achieve correct connectivity (Fig. 4.7).

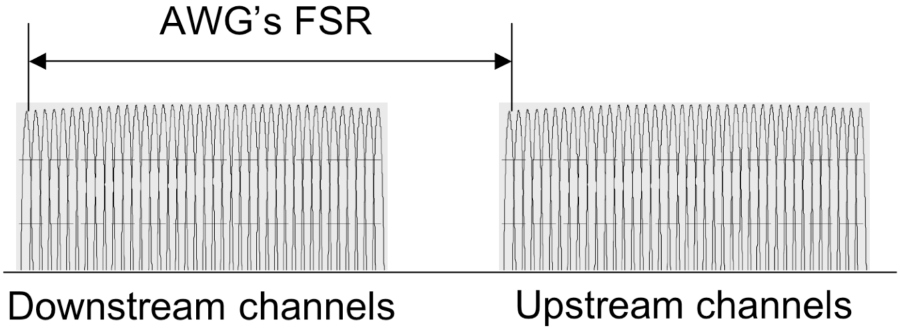


Fig 4.7 AWG routing plan

The OLT is based on an array of lasers. A laser for each ONU is needed, as constant connectivity is required to establish the Ethernet links. To multiplex all the lasers, an AWG identical to the one used at the remote node is used. After the multiplexing stage, an optical circulator (or, alternatively, by a coarse DeMUX) separates upstream and downstream transmissions. The upstream reception branch is formed by an AWG (identical to the others) and an array of photo-receivers.

The ONU is based on a coarse demultiplexer to isolate downstream and upstream traffic. Downstream traffic is then photo-received and upstream traffic is sent to the OLT by directly modulating the laser.

Fig. 4.8 depicts the outside plant, OLT and ONU designs.

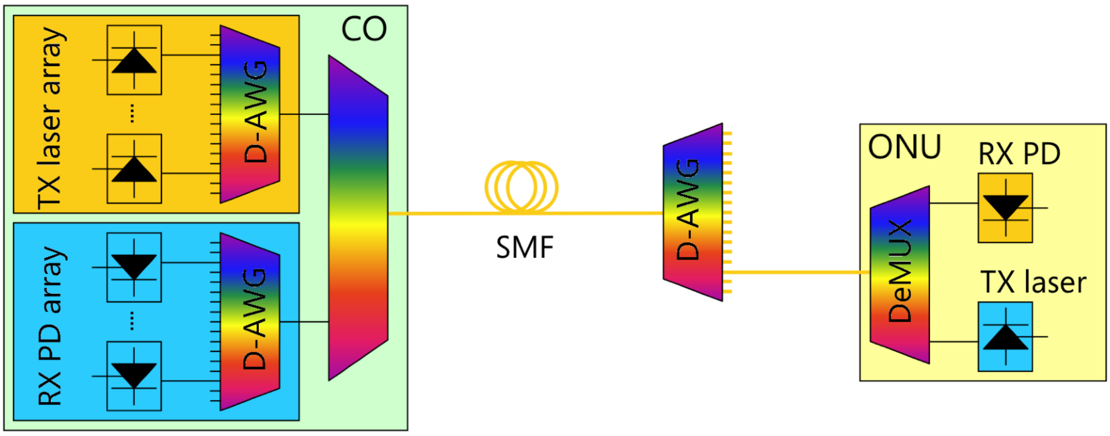


Fig 4.8 Optical layer design

4.3.1.2 Sub Carrier multiplexing stage

In order to multiplex the Ethernet services that will be offered to the end users, we use sub carrier multiplexing. The objective is to efficiently use the available electrical spectrum of the laser, to transmit the number of channels needed at that ONU location. As we are transmitting many channels, we propose to perform this action in the digital signal processing (DSP) domain, to avoid the necessity to have *N* local oscillators, where *N* is the number of services that we are multiplexing on the same laser. This concept is applicable on both, the OLT and the ONU. Therefore, we propose a Field-Programmable Gate Array (FPGA) to perform all the functions that are required, which are: A/D conversion, up and down converting, filtering and D/A conversion. Fig. 4.9 presents a block diagram of the functional blocks and the equivalent process in the analogical domain.

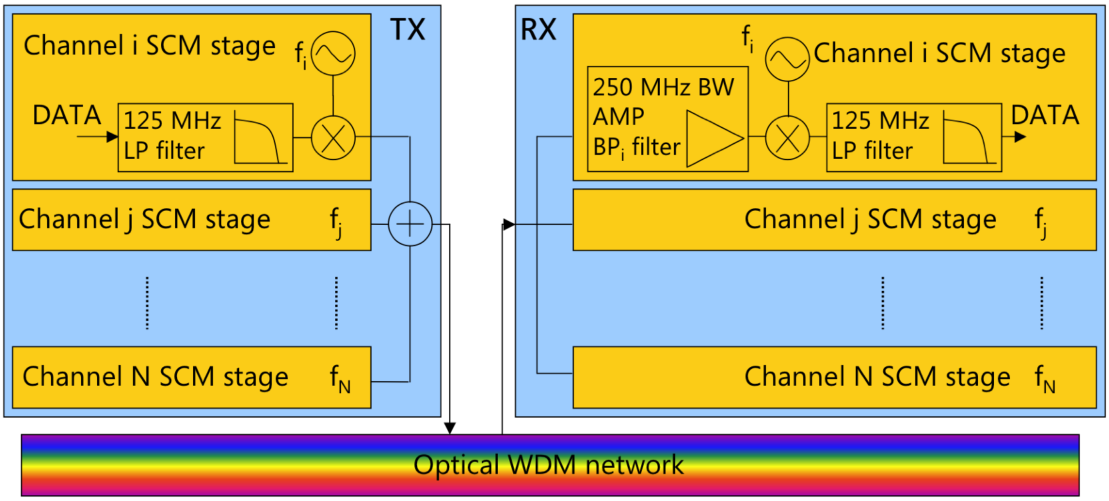


Fig 4.9 SCM stage

The advantage of using digital processing to perform the sub-carrier multiplexing is also the easier implementation of the filters required to filter the channels located in the upper frequencies. To implement sharp-edge filters of a few MHz on a GHz band is a challenging task in the analogue domain.

4.3.1.3 Ethernet service layer

By using the hybrid technique described above for multiplexing channels using WDM on the optical domain and SCM on the electrical links, a transparent point-to-point connection from the OLT to the end subscriber can be established. The limiting factor is the available bandwidth of the SCM channel, which will define the services that can be deployed. The channel count limitation is the available electrical bandwidth of the laser and the DSP. A cost effective approach is to use 2.5GHz lasers. As cost is a limiting factor, we propose to use direct modulation of the laser, instead of external modulation, although this second technique can increase electrical bandwidth up to approximately 10GHz. To calculate the number of Ethernet signals that can be accommodated on a single wavelength, we assume that 10% excess spectrum is required for filtering purposes. Table 4.1 presents the three Ethernet services that are proposed (10/100/1000Base-T) and their coding and spectrum specifications [IEEE802.3], including the number of services that can be multiplexed. Figure 4.10 presents the spectrum of the three Ethernet services under analysis.

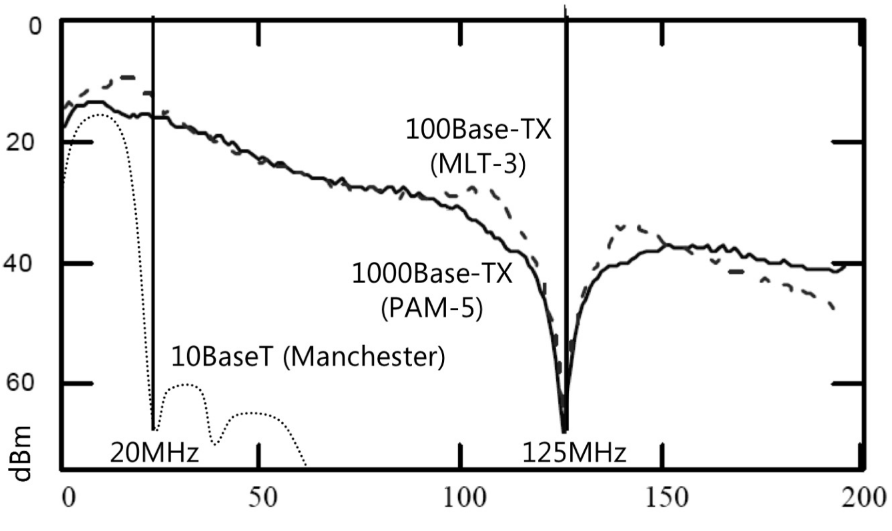


Fig 4.10 Spectrum of 10/100/1000Base-T services

With DSP one can have full control of the service bandwidths and the sub-carrier frequencies, thus automatically reconfigure the electrical spectrum and, in consequence, the service level to the individual users, featuring SLA. Also, different advanced modulation formats can be implemented in order to increase bandwidth efficiency and multiplex more channels.

Service	Data rate	Line rate	Modulation	BW	# channels (*)
10BaseT	10Mbps	10Mbps	Manchester	20MHz	113
100Base-TX	100Mbps	125Mbps	4B/5B,3-MLT	125MHz	20
1000Base-TX	1000Mbps	1.25Gbps	5-level PAM	4x 125MHz	5

(*) Assumptions: 2.5GHz BW with IM modulation, 10% excess spectrum for 10BaseT

Table 4.1 Ethernet services

4.3.1.4 Dimensioning, applications and users

The number of users that can be served by a single feeder fibre run from the OLT depends on two factors: the wavelengths on the WDM optical link and the number of SCM on each wavelength. This last parameter also depends on the Ethernet service that is delivered, which requires a compromise between bandwidth per user and number of users connected to the network. As we are using digital processing to SCM, the network can switch between different speeds depending on the user demands and on the use of the electric spectrum, which is affected by the number of simultaneous links. Noting that the price of 10/100/1000Base-T LAN cards is now very economic, this feature does not increment the network cost.

ONUs are deployed with the maximum number of ports (defined by the number of simultaneous 10Base-T connections). This is set at 96 to be a multiple of the Ethernet switching standards (2x 48) although it is theoretically >100. Depending on the number of simultaneous connections, the 2.5GHz available bandwidth is tailored to serve the end users, by limiting the links from GbE to Fast Ethernet and from Fast Ethernet to Ethernet services. Obviously, this feature can be adapted to a SLA for specific end users.

On the subject of dimensioning, noting that the maximum number of users served by a single ONU is 96, and that a commercially-available AWGs offers 40 ports, the network can offer 10Mbps full-duplex connectivity to 3,840 users in a very cost effective way. If we guarantee 100Mbps Fast Ethernet service, 800 users can be simultaneously connected. This means that by deploying 3,840 ports we are guaranteeing 100Mbps if the simultaneity factor is 20%. Finally, Gigabit services can be offered to 200 users at the same time. An important feature is that we can combine different services on the same network in a straightforward way. Only the ONU has to be configured so as not to exceed the available electric bandwidth.

4.3.2 Experiments

In order to demonstrate the feasibility of our proposal, we implemented a WDM PON and modulated a laser accommodating several Ethernet services. The network test bed is presented in Fig. 4.11. We used IM analogue techniques to multiplex two Fast Ethernet services and modulated a DFB laser at the OLT to transmit 3dBm output power at 1543.73nm. Between the OLT and the remote node, 20 km of SMF were added to emulate a real FTTH implementation. An athermal 32-port AWG with 100-GHz channel spacing was used as a remote node. Losses of the AWG were 3.9 dB. The ONU was based on a 30-nm CWDM two-port demultiplexer to separate downstream and upstream transmissions. A PIN photodiode receiver was used.

The SCM stage was implemented by transmitting one channel on baseband and another one upconverted to 500-MHz. A 125-MHz low pass filter was used to avoid any overlap between the two transmitted signals. We used a pattern generator to simulate Fast Ethernet data (data rate = 125 Mbps) in order to be able to obtain sensitivity and BER results.

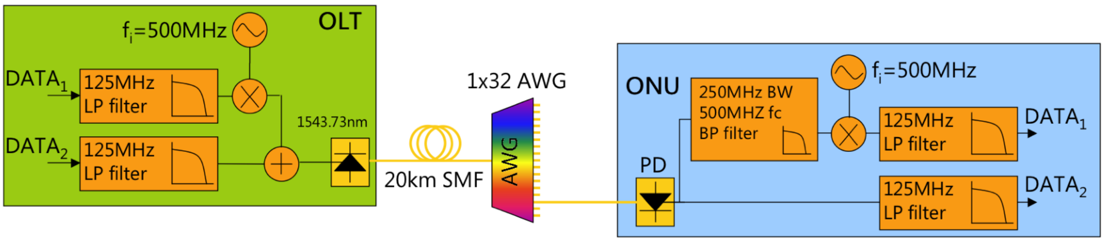
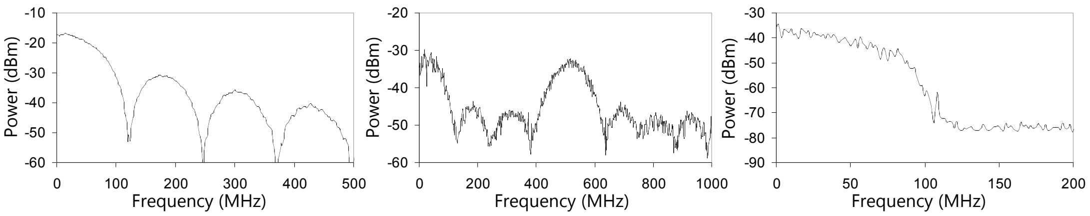


Fig 4.11 Network testbed

Transmission and reception were achieved without problems having a receiver sensitivity (BER=10-9) of -30 dBm for the baseband modulated signal and of -26 dBm for the 500-MHz upconverted one. This degradation on the sensitivity is due to the mixing process involved in the frequency shifting of the signal. Fig. 4.12 depicts spectrums of the transmitted signals in different points.



(a) (b) (c)

Fig 4.12 Spectrum of the transmitted signals; a: 125-Mbps PRBS Data input, b: SCM signal at OLT laser input, c: received signal after down converting and filtering

4.3.3 Conclusions

This section presents an innovative way to transmit electric switched Ethernet signals over an access infrastructure. With this technique, the distance limitations of electric transmission are avoided and the switched environment sets no logical distance limitation due to the CSMA/CD or TDM-PON access protocols.

The network is based on a hybrid WDM/SCM technique and is able to offer up to 3,840 ports using 40 optical carriers and IM SCM, achieving efficient resource sharing of the optical equipment. Furthermore, by optimizing the electric bandwidth channel allocation using advanced digital modulation formats the system capacity can be further increased. A testbed implementation demonstrates the validity of the proposal.

4.4 Conclusions

An economically viable upgrade path is mandatory to offer a gradual transition from the existing copper infrastructure to a passive optical access network. As existing xDSL copper-based standards cannot provide the required bandwidth for future applications, so the migration is inevitable. However, this migration should be done gradually, so network operators can justify the investment.

A FTTC model using xDSL for the last segment of the network reduces the copper link thus offers higher transmission datarates and at the same time closes the fiber to the end users. We have presented two possible implementations of the system, both of them offering low power consumption requirements in field, as powering in field is a critical issue.

Another step that further reduces the copper segment is presented in a FTTB approach for condominium buildings based on SCM of switched Ethernet signals. This system further increases transmission capabilities and prepares the outside plant for a complete FTTH upgrade in the short term.

5 Advanced Topologies for FTTH

This section presents different topologies to deploy high-density access networks for a complete FTTH deployment. Three different topologies will be analyzed in detail, two of them based on a combined ring + tree infrastructure and another one based on a tree outside plant. Each of them has special features and peculiarities and offer different access solutions depending on transmission, quality and topology requirements.

The main characteristics of the network topologies that will be presented, which constitutes the base of this thesis, are:

- ✓ Combined WDM / TDM access
- ✓ Passive outside plant
- ✓ High-density (+1,000 users)
- ✓ Possibility to use reflective and wavelength agnostic ONUs
- ✓ Optimized CO design to optimize utilization of optical resources
- ✓ Simple ONU design for cost-effectiveness

The election of the features listed above is because we believe those are the requirements for future access networks in order to provide the highest performance at the lowest cost.

5.1 AWG^2 WDM/TDM PON in a tree configuration (RAFOH Tree)

This section presents an advanced Time/Space/Wavelength Division Multiplexing architecture. A shared tunable laser and photo receiver stacks offer dynamic bandwidth allocation and remote modulation are used for transmission and reception in order to optimize utilization of optical resources. The network topology is based on a concatenation of two stages of AWGs.

Transmission tests show proper operation at 2,5 Gbps to 30 km reach, and network performance calculations using queue modeling demonstrate that high-bandwidth-demanding application could be deployed on this network.

5.1.1 Introduction

Optical Access Networks present the future-proof alternative to the currently deployed copper access infrastructure. With the standardization of TDM-PONs, a cost effective access technology based on optics has been developed. However, further development needs to be done in order to fully exploit the benefits of optical fiber technology. WDM-PONs is an option, where capacity per user can be very high, but their cost does not make them attractive for a practical implementation nowadays [Maier00]. Other references of network topologies combining WDM and TDM to optimize network performance and resource utilization can be found on [An04] and [Tsalamanis04].

The architecture that we propose finds a compromise between WDM-PONs and TDM-PONs in terms of capacity and cost while offering centralized management and bandwidth allocation from the Optical Line Terminal (OLT), simplifying the TDM upstream protocol. This is possible by using wavelength routing, based on two stages of matched AWGs, which create a virtual point-to-point connection between the OLT and the Optical Network Unit (ONU).

Another advance is the introduction of agile WDM, which combined with TDM leads to a promising level of capacity and resource utilization efficiency. Also, convenient characteristics are the use of one single fiber for both up- and down-stream transmission, to reduce the size of the external plant and the complexity of the Optical Network Unit (ONU) at the Customer Premises Equipment (CPE).

5.1.2 Network design

Network architecture is depicted in Fig. 5.1. It is based on two cascaded AWGs. The first stage is an M x M AWG, located at the OLT or outdoor. The functionality of this AWG is to route optical signals generated by the OLT laser stack to each of the network branches to which the OLT will serve. The second stage is a 1xN AWG located at the remote node. Its task is to demultiplex the N incoming wavelengths to each of the output ports, which connect to the

ONUs. The entire network routing intelligence is located at the OLT in order to provide easy upgradeability and easy integration with the backbone.

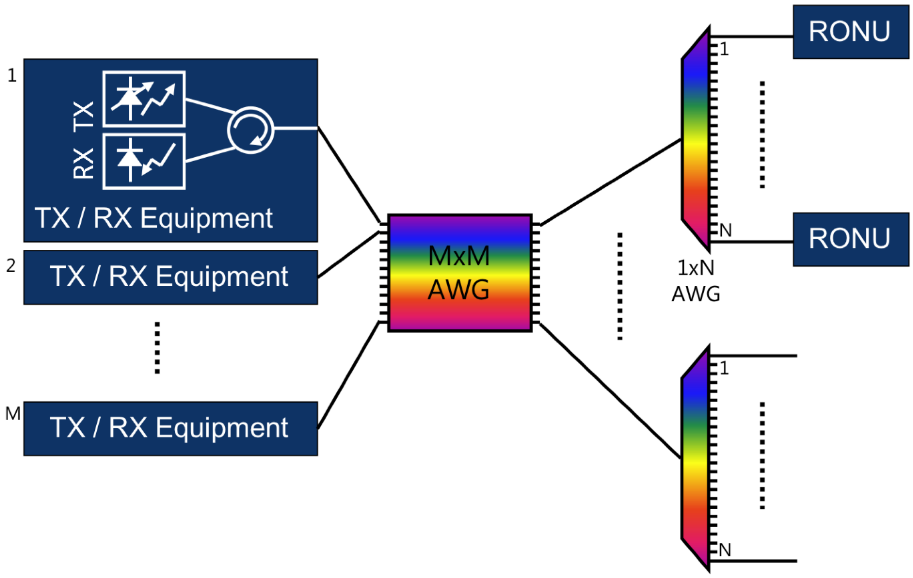


Fig 5.1 Network architecture

We here make use of the FSR periodical routing property of AWGs [Smit96], to route more than one wavelength to each output port. This offers an extra degree of flexibility, more scalability and does not restrict the topology to the case where $N = M$ [Parker00]. The use of the FSR for routing purposes requires that both the central and remote AWGs are designed to match the band pass wavelengths.

