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Optical Switching for Dynamic Distribution of Wireless-over-Fiber Signals in Active Optical Networks

Ingeniería Técnica Electrónica Industrial

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ABSTRACT

The ever growing demand of bandwidth by end users has put a lot of pressure on access networks. Access networks, mainly employing wireless technologies, are turning to optics to support such large bandwidth requirements. Depending on the requirements and features of the end users, optical access networks have evolved in different directions. In residential and urban environments, users demand fix connections with high capacity at low price. Passive optical networks (PON) have fulfilled these requirements and are the operators chosen technology. In business environments, in which quality assurance and security are key issues, active optical networks (AON) have found their niche, providing flexibility, adaptability and high throughput while supporting tight management systems.

Vendors are now turning their eye to new markets where optics can be used effectively. Mobile backhaul is a target market, since mobile traffic is growing exponentially – new gadgets along with killing applications are fueling such growth.

Baseband technologies can support mobile backhaul effectively at current rates. However, due to the location of new license-free available frequency bands and the development of radio-over-fiber (RoF) technologies – allowing generation, distribution and reception of micro- and millimeter wave band signals optically, migration towards wireless-over-fiber scenarios are likely. Furthermore, concerns on security and high mobility seem to indicate active solutions may be in favor of system designers, provided that cost and energy consumption are maintained within reasonable limits.

In this thesis, an optical access network based on radio-over-fiber technologies was designed. An active optical switch based on active components (semiconductors optical amplifiers (SOAs)) was used as main building block; the rest of the network was designed according to the channel distribution over the optical spectra required by the optical switch. An experimental validation was conducted. The experiment consisted in the implementation of a four channel system operating on a worldwide interoperability for microwave access (WiMax) frequency band, and employing an orthogonal frequency-division multiplexing (OFDM) modulation at 625 Mbit/s per channel, transmission of the data over 20 km of optical fiber, and active switching in a one-by-sixteen active optical switch. The results show a negligible power penalty on each channel, for both the best and the worst case in terms of inter-channel crosstalk. The system meets the requirements for an AON for wireless-over-fiber for optical access networks (OAN).

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Resumen

El continuo crecimiento de ancho de banda demandado por los usuarios finales está provocando una gran exigencia sobre las redes de acceso. Estas exigencias sobre las redes de acceso, que principalmente emplean tecnologías inalámbricas, están migrando hacia el dominio óptico con el fin de soportar estos altos requerimientos de ancho de banda. Dependiendo de los requerimientos y características de los usuarios finales, las redes de acceso óptico han evolucionado en diferentes direcciones. En entornos residenciales y urbanos los usuarios demandan conexiones fijas de alta capacidad y bajo coste. Las redes ópticas pasivas (PON) han cumplido estos requerimiento y son las tecnologías elegidas por los operadores. En los entornos empresariales, en los cuales la calidad y la seguridad son piezas clave, las redes ópticas activas han encontrado su hueco proveyendo flexibilidad, adaptabilidad, alto rendimiento y al mismo tiempo dando soporte a sistemas de control de redes.

Los proveedores de equipos están ahora girando su vista hacia nuevos mercados, donde soluciones ópticas puede ser usado eficientemente. El transporte de datos de redes de móviles (o mobile backhaul en ingles) es un mercado que se ha convertido en objetivo principal, ya que el tráfico inalámbrico está creciendo exponencialmente. Nuevos dispositivos, junto a las aplicaciones de gran consumo de ancho de banda, son los principales motivos de este crecimiento.

Las tecnologías de banda base puede soportar sobradamente mobile backhaul a las actuales velocidades de transmisión. Sin embargo, debido a la ubicación de nuevas licencias libres disponibles en la banda de frecuencias y el desarrollo de las tecnologías radio a través de fibra permitiendo generación, distribución y recepción óptica de señales, la migración hacia escenarios en los que se use señales inalámbricas a través de fibra son mas probables. Además, teniendo en cuenta aspectos como la seguridad y alta movilidad de los usuarios, todo parece indicar que soluciones activas son más atractivas, siempre y cuando que los consumos de energía se mantengan dentro de límites razonables.

En esta tesis, se diseñó una red óptica de acceso basada en tecnologías de radio a través de fibra. El bloque principal de la red fue un conmutador óptico basado en componentes activos (amplificadores ópticos semiconductores); el resto de la red fue diseñada acorde a la distribución por canales del conmutador óptico. Utilizando este conmutador óptico, se realizó una validación experimental de la red. El experimento consistió en una implementación de un sistema de cuatro canales operando en la banda de frecuencia WiMax y empleando una modulación llamada multiplexado de división ortogonal en frecuencia

(OFDM) a 625Mb/s por canal. La información fue enviada a través de 20 km de fibra óptica, y el redireccionamiento de la señal fue llevado a cabo por un conmutador de 1 entrada y 16 salidas. El resultado es una degradación imperceptible de la señal en cada canal en el mejor y en mejor escenario en términos de interferencia entre canales. Este sistema cumple con los requisitos de una red de acceso activa para señales de radio a través de una red de acceso óptica.

Planteamiento del Problema

Las comunicaciones inalámbricas están generando una cantidad sustancial de tráfico de información, principalmente debido a la proliferación de dispositivos inalámbricos y de aplicaciones de gran consumo de ancho de banda. Éste tráfico usualmente acaba siendo absorbido por las red ópticas que sustentan las redes inalámbricas. Como será explicado en el próximo capítulo (Sección 2.2), las redes ópticas de acceso son principalmente redes pasivas. Aunque, las redes pasivas son inherentemente eficientes en términos de coste, no tienen una eficiencia de reparto de información debido a sus características de diseño, por lo que es necesario encontrar otra arquitectura con la cual sea posible satisfacer otras características extra en el reparto de información, como por ejemplo:

- Proveer seguridad en la transmisión.
- Estructura reconfigurable de información a un destinatario o varios.
- Alto rendimiento en la transmisión.
- Reducido tiempo de conmutación de señales en el conmutador.
- Escalabilidad del numero de conexiones salientes
- …

Una solución para proveer una respuesta técnica a estos requerimientos son las redes ópticas activas (Active Optical Networks - AON). La parte central de un sistema AON es un conmutador óptico, un elemento capaz de redireccionar señales ópticas. Los sistemas AON han sido históricamente utilizados para comunicaciones en banda base. Sin embargo, la mayoría del trafico generado en un entorno de acceso es basado en señales inalámbricas. Habilitando sistemas en los cuales estas señales operan directamente a través de redes ópticas, podemos proveer algunos beneficios, especialmente en términos de coste. Las tecnologías de radio a través de fibra han sido estudiadas en profundidad durante la ultima década, precisamente estudiando como generar, distribuir y recuperar señales inalámbricas directamente en el dominio óptico.

Por consiguiente, esta tesis, ha sido enfocada a estudiar experimentalmente una solución técnica particular para redireccionar señales radio a través de fibra. Los principales conceptos que se van a abordar en esta tesis son:

- Evaluar experimentalmente la adecuación para redes de acceso junto con señales de inalámbricas, del conmutador óptico propuesto en el proyecto OSMOSIS (descrito en el capitulo 3).

- Evaluar experimentalmente y cuantitativamente el impacto de la concatenación de amplificadores ópticos (SOAs) sobre la calidad de la señal, en términos del ratio de errores (BER), de una señal WiMax (Worldwide interoperability for microwave access) a través de una fibra óptica.
- Proveer directrices para futuros trabajos y continuación de las actividades en el área de conmutación óptica para señales inalámbricas a través de fibra óptica.

En conclusión, el principal objetivo de la tesis es evaluar la sostenibilidad de un conmutador óptico en una red óptica de acceso, lidiando con señales inalámbricas. Es importante remarcar que el estudio ha sido llevado a cabo experimentalmente y solo considerando la parte óptica. Aspectos de redes y consideraciones de la arquitectura del conmutador están fuera del propósito de esta tesis.