Also, we propose a tunable laser stack that is shared among the N x M ONUs. This laser stack can be dimensioned and scaled depending on the bandwidth requirements of the users.

The combination of these two ideas makes this topology flexible, innovative and future proof. Also, dynamic bandwidth allocation is possible as the lasers can serve specific ONUs from different remote AWG segments depending on the network load [Bock04].

The lasers generate N wavelengths. Each ONU has an assigned wavelength that connects it to the OLT (this is comparably more secure than a classic TDM-PON scheme where ONUs listen to a broadcasted transmission). We propose that the ONU operates in reflection mode based on remote re-modulation [Takesue03], [Hung03], [Koonen01], [Prat05]. We used both an optical $LiNbO_3$ modulator and a Reflective Semiconductor Optical Amplifier [Prat05a].

The use of reflective ONUs has the advantage that with such devices, all ONUs can be identical no matter which port of the AWG they are attached to.

Parameters to be designed are the number of lasers at the OLT (typically this value should be the same as the input ports of the first AWG), number of input & output ports of the central AWG (*M*) and number of ports of the distribution AWG (*N*). For cost sharing purposes, the number of lasers, and thus the number of ports of the central AWG (*M*) is much smaller than the number of users connected to each remote AWG (*N*). This is achieved by using multiple FSRs of the central AWG as a multiplying factor for wavelength routing, defined as $N / M = K \in \aleph$ (Number of used FSRs). The explanation of this routing technique can be better understood by analyzing the routing plan of Fig. 5.2. Each laser alternatively serves $K \cdot M = N$ ONUs connected to all the remote AWGs; *K* users connected to each remote AWG are served by the same laser.

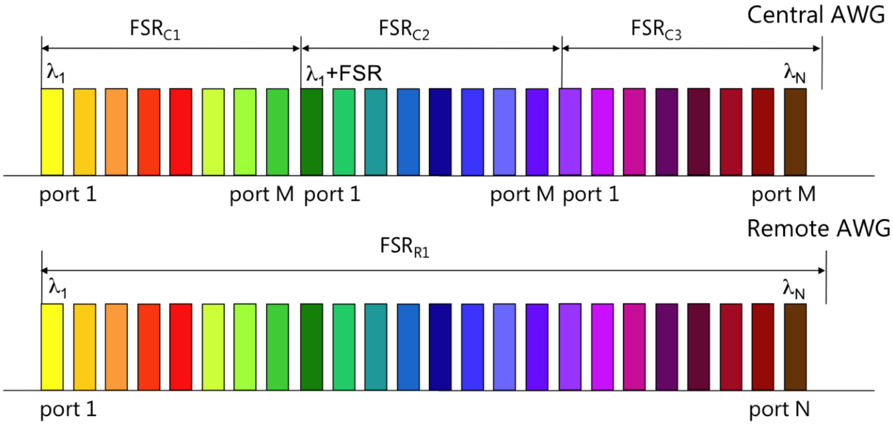


Fig 5.2 Routing plan

Since each laser is shared among *N* ONUs, a dynamical time allocation protocol can be used (although static TDM is also possible). The OLT has the control of the assigned bandwidth by offering the laser source to a specific ONU during a certain period of time. There is also the need to tune to each ONU regardless of the fact they have data to be transmitted or not. This is because they are designed to work in reflective mode, without any light source, which means that the optical carrier needs to be sent from the Central Office. Prior to the laser stack, a data switch is required to route the information to the corresponding laser depending on the ONU.

This time slot duration is shared between downstream data and upstream carrier transmission as can be seen in the downstream signal plot in Fig. 5.3. ONUs cannot generate light so it needs to be sent from the OLT. The solution of sending the downstream data and the upstream carrier from the OLT is interesting because collisions in the upstream are avoided as the OLT has information about all the data and time references sent to all ONUs and, at the same time, no grant and request packets need to be sent between ONU and OLT.

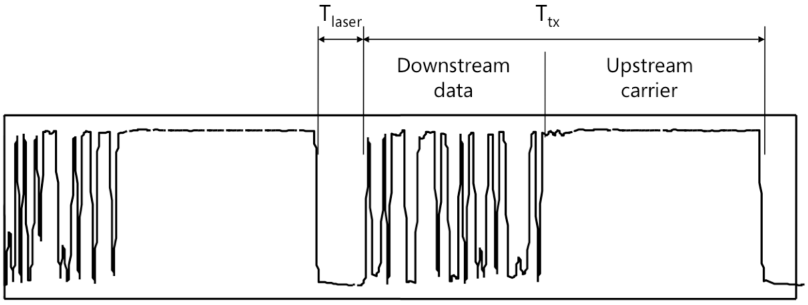


Fig 5.3 Downstream and upstream slot assignation

In a real implementation, we propose the use of a dynamic bandwidth assignment protocol, which would vary window time accordingly, adjusting it to network conditions and user requirements [Kramer02]. As ONUs do not have any light sources, the access protocol needs to send discovery packets regularly in order to detect whether the ONU is online or switched off. In the network performance section, this aspect will be developed.

Another important consideration about laser assignment is the transmission versus tuning time ratio. Each laser switches to N wavelengths in order to reach all ONUs it serves. T_{laser} is defined as the time required to process and to tune a desired wavelength. Depending on laser technology there is a compromise between tuning speed and tuning range [Su04]. T_{laser} in the range of 1 to 10 μs is required in order to offer good performance using data rates of 1 to 2.5 Gbps as we will show later. For higher data rates, tunable lasers with tuning capabilities in the range of hundreds of nanoseconds are required.

Considering this, the minimum bandwidth per user that could be offered in a saturated scenario, where ONUs transmit at their maximum capacity:

$$BW_{user} = \frac{L \cdot b \cdot T}{N \cdot M \cdot \left(b \cdot T + T_{laser}\right)} \tag{5.1}$$

where L is the number of lasers at the OLT (typically $L = M$), b is the data rate and T is the time slot assigned to each ONU in time units. To reduce the effect of T_{laser} the solution is to increase T. However, in that case, the interval of service to serve the same ONU (latency) may be too high for certain applications (e.g. real time applications). Therefore, a compromise must be met combining BW_{user} and latency parameters. Maximum latency, also called T_{window}, is:

$$T_{window} = \frac{N \cdot M}{L} \cdot \left(b \cdot T + T_{laser} \right) \tag{5.2}$$

These equations have been developed supposing a deterministic situation where the users are transmitting at full rate under TDM conditions.

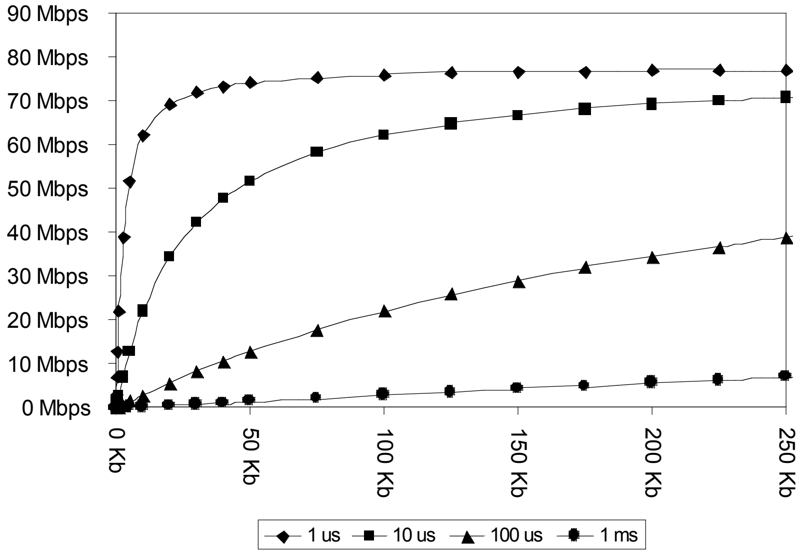


Fig 5.4 Bandwidth per user depending on laser tuning time and time window (other parameters: L=16 lasers, b=2.5 Gbps, $N \cdot M$=512 ONUs)

Fig. 5.4 presents the relationship between the guaranteed bandwidth per user and the average time slot assigned to each user. The conclusion from this figure is that tuning times in the range of μs offer good network performance at data rates of 2.5 Gbps. Slower lasers in the range of ms should not be used because network performance would be degraded to very poor levels.

Fig. 5.5 presents average maximum network latency against time slot duration. There is a minimum in time window time, which is $N \cdot Tlaser$ and the supposition that no user is transmitting (T_{tx} = 0). This minimum, when using a laser with tuning time of 1ms is simply too long for real time applications and therefore, not suitable for being used in our network.

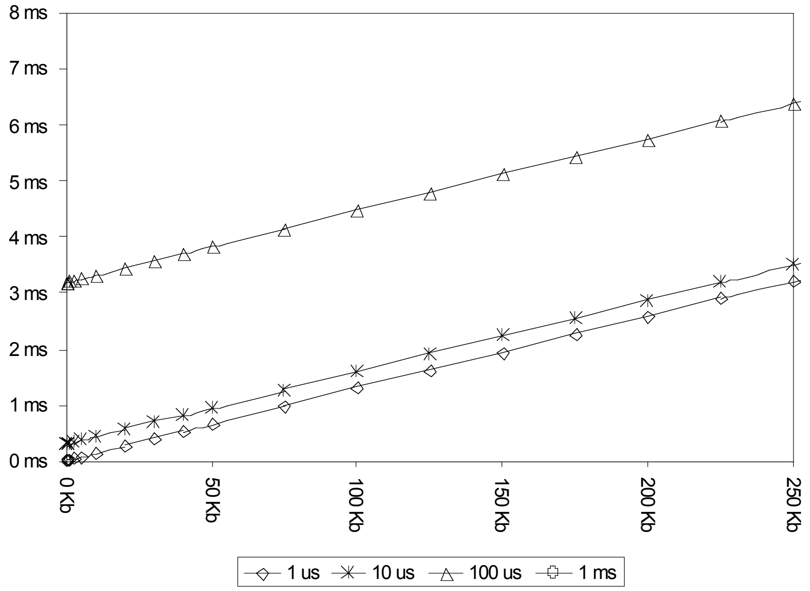


Fig 5.5 Time window per user depending on laser tuning time and time window (other parameters: L=16 lasers, b=2.5 Gbps, $N{\cdot}M$=512 ONUs)

Finally, it should be noted that these results are based on the assumption that ONUs are equidistant from the OLT, so no ranging strategy is required. To consider different distances among ONUs, T_{laser}, which is the guard time between two consecutive transmissions, needs to be adapted to guarantee that there are no collisions at the OLT photo receiver once the upstream data is transmitted. The time margin for ranging purposes is $T_{laser}+T_{down}$, where T_{down} is the time slot assigned to downstream transmission, as downstream data is not sent back to the OLT [Bock05b], The condition to avoid collisions at the OLT photo receiver is then:

$$\Delta d_{prop} \le \frac{v_{prop}}{2} \cdot \left(T_{laser} + \frac{b_{down}}{r} \right) \tag{5.3}$$

where v_{prop} is the propagation speed, b_{down} is the bit length assigned to downstream transmission and r is the data rate. As an example, with T_{laser} = 1 μs and a downstream burst of 50,000 bits at 2.5 Gbps the parameter Δd_{prop} is 2.1 km.

As a general guide to time slot duration, with T_{laser} = 1 μs a value between 50 and 100 kbits is a good compromise for both time window and network performance. Maximum time window is in the range of 1 to 2 ms and network utilization in the range of 85 to 99%.

5.1.3 Network scalability

Bandwidth scalability and addition of new users are among the most important features that an access network must provide in order to be future proof. In this section, we propose several strategies in order to increase network performance and the number of connected users once the infrastructure has already been deployed.

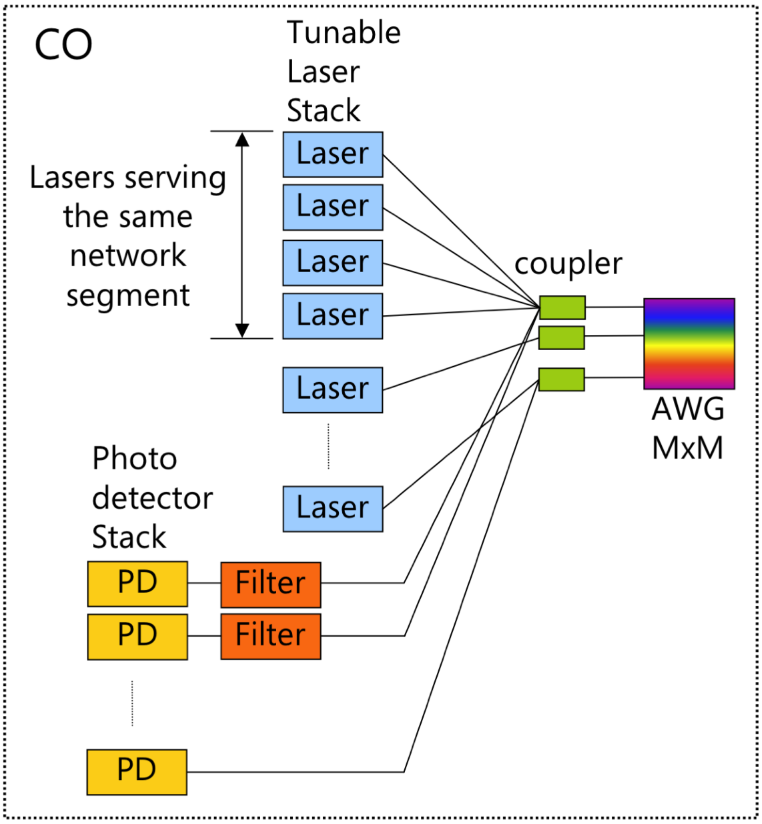


Fig 5.6 Bandwidth increase by means of addition of more lasers

In order to increase the bandwidth per user, we have two basic alternatives: to increase data rate or to increase the number of lasers. The first one would need major investment as all ONUs should be adapted to the new data rate. To add more lasers at the OLT is the best solution from the cost and performance point of view and is completely transparent from the user side Since the *M* ports of the first AWG would be already in use, we would need to add a coupler to install additional lasers. All the lasers connected to a same coupler would serve the same ONUs so bandwidth would be incremented on those ONUs by a factor equal to the number of lasers connected to the same coupler. In addition, the number of photo detectors at the OLT would need to be increased to match the number of lasers. Also tunable filters would need to be added before the photo detectors to receive data transmitted on different wavelengths simultaneously from different lasers (see Fig. 5.6). This strategy allows network design depending on the end user bandwidth requirement needs, being the limit one laser per subscriber. This limit, however, is just theoretical because would lead us to a standard WDM PON solution. Finally, the laser control protocol should guarantee that two or more lasers connected to the same port do not tune the same wavelength simultaneously, as this would cause collisions between the optical signals and thus improper system operation. Another advantage of this approach is that by adding more lasers, we are also adding redundancy to the system so in case of a laser failure, the network could continue working. This is an important feature, which is not present nor on the initial architecture, nor on TDM or WDM PONs neither.

As far as the addition of new users is concerned, when all the output ports of the remote AWGs are full and further ONUs need to be connected to the network, we can go for two different alternatives: to change the central AWG for another one with more ports and then add extra remote AWGs or to substitute an ONU by an optical splitters in a TDM-PON approach. The first solution is the best one in terms of performance but its cost may be prohibitive.

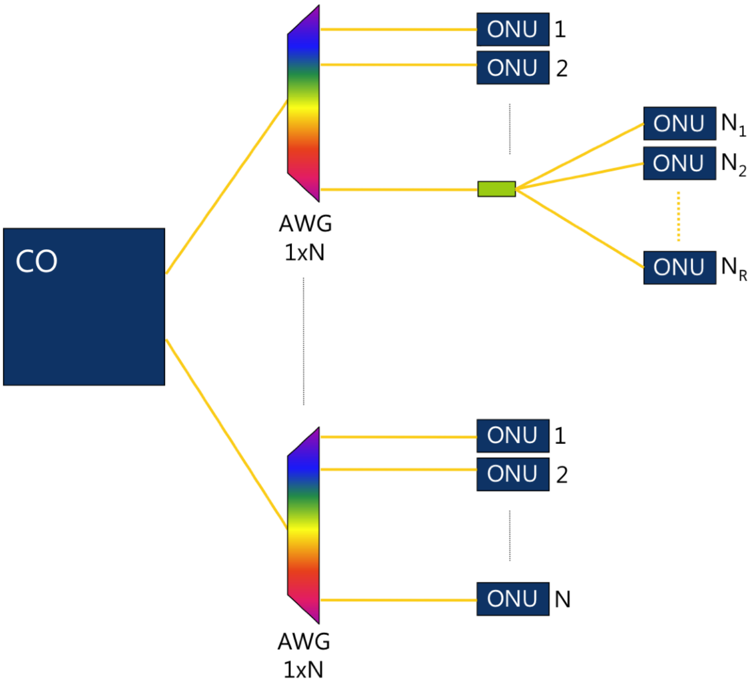


Fig 5.7 Addition of more users dynamically on a TDM-PON approach

This second solution, which is presented in Fig 5.7, presents a very easy upgrade path in case the number of users increases. The addition of power splitters to the network greatly increases network connectivity. If 100% of the ports were scaled, an access network of *M* x *N* x *K* users would result, where *K* is the splitting ratio. If we take *M*, to be 16, *N* to be 32 and *K* to be 16 or 32 (realistic values), then 8,192 or 16,384 users respectively could be served. Also, this strategy allows having different types of users with different transmission requirements. For instance, businesses could be directly connected to the RN1 to have greater bandwidth, on the other hand, home users could be connected to the TDM-PON branches, to have reduced transmission capabilities at a lower price.

If we use TDM after the final AWG to increase the number of users, we led to a hybrid WDM/TDM^2 topology where MAC of TDM-PON standards can be easily implemented [Kramer02a], [ITUTG683.1].

5.1.4 Comparison with WDM and TDM PONs

To justify the proposed network topology, in this section we will compare it with a pure TDM PON and with a pure WDM PON. The comparison will be done in terms of transmission capabilities and in terms of network performance. Also some costs considerations will be taken into account. Note that the logical comparison in terms of costs is to compare our network with M TDM or M WDM PONs. In terms of network performance, the results are the same for the case of 1 or M.

Optical transmission capabilities of our topology are very similar to a pure WDM PON. It offers the advantage of lower loses, when routing the different wavelengths, in comparison with the use of optical splitters. An average 40-port AWG offer insertion loses in the range of 5 to 7 dB, while the equivalent 32-port splitter has insertion loses of 16 to 17 dB. This fact is very relevant as we are using reflective ONUs without light sources and therefore optical power budget is critical. The 10 dB extra power budget turns into 20 dB if we take into account down and upstream transmission.