Summary of Original Work

The following original publications have been reached as result of the research within this Bachelor's Thesis:

PAPER 1: G.A. Rodes, J.J. Vegas Olmos, F. Karinou, I. Roudas, L. Deng, X. Pang, and I. Tafur Monroy, "Optical Switching for Dynamic Distribution of Wireless-over-Fiber Signals," Accepted for publication at the 16th International Conference on Optical Network Design and Modeling, Essex, UK, April 2012.

PAPER 2: J.J. Vegas Olmos, G.A. Rodes, F. Karinou, I. Roudas, L. Deng, X. Pang, and I. Tafur Monroy, "Optical Switching for Dynamic Distribution of Wireless-over-Fiber Signals," Submitted for OSA Journal of Optical Communication and Networking (JOCN).

Table of contents

Acronyms

10G-EPON	10 Gigabit Ethernet PON
AON	Active optical network
APON	Asynchronous PON
ArbWG	Arbitrary waveform generator
AWG	Arrayed waveguide grating
B2B	Back-to-back
BER	Bit error rate
BPON	Broadband PON
BS	Base estation
CAGR	Compound annual growth rate
CH	Channel
CO	Central Office
DSO	Digital sampling/storage oscilloscope
DSP	Digital signal processor
EB	Exabytes
ECC	Error-correction code
EPON	Ethernet
FEC	Forward error correction
FTT	Fast Fourier transform
FTTH	Fiber-to-the-home
FTTP	Fiber-to-the-premises
GPON	Gigabit PON
IF	Intermediate frequency
L0	Layer 0
MOD	Modulator
MZM	Mach-Zehnder modulator
NG-PON	Next generation-PON
OAN	Optical access network
ODN	Optical distribution network
OFDM	Orthogonal frequency-division multiplexing
OLT	Optical line terminal
ONT	Optical network termination
ONU	Optical network unit
OSMOSIS	Optical shared memory supercomputer interconnect system
PC	Polarization controller
PON	Passive optical network
QAM	Quadrature amplitude modulation

QPSK	Quadrature phase-shift keying
RAP	Radio access point
RAU	Remote antenna unit
RF	Radio frequency
RoF	Radio-over-fiber
RSOA	Reflective semiconductor amplifier
SMF	Single mode fiber
SOA	Semiconductor optical amplifier
TDM	Time division multiplexing
TDMA	Time division multiplexing amplifier
VSG	Vector signal generator
WDM	Wavelength division multiplexing
WiMax	Worldwide interoperability for microwave access
WLAN	Wireless local area network
XG-PON	10 Gigabit-PON
XPM	Cross-phase modulation

List of Figures

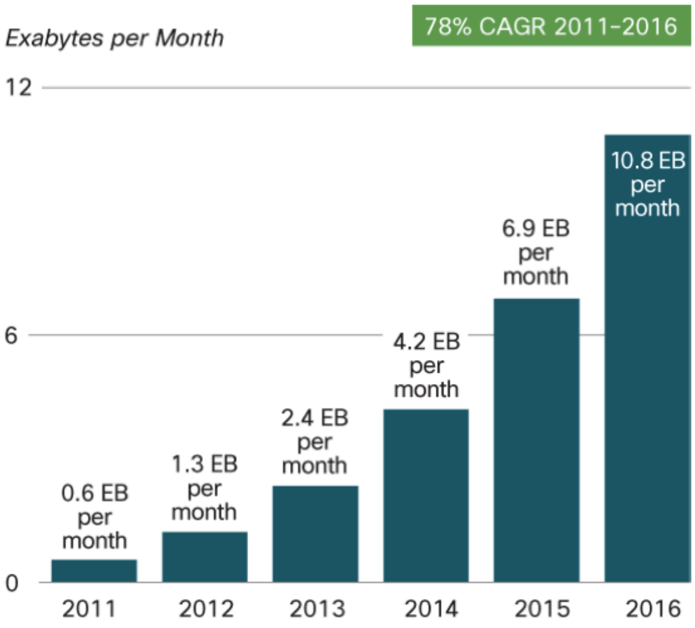
List of Tables

1

Introduction

The drastic increase of the number of mobile devices, capacity demands, new multimedia and data services in the last years, are driving the needs for high-performance and high-utilization of the wireless networks.

According to the state of the art of Cisco, the overall mobile data traffic is expected to grow to 10.8 Exabyte (EB) per month by 2016, an 18-fold increase over 2011. Mobile data traffic will grow at a compound annual growth rate (CAGR) of 78 percent from 2011 to 2016, as shows Figure 1.1 [1]. This information relates only to mobile traffic; needless to say, the overall bandwidth growth due to broadband fix access follows a similar trend.



Source: Cisco VNI Mobile, 2012

Figure 1.1. Evolution of the Mobile Data Traffic.

This amount of mobile data, first handled by wireless systems, is always supported by an optical infrastructure located in the physical layer. There is a heterogeneous mix of topologies and technologies employed to construct such optical infrastructure, depending on diverse and unrelated factors such as geography, legal framework, legacy network, operators´ choice of vendors, market demand, …

Due to cost reasons, the most widely adopted optical technology in the access segment is passive optical network (PON). This is a point-to-multipoint technology, which uses passive optical devices (splitters) to distribute the signal among the final ends of the network. Passive optical devices provide advantages as: easy installation, no maintenance, no power consumption, and low cost. However, as we will show in further sections, PON systems have some drawbacks related to security and network efficiency.

In contrast, active optical networks (AON), a point-to-point approach, are becoming increasingly used. In AONs, an optical switch is employed instead of a splitter to dynamically distribute the data flows through the network. Active devices such as optical switches provide advantages as: no bandwidth sharing, control and efficient use of bandwidth and eavesdropping prevention. A more detailed assessment of PON and AON technologies will be given in Chapter 2.

1.1 Problem Statement

Wireless networks are generating a substantial amount of data traffic mainly due to a continuous mushrooming of portable gadgets and killer applications. This traffic usually ends up being absorbed by optical networks operating underneath the wireless networks. As will be explained in the next chapter (Section 2.2), optical access networks are primarily passive networks. Although passive networks are inherently cost effective, they may not effectively deliver design features. It is necessary to find another architecture which achieve to satisfy the deliver design features, such as:

- Provide secure traffic (vs multicast distribution).
- Reconfigurable broadcast and unicast delivery on demand.
- High throughput data.
- Minimum switching time.
- Scalable number of output connections.
- ….

A solution to provide a technical answer to these requirements is AON. AON systems´ key block is the optical switch, an element capable of switching optical signals seamlessly. AON systems have been historically used for baseband communications. However, since most of the traffic generated in access environments is wireless-based, enabling systems in which wireless signals operate directly over the optical network may provide some benefits, especially in terms of cost. Radio-over-fiber technologies have been studied in depth for the last decade, precisely studying how to generate, distribute and recover wireless signals directly on the optical domain.

Accordingly, this thesis has been devoted to study experimentally a particular technical solution to switch wireless-over-fiber signals. The main concepts this thesis tackles are:

- Experimentally assess whether the optical switch proposed in the optical shared memory supercomputer interconnect system (OSMOSIS) project (described in Chapter 3) is suitable for access networks dealing with wireless signals.
- Experimentally assess and quantify the impact of concatenating semiconductor optical amplifiers (SOAs) over the quality in terms of bit error rate (BER) of a worldwide interoperability for microwave access (WiMax)-like wireless-over-fiber signal.
- Provide guidelines for future work and follow up activities within the area of optical switching for wireless-over-fiber signals.

In conclusion, the main objective of this thesis is to evaluate at a system level the suitability of the OSMOSIS optical switch in optical access network scenarios dealing with wireless signals. It is important to remark that the study have been carried out experimentally and only considering the optical layer. Network aspects and architectural considerations of the switch are also out of the scope of this thesis.