Another important benefit of our topology is security. As each ONU received a single and dedicated wavelength, the rest of the ONUs cannot gain access to the communication between another ONU and the OLT. This is not the case in TDM PONs, as on those networks, the ONUs listen to a broadcast channel and receive the information that it is sent to all the rest of the ONUs.

In terms of network performance, the first thing to mention is that while on a pure WDM PON there is a permanent point to point connection between the OLT each ONU, on both, our hybrid network and TDM PON, transmission resources are shared among a number of users. Therefore, the network solution that offers the best network performance is the pure WDM solution, where there is a dedicated laser for each ONU.

When we compare the pure TDM solution and the hybrid network that we propose, it is important to note that network performance mainly depends on the logical protocol that it is chosen to assign the time slots to each ONU. Implementation of this protocol however, is much simpler on our proposed network as the algorithm needs just be run on the OLT. Another advantage of our topology is bandwidth scalability. We can easily add more lasers to increase network performance while on the pure TDM PON just one laser is used for the transmission. Therefore, while on a TDM PON the theoretical bandwidth per user is BW / N, on our proposed network it is $L \cdot BW / N$, where L is the number of lasers dedicated to one network segment. Also, dynamic assignation of resources is more efficient on our hybrid topology as we can concentrate bandwidth on specific network segments depending on the user needs by assigning wider time slots to the ONUs connected on a specific network segment. We call this concept Geographical Bandwidth Allocation (GBA).

The impact of GBA on network performance is very noticeable, especially when the traffic patterns for the different subnets is heavily unbalanced. We simulated the difference of using GBA and a statistical allocation protocol using $M/M/c/k$ queue models with variable T_{serve} and found a throughput gain of GBA under high load conditions of 30% when input traffic has a deviation of 0.5 among subnets (see Fig. 5.8). Network delay performs in the same way. GBA optimizes laser assignation thus reduces delay when non-uniform traffic is transmitted (20% improvement for 0.5-deviation on subnet inputs). Further analysis is developed in the next chapter.

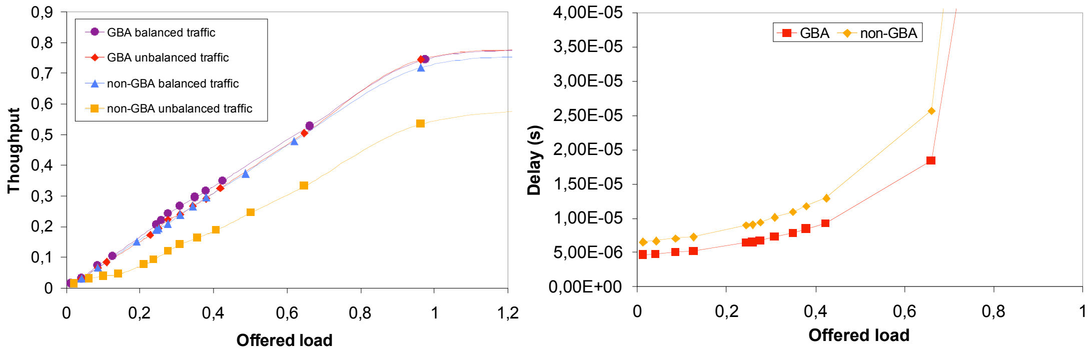


Fig 5.8 Network performance comparison with / without GBA

Finally, as a guide to costs, the solution that is most cost effective is the pure TDM PON. On the other hand, the most expensive one is the WDM PON as one dedicated laser is needed for each ONU. Also, the WDM equipment located at the outside plant (AWGs) is more expensive than optical splitters. The solution that is proposed is an intermediate point between TDM and

WDM in terms of costs. The outside plant is similar to a WDM PON but on the OLT side, there is no need to have one laser for each ONU. It is true that the cost of the tunable lasers that we need for the transmission is higher than fixed WDM ones but on the other hand, the number of devices that we need is much lower ($L << N$).

In conclusion, when compared to *M* pure WDM and TDM PONs, our topology presents the following advantages: more secure, scalable and flexible than TDM PONs also offering higher network performance. At the same time, it is less costly than a pure WDM PON implementation, whereas offering good transmission capabilities. Finally, it also features the novelty of geographical dynamic bandwidth allocation.

5.1.5 Transmission experiments

Optical transmission tests were implemented to demonstrate optical transmission capabilities using the following routing devices: an athermal 16x16 AWG (M = 16) with 100GHz channel spacing as central router and an athermal 1x32 AWG (N = 32) as remote node. The use of athermal AWGs is recommended in the outside plant in order to avoid powering them. These kind of AWGs have improved their performance greatly recently and offer similar performance as powered AWGs with temperature control. Compete network testbed can be seen in Fig. 5.9.

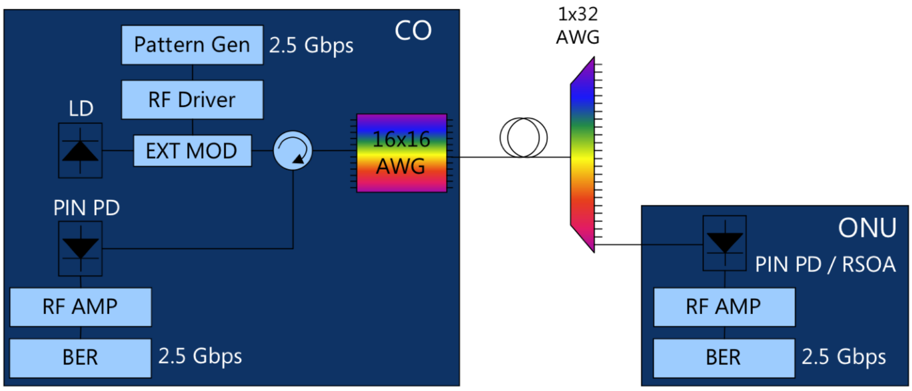


Fig 5.9 Network testbed

The AWG main pass band first wavelength was 1542.40 nm and the last one 1554.59 nm. The first FSR extended from 1555.40 nm to 1567.59 nm. The key of this configuration is that the output ports of the remote AWG and the ports of the central AWG have a relation 2 to 1 which means that the main pass band and one FSR of the central AWG are used. So, as discussed in the previous section, $K = N / M = 2$. It is also essential that output wavelengths of the central AWG match with the routing scheme of the secondary AWG in order to achieve the desired wavelength routing.

Tests on optical connectivity were performed in order to demonstrate that the outputs of the central AWG router were periodic in terms of wavelength (periodicity was 16 x 0.8nm = 12.8nm), and that tuning lasers reach the different access ports. These tests were done using optical carriers in order to obtain specific channel losses depending on input port and wavelength. We obtained insertion losses of 7.10dB for the central AWG and 2.98dB for the remote one. Routing loses ar then of 10.08dB, which is a very good figure considering the very high splitting ration of our network (16 x 32 = 512 users).

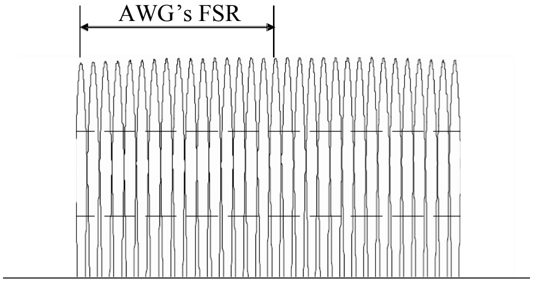


Fig. 5.10 Central AWG wavelength routing (FSR = 12.8nm)

Data transmission tests have been performed to verify that transmission was satisfactory. A Grating-assisted co-directional Coupler with rear Sampled Reflector laser (GCSR) was used as light source, providing WDM tuning capabilities. To modulate data, a $LiNbO_3$ modulators was used

A PIN photo receiver was used for downstream detection. A RF amplifier was inserted after the photo receiver once the data was in the electrical domain. An alternative testbed using a Reflective Semiconductor Optical Amplifier as a reflective ONU was also implemented to modulate upstream data.

2.5 Gbps data has been sent both, upstream and downstream, using several wavelengths. Sensitivity in the range of –30dBm was achieved on all the wavelengths of the main pass-band of the AWG. Consistency among all wavelengths was very good and the response of all of them was very similar. Fig. 5.11 depicts BER against received power for several wavelengths (worst & best cases).

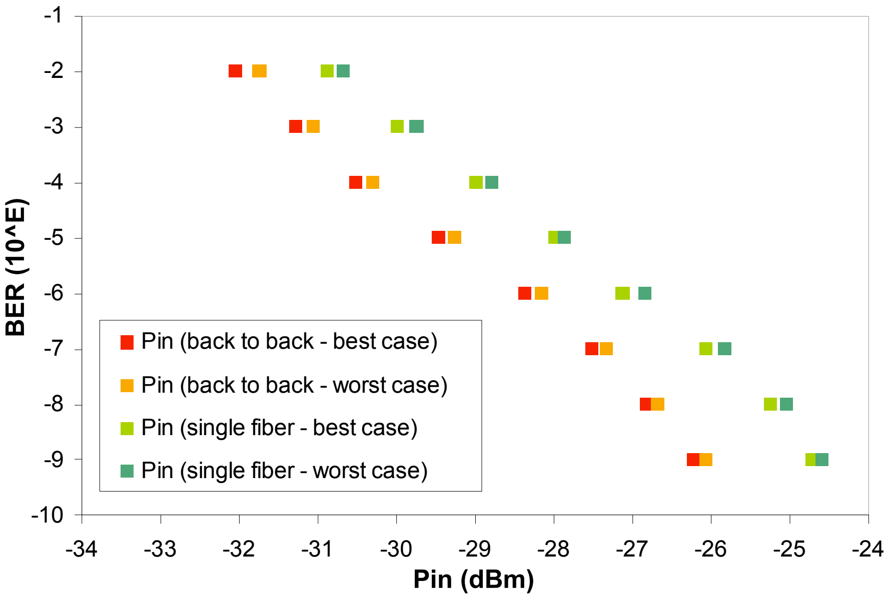


Fig. 5.11 Transmission results for best and worst wavelengths

Back-to-back and 30 km SMF results are almost identical in unidirectional transmission as fiber dispersion is negligible at those data rates and distances. Also bidirectional transmission tests using a single fiber have been performed, using the RSOA. Due to Rayleigh scattering [Gysel90] additional penalty of 4 dB in sensitivity has been measured when transmitting the upstream signal. At the OLT, sensitivity of -24 dBm was obtained. This last result was obtained sending unmodulated optical carrier pulses together with downstream data and modulating upstream data using the RSOA.

5.1.6 Network performance analysis

To calculate network performance, an analysis based on queue modeling was implemented. *M/M/k/c* models were used as a starting point and improved to implement advanced functionalities. We simulated a network based on the specifications of the test bed: a central AWG of 16x16 and remote AWGs of 1x32. The total number of users connected to the network was 16x32 = 512 users. We assumed a basic scenario with 16x 2.5Gbps tunable lasers (one laser per input port of the central AWG). We implemented a Dynamic Bandwith Allocation (DBA) algorithm in order to maximize network equipment utilization.

The calculations that were done supposed a markovian queue model with a variable time of service ($T_{service}$), being equal to T_{laser} + T_{tx}, where T_{tx} is the time needed to transmit a data packets. The election of T_{tx} or, what is the same, the length of the time slot assigned to each ONU is critical and compromises network latency against network performance, as has already been explained this same chapter. As the laser is switching among different wavelengths to reach different ONUs, each switching implies that T_{laser} is required for tuning purposes

We evaluated network throughput and network latency, taking into account time between accesses to the same ONU. It is important to note that one laser serves N ONUs. There is no total connectivity from the M lasers to the $N \cdot M$ ONUs because of the routing properties of the two AWG stages of the network. Thus, the performance analysis can be reduced to one laser serving N ONUs.

In order to simulate the performance of the network on a scenario offering triple play services (voice, video and data). We categorized traffic, marking it as high priority voice traffic, medium priority video traffic and low priority data traffic. Voice traffic demands low bandwidth but requires very low latency and is bidirectional. Video traffic requires high bandwidth, latency is not as critical but must remain constant and it is an asymmetric downstream service. As far as data traffic is concerned, it was considered best effort, without any bandwidth, latency or losses restrictions.

The simulations were implemented considering T_{laser} of 1μs. The three different services offered on the network were encapsulated on different packet structures in order to improve network performance. Voice packets had a length of 3,200 bits (1.28 μs @ 2.5 Gbps), Video data was encapsulated using packets of 80,000 bits (32 μs @ 2.5 Gbps) and finally, generic best effort data traffic used packets of 160,000 bits (64 μs @ 2.5 Gbps). Traffic was considered to be 2% voice traffic, 43% video traffic and 55% best effort traffic. We used a classical priority model offering the highest priority to voice and the lowest to data.

We considered the three services to be independent and we did not implement any aggregation technique among different services to reduce the number of laser tuning switches. This fact affects network performance but guarantees low latencies for voice and video communications as voice requests were served independently from the rest of the traffic. However, packet aggregation inside each service was used to increase network throughput.

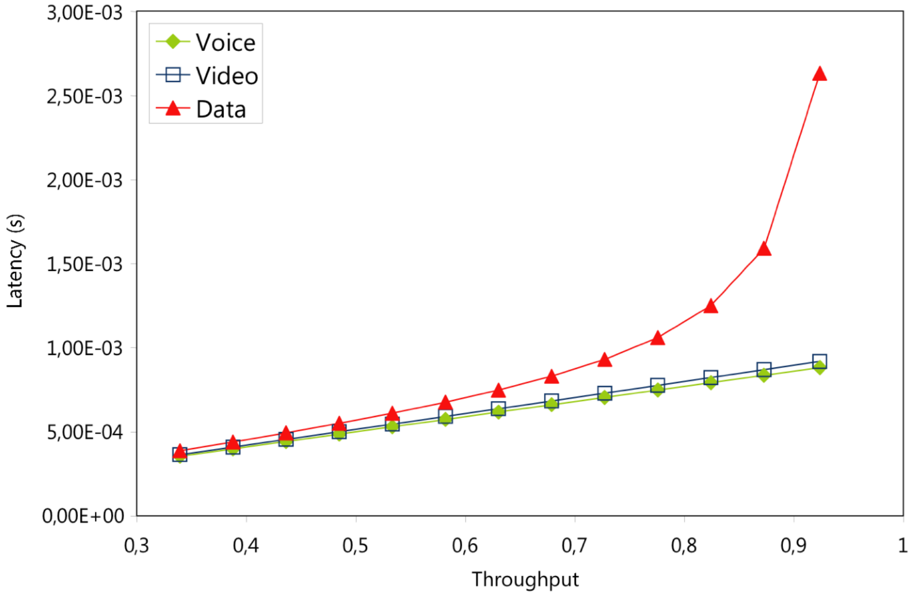


Fig. 5.12 Latency vs network throughput for the three classes of services

Fig. 5.12 presents the latency results obtained for the simulation depending on the network throughput considering both, upstream and downstream traffic. The two conclusions that can be derived from the figure are that the use of priorities really improves the performance of voice and video traffic, allowing latencies below 1ms even under congestion situations. This justifies the use of different queues for data and the rest of the traffic. The other conclusion is that the use of a separate queue for voice and video is not justified because the improvement on voice traffic latency in comparison to video traffic is almost negligible. The reason for this effect is the duration of T_{window}. As we need to switch to all active ONUs on the network segment, there is a delay between the packet generation and the moment when the system is prepared to process it defined as

$$\overline{T}_{window} = \rho \cdot \frac{N}{2} \cdot \left(\overline{T}_{tx} + T_{laser}\right) \qquad (5.4)$$

where ρ is the network utilization, N the number of users and T_{tx} the average time slot per user. This parameter is also known as network latency. Note that this equation describes the average time window duration and not the maximum time window under deterministic situations as in (5.2) and is particular for the case where the number of lasers serving a network segment is equal to 1.

The results also reaffirm the ability of our network to handle a triple play solution, offering voice, video and data services to the users. In a saturated environment, the network can offer up to 100Mbps to each of the 512 users under QoS basis using 16 x 2.5 Gbps lasers.

5.1.7 Conclusion

An advanced access topology based on spatial and wavelength multiplexing using the inherent periodicity of AWGs and a shared tunable laser stack has been presented. By means of optical transmission tests and network traffic analysis we demonstrated that this architecture is feasible and offers good performance for applications demanding both, low latency and high bandwidth. It presents low optical loss and simple control, compared to other PON architectures.

Transmission tests showed that the communication between the Central Office and the end users was possible at data rates of 2.5 Gbps and distances up to 30 km offering good levels of sensitivity.

Network simulations demonstrated the capability of the proposed network to offer triple play services to 16 network segments of 32 users sharing a single laser (512 ONUs). Even under high occupation environments, network latency for voice and video remains below 1 ms, offering 100 Mbps per user. The only traffic that was affected by network occupancy was data traffic, which operated under best effort basis and is much more tolerant to delays and loses. Results showed the capabilities of the network to deliver multimedia, voice and data contents to the end users using 3-class priority.

Finally, the network is very easy to scale in number of users thus provides a future-proof platform that can be dimensioned on demand depending on the end user requirements. In this direction, different TDM-PON subsegments can be deployed to different types of users depending on their transmission requirements thus businesses and end users can easily coexist on the same infrastructure.

5.2 AWG^2 WDM/TDM PON in a combined ring - tree configuration (RAFOH Ring)

This section presents a combined WDM and TDMA access network based on a combined ring-tree outside plant. This is an extension of the AWG^2 WDM/TDM PON to a ring topology and using TDM-PON subsegments to increase the total number of users.

The benefits of this network architecture are high density of users and an optimal allocation of network resources together with resilience in case of a fiber cut in the main ring. It is implemented by means of an advanced routing profile at the Central Office (CO) and two outside plant multiplexing stages.

5.2.1 Introduction

End user bandwidth requirements are growing dramatically lately and this is encouraging the development of advanced access solutions that can provide high bandwidth while keeping costs low. End users demand more bandwidth but they are not prepared to pay on bit/$ basis so future access networks need to be simple and efficient in order to maximize bandwidth utilization. To maximize efficiency while keeping costs low, highly shared optical interfaces serving a large number of users represent a good solution [Davey05].

Several combined ring-trees topologies have been presented, offering resilience capabilities and high density [An04], [Wang06]. However, those topologies do not have a totally passive outside plant and do not implement mechanisms to maximize network utilization.

In this section, we present a high-density access ring able to serve a very large number of users (from 8,192 to 65,536) by means of a physical ring-tree low-loss topology and a reduced number of network interfaces. As sharing factors are high, the network proposes an efficient use of optical resources by means of a dynamic bandwidth allocation. Also, as a large number of users are connected, resilience in case of a link failure is also implemented.

5.2.2 Network design and dimensioning

A primary distribution ring and secondary trees to reach the end users compose the outside plant (see Fig. 5.13). A combined Wavelength, Space, Time multiplexing scheme gives connectivity to the users. The dimensioning of the system is quite strict and required a concrete number of wavelengths, fibers and remote nodes to perform correctly. There is a direct relationship 1:1 between the number of fibers of the primary ring, the number of remote nodes, the number of wavelengths and the number of trees (also called TDM PON subsegments) that are attached to each remote node. This design parameter (M), together with the splitting ratio of the TDM PON subsegments (K) determines the number of users that the network serves, being the total number of users $M^2 \times K$.

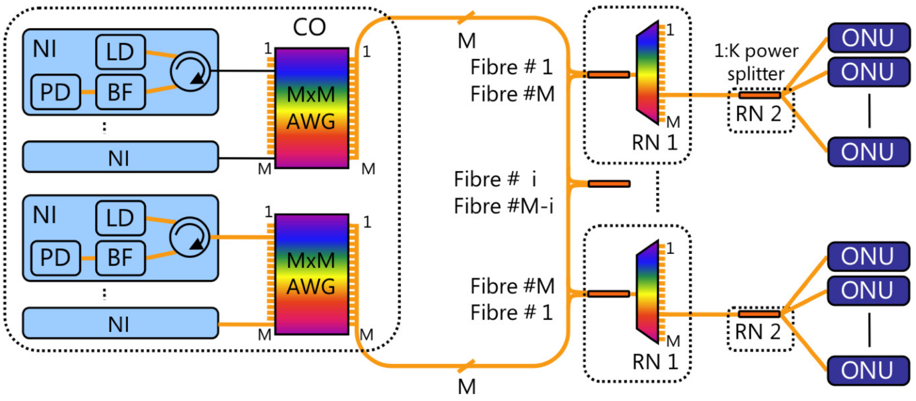


Fig 5.13 Network topology and CO equipment

The number of optical transmission interfaces that are required at the CO is 2 x *M*, so each laser is shared among *M*/2 x *K* users. Two *M*x*M* AWGs are used at the CO to interconnect the lasers to the remote nodes combining wavelength and space multiplexing.

5.2.3 Advanced features

Lasers are tunable so depending on the wavelength, the data stream is routed to a different output fiber and thus, to a different remote node. Depending on the network load, transmission resources can be directed to concrete remote nodes offering dynamic bandwidth allocation capabilities. End users connected to the same remote nodes are served by different network interfaces and as the remote nodes are geographically distributed, the network can concentrate bandwidth to different locations depending on the time of the day and the network load by changing the laser assignation times to each network subsegment (see Fig. 5.14).

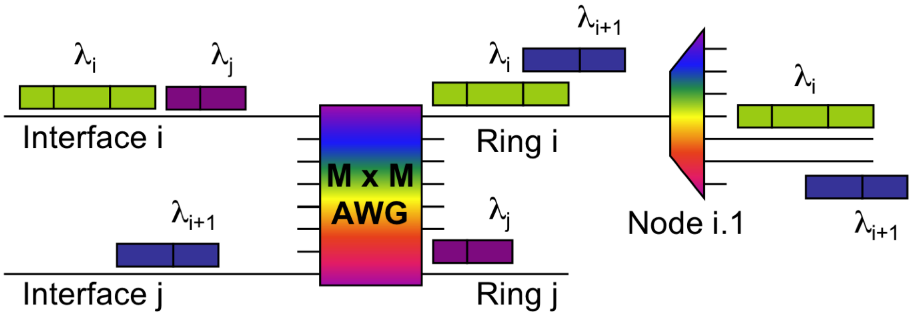


Fig 5.14 Plot of a dynamic laser assignation trace

Each remote node can be reached from both directions of the ring. A 3dB coupler connects the ring to a 1 x *M* AWG that connects to *M* x TDM PON network subsegments, each of them serving *K* users on TDM basins. Upstream transmission is symmetrical and uses the free spectral range feature of AWGs transmitting upstream data on a different wavelength. At the RN, the 3dB coupler transmits the upstream signal along both fiber directions so it is redundantly received at the CO. In case of a fiber cut in the ring there is always a path to reach every single remote node. This ensures total network connectivity. Under those circumstances, the laser assignation times have to be readjusted to minimize the impact of a fiber cut on the overall network throughput.

Additional power losses introduced by the routing and protection profile on the outside plant are due to the 3dB coupler and the 1xM AWG at the first remote node stage. Typical losses of AWGs are between 3 and 6dB so the reduction on the power budget margin over a classical TDM PON is of just 6 to 9dB.

As a guide to realistic design values, one can suggest M = 16 / 32 and K = 32 / 64. With these parameters, the number of users would be from 8,192 (M = 16, K = 32) to 65,536 (M = 32, K = 64).

5.2.4 Compatibility with existing standards

The presented network topology combines WDM and TDMA but its compatibility with existing IEEE802.3ah Gigabit Ethernet PON and ITU-T G.984 Gigabit PON is straightforward.

At the ONU side the major change is the laser transmitter replacement to make it compatible with the upstream WDM channel that is assigned to the network segment. In this sense, there are several options to make the ONU wavelength agnostic, using reflective and remodulation techniques [Genay05]. Then minor modifications on the logic of the downstream reception part should be programmed to allow burst mode reception.

At the OLT side, tunable laser sources should be used and advanced switching protocol logic and equipment should be implemented to assign bandwidth on demand to the different remote nodes, manage laser tuning times and monitoring link status. In any case, as this is a centralized location owned by the network operator, a custom CO design is not a major drawback to make the topology commercially feasible.

The advantages of this network topology in comparison to a classical PON deployment are the minimization of optical resources offering similar network performance. A simple design with $M = 8$ and $K = 32$, dimensioned for 2,048 subscribers would require 64 transmission interfaces. In our network, just 16 interfaces are needed with the additional benefit of the network resilience feature. Transmission equipment sharing ratios are higher in our network but this can be compensated by the advanced routing profile that interconnects each network interface with a virtual-TDM PON of users with very different traffic patters, so simultaneity factors are reduced [Hajduczenia06]. However, the reduction of the simultaneity factor depends on every single implementation so it can just be calculated by means of empiric analysis.

In terms of power loss penalties, our proposed network design adds on the outside plant insertion losses due to the addition of $RN_{1.i}$. This is a totally passive device built by a 3-dB power coupler and a 1xM AWG with typical insertion losses of 3 to 4 dB and 3 to 6 dB respectively. This means that power penalty to the power budget is just between 6 and 10 dB, which is perfectly acceptable taking into account the advanced benefits of the topology.

5.2.5 Network experiments and result

To demonstrate the correct performance of the network, a network testbed was implemented to verify correct optical connectivity (see Fig. 5.15). The test bed was implemented to serve a population of 2,048 users, with $M = 8$ and $K = 32$ as design parameters. This design requires 8x $RN_{1.i}$ remote nodes, 16 transmission interfaces and 2 x 8x8 AWGs. A classical TDM-PON approach would require 64x standard-TDM PONs.

2x Tunable GCSR lasers transmitting at 2.5Gbps were used for the experiments transmitting on different wavelengths to reach the same primary ring but in different directions. Data rate is, in any case, totally independent of the network topology so 1Gbps or 10Gbps transmissions are also possible using the adequate transmission and reception equipment.

A 16x16 AWG was used to interconnect the transmission equipment to both directions of the ring. It was split into 2 x 8x8 AWG's using the cyclical routing properties of the device [Smit96]. Then, ports 1 and 9 of the AWG were coupled using the 3dB coupler and then connected to a 1x8 AWG. This AWG located at the first Remote Node ($RN_{1.i}$) would route each incoming wavelength to an outgoing port thus transmitting a single wavelength to each TDM PON subsegment. A 1:32 power splitter at the second RN provided then connectivity to all the users of the sub network. Between the remote nodes and between the first remote node and the CO a 5 km and 20 km single fiber spools were inserted to obtain more realistic values.

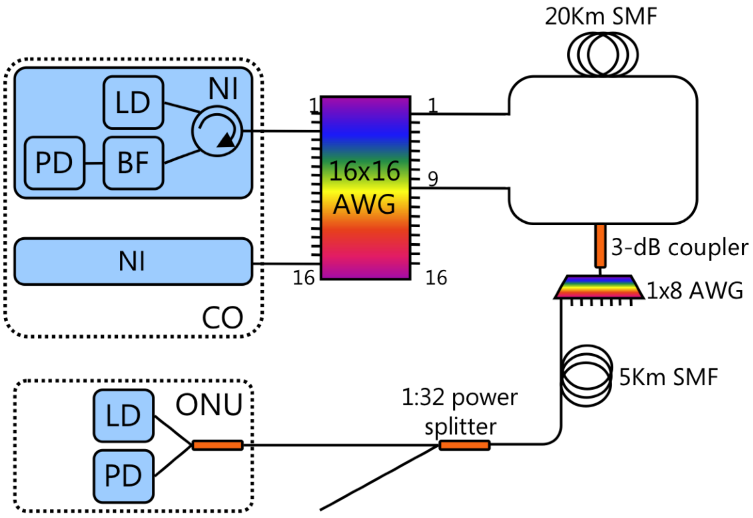


Fig 5.15 Network testbed

The wavelengths used were from the 100-GHz ITU-T G.694.1 DWDM grid, from 1,550.12 to 1,555.75 for downstream and from 1,543.73 to 1,549.32 for upstream.

Output power at the OLT was 8 dBm for each channel, after passing through the 16x16 AWG. Power losses along the 20 km SMF spool were of 4.2 while losses at the first remote node ($RN_{1,i}$) were of 6.1 dB, split into 3.12 dB for the 3-dB coupler and 2.98 dB for the 1x8 AWG respectively. The 5 km SMF spool between the first and second remote nodes had 1.1 dB losses. Finally, power losses at the 1:32 splitting stage were of 16.05 dB.

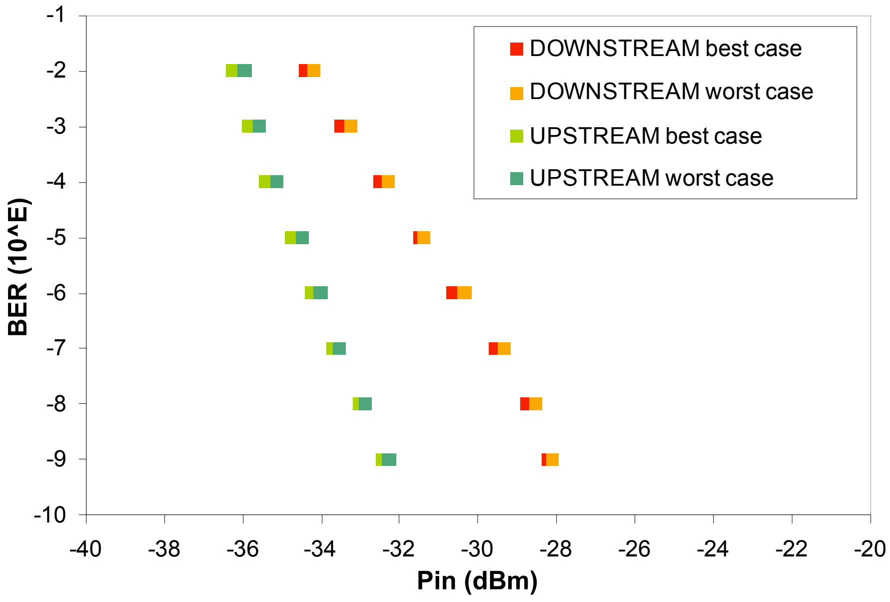


Fig 5.16 Downstream and Upstream BER results

Fig. 5.16 presents downstream and upstream transmission results. All the 8 wavelengths were monitored and the worse downstream sensitivity at the ONU side was measured to be -28 dBm. ONUs were implemented with a PIN-TIA photo receiver. Taking into account that overall losses were of -27.45 dB and that output power at the OLT was 8 dBm, the system power budget margin was 8.55 dB for downstream transmission. For upstream transmission, outside plant power losses were almost identical, as the optical path was symmetric. However, upstream laser output power was limited to 0 dBm. To compensate this, an APD photo detector was used at the CO. A sensitivity of -32.2 dBm was achieved. Upstream power budget margin was then 4.75 dB. All these results are fully compatible with ITU-T G.984 GPON Class-B+, which recommend a power budget of 28 dB.

To make both transmission paths symmetric in terms of power budget margin, output power at the OLT could be reduced to 4dBm. This is really recommended because to reach an outside power level of 8dB at the OLT required the use of boosters between the GCSRs and the *M* x *M* AWG, while if output power at the OLT is of 4 dBm those boosters are not required.

Laser switching time was achieved to be as low as 15 ns, which allows fast tuning of short packets with no penalty on network throughput.

5.2.6 Conclusion

This section presents a low-loss high-density access network based on a primary ring and secondary trees. By means of an advanced routing profile using cascaded AWGs the network provides dynamic bandwidth allocation features. At the same time, the primary ring topology provides resilience capabilities in case of a fiber cut. Furthermore, using ring overlay the network can be dimensioned to serve a very large number of users with very limited optical equipment.

Optical transmission experiments show correct transmission and reception up to 2.5Gbps showing total compliance with ITU-T G.984 GPON Class-B+ transmission recommendations in both, standard and resilient-mode operation.

This network topology has the advantage compared to a classical PON deployment that the number of optical interfaces required to provide service is lower, as bandwidth can be routed on demand to the different remote nodes depending on the network utilization.

This network topology can be seen as an extension to the tree-based AWG^2 WDM/TDM PON that was presented in the previous section, with the addition of resilience and higher density of users.

5.3 WDM/TDM PON in a combined ring - tree configuration with transparent passive remote nodes (RA^{4}D Ring SARDANA)

This section describes a novel single-fiber ring-tree topology overlying multiple Time-Division-Multiplexed (TDM) Passive Optical Networks (PON). Each TDM service is overlaid on a different Wavelength Division Multiplexing (WDM) channel.

A concatenation of advanced coupler-based remote nodes distributes the channels in an optimal geographical distribution to secondary trees, which connect to the end users. With the proposed configuration, the network features flexible deployment and provides resilience capabilities in case of a fiber cut. To compensate power losses and fulfill ITU-T G.984 / IEEE 802.3ah recommendations in terms of power budget and sensitivity; remote amplification is implemented at the remote nodes. This technique amplifies the dropped wavelengths at each remote node while keeping a totally passive outside plant. A power budget study together with optical transmission experiments and network dimensioning simulations demonstrate the feasibility of the network design.

5.3.1 Introduction

Passive Optical Networks (PONs) are becoming consistent alternatives to offer access solutions in a fibre to the home (FTTH) environment. PONs offer more bandwidth than copper-based solutions and they are substantially more inexpensive than optical point-to-point solutions [Sananes05]. Also, PONs are based on a totally passive outside plant, requiring no external powering thus there is no need to find environment-controlled facilities to install equipment in the field.

Ethernet PON (EPON) and Gigabit PON (GPON) are the two standards that are competing now to have a predominant position in the FTTH market. GPON, developed by the ITU-T (FSAN), delivers up to 2.488 Gpbs of downstream bandwidth and 1.244 Gbps of upstream bandwidth. One of its main features is that GPON Encapsulation Method (GEM) allows efficient packaging of user traffic, with frame segmentation to allow Quality of Service (QoS) which prepares the network to deliver multimedia content, such as voice and video streaming. On the other hand, EPON standard (IEEE 802.3 ah), developed by the IEEE and based on Ethernet, delivers 1 Gbps symmetrically transmitting Ethernet frames. It is not as efficient as GPON in terms of bandwidth management and QoS provisioning but can provide a more cost effective solution.

PON standards have been developed for tree physical topologies. Tree topologies offer a good power balance and assure that all the users have similar power budget requirements although the quantity of deployed fiber is not optimal and does not provide any resilience in case of a fiber cut. On the other hand, rings offer a more optimized deployment in terms of fiber quantity but are not a power budget optimal solution when there are many nodes, due to accumulative losses when passing nodes. Rings, on the other hand, offer resilience in case of fibre cuts as there are always two ways to interconnect the nodes with the CO.

In this section, we present an extended hybrid ring-tree infrastructure overlaying EPON/GPON services. The network design is protocol independent and requires minor modifications of the optical transmission equipment of commercial devices, which are due to the use of WDM to overlay the different services.

The proposed topology offers high density on the trunk fiber and resilience capabilities in the distribution ring. Scalability is also guaranteed, as adding additional remote nodes is a simple task. Also, different services can be accommodated on different wavelengths to serve different users with different transmission requirements, offering a very flexible network.

From the technical point of view, the remote nodes are coupler-based and totally wavelength transparent in the passing way, offering low passing losses. Dropping wavelengths, however, require optical amplification, which is performed using erbium-doped fibers that are remotely pumped.

5.3.2 Network Architecture

Fig. 5.17 presents the network topology. Two PON trees are connected to the central distribution ring by each remote node (RN). As downstream and upstream are wavelength multiplexed, each RN drops two downstream wavelengths and inserts two upstream ones from / to the ring. Thus, the relationship between the number of RNs (N) and the number of wavelengths (M) is a fixed design parameter, which is $M / N = 4$.

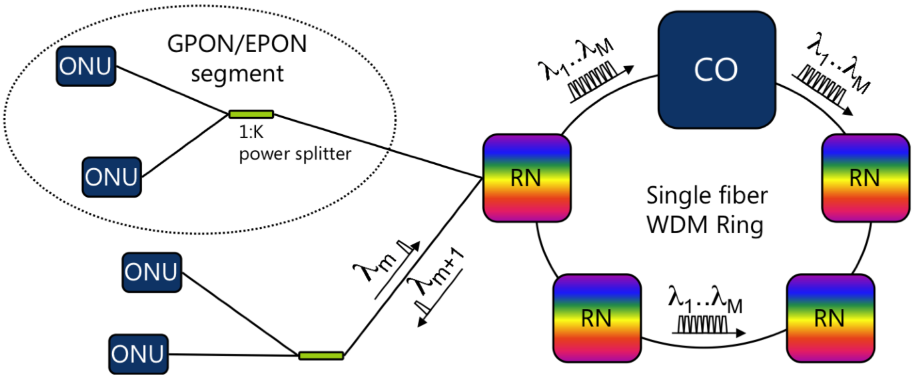


Fig 5.17 Network architecture

The remote node design is presented in Fig. 5.18. RNs are based on three power couplers and wavelength filters. Power couplers that are connected to the ring are x / y ($x + y = 1$), which are designed depending on the number of remote nodes to minimize power losses. The design parameters x and y are fully analyzed in section 4. The third coupler, which ensures connectivity to the two directions of the ring, is 50/50. At the output of the 50/50 coupler, two filters (thin film specifically in our set-up) select the specific downstream and upstream wavelengths for the two tree PON sections that are connected to the RN. With this design, the remote node performs transparently independent of the direction of the incoming downstream light and transmits upstream signal to both directions of the ring. This feature is the key to provide resilience in case of a fiber cut in the central ring.