1.2 Methodology

In order to analyze at a system level the suitability of the OSMOSIS optical switch in optical access network scenarios dealing with wireless signals, an optical switch compost of three SOAs and three arrayed waveguide grating (AWG) has been proposed to solve the not effectively deliver design features: provide secure traffic, reconfigurable broadcast and unicast delivery on demand, high throughput data, minimum switching time, etc. Then, an experiment based on the optical switch proposed has been carried out for AON scenario dealing with wireless signals, to evaluate if it fulfills the features developed in the Problem statement (Section 1.1).

1.3 Contributions

The main contribution of the presented work within this thesis is the suitability at a system level of OSMOSIS optical access network scenarios dealing with wireless signals. The analysis is performed by an experiment consists of a four wavelength division multiplexed (WDM) channel system operating on a WiMax frequency band, and employing an OFDM modulation at 625 Mbit/s per channel, transmission of the data over 20 km of optical fiber, and active switching in a one-by-sixteen active optical switch.

Besides the present report, the work within this thesis has lead to two papers, one published and another submitted. The papers, apart from presenting the experimental setup for the *Optical Switching for Dynamic Distribution of Wireless-over-Fiber Signals in Active Optical Networks*, presents the analysis and the results obtained from the experiment.

1.4 Thesis Outline

The remainder of the report is organized as follows. In Chapter 2, a general overview of the main concepts of Optical Access Networks technologies, including Radio-over-fiber Technologies and architectures of an AON supporting radio-over-fiber (RoF), is reported.

Chapter 3 presents a summary of technologies and characteristics in optical switching, highlighting the main characteristics of the optical active switch based on SOAs.

Chapter 4 provides a detailed description of the experimental setup built and examined during the experimental phase of this project. A detailed characterization of the active components used in the experiment is also reported in this chapter.

In Chapter 5, the obtained experimental results for three scenarios are presented, including a detailed analysis of the bit error rate measurements.

Finally, in Chapter 6, the main conclusions of the thesis are summarized and the statement of future work is proposed.

2

Access Optical Networks

This chapter presents a global vision about access optical networks. It particularly focuses in the two major architecture types for access optical networks (i.e. passive and active optical networks), highlighting their characteristics and their differences. In addition, this chapter explains the RoF technologies and the reason of the use of fiber. Finally, it describes the advantages of an AON system used for wireless-over-fiber delivery employing RoF technologies.

2.1 Access Optical Networks

There are two major architecture types in the area of access optical networks: actively switched and passively split. AON contain an active element, a switch aggregator, between the central office or headend switch and the customer-premises equipment.

PONs do not contain any electronics between the central office/headend switch and the customer-premises equipment. The trade off is one additional active or powered element versus a passive unpowered splitter with an inherently lower failure rate but no ability to isolate faults, switch local traffic or provision narrow or uni-cast transmissions.

2.1.1 Passive Optical Networks

PONs are point-to-multipoint networks, which consisting of an optical line terminal (OLT) at the service provider's central office and a number of optical network units (ONUs) near end users. The signals are distributed by using unpowered optical splitters. Typically, the splitting ratio is 32 and the maximum distance between the central office (CO) and the end user is 20 km. These two parameters have been traditionally chosen because they ensure a sustainable loss in the optical fiber and an adequate level of light radiation at the end user site (safety).

The OLT is located at the central office (CO), where it interfaces with the metropolitan network. Its main functionality is to adapt the incoming traffic from the metropolitan rings into the PON transport layer. ONU is the interface between the customer equipment and the PON and it is located outside the customer premise, as illustrated in Figure 2.1.

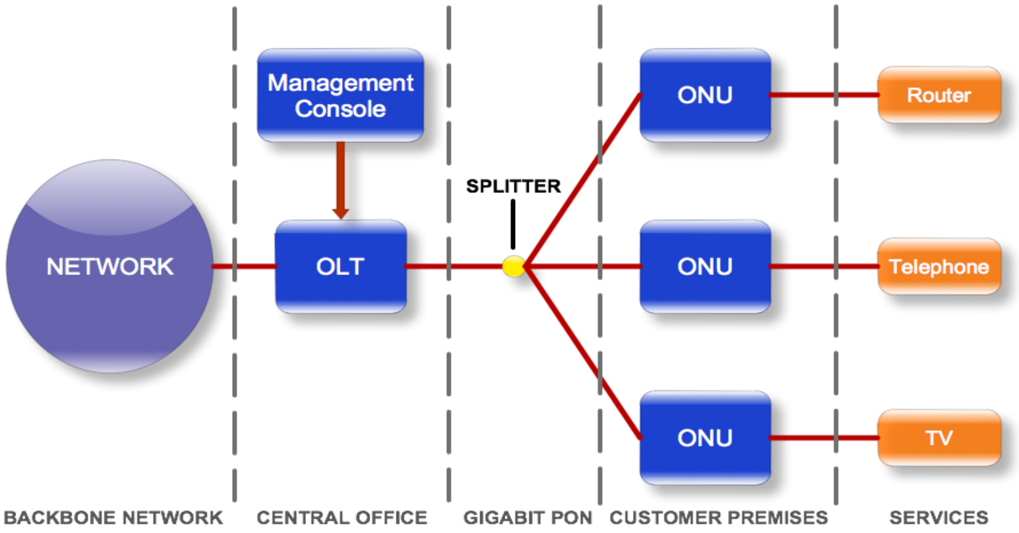


Figure 2.1. Architecture Passive Access Network.

The main advantage of this approach is its low cost, because of the extensive usage of passive devices, which work unpowered, avoiding incurring in any power consumption.

However, it has some drawbacks because the downstream signal is distributed to all the end users, which means that all receive copies of the downstream regardless whether they are the recipients of the data or not. This fact can become a potential problem because of the possibility of eavesdropping. Furthermore, the traffic within the network is not handled efficiently, since, the ONUs are constantly reading unnecessary data in order to select their own information.

Next, the upstream and downstream traffic systems and the differences between transmitting data downstream and transmitting data upstream will be explained.

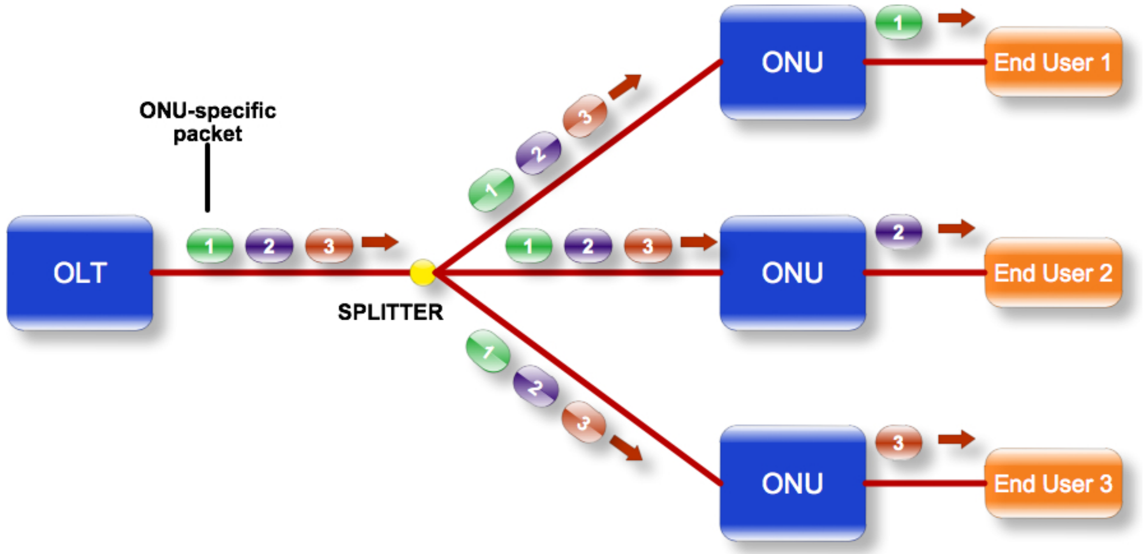


Figure 2.2. Downstream Traffic Flow in a PON.