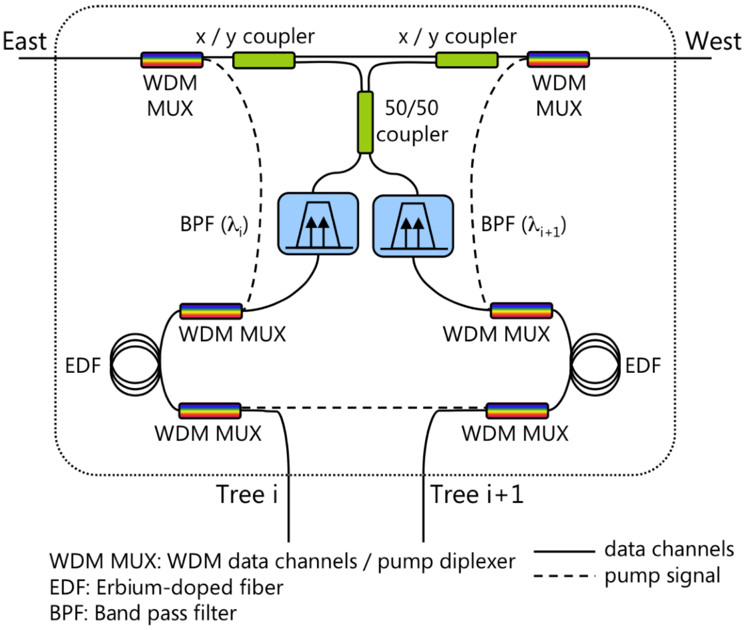
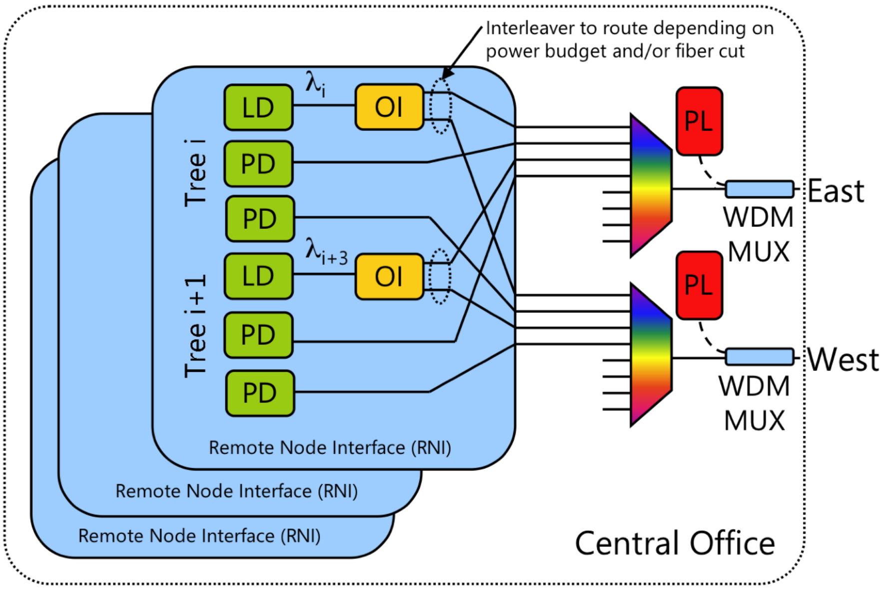


Fig 5.18 Remote Node (RN) design and wavelength routing profile

At the Central Office (CO), two lasers and four photo-receivers compose each remote node interface (RNI), as presented in Fig. 5.19. Each laser is coupled to both directions of the ring by means of an optical interleaver. By fine adjusting of the laser transmission wavelength the interleaver routes the signal to the direction of the ring that maximizes the power budget margin, depending on the number of passed remote nodes. This can be done by monitoring the upstream power levels and switching to the direction that offers higher received power. The redundant photo receivers detect the incoming signals from both directions of the ring and select the one with better power level. This feature also possibilities to offer resilient capabilities. In case of a fiber cut, the laser will change the transmission wavelength to select the only possible direction to serve the RN while one of the photo receivers will still receive the upstream transmission signal.

On the Optical Network Unit (ONU) side, the only changes that is required to a commercially available EPON/GPON ONU is the substitution of the 1310nm upstream transmission laser by a laser to transmit on the wavelength assigned to that specific PON segment. The rest of the equipment and logical control remains invariant.



LD: Laser diode
PD: Photo diode
OI: Optical interleaver
PL: 1480-nm pumping laser
WDM MUX: WDM data channels / pump diplexer

Fig 5.19 Central Office (CO) remote node interfaces

An important design parameter to make the network compatible with EPON/GPON standards is related to power budget restrictions. In addition to the tree splitting stage, the proposed network adds pass-through and dropping losses, together with wavelength filter insertion losses. To overcome those losses in the main ring while keeping a passive outside plant, remote amplification is convenient [Lazaro06]. For this purpose, two 1480 nm pumping lasers (one at each ring direction for resilience) are included in the CO of Fig. 5.19.

5.3.3 Resilience and power budget optimization

The proposed network design provides resilience and power budget optimization features by means of an optical interleaver and fine adjustment of the transmission wavelength at the RNI at the CO. Each remote node has a default path that is selected when the system is powered up. This default path corresponds to the path with lower losses and it is measured by monitoring the received power coming from both directions of the ring. This determines the default transmission wavelength. In case of a fiber cut affecting the connectivity to the RN, the RNI slightly changes the transmission wavelength and reaches the RN though the other direction of the ring.

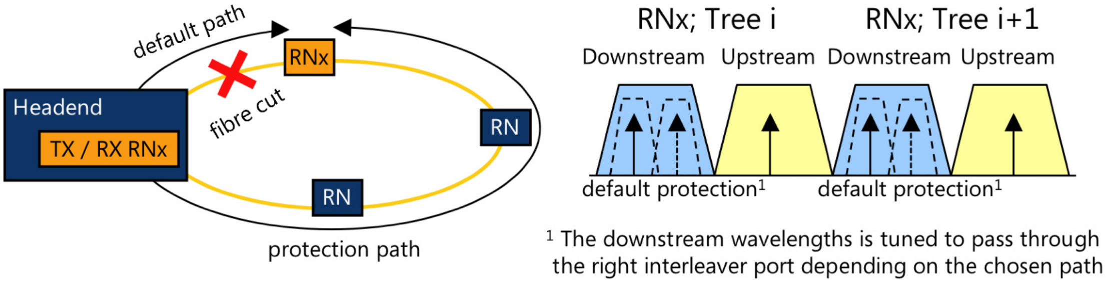


Fig 5.20 Power budget optimization and resilience mechanisms

The wavelength plan for upstream and downstream transmissions and the resilience mechanism are described in Fig. 5.20. The network interleavers have to be half of the wavelength channel spacing so both default/protected and upstream transmission wavelengths pass through the filters to reach the appropriate network subsegment. The selection of the output port of the interleaver is done by finely tuning the laser-emitting wavelength. This functionality does not require the use of a tunable source as adjusting the temperature of the laser can do the tuning.

5.3.4 Network analysis and experiments

An analysis of power budget margins was performed to demonstrate the feasibility of the proposed network. As WDM is totally transparent to TDM/TDMA protocols of G/EPON, the optical experiments have been addressed to verify correct reception of pattern-generated data streams while calculations have been done to verify correct power levels at the receivers.

5.3.4.1 Network dimensioning

The number of remote nodes (*N*) is a key parameter in terms of network performance because it determines the number of wavelengths (*M*) of our network and thus, the total network capacity. Other parameters that also affect on the network performance is the data rate and the splitting ratio (*K*) of the network subsegments but those parameters are intrinsic of each network subsegment and do not affect the design of the number of nodes.

The total number of users (*U*) is determined by the number of remote nodes and the splitting ratio in the network subsegment: $U = 2 \cdot N \cdot K$ and both, *N* and *K* affect on the power losses, total network capacity and bandwidth per user. When *N* increases the network can offer more bandwidth because more wavelengths are transmitted but at the same time, power losses increases. In order to minimize power losses, total link losses presented in Equation 5.5 should be minimized.

$$L_T = (N-1) \cdot 20 \cdot \log x^{-1} + 10 \cdot \log y^{-1} + N \cdot L_{EX} + 3 \cdot \log_2 K + L_S \qquad (5.5)$$

where Ls are additional losses due to fiber, insertion losses of optical equipment and wavelength filtering. The *x* and *y* are the coupling factors for the coupler pass-through and drop branch respectively. The relationship between them is $x + y = 1$; finally, L_{EX} represents coupling excess losses of each RN due to manufacturing, aligning and installing processes. The number of N that minimizes (5.5) is:

$$N = \frac{3}{\ln 2} \cdot \left(20 \cdot \log x^{-1} + L_{EX}\right)^{-1} \qquad (5.6)$$

The most important conclusion of (5.6) is that the optimal number of nodes is independent from the total number of users (*U*). This means that *U* is just limited by the power budget and that to increase the number of users it is more efficient, from the power losses point of view, to increase the splitting ratio than to insert additional remote nodes. However, this reduces network capacity because then the sharing factor per laser increases. Therefore, when designing a network deployment, a compromise should be met between optimizing power losses and optimizing network performance. Fig. 5.21 presents losses as a function of the number of *N* for different coupling factors.

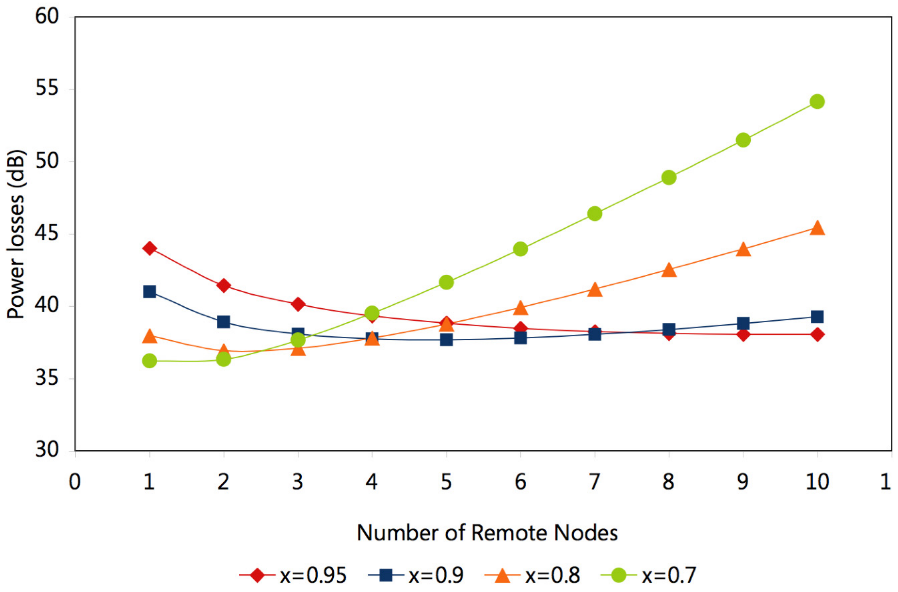


Fig 5.21 Power losses as a function of N for x = 0.95 ... 0.7

From (5.5), it can be demonstrated that an increase of the number of users (*U*) in the system for a given number of RNs adds a vertical offset to power losses and thus reduces power budget margin in a constant value. Also it can be seen from Fig. 5.21 that when coupling factor x tends to 1 the curve flattens and to increment the number of RNs does not affect power losses dramatically. So, if we plan that the network will grow in the number of remote nodes due to an increase in the number of users or in the network bandwidth requirements, to choose x close to 1 is the long-term preferred option.

Realistically, the number of RN (*N*) is also determined by the geographical distribution of end users so the best option to design the network is to fix the number of RN (*N*) and the network bandwidth per user and to calculate the other design parameters accordingly.

Network capacity is related to the splitting ratio (*K*) in each network subsegment. Each wavelength is assigned to a network subsegment so network performance for a given splitting ratio is just related to the chosen PON protocol. Based on [Angelopoulos04], depending on *K*, bandwidth per user for *K* = 16, *K* = 32 and *K* = 64 are respectively 125, 62.5 and 32.25 Mbps in a GPON at 2.5Gbps in case of network saturation. *K* = 64 is the largest splitting ratio that GPON supports up to now, hence in case we want to exceed this value, the addition of remote nodes is obligatory. Fig. 5.22 presents the total number of users depending on the number of remote nodes for different values of K.

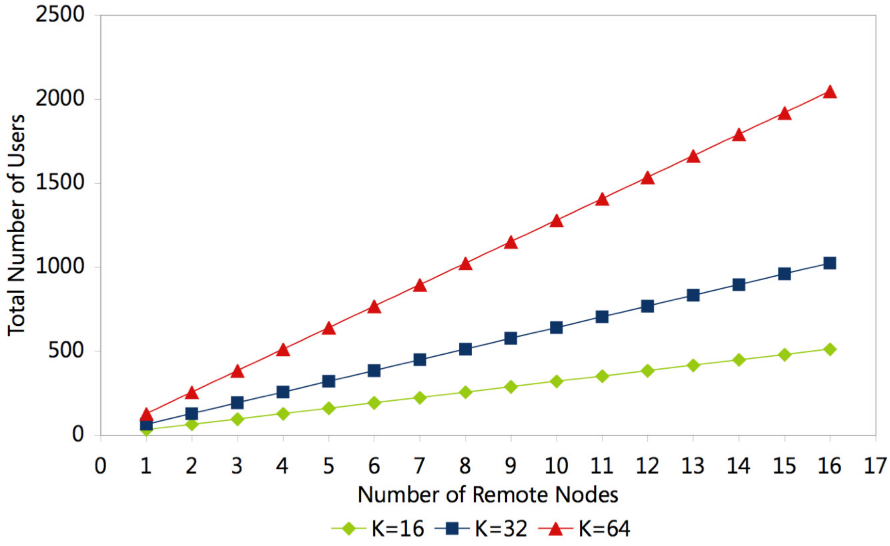


Fig 5.22 Number of users depending on *K* and *N*

The last parameter to be optimized is the coupling factor of the main ring couplers. Minimizing L_T with respect to x in (5.5) leads to the following results:

$$x = \frac{2 \cdot N}{2 \cdot N + 1} \qquad y = \frac{1}{2 \cdot N + 1} \tag{5.7}$$

which are represented in Fig. 5.23.

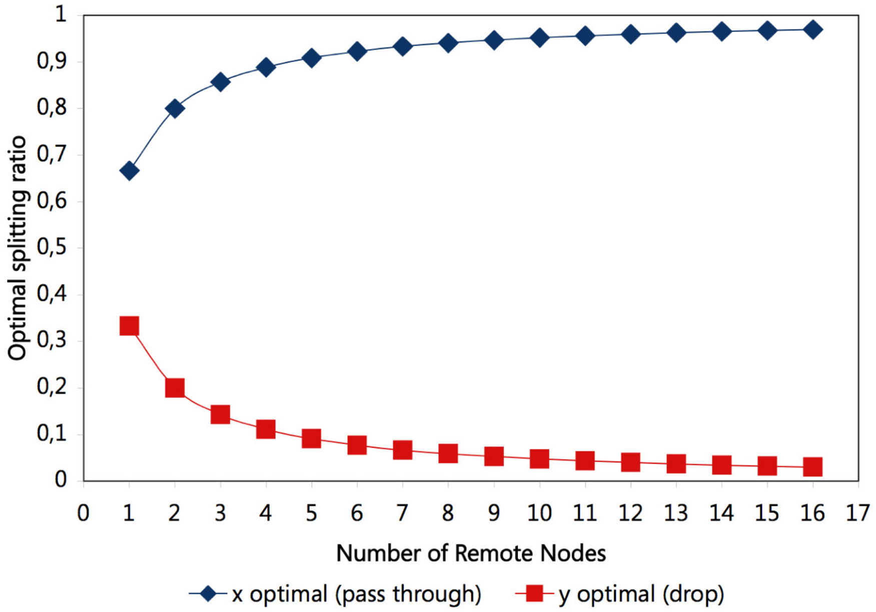


Fig 5.23 Optimal splitting factors as a function of the number of remote nodes

Results from Fig. 5.23 show a tendency to stabilize for N ≥ 4. This is consistent with the results of Fig. 5.21 and confirms that the use of commercial 90/10 (x = 0.9 and y = 0.1) couplers offers a good compromise between having a flexible and scalable solution while keeping total losses low.

The results from Fig. 5.23 do not take into account transmission constraints and losses. Additional power losses due to passing through RNs reduce power budget and limit the network size. By working out (1) incorporating the remote amplification gain (*G*) and restricting losses to be less than power budget (*PB*) we can express it as:

$$PB \geq (N-1)\cdot 20\cdot \log x^{-1} + 10\cdot \log y^{-1} + N\cdot L_{EX} + 3\cdot \log_2 \frac{U}{2\cdot N} + L_S - G \quad (5.8)$$

Values of *PB* are in the range of 20 to 30dB for commercial equipment following both ITU / IEEE recommendations, proposing *PB* = 20 dB for Class A to PB = 30 dB for Class C equipment. A realistic value for L_S is 10 dB. Fig. 5.24 presents the power budget margin depending on *K* and *G* using the optimal design parameter of *x* and *y*. Horizontal lines represent the PB for different classes of equipment.

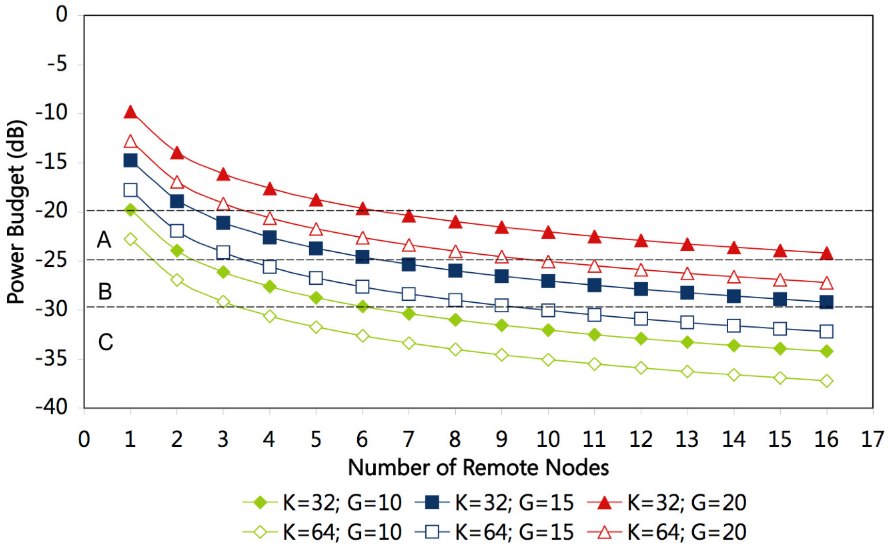


Fig 5.24 Total number of users as a function of G and K

All the points that are above the class A/B/C lines correspond to combinations that can be deployed using Class A/B/C equipment. Using class C equipment offers a vast number of combinations but this equipment is also more expensive than class A devices. There is also a balance between remote amplification gain, number of nodes and class of equipment to achieve a valid configuration. For a number of nodes *N* > 8 the use of *G* = 20 dB and class C equipment is very recommendable but for smaller configurations, a more cost effective approach can be implemented.

As an example, if the deployment consists in an access network to offer service to 1,024 users the network would be optimally deployed using *K* = 64 splitting ratio and *N* = 8. This would lead to an optimal coupling factor of *x* = 0.94; *y* = 0.06 (typically 0.9 / 0.1 couplers will be used) and to achieve correct transmission, we can amplify with *G* = 20 dB and use class B equipment or amplify with *G* = 15 dB and use class C equipment.

Remote optical amplification makes available lager PBs in passive optical networks, but it also produces a reduction of the Optical Signal to Noise Ratio (OSNR). Making use of [Desurvire02] and results form (1), it can be deduced that the OSNR is always higher than 26 dB for the downstream and higher that 34 dB for the upstream. Such OSNR values do not significantly affect the sensitivity of the receivers, still mainly limited by thermal noise and being the PB calculations still valid.

5.3.4.2 Optical transmission experiments

To demonstrate the feasibility of the network and corroborate the calculations of the previous section, a network testbed was implemented and analyzed to measure transmission losses and remote amplification gains. Fig. 5.25 presents this testbed. The number of remote nodes was chosen to be *N* = 8 and the splitting ratio *K* = 64, leading to a configuration to serve 1,024 users.

Output power at the OLT was +10 dBm. A 20 km fiber spool was inserted in the primary ring to simulate a realistic deployment. Remote amplification was implemented using 12-meter erbium-doped fiber (HE980 EDF) segments at each remote node. This erbium-doped fiber provided 1.4dB/m of gain, although this gain was variable depending on the received power from the 1480-nm pumping lasers located at the CO. Optical output power of pumping lasers at the CO was 20dBm. These lengths of erbium-doper fiber and pumping laser output power were designed to compensate drop losses at the RN, providing with *G* of approximately 15 dB. Finally, a 1:64 power splitter distributed the dropped wavelength among the ONUs connected to the PON subnetwork.

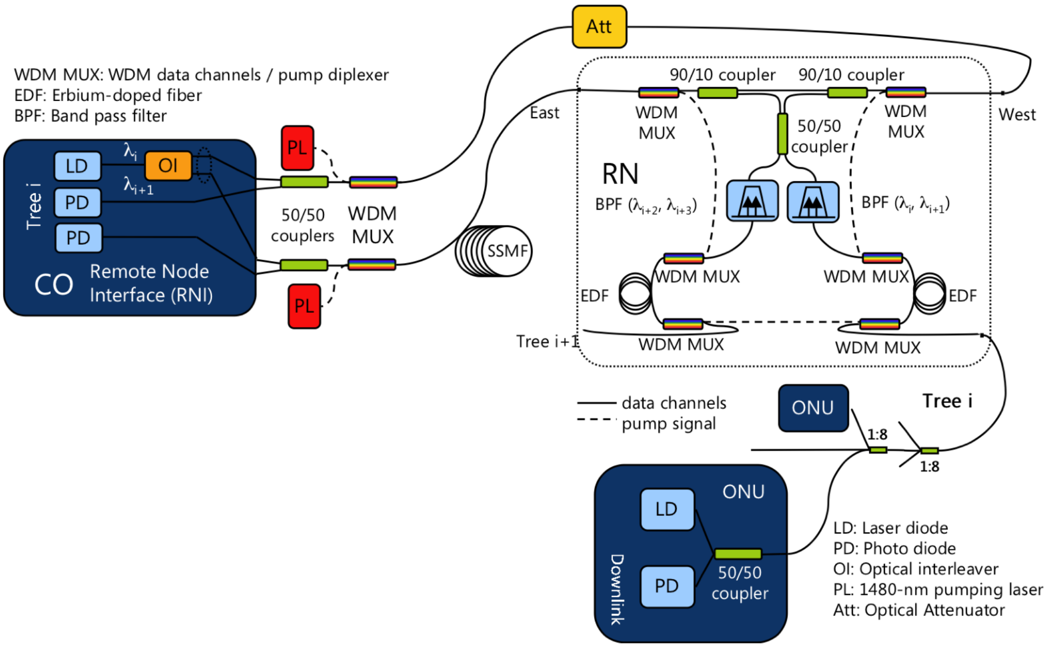


Fig 5.25 Network testbed

Downstream and upstream transmission experiments were carried out to verify correct reception. Downstream and upstream path is totally equivalent so results for both directions are almost identical. Fig. 5.26 presents BER upstream transmission results at the critical remote nodes and in a back-to-back configuration.

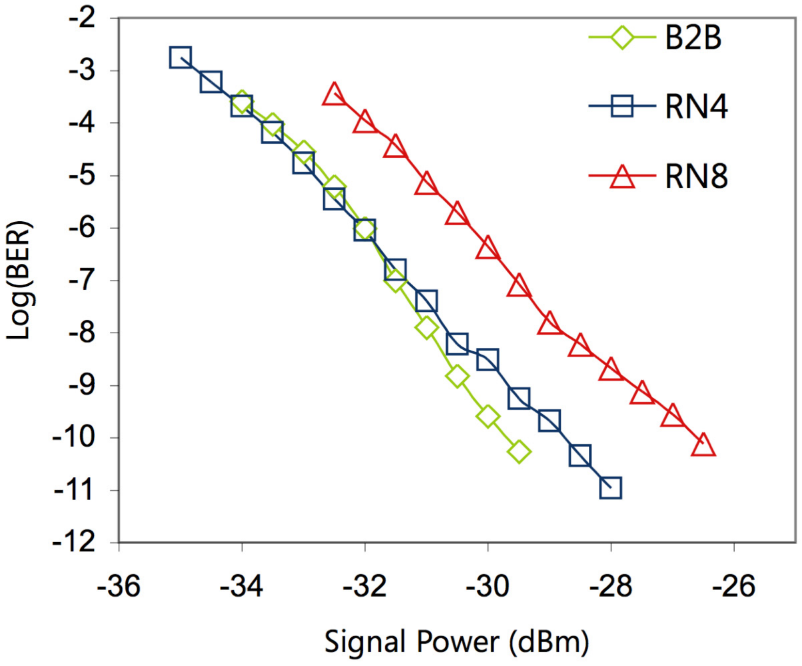


Fig 5.26 Transmission measurements

In standard operation, the node that has more losses is RN4, as is has three pass-through stages. In case of a fiber cut, the most critical case is RN8 when the fibre cut happens in the link between the CO and RN8. Therefore, RN4 corresponds to the highest losses in standard operation and RN8 to the highest losses in resilient mode.

BER decreases when more RNs are passed, as can be seen in Fig. 5.26 but in any case, no BER floor was found.

5.3.5 Conclusions

This network topology is presented as an extension for EPON/GPON services in a combined ring – tree topology. The extension is based on a single fibre ring and a totally passive outside plant providing overlay capabilities and resilience to increase both, the number of users and the robustness of the system. The network is flexible as each wavelength can deliver different services to different types of users using different data rates and splitting ratios.

By choosing optimal design parameters, the network can offer service to a large number of users (more than 1,024) in a cost effective way. Many combinations are possible and scalability is guaranteed.

A simulated network to give access to 1,024 users was designed, using $N = 8$ and $K = 64$ and a testbed was implemented to demonstrate correct optical connectivity. Experimental results showed correct functionality in both, standard and resilient mode operation. No BER floor was found so configurations with more remote nodes and higher splitting ratios are also possible.

6 Advanced Media Access Control protocols for FTTx

This section presents combined WDM / TDMA access protocols specifically designed for access networks. Two different versions will be discussed, the first one targeted for access networks with reflective devices and the second one with tunable laser sources. The peculiarity of the first approach is that each packet sent from the CO is divided in two sections: the downstream data and an optical carrier signal to modulate upstream data. On the other hand, the second approach just sends downstream data and grants for upstream transmission.

By using shared tunable laser sources located at the Central Office (CO) and a dynamic time assignation protocol there is no need to synchronize upstream transmission as the CO gives access to the shared media. This hybrid access protocol is scalable in terms of number of lasers and offers flexible bandwidth allocation and is suitable for all wavelength-selective network topologies, including the ones presented in the last chapter.

These protocols were evaluated by means of mathematical analysis and simulations. A network simulator based on NS–2 was implemented in order to obtain results about throughput and network delay.

If the proposed protocol is implemented in a AWG^2 WDM/TDM PON, the network can offer bandwidth on demand to different locations, leading to the concept of geographical bandwidth allocation (GBA), which is demonstrated to be more effective than classical TDM-PON approaches on both, throughput and network latency.

6.1 Optimized protocols for access networks combining WDM and TDM media access controls

Many investigations have described the benefits of combining these two technologies (TDM and WDM) to optimize network performance and resource utilization. This architecture is known as hybrid WDM/TDM PON and mainly offer centralized management and bandwidth allocation in the CO, simplifying the upstream protocol. Although TDM PONs are the most cost effective solution, from the performance point of view TDM-PONs have several drawbacks. Bandwidth scalability is not easy once the network is deployed, it does not offer secure connections due to its broadcast nature and upstream transmission requires complex synchronization between the CO and each of the ONUs connected to the network [Jang00], [Ma03].

On the other hand Wavelength Division Multiplexing (WDM) PONs solve the drawbacks of TDM-PONs offering virtual point-to-point connections and assigning a specific wavelength to each ONU but the costs are nowadays very high. Also, light sources are not efficiently used.

Here in this section we propose an access protocol for PONs which tries to overcome the above limitations by means of a combined Wavelength Division Multi-Access (WDMA) / Time Division Multi-Access (TDMA), using tunable laser sources at the CO and ONUs which use remote modulation without active light sources to transmit upstream data [Frigo94]. Another version for tunable lasers will also be discussed. This access protocol is a solution in between TDM/PONs and WDM/PONs in terms of both, cost effectiveness and network performance.

The network topology is flexible and both ring and tree topologies are suitable. However, it is interesting to note that wavelength selectivity at the ONU is a requirement to ensure correct performance. This can be achieved by means of multiplexers at the outside plant or optical filters at the ONU side.

6.2 Network Architecture

The access protocol that is proposed locates all the intelligence and costly optical equipment at the CO, in order to share it among all the users connected to our network. This allows creating a cost effective and easily upgradeable infrastructure.

The protocol is based on the use of a tunable laser stack in order to have simultaneous transmissions to several users at the same time. To avoid collisions, each ONU needs to be wavelength selective. There are several options to fulfill this criterion. Dynamic ones based on tunable filters are the most flexible but they are also the most expensive. Static ones like fixed optical filters or the use of a wavelength router at the remote node presents less flexibility but are much more cost effective. As routing flexibility can be implemented at the CO, the second option is preferred from the costs point of view.

Each tunable laser at the OLT is shared among the ONUs connected to the network in time-slotted basis. This means that the total bandwidth that can be allocated depends on the number of lasers (L) that are present at the OLT. Other important parameters that are involved in bandwidth allocation are the number of ONUs connected to the network (N), the data rate (r) and the laser tuning time (T_{laser}). Bandwidth allocation equations will be presented further in this chapter.

To achieve a cost effective approach, L needs to be much smaller than N. $L = N$ is the case of one laser assigned to each ONU so there is no sharing of light resources and we have then a classic WDM-PON. On the other hand, $L = 1$ represents the TDM-PON scenario. On both cases, no tunable sources would be needed because we would have pure WDM or TDM access protocols respectively.

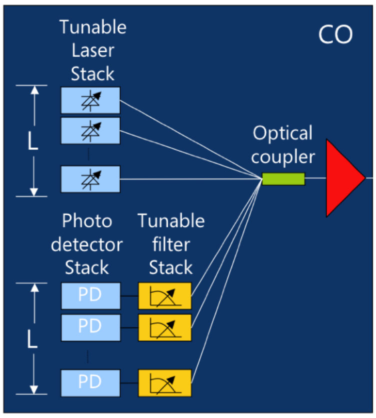


Fig 6.1 OLT design using tunable filters for the reception section

To receive data from the ONUs a photo detector stack is required at the OLT side. The number of photo detectors needs to be equal to the number of lasers (L). Also, in order to avoid interferences among different signals arriving at the same time, tunable filters are required to separate optical signals being transmitted at different wavelengths. Another option would be to locate N photo detectors at the OLT and an Arrayed Waveguide Grating (AWG). In that case, each ONU would have a dedicated receiver at the OLT. The main advantage of this second option is that control and management is much simpler. A complete schematic of the OLT can be seen in Fig. 6.1.

As far as the ONU is concerned, it can work in reflective mode without any light source or with a tunable laser [Schneider02], [Takesue02], [Prat05a]. Also, it is convenient to be wavelength independent (colorless) in order to simplify stocks and management.

When a reflective device is used, the ONU has two modes of operation: reception of downstream data and modulation of upstream data using an optical carrier sent from the CO. This means that the time slot that is assigned to each ONU is divided in two sections: downstream traffic and unmodulated optical carrier for upstream remote modulation purposes. These two sections are transmitted with a guard band (T_{guard}) which is the time required to switch between the two modes of operation.

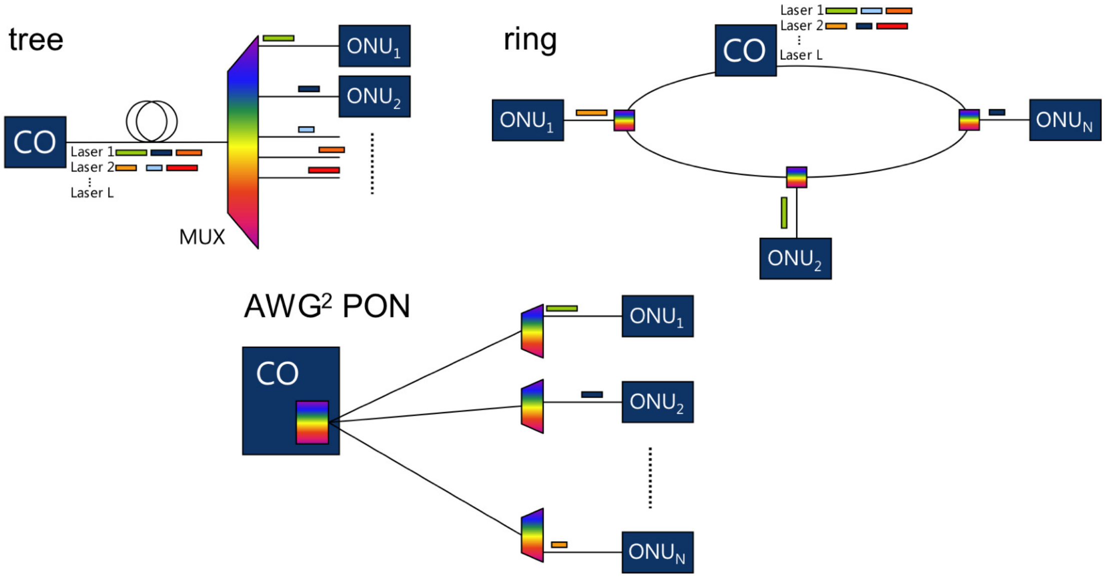


Fig 6.2 Suitable access network topologies (ring, tree and AWG^2 PON)

Any network topology featuring colorless ONUs receiving a single wavelength are feasible to deploy the proposed access protocol. On a tree topology, this can be easily achieved by locating an Arrayed Waveguide Grating (AWG) at the remote node. This is a very interesting option because power loses at the AWG are much lower than using optical splitters (specially for high splitting ratios) and allows also secure connections between the ONU and the OLT as other users do not have access to the data that are being transferred by other ONUs because it is being sent on different wavelengths.

A ring topology is also possible. In this case, each ONU requires a specific wavelength to be added and dropped. This can be done using tunable Bragg gratings or fixed ones. This topology may offer resiliency capabilities and more flexibility in terms of bandwidth allocation as we can use both directions of the fiber to transmit data. However, the cost that we have to pay is more complex equipment at the end user premises.

In any case, the best network topology to implement the combined WDM/TDMA protocol is in a AWG^2 WDM/TDM PON, where Geographic Bandwidth Allocation can be implemented and the overall network performance increased (see Fig. 6.2).

6.3 Frame structure for reflective ONUs

One of the benefits of the proposed access protocol is that no upstream synchronization is required. In the reflective ONU case, this is due to the fact that the ONU is unable to transmit data if it is not provided with an optical carrier sent from the CO. This optical carrier is sent after the downstream data. It is then modulated with the upstream data and sent back to the CO.

The limiting factors and parameters that have to be taken into account are the round trip time (RTT), the propagation time difference between ONUs and the number of tunable lasers at the OLT.

Fig. 6.3 presents the typical frame structure and the guard times required for proper operation. There are two relevant guard times: between the transmission of the downstream data and the unmodulated carrier (T_{guard}) and between the transmission to two consecutive ONUs ($\mathrm{T_{laser}}$).

T_{guard} depends on the switching specifications of our ONU electronics. On the other hand, T_{laser} depends on the tuning speed capabilities of the lasers at the CO and also on the RTT difference between two consecutive ONUs. This is crucial in order to avoid collisions at the CO photo detectors. Due to different propagation times, upstream data could collision at the photo detector avoiding proper reception of one of the upstream signals. In order to avoid this to happen, T_{laser} should be extended. As the downstream signal is not sent back to the OLT, the margin for the RTT difference between two consecutive ONUs (n and n+1) is $T_{laser} + T_{downONUn+1}$. In case RTT difference were extremely high, nesting strategies could be used. This consists in sending data for the nearest ONU after the farthest and receive the nearest upstream data before the farthest. This concept is more widely explained further in this chapter.

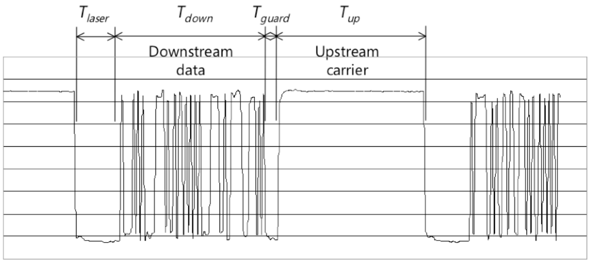


Fig 6.3 Frame structure and transmission diagram

6.3.1 ONU Discovery procedure

The CO needs to periodically search for ONUs as they are unable to send data without an optical carrier sent from the OLT. The discovery procedure consists on sending an unmodulated optical carrier pulse on each wavelength used in the system and wait for the reply from the ONUs (see Fig. 6.4). By doing this, the CO registers the active ONUs on the system and calculates the RTT to each ONU. To obtain RTT, the ONU measures the time needed to transmit the discovery packet and receive the reply from the ONU. These are the two parameters required to synchronize the network. Note that T_{laser} in this case needs to be much wider than in the case of working on standard transmission mode. This is because there is no information about the RTT. The time margin (T_{guard}) between consecutive pulses limits the logical range of our network, which depends on the following equation:

$$T_{guard} \geq \frac{2 \cdot d}{v_{prop}} \tag{6.1}$$

where d is the maximum logical distance and v_{prop} the propagation speed, typically ~$2{\cdot}10^8$ m/s. This means that for an access network of 30 km, T_{guard} should be of 300 μs, 400 μs for 40 km and so on.

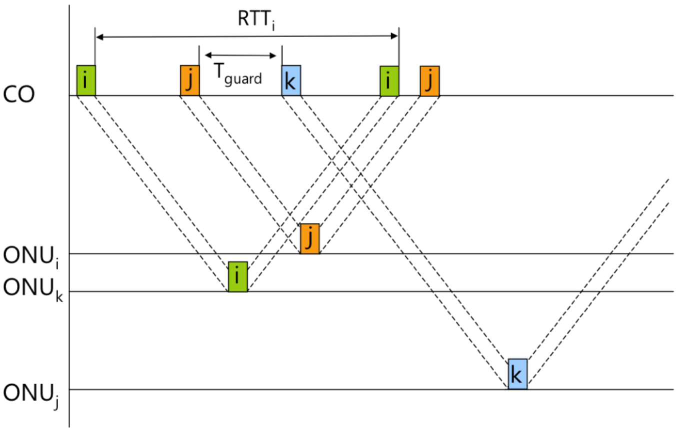


Fig 6.4 Polling cycle to detect live ONUs

Polling cycles can be done each *k* seconds. ONUs are fixed and do not move so by establishing polling cycles each *k*=1 to 5 seconds the network monitors the status of all ONUs without severely affecting network throughput. Also, the network needs to poll just the ONUs that are disconnected, as online ONUs are already registered with information about activity and RTT.

6.3.2 Control Data

Further to the optical signals that are transmitted along the network, inside each time slot, control data need to be sent in order to provide robustness and flexibility. These data are inserted by the ONU on the upstream data packet. The parameters are: ONU_ID, Window Request (request for *x* bits to transmit on the next packet) and a timestamp. The first one is required to determine which ONU is transmitting, the second determines the duration of the optical carrier pulse that is sent from the CO. The time stamp is required to monitor RTT. From the OLT to the ONU ONU_ID, Window Granted (duration of the carrier pulse allowed to transmit upstream data) and a timestamp need to be sent.

Fig 6.5 Control Data fields

The discovery packet data sent from the ONU to the CO are identical to the one sent during standard operation.

Not all the parameters are mandatory but with the described control fields, the transmission from the OLT to the ONUs and from the ONUs to the CO is symmetric.