Figure 2.2 shows the downstream traffic in a PON. As explained above, the downstream signal is passively distributed to all branches of the PON, which means that all ONUs receive copies of the downstream. When the information arrives to the ONU, each ONU only read the content of the data that is addressed to it. Finally the end user receives only the information required in each moment.

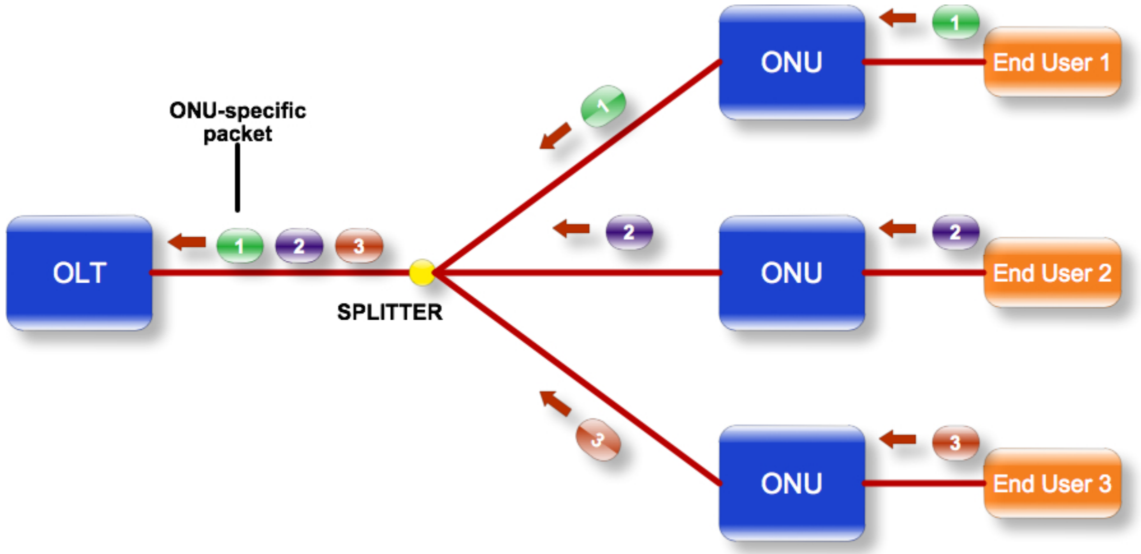


Figure 2.3. Upstream Traffic Flow in an PON.

Figure 2.3 shows the upstream traffic in a PON. In this case, the information from each end user is combined in the splitter and goes together to the OLT. Unlike in the downstream, the ONUs in the upstream do not receive the all the information, just the ones from its end user.

2.1.2 Active Optical Networks

AON rely on some sort of electrically powered equipment at the optical distribution network (ODN) to distribute the signal, such as a switch or router. ODN consists of the fibers and switches between the OLT and the ONU.

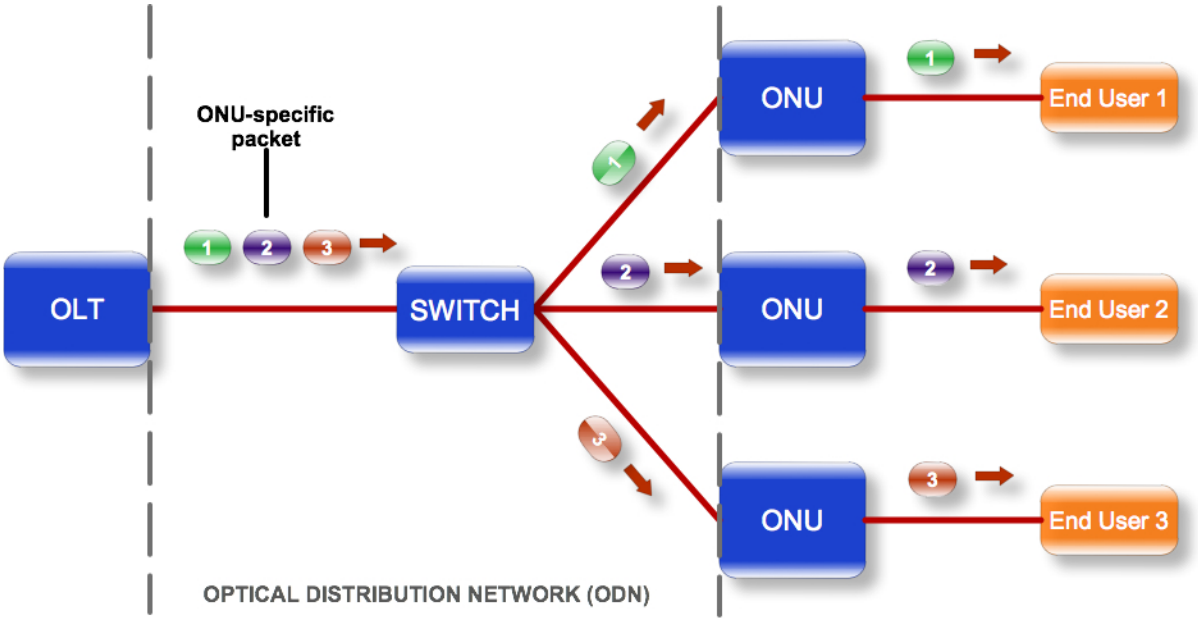


Figure 2.4. Downstream Traffic Flow in an AON.

Figure 2.4 shows the downstream traffic in an AON. Each packet of the downstream signal is routed by the switch to its specific end user. After that, in each branch there is only the information for its recipient. Unlike the downstream in a PON, the ONUs do not receive the information for the rest of the ONUs. The upstream traffic flow in an AON is similar to the upstream in a PON, the information from each end user is combined in the switch and goes together to the OLT. In contrast to the upstream in a PON, in this case an optical switch is used instead of a splitter.

In the downstream, each leaving signal from the central office is directed only to the customer for which it is intended. In the upstream, incoming signals from the customers avoid colliding at the intersection (switch) because the powered equipment provides buffering.

The advantages of AON architecture when compared to PON are:

- The bandwidth in each port of the aggregation switch is dedicated to an individual ONU, and therefore there is no sharing of bandwidth.
  - Reduction of the potential problem of eavesdropping because there is no data multicasting among the ONUs.
- The bandwidth can be limited/ controlled per port.
  - Efficient use of the bandwidth. Each user can have a bandwidth plan tailored to its requirements. Flexibility in implementing dynamic bandwidth allocation algorithms.

Active optical networks, however, also have drawbacks:

- They require switches:
  - Higher cost compared to passive splitters.
  - Scalability is limited.
- Electrically powered:
  - Energy consumption versus not consumption of PON.
  - Maintenance.

The next table (Table 2.1) shows a summary of the advantages and disadvantages of an AON.

AON	
ADVANTAGES	DISADVANTAGES
No sharing bandwidth	High cost
Controlled bandwidth	Scalability is limited
Efficient use of the bandwidth	Energy consumption
No eavesdropping	Maintenance

Table 2.1. Advantages and disadvantages of an AON.