The precision of the time stamp, and in general of all the timings of the network, depends on the data rate and average time slot we allocate to each ONU. As an example, using laser sources @ 1Gbps, average time slots of 64kbits and laser tuning times of between 1 and 10μs, a time stamp precision of 0.5μs would be enough to guarantee correct performance (RTT error compared to transmission time less than 1%).

6.4 Frame structure for ONUs with tunable sources

All the parameters and distance calculations for the reflective mode are valid when the ONU is equipped with a tunable laser source. The only difference is that there is no need to transmit the upstream carrier from the CO, which means that the system can operate in full duplex mode, thus network performance increases by 100%. In any case, T_{guard} should be maintained to avoid collision at the CO's photo receiver side.

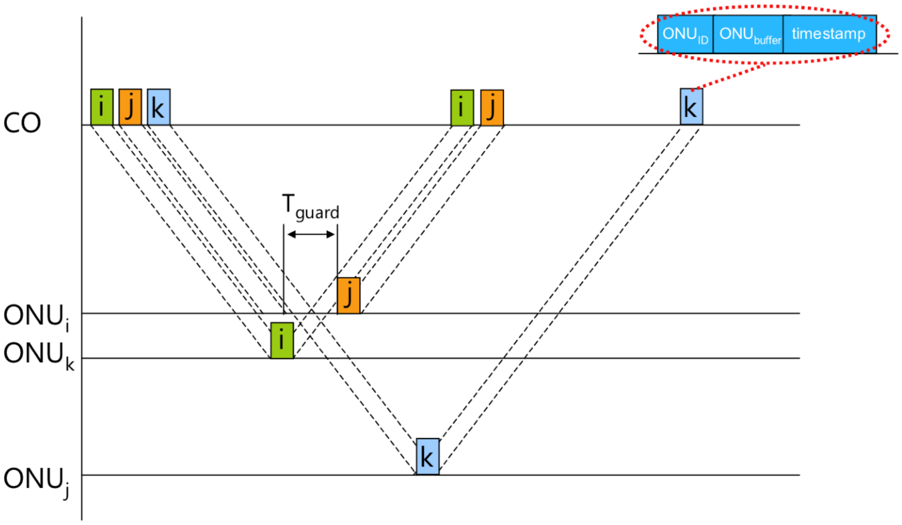


Fig 6.6 Frame structure and transmission diagram

6.5 Network Performance

In order to evaluate the network performance of the proposed protocol, both mathematical analysis and performance simulations were implemented.

6.5.1 Available bandwidth and network latency

The calculations that were done supposed a markovian queue model and L lasers with $T_{service}$ being exponential and equal to T_{laser} + T_{down} + T_{guard} + T_{up} were T_{down} is the time needed to transmit downstream data and T_{up} the time assigned for the upstream transmission.

6.5.1.1 Reflective ONUs

With these parameters, guaranteed bandwidth per user is:

$$BW_{user} = \frac{L}{N} \cdot r \cdot \frac{T_{up} + T_{down}}{T_{service}} \tag{6.2}$$

where L is the number of lasers, N the number of users and r the data rate.

T_{laser} in the range of 1 to 10μs is realistic taking into account nowadays technology (some examples of tunable lasers in the range of nanoseconds have already been reported [Su04]). T_{guard} depends on the data rate. 10 bits should be enough to commute between the two operation modes. T_{up} and T_{down} can be dynamically defined depending on network congestion and ONUs transmission requirements. In any case, on a saturated environment, where ONUs transmit at their maximum data rate, time window needs to be much wider than T_{laser} + T_{guard} in order to increase network performance.

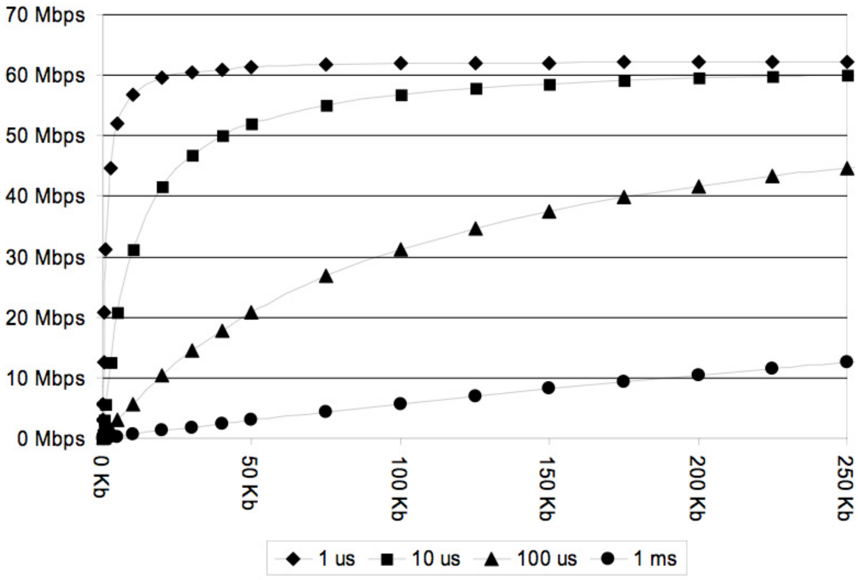


Fig 6.7 BW per user (fixed parameters: L=8lasers, N=128users, 1/T=1Gbps)

Fig. 6.7 presents bandwidth per user on a saturated scenario depending on T_{up} + T_{down}. With T_{laser} in the range of 1 to 10μs, available bandwidth is acceptable for short time windows. On the other hand, T_{laser} in the range of 100μs to 1ms are simply too long. More time is required to tune from one wavelength to another than to transmit data. It is also important to mention that if data rate is increased, laser tuning time must be reduced. Transmitting at data rates of 10Gbps means to use tunable lasers tuning in the range of 1μs to 100ns.

The theoretical maximum throughput is defined by the following equation:

$$\rho = 1 - \frac{T_{guard} + T_{laser}}{T_{service}} \tag{6.3}$$

Network latency is another important parameter, especially for real-time applications. A very important parameter is the time we require to serve the same ONU after being served. This limits real time applications and determines maximum network latency in the case of full buffers. We define this parameter as T_{window} and in a saturated scenario it follows the equation:

$$T_{window} = \frac{N}{L} \cdot T_{service} \tag{6.4}$$

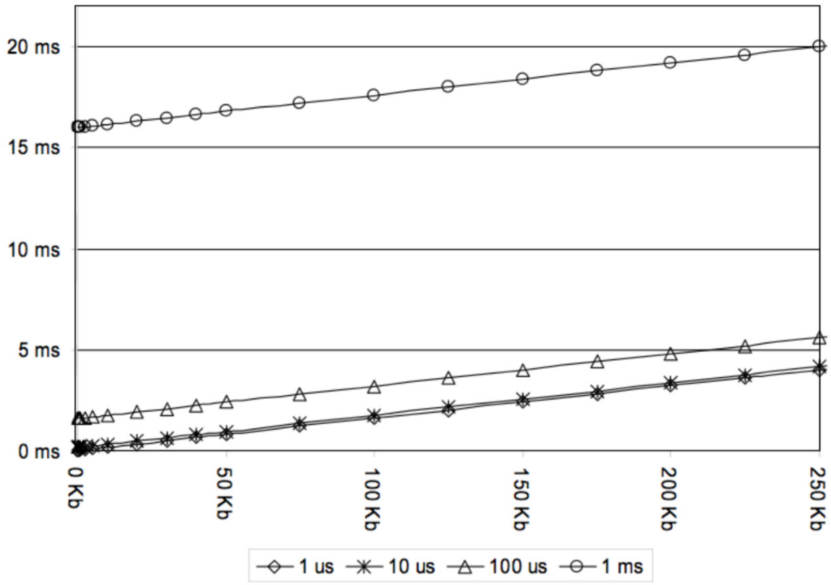


Fig 6.8 Time window per user depending on laser tuning time and time window (other parameters: L = 8 lasers, b = 1 Gbps, N = 128 ONUs)

Fig. 6.8 presents the time that an ONU has to wait between transmissions. There is a hard implication of the laser tuning time on the results. Also note that depending on the time slot duration time window increases. We arrived to the same conclusion for the bandwidth per user analysis. Laser tuning times need to be in the range of 1 to 10μs or below for data rates of 1Gbps. Also, variable time slots ranging 10,000 to 100,000 bits are preferred as they offer good balance between network performance and latency.

6.5.1.2 Tunable lasers

When ONUs have tunable lasers there is no need to transmit the optical carrier from the CO. This increases throughput as now the laser can use the time that was reserved to just transmit an optical carrier to transmit data. $T_{service}$ is now defined as T_{down} + T_{laser} and there is no need to have a guard time between transitions, so T_{guard} is not required.

In this scenario, the new equations that parameterize network performance are:

$$BW_{user} = \frac{L}{N} \cdot r \cdot \frac{T_{down}}{T_{service}} \tag{6.5}$$

for downlink and

$$BW_{user} = \frac{L}{N} \cdot r \cdot \frac{T_{up}}{T_{service}} \tag{6.6}$$

for uplink transmission. This means that bandwidth per user is increased by a factor of 2. Network throughput is increased to:

$$\rho = 1 - \frac{T_{laser}}{T_{service}} \tag{6.7}$$

Again, this is indistinctively for downstream and upstream transmission.

Finally, T_{window} has the same mathematical expression as in (6.4) but one should note that now $T_{service}$ is just T_{down} + T_{laser} so T_{window} is reduced by a factor of 2. In general, throughput is increased by a factor of 2 while latency is reduced in the same way. This is because now transmission equipment is increased and no transmission time of the CO lasers is used to send unmodulated carriers to the ONUs to allow upstream transmission.

6.5.2 Ranging

In order to avoid collisions at the CO photo receptors, distance difference between two consecutive ONUs can not be longer than the guard time between received packets (see Fig. 6.9).

6.5.2.1 Reflective ONUs

When we have reflective ONUs, he guard band is defined as T_{laser} plus the time required for downstream transmission:

$$\Delta d_{prop} \leq \frac{v_{prop}}{2} \cdot \left(T_{laser} + \frac{b_{down}}{r} \right) \tag{6.8}$$

where v_{prop} is the propagation speed, b_{down} is the bit length assigned to downstream transmission and r is the data rate (this restriction only applies when the second ONU is farther than the first one). If a dynamic bandwidth allocation protocol is implemented, the system needs to guarantee that the above restriction is fulfilled in order to achieve proper network operation.

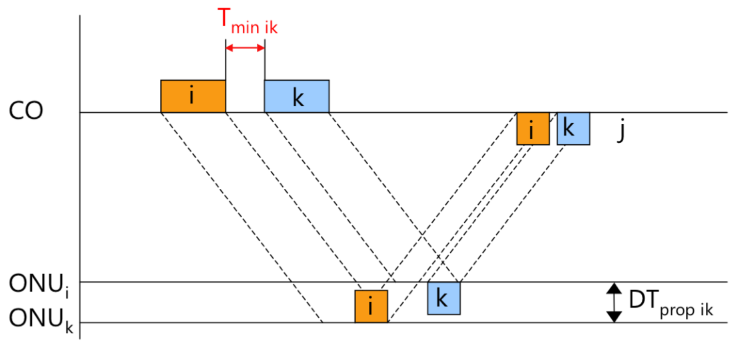


Fig 6.9 Minimum distance to avoid collisions

As an example, with T_{laser} = 1μs and a downstream burst of 32,000 at 1Gbps the parameter Δd_{prop} is 6.6 km.

If the distance difference between ONUs were very large (the second farther than the first one), then nested ranging protocols cold be used. This strategy consists on sending before information to the ONU that is farther and later to the one that is closer. If the propagation difference is large enough, data from the closest ONU will be received before data from the farthest one. Fig. 8 depicts both cases, standard and nested ranging. For a nested strategy, the relationship between the distance difference and the transmission parameters is:

$$\Delta d_{prop} \geq \frac{v_{prop}}{2} \cdot \left(T_{laser} + \frac{b_{down} + b_{up}}{r} \right) \tag{6.9}$$

Note that we did not consider T_{guard} in the above expressions because it is much shorter and therefore can be ignored in comparison to the other terms.

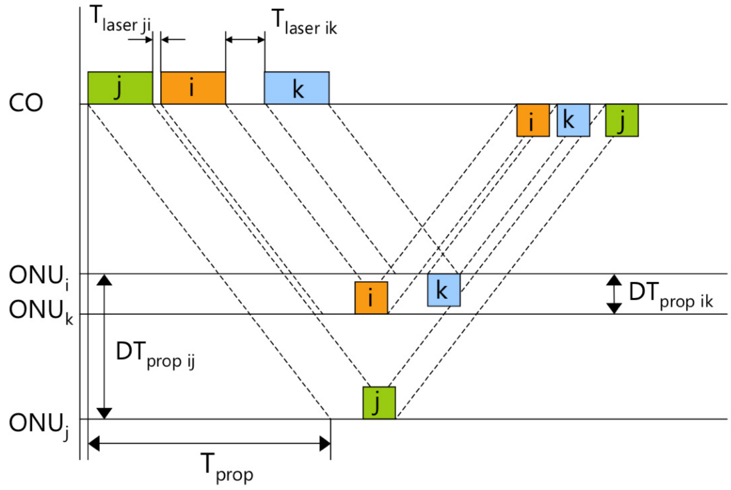


Fig 6.10 Standard (i to k) and Nested (j to i&k)

The OLT should schedule the time to serve to each ONU depending on their relative distances in order to maximize network utilization and reduce waiting times. Fig. 6.10 presents a general example in which the OLT uses nesting between ONU j and ONUs k and i and T_{laser} extension between ONU i and k.

6.5.2.2 Tunable lasers

However, in the case we have ONUs with tunable lasers, there is no need to have any guard time in downstream transmission. Upstream and downstream are uncorrelated an as there is a laser at the ONU side, the network has just to inform when the ONU can start transmitting to avoid an upstream collision (see Fig. 6.11). T_{guard} in each case is send in the head of the incoming downstream packet.

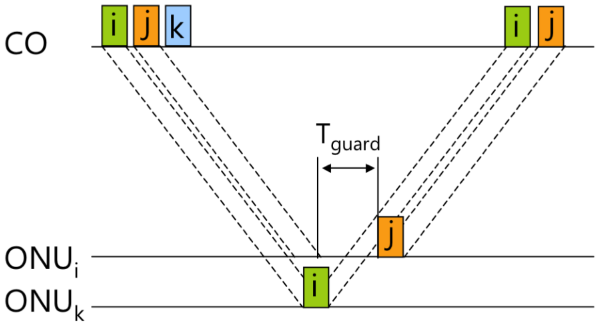


Fig 6.11 Ranging in tunable-laser based network

This simplifies the transmission protocol and enhances network performance, as no guard time is required in downstream to avoid upstream collisions.

6.5.3 Network simulations

In order to simulate the network performance of the protocol we modeled an access network based on the following parameters: 128 users, 8 lasers @ 1Gbps with tuning time of 1μs. A markovian G/G/c/k simulator, defining T_{serve} exponential of duration $T_{up} + T_{guard} + T_{down} + Tl_{aser}$, was used to determine network latency and throughput. As T_{guard} is much smaller than the rest of the times for some calculations it was not considered.

The queues were limited to allow maximum delay of 2ms, which is an adequate value in an access network to allow real-time applications.

To obtain network latency we took into account time at the queue, time at service and ONU time slot window waiting time. This last parameter is defined as:

$$T_{w\_slot} = \rho \cdot \frac{N}{L \cdot 2} \cdot \left(T_{up} + T_{guard} + T_{down} + T_{laser} \right) \tag{6.10}$$

where ρ is the network throughput, *N* the number of users and *L* the number of lasers.

Network latency results against throughput are depicted in Fig. 6.12 for several average time slot durations (10, 64 and 100μs) and two laser tuning times (1 and 10μs). It can be clearly seen that throughput is affected by the relationship between the average time slot duration and the laser tuning speed. If $T_{tx} = T_{up} + T_{down}$ is reduced, throughput limit is also reduced, limiting transmission capabilities of the network.

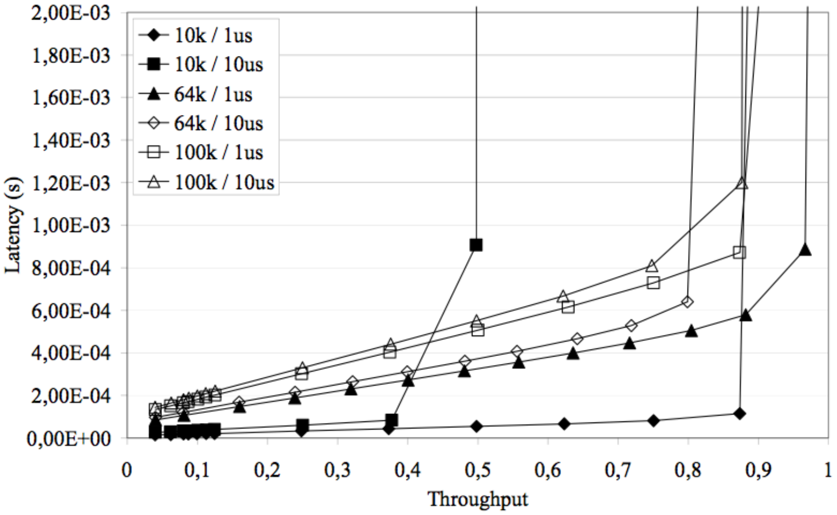


Fig 6.12 Network latency results

A good compromise is to keep T_{tx} in the range between 25,000 and 75,000 bits. In this range, network latency is in the range of hundreds of microseconds, a very acceptable value for real time applications in an access environment, and network maximum throughput between 0.8 and 0.95.

6.6 Geographic Dynamic Bandwidth allocation

GBA stands for Geographic Bandwidth Allocation. Optimization of tunable laser utilization by sharing it for different traffic patterns is the main goal of this novel concept.

GBA is based on the concept that the geographic distribution of users in an area is similar to their traffic patterns. This is, users with similar traffic patters are concentrated in short distances and thus connected to the same remote node. This creates a throughput problem as they have similar resource necessities along similar periods of times, thus their traffic patters are similar.

If this is extended to a wider area, i.e. a city, one can find different locations with different types of users. We will distinguish three main categories: home users, businesses and commercial users. Each of them have their characteristic traffic patters which vary from one group to the other but are more or less similar inside the group.

In a classical network approach, users with similar traffic patters are connected to the same remote nodes (see Fig. 6.13). This is not optimal as during the day, network occupancy varies depending on the types of users that are connected to the remote node. As an example, in the mornings remote nodes that connect businesses will have much higher occupancies than home users' remote nodes while in the evening the behavior will be the opposite.

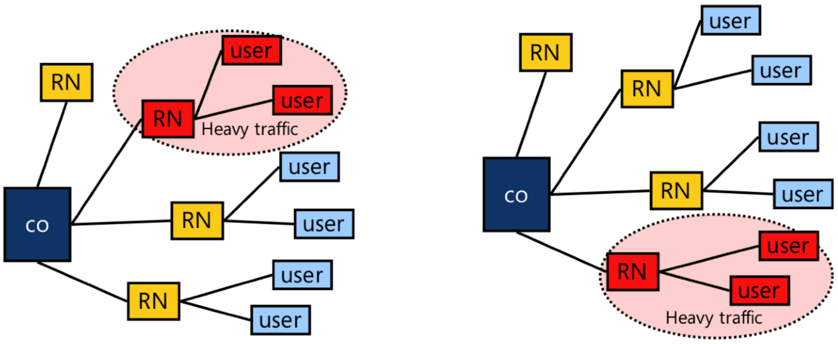


Fig 6.13 GBA principle

The solution to this would be to interconnect different types of users to the same remote node, with complementary traffic patterns that compensate one with the other to have overall constant bandwidth requirements. However, this is not feasible in most cities as users are normally aggregated in neighborhood basis.