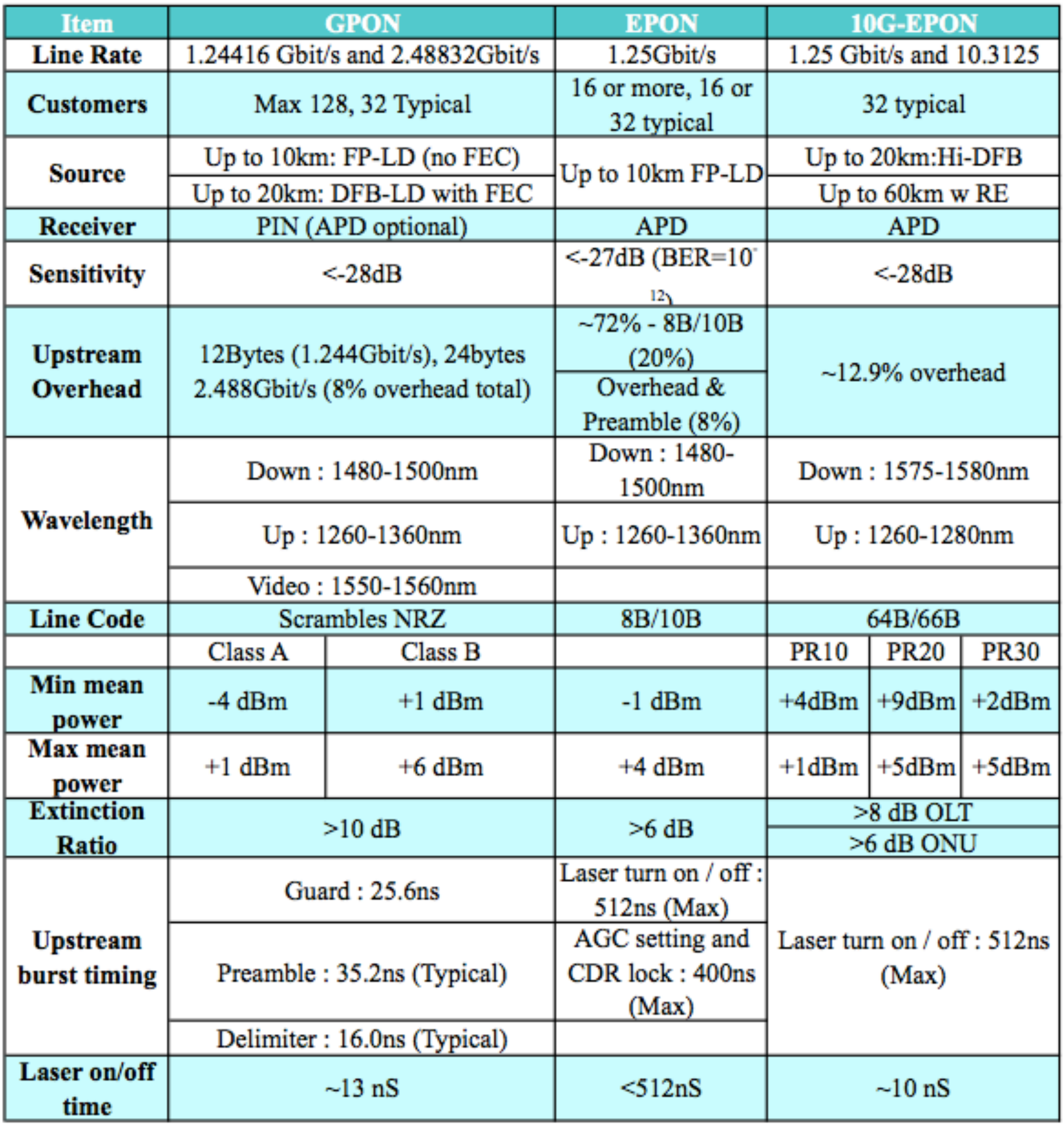
2.2 State-of-the-art: Optical Access Networks Technologies

Because of technological developments in the area of photonic technologies, transport networks have experienced an extraordinary increase in transmission capacity during the last years. In the meantime, at the end user, improvement of electronic devices has made possible expanding multimedia applications such as high definition TV (HDTV), video-on-demand, interactive games, and videoconferencing. Such applications with a high demand of bandwidth have become part of our daily lifes, and the bandwidth has become a commodity. As a result, it is expected that users will require more and more bandwidth per user in the near future.

On one hand, to satisfy this bandwidth demand, a number of PONs have been standardized over the years: asynchronous transfer mode PON (APON), broadband PON (BPON), Gigabit PON (GPON), Ethernet PON (EPON) and 10 Gigabit Ethernet PON (10G-EPON) to provide broadband access services. All these networks employ time division multiplexing (TDM) technologies and have been widely adopted as current-generation optical access solutions [2].

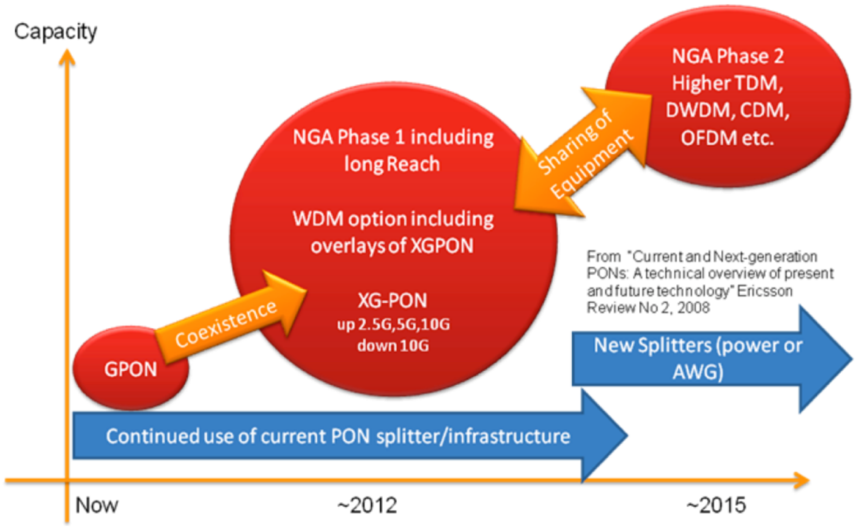
The current state of the art in PON technology is represented by the GPON recommendation and the EPON standards, both widely deployed worlwide. The 10G-EPON standard, approved in late 2009, is also entering the market. However, the penetration is slow in comparison to GPON and EPON due mainly to cost issues. A summary of the key attributes of the GPON/EPON/10G-EPON standards is provided in Table 2.1. The standards also contemplate wavelength bands allocated to additional services. This includes ‘enhancement bands’ from 1539 nm to 1550 nm and from 1560 nm to 1565 nm and radio frequency (RF)/Video Distribution band from 1550 nm to 1560 nm.

The data rate provided by these systems will depend on the type of PON (GPON/EPON/10G-EPON) and the number of customers (split ratio) provided but typical, uncontended data-rates are in the region of 60 Mbit/s maximum.



Item	GPON		EPON	10G-EPON		
Line Rate	1.24416 Gbit/s and 2.48832Gbit/s		1.25Gbit/s	1.25 Gbit/s and 10.3125		
Customers	Max 128, 32 Typical		16 or more, 16 or 32 typical	32 typical		
Source	Up to 10km: FP-LD (no FEC)		Up to 10km FP-LD	Up to 20km:Hi-DFB		
	Up to 20km: DFB-LD with FEC			Up to 60km w RE		
Receiver	PIN (APD optional)		APD	APD		
Sensitivity	<-28dB		<-27dB (BER=10^{-12})	<-28dB		
Upstream Overhead	12Bytes (1.244Gbit/s), 24bytes 2.488Gbit/s (8% overhead total)		~72% - 8B/10B (20%)	~12.9% overhead		
			Overhead & Preamble (8%)			
Wavelength	Down : 1480-1500nm		Down : 1480-1500nm	Down : 1575-1580nm		
	Up : 1260-1360nm		Up : 1260-1360nm	Up : 1260-1280nm		
	Video : 1550-1560nm					
Line Code	Scrambles NRZ		8B/10B	64B/66B		
	Class A	Class B		PR10	PR20	PR30
Min mean power	-4 dBm	+1 dBm	-1 dBm	+4dBm	+9dBm	+2dBm
Max mean power	+1 dBm	+6 dBm	+4 dBm	+1dBm	+5dBm	+5dBm
Extinction Ratio	>10 dB		>6 dB	>8 dB OLT		
				>6 dB ONU		
Upstream burst timing	Guard : 25.6ns		Laser turn on / off : 512ns (Max)	Laser turn on / off : 512ns (Max)		
	Preamble : 35.2ns (Typical)		AGC setting and CDR lock : 400ns (Max)			
	Delimiter : 16.0ns (Typical)					
Laser on/off time	~13 nS		<512nS	~10 nS		

Table 2.2. Comparison of GPON, EPON and 10G-EPON specifications.



From "Current and Next-generation PONs: A technical overview of present and future technology" Ericsson Review No 2, 2008

Figure 2.5. Access Network Evolution Path [3].

The next evolution of PON that has been standardized and is seeing its first trials and early deployments is a group of technologies that is often named as next generation-PON1 (NG-PON1). This includes the 10 gigabit-PON (XG-PON) (ITU) and 802.3av (IEEE). The roadmap for future systems is shown in Figure 2.5. These systems provide increased data-rates with either asymmetric or symmetric options. XG-PON supporting 2.5 Gb/s upstream and 10 Gb/s downstream line rates is referred to as XG-PON1. XG-PON supporting 10 Gb/s symmetric line rates is referred to as XG-PON2. The architecture of these systems is identical to the lower rate PONs, however, new wavelength bands have been proposed to enable coexistence with GPON equipment [3]. There still exist options for additional services in unused wavelength bands although the exact wavelength bands used is still not certain.

Beyond these systems, which are currently in the final states of development, systems are coming up which are named NG-PON2. These introduce new technologies in the access network space and typically attempt to leverage WDM technologies to offer higher rate and more flexible services to customers. To date there have been many research projects that have considered WDM access networks including SUCCESS [4], FP-6-PIEMAN [5], FP-7-SARDANA [6], etc. as well as a commercial system from Novera [7]. The challenge in all of these systems is to allocate an individual wavelength to each customer (or set of customers in hybrid TDM/WDM PON schemes). Technologies that have been proposed for this include OFDMA (FP-7-ACCORDANCE [8]), tuneable laser source (PIEMAN [5]), spectrum sliced sources, reflective sources such as reflective SOAs (DAWN), Seeded Fabry Perot laser (NOVERA [7]), and most recently ultra-dense WDM using coherent techniques such as those proposed by NSN and also investigated in the EU Project OASE [9]. Figure 2.6 shows un example of a WDM PON architecture.

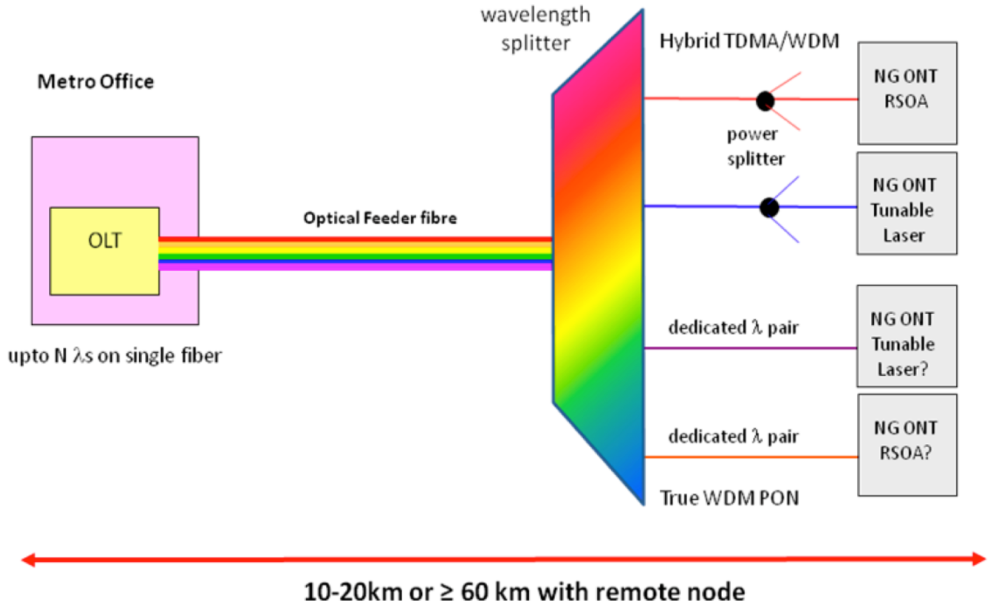


Figure 2.6. Example of a WDM PON architecture. Time division multiplexing access (TDMA). Next generation (NG). Optical network terminal (ONT). Reflective semiconductor amplifier (RSOA).

On the other hand, AON are starting to be taken into account as an alternative solution. The main idea is to provide reconfigurability to the network, enabling point-to-point connections at the physical layer using active components. The main advantage of this approach is efficient use of bandwidth and the security provided in the data transmission to prevent eavesdropping. The downside is the requirement of electrical power from the active equipment, the higher cost of installing and maintaining powered equipment cabinets.

In short, in access networks, the question is not copper versus fiber but whether you build a passive power splitting or an actively switched Ethernet optical network [10].

2.3 Radio-over-fiber Technologies

RoF refers to a technology whereby light is modulated by a radio signal and transmitted over an optical fiber link to distribute RF signals from a central location (headend) to Remote Antenna Units (RAUs). Although radio transmission over fiber is used for multiple purposes, such as in cable television, networks and in satellite base stations, the term RoF is usually applied when this is done for wireless access as in this thesis. Figure 2.7 shows the architecture of a RoF for wireless access.

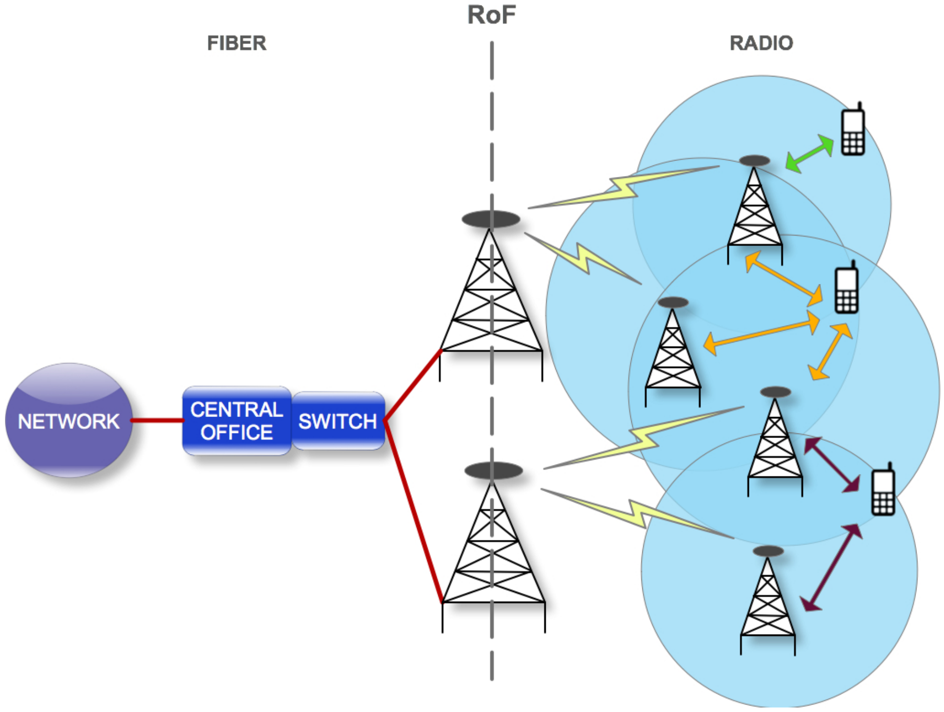


Figure 2.7. Radio over fiber architecture for wireless acsess.

In narrowband communication systems and Wireless Local Area Networks (WLANs), RF signal processing functions, such as, frequency up-conversion, carrier modulation, and multiplexing, are performed at the Base Station (BS) or at the Radio Access Point (RAP), and immediately fed into the antenna. RoF allows to centralize the RF signal processing functions in one shared location (headend), and then to use optical fiber, which offers low signal loss (0.3 dB/km for 1550 nm, and 0.5 dB/km for 1310 nm wavelengths) to distribute the RF signals to the RAUs.