To overcome this and offer higher network performance while keeping costs low, we presented in the last chapter the AWG^2 WDM/TDM PON network topology, which allows the GBA concept. The main idea is to use a NxN AWG to uncorrelate the transmission interfaces with the output ports, thus all the remote nodes are accessed by all the network interfaces (see Fig. 6.14). This, together with a dynamic TDM bandwidth allocation protocol offers to the network the possibility to assign bandwidth on demand to all the remote nodes.

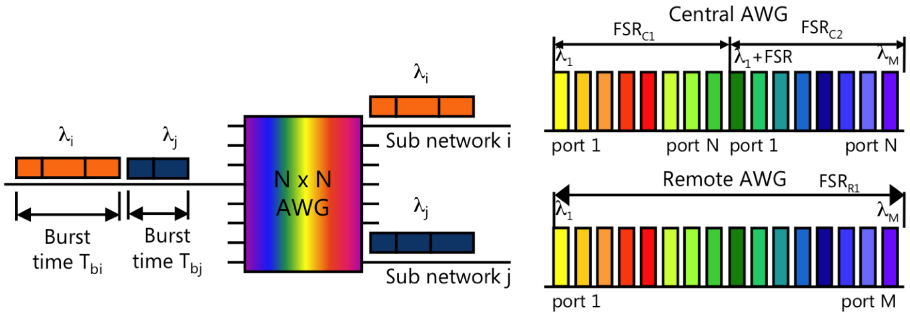


Fig 6.14 AWG^2 WDM/TDM PON routing profile

Each transmission interface servers a subnetwork in each remote node, thus each transmission interface cyclically transmits to one subnetwork from each remote node, sharing the bandwidth in TDM basis. By adjusting the TDM slots, the network can then concentrate bandwidth on demand and at the same time, improve resource allocation and network performance.

GBA then, is a combination of the WDM/TDM that has already described and analyzed in this chapter, implemented in an AWG^2 WDM/TDM PON and constitute one of the main contributions of this thesis, together with the advanced topologies described in the previous chapter.

The next section covers the simulations that have been carried out to justify and demonstrate the GBA concept.

6.7 Network performance

A basic scenario with is an AWG^2 WDM/TDM PON in a tree ouside plant, with 16 tunable lasers @ 2.5Gbps and 16x remote nodes implemented by 1x16 AWGs. Design paramenters of the topology are then $L = M = N = 16$ (see previous chapter for further reference). The splitting ratio (k) was chosen to be 32. The resulting access network is then of 8,192 users ($M \times N \times k$), and each laser serves $N \times k = 512$ ONUs.

Three classes of users were simulated: business customers, commercial customers and home users. From the total 8,192 ONUs, 37'5% of them were businesses, 18'75% were commercial customers and finally 43'75% were homes users. This distribution represents a typical mid-size town with a broadband penetration factor of 70%.

Each class of users has their own traffic patterns (see Fig. 6.15), which is distributed along the day in the following way: network occupancy in home user's network branches in the morning (in working days) will be low.

However, in businesses segments there will be heavy traffic. In the evenings the traffic patterns will be opposite, with businesses having low load and home users with high bandwidth requirements. Commercial users requirements are similar to businesses with the difference that during weekends their transmission requirements are higher.

From this, one can clearly see that to user dedicated and separate lasers to homes users and will not optimize laser utilization Thus, a dynamic assignation of resources is more efficient as bandwidth can be concentrated on specific network segments depending on the user needs, by assigning wider time-slots to the customers connected them.

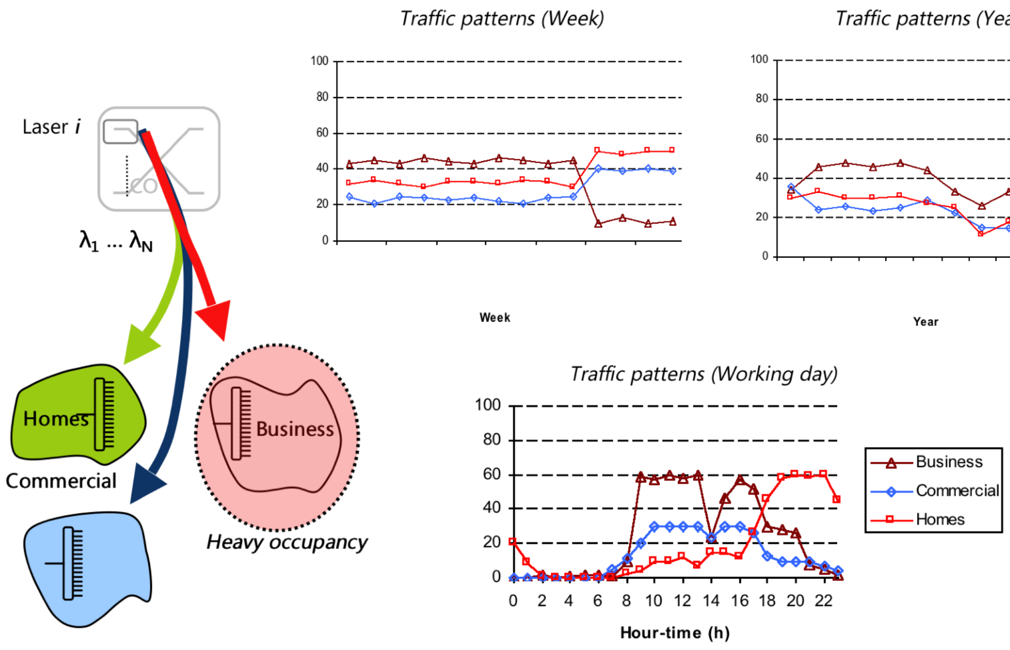


Fig 6.15 Traffic patterns for each class of user

In terms of classes of services, triple-play services traffic (voice, video, and data) were offered. These different flows are marked as high-priority voice traffic (packets of 64 bytes length), medium-priority video traffic (500 B), and low-priority data traffic (1500 B) in class-based queues. Their traffic patters are very different and their network requirements, too. Voice requires low latency but not huge bandwidth. Video is very bandwidth hungry (depending on the quality) and requires a constant latency (constant jitter). Finally, data traffic is considered best effort with no restrictions.

6.7.1 Classes of services

In order to evaluate the benefits of GBA, three traffic distributions have been designed by simulating different situations: morning, evening and weekend. Under a high utilization of laser equipment, morning scenario supposes a business segment heavy occupancy with 60% of total traffic, 30% for commercial segment and 10% for homes segment. Evening scenario is defined as 30% for business segment, 10% for commercial as well as 60% for homes segment. Finally, in weekend there is a traffic distribution of 10% for business segment, 40% for commercial segment and 50% for homes segment (see table 6.1).

Timeframe	Traffic type	% occupancy
morning	business	60
	commercial	30
	homes	10
evening	business	30
	commercial	10
	homes	60
weekend	business	10
	commercial	40
	homes	50

Table 6.1 traffic distributions

Results of the simulations are shown in Figs. 6.16-6.19. We have found a gain in laser equipment utilization using GBA under high-load conditions when input traffic is heavy unbalanced, while in pure TDM-PONs this is not possible as bandwidth can not be shared between different PON sub networks.

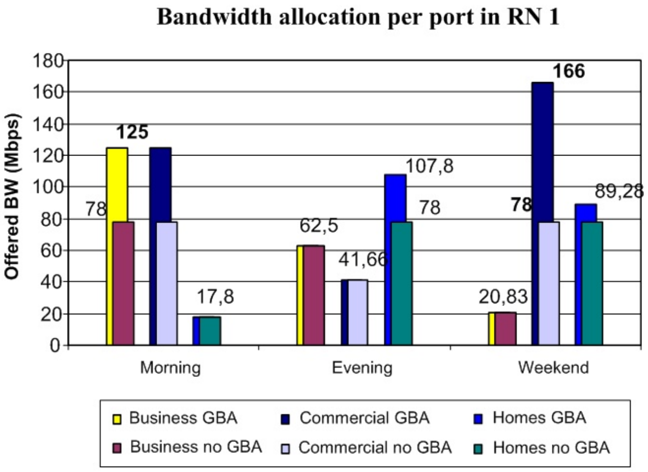


Fig 6.16 Impact of GBA for different traffic profiles

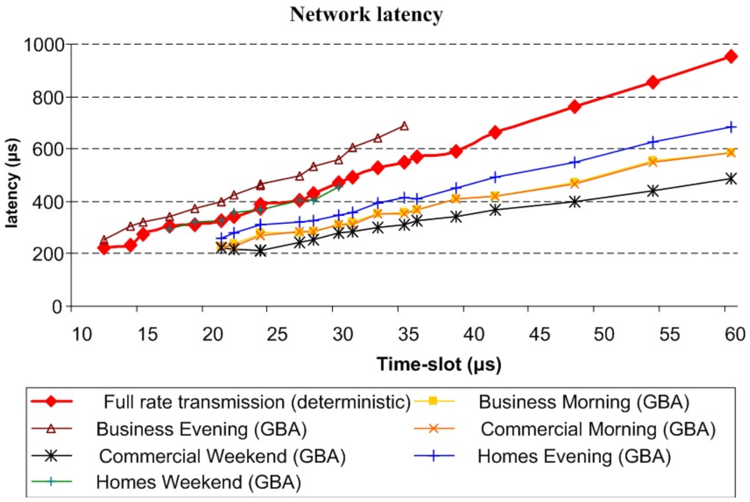


Fig 6.17 Network latency for different traffic profiles, with and without GBA

Available bandwidth for each type of customers is dynamically distributed depending on their necessities on the three simulated network traffic scenarios. Figure 6.16 shows bandwidth allocation with and without GBA. Gain with GBA is possible because heavy-loaded segments are balanced with lower ones and available bandwidth is distributed. One can see for instance that using GBA in business links increase bandwidth per user from 78 to 125Mbps (60% increase) in the mornings and that home users increase their transmission capabilities from 78 to 108 Mbps (38% increase) in the evenings when GBA is implemented.

Furthermore, results obtained in (6.2) and shown in Fig. 6.7 are improved, because with GBA unused bandwidth from low-loaded segments can be used to serve higher-loaded ones. However, this improvement in bandwidth per user has its payback in higher latencies for lower-loaded traffics. As shown in Figure 6.17, in low occupancy segments latency will increase if GBA is implemented. This is because T_{window} becomes wider due to the insertion of traffic for heavy-loaded segments from other remote AWG segments. On the other hand, in heavy-loaded segments latency is reduced on base of the same principle, and almost all situations improve the previous network latency results.

Simulations results also verify the theoretical traffic patterns presented in Fig. 6.15. As can be seen in Fig. 6.18, business customers require high bandwidth during the morning that decreases in the evenings and at weekend. On the other hand, home users demand more bandwidth during weekends and in the evening and decreases during mornings. Commercial customers have an almost independent-with-time demand.

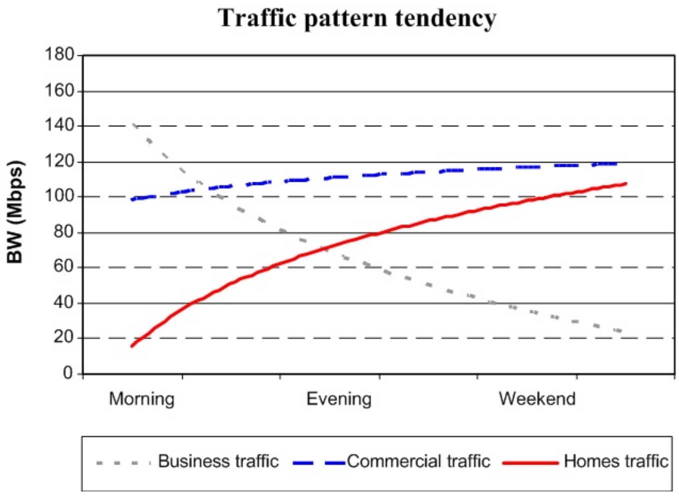


Fig 6.18 Tendency of the three traffic patterns

As far as triple-play services is concerned, results demonstrate that the use of priorities improves the performance of voice and video traffic. An analysis in a heavy-loaded scenario is showed in Figure 6.19; voice and video traffic transmission are prioritized over data traffic. While time slot is shorter, these priority levels accentuate the differences between each service parameters in network. However, when time slots increase latency is not further improved, as latency is then mainly due to the time required to pool the rest of users served by the same laser. Also, simulations demonstrate that to use separate queues for voice and video traffic is not fully justified as the improvement in voice traffic latency in comparison to video traffic (with low priority) is negligible.

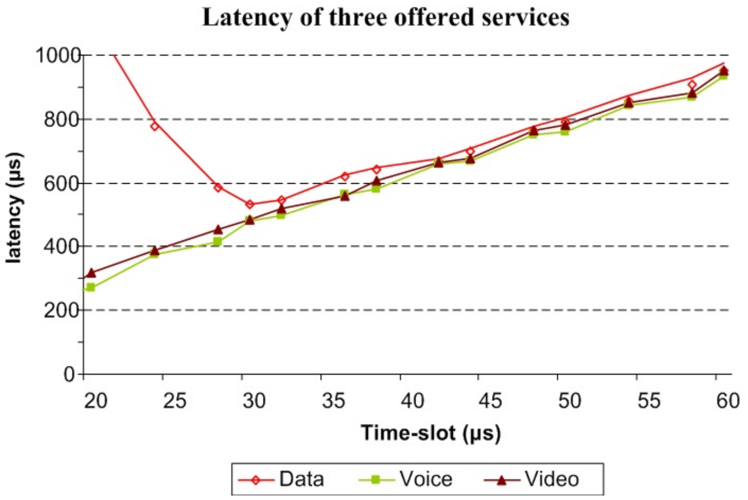


Fig 6.19 Latency depending on Qos and traffic pattern tendency

6.8 Conclusions

This section presents a protocol combining WDMA and TDMA for PON is presented. It offers a compromise between high transmission capabilities of WDM-PONs and simple and cost effective TDM-PONs. It solves the TDM upstream synchronization problem of TDMA and allows flexible bandwidth assignation by means of a centralized control protocol at the CO.

The topology is easily scalable by adding more lasers at the OLT without the need of any change at the ONU side. Another important consideration is that the protocol can be implemented on any access network topology. The only restriction that is required is that each ONU needs to receive a unique wavelength.

Mathematical analysis and simulations show that a compromise needs to be met when deploying the network in terms of laser tuning time and average time slot assignation per ONU. Ideally, laser tuning times need to be as small as possible while time slot duration needs to be narrow enough to allow low latency but wide enough to be much wider than T_{laser} to spend as less time as possible switching between ONUs.

This WDM/TDMA protocol can be implemented on an AWG^2 WDM/TDM PON, offering Geographic Bandwidth on Demand.

This technique combines the proposed WDM/TDM access protocol with an advanced access topology based of a concatenation of an MxM AWG and a 1xN AWG to uncorrelate laser interfaces and end users in order to homogenize traffic patterns.

By sharing each laser to different network geographic branches, different traffic pattern customers are served, which is optimizes laser utilization along periods of times when some users had low latencies while other high transmission requirements.

Network delay and throughput improvements depend on traffic correlation between users. The most different the traffic patterns, the most improve in network throughput when using GBA is reported.

Simulations on a realistic deployment to serve +8,000 users show that GBA can improve bandwidth per user up to 60%, taking advantage of unused bandwidth from lowly occupied PON segments.

7 Conclusions

This thesis presents an upgrade path from the existing copper-based access infrastructure to an all-optical access solution. The investment that is required has to be done gradually and this is the main reason to present the upgrade path in several intermediate stages.

First, a FTTC / FTTCab combined optical / VDSL solution would incorporate fiber in access and adequate the truck segment of the access infrastructure. Then, a second upgrade will deploy fiber to the building (FTTB) using a combination of FTTB + Ethernet. With this stage, most of the access infrastructure will be already prepared for FTTH.

Combined FTTC/Cab with final VDSL links have been demonstrated to offer relatively high transmission capabilities but their active-in-field nature makes them unattractive for the long run as maintenance costs will go high if this solution is deployed massively, due to the footprint required to install the aggregation equipment, which needs to be installed in the field, near the end users. We have demonstrated correct transmission of VDSL links on distances of 45 km with datarates up to 40Mbps.

FTTB with final switched Ethernet links is a more refined solution that reduces the existing copper link and would be the last fiber-copper combined stage. It is a potential long-term solution for condominium buildings, where optical equipment would be installed in the basement and then distributed to the apartments by UTP cables. Our experiments have demonstrated Fast Ethernet (100Mbps) services on optical links up to 20 km.

Finally, the last upgrade will drop fiber to every single home offering almost unlimited transmission capabilities to the user. In this scenario, due to the highest costs of optical components in comparison with electric ones, advanced algorithms to manage the equipment in order to increase utilization are very recommended. Therefore, advanced topologies using combined access control based on WDM and TDM have been developed. By using agile routing and dynamic assignation of optical resources the proposed networks offer high transmission capabilities with minimum number of optical devices. This, together with the use of reflective ONUs make the topologies very interesting for future deployments of access networks, going one step further than present TDM-PON solutions.

This combined WDM/TDM protocol, together with the AWG^2 PON topologies that have been developed offer the possibility to develop the Geographic Bandwidth Allocation concept, which offers dynamic bandwidth assignation to different RNs of the access infrastructure by combining the routing features of AWGs with agile laser tuning at the CO.

To verify the correctness of the results, laboratory testbeds have been developed for all the presented topologies, which demonstrate that all the proposed topologies are feasible from the optical-connectivity point of view, achieving correct transmission and reception up to 2.5Gbps in 30 km links, which corresponds to the datarate and distance of the most advanced PON protocol at present. Furthermore, network simulations have been developed to corroborate that the GBA concept works and offers real improvement over classical TDM bandwidth assignation protocols. Improvements of up to 60% have been measured by means of simulation implementing a realistic traffic profile on an advanced network serving to different classes of users.

However, the success of the upgrade path is also linked to the evolution of optical devices, both in terms of costs and performance, especially of tunable lasers and reflective modulators. These two components, together with AWGs are the main pillars of the topologies that are presented. AWGs offer at present good performance and with the late deployment of athermal AWGs, AWGs can be installed in field without restrictions. The only evolution on AWGs should be a reduction of their cost. AWGs are integrated devices so due to economies of scale; it is reasonable to expect their price to approximate to the cost of power couplers.

Tunable lasers require further improvement, especially on tuning speed. Agile WDM tuning requires stable tuning between wavelengths in timescales of hundreds of nanoseconds in order not to degrade network performance due to excessive guard times. Also, their cost should be reduced to be similar to fixed lasers. This is especially important if tunable lasers are used on the ONU side as price is one of the main issues on the end-user equipment.

Finally, the devices that require more development are reflective-type devices for ONUs. In this direction, two approaches are gaining momentum: RSOAs and the combination of SOA+EAM. These two devices offer modulation features and can be integrated. RSOAs have been developed intensively in the last years and offer good specifications as reflective modulators but they are limited on bandwidth so they are not the right choice for +2.5Gbps data streams. SOA+EAMs offer much higher bandwidth +10Gbps but are now in a more incipient developing stage.

All this effort is developed to offer higher transmission capabilities so new applications can be developed on access networks. This is in reality what justifies the entire work, because the network by itself has no sense if there are no applications to run on those networks to give added value to the end customers and make their lives easier and more comfortable.

This thesis then tries to establish a realistic and feasible upgrade path to deploy the information highways of the future.

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