By so doing, RAUs are simplified significantly, as they only need to perform optoelectronic conversion and amplification functions. The centralization of RF signal processing functions enables equipment sharing, dynamic allocation of resources, and simplified system operation and maintenance [11]

There are several possible approaches for transporting radio signals over optical fiber in RoF systems. They are usually classified into two categories: RF-over Fiber and Intermediate Frequency (IF)-over-Fiber depending on the frequency range of the radio signal to be transported.

In **RF-over-Fiber** architectures, a data-carrying RF (Radio Frequency) signal with a high frequency (usually greater than 10 GHz) is imposed on a lightwave signal before being transported over the optical link. Therefore, wireless signals are optically distributed to base stations directly at high frequencies and converted from the optical to electrical domain at the base stations before being amplified and radiated by an antenna. As a result, no frequency up/down conversion is required at the various BSs, thereby resulting in simple and rather cost-effective implementation.

In **IF-over-Fiber** architecture, an IF radio signal with a lower frequency (less than 10 GHz) is used for modulating light before being transported over the optical link. Therefore, before radiation through the air, the signal must be up-converted to RF at the base station.

The well known advantages of optical fiber as a transmission medium such as low loss, light weight, large bandwidth characteristics, small size and low cable cost make it the ideal and most flexible solution for efficiently transporting radio signals to remotely located antenna sites in a wireless network. In addition to its transmission properties, the insensitivity of fiber optic cables to electromagnetic radiation is a key benefit in their implementation as the backbone of a wireless network [13].

2.4 Architecture of an Active Optical Network supporting Radio-over-Fiber

PON systems have become very popular because they offer low-cost-per-bit on an optical fiber in terms of equipment and very low operational expenditures once they are deployed. PON efficiency is however low in terms of bandwidth utilization. Furthermore, the intrinsic nature of the distribution approach (point-to-multipoint multicast) may raise concerns in terms of security, especially in industrial or business environments. AON approaches are emerging in this area to cope with such problems: data can be effectively managed at a traffic engineering level (i.e., path control, bandwidth reservation, prioritization, etc.), while ensuring secure unicast distribution and simple and flexible designs. When considering AON networks, in the context of wireless systems, the advantages are clear: we can better handle data distribution while preserving the mobile nature of the end users. Figure 2.8 shows a distribution system of wireless signals employing a consolidated central office (CO). A consolidated CO serves several clusters of access networks (either AON or PON networks) centralizing the management of the system and employing a single physical platform.

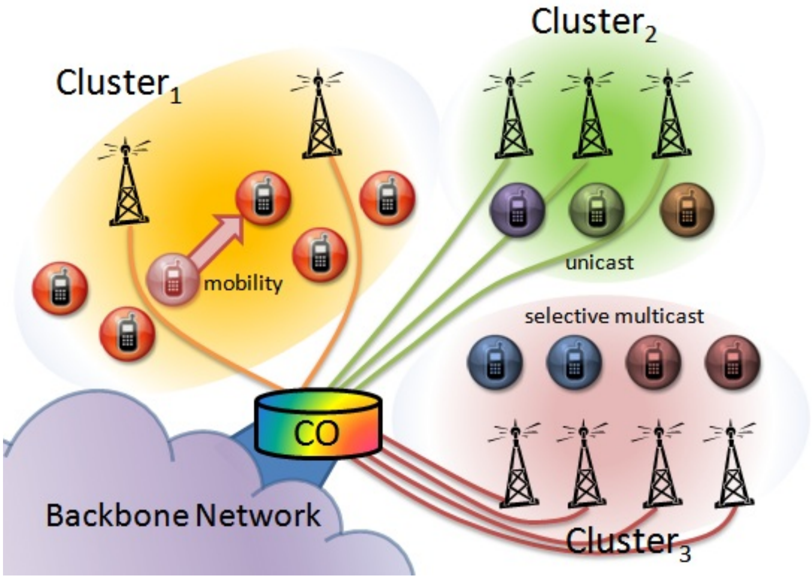


Figure 2.8. General architecture of an active optical network for mobile applications, including unicast and selective multicast capabilities.

Furthermore, concerns on security [12] and high mobility [14] seem to indicate active solutions such AON may be in favor of system designers, provided that cost and energy consumption are maintained within reasonable limits. AON networks, in combination with RoF technologies, are hence an interesting way of enabling a higher degree of reconfigurability in scenarios in which the end user is mobile per se, and requires low-latency, high-throughput and Layer 0 (L0) security features.

3

Optical Switching

The first section of this chapter presents the evolution of the switching technologies and the characteristics of each type of switch. The second section explains the optical active switch based in SOAs, which is the type used during the experiment of this thesis.

3.1 Switching technologies

All-optical switching fabrics play a central role in allowing switching in the optical domain, avoiding the need for O/E/O conversions [15]. There are a plethora of technologies used to construct complex optical switches (i.e. more than two output ports). Optomechanical switches were heavily studied during the 80-90s because their fabrication process was well mastered and the technology requirements were in line with the features such switches offered (i.e. 1.544Mbit/s) [16]. These switches offer low insertion losses and low crosstalk, along with low fabrication costs. However, as optics evolved enabling higher bitrates, optomechanical switches started showing deficiencies in terms of scalability and slow switching time. Microelectromechanical system (MEMS) devices filled the gap by offering fast switching, with low insertion losses and low driving power [17]. MEMS are in fact optomechanical switches that employ tiny reflective surfaces to redirect the light beams. Scalability to large port counts is however difficult because the complexity of the feedback system needed to control every single micro-mirror. It also presents difficulties the ensuring repeatability of material properties and the uniformity of processing techniques during fabrication [18].

Advances in materials led to the proliferation of electrooptic switches, in which the refractive index of a substrate is changed and hence light propagation can be controlled. Lithium niobate ($LiNbO_3$) is probably the most used material, especially in optical modulators in which high response is the most important factor [19]. High cost and high insertion losses are the main drawback of electrooptic switches, although recent research is overcoming these limitations and showing scalable switches operating in the nanosecond and subnanosecond regime at high bitrates by using new configurations (i.e. active vertical coupling [20], microring resonators [21], etc.). New developments in materials also allowed for thermooptic switches, in which changes in the refractive index of a dielectric material is due to temperature variations of the material itself. Because the system employs heat as controlling parameter, the power consumption of these devices is usually high, since electro-heat conversion and a dissipation system are needed. Current research in this area works mainly towards reducing the power consumption [22]. It is worth noting that both electrooptic switches and thermooptic switches usually rely on interferometric configurations such as Mach-Zehnder interferometers (MZI), microring resonators, photonic crystal structures, and so on to improve the performance and to fully exploit the physical properties of the operating principles.

All these fabrics are passive in nature, meaning that no gain occurs. Hence, there are inherent limitations in terms of scalability due to the decay of power when several individual switches are cascaded. Semiconductor optical amplifiers (SOAs) are promising alternatives as switch fabrics precisely because they can provide gain along with fast switching time [23].

3.2 Optical active switch based on semiconductor optical amplifiers

The optical switch fabric employed to demonstrate active switching of RoF signals is based on a three-stage architecture, initially proposed for the optical shared memory supercomputer interconnect system (OSMOSIS) project [24][25]. The OSMOSIS interconnect is a broadcast-and-select optical switch fabric using SOAs, acting as on-off gates, and AWGs as filters. Such architecture was initially intended for supercomputer interconnects, in which high-speed, low-latency and high-throughput are key. This optical switch can serve several clusters, each cluster being composed of several and identical wavelength channels; the clusters are orderly placed on the optical domain and processed independently. Figure 3.1 shows the wavelength allocation, consisting of *N* clusters, of *M* base stations (BSs) each.

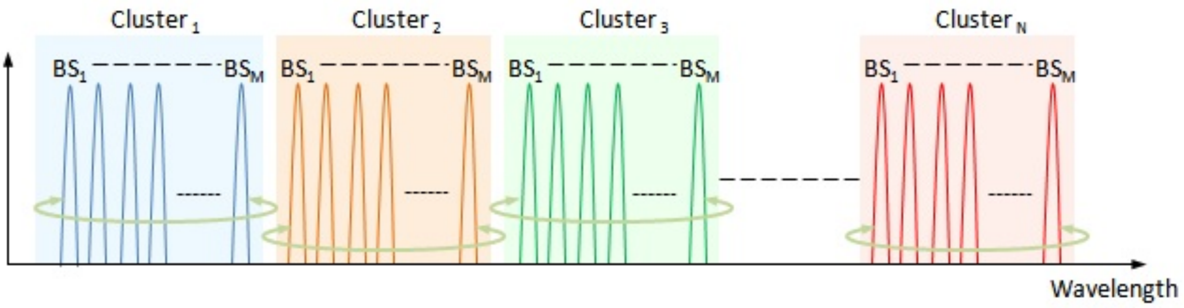


Figure 3.1. Wavelength allocation. Clusters 1-*N* comprise base station channels 1-*M*. BS: base station

Figure 3.2 shows the internal architecture of a generic switch fabric. The input of the optical switch conveys the spectra shown in Figure 3.1. SOA_1 amplifies all the clusters while AWG_1 separates the clusters. The second set of SOAs, namely SOA_2, act as on-off gates for each cluster, which is further disassembled by the second set of AWGs, in this case AWG_2. At this stage each channel has been already separated, and a final round of SOAs, SOA_3, decides whether the channel must be fed into the BS through one last AWG. Hence, the switch allows to unicast the channel to a single BS, or selective multicast the channel to the desired BSs by making use of the last round of SOAs. In the event of activating all the amplifiers corresponding to the SOA_3 round, the system emulates in fact a conventional point-to-multipoint PON system.

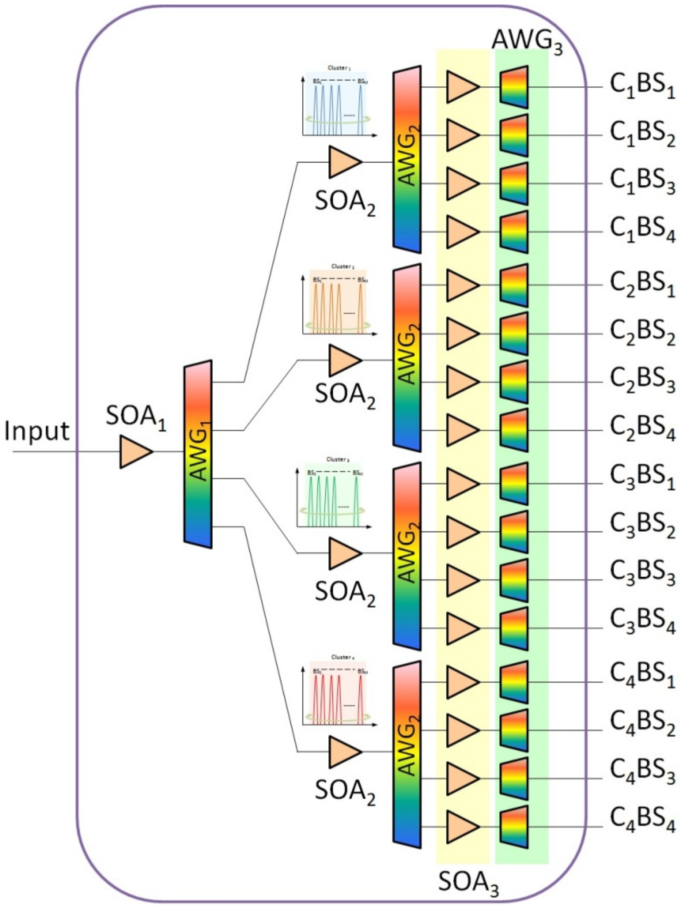


Figure 3.2. Internal schematic of a generic switch. SOA: semiconductor optical amplifier, AWG: arrayed-waveguide, C: cluster, BS: base station.

Although the experimental demonstration conducted in the next chapter was done with discrete components, the proposed architecture can be photonically integrated, using for example active-passive InGaAsP-InP epitaxy as in [26]. Current technologies allow combined integration of passive and active components, drastically reducing the footprint and decreasing the power consumption of the active devices while preserving their features.

Specifically, SOAs can be designed to operate at the desired wavelength ranges and gain levels. Furthermore, whereas employing SOAs for baseband signals has limitations in terms of bitrate due to the natural recovery time of the gain of the SOA (typically ~100ps) [27], RoF signals employing OFDM modulation are less likely to experience degradation due to this effect on the SOA because OFDM signals utilize a plurality of carriers to convey the data, effectively reducing the bitrate. SOAs are also fairly transparent to phase information, enabling their usage together with advanced modulation formats.

4

Experimental setup

This section presents an experimental proof of concept demonstration of an active optical network for RoF systems. First, a description of the setup is given. Second, a characterization of the active components is done, in particular the characterization of the modulator and the three SOAs. Moreover, the additional contributions to the power consumption are presented. Finally, section 4.3 gives an explanation about the non-linear effects due to power saturation at the SOA.

4.1 Experimental setup

In order to demonstrate an active optical network for RoF signals, a proof of concept experiment was designed. The block diagram of such experiment is shown in Figure 4.1.

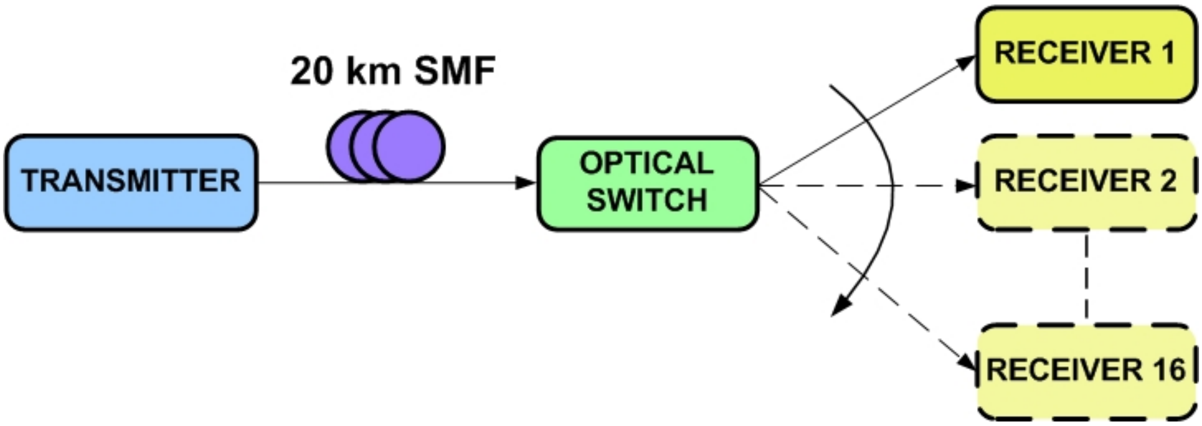


Figure 4.1. Block diagram of the setup.

Figure 4.1 describes in a simplified way by a block diagram the different parts of the experiment. The transmitter generates the optical signal and modulate it with the WiMax electrical signal in the modulator. This signal is a communication technology for wirelessly delivering high-speed Internet service to large geographical areas. WiMax was set with an OFDM 4QAM modulation, 5 GHz of RF carriers, 128 subcarriers, resulting in bandwidth of 312.5 MHz and data rate of 625 Mbps. The signal is transported through 20 km of fiber.

Then, the switch carries out the amplification and distribution of the signal to the different receivers. These receivers convert the signal from optical to electrical by a photodiode, for digital demodulation afterwards.

Figure 4.2 depicts the setup employed during the experiments. As it can be observed, four equally spaced channels were generated.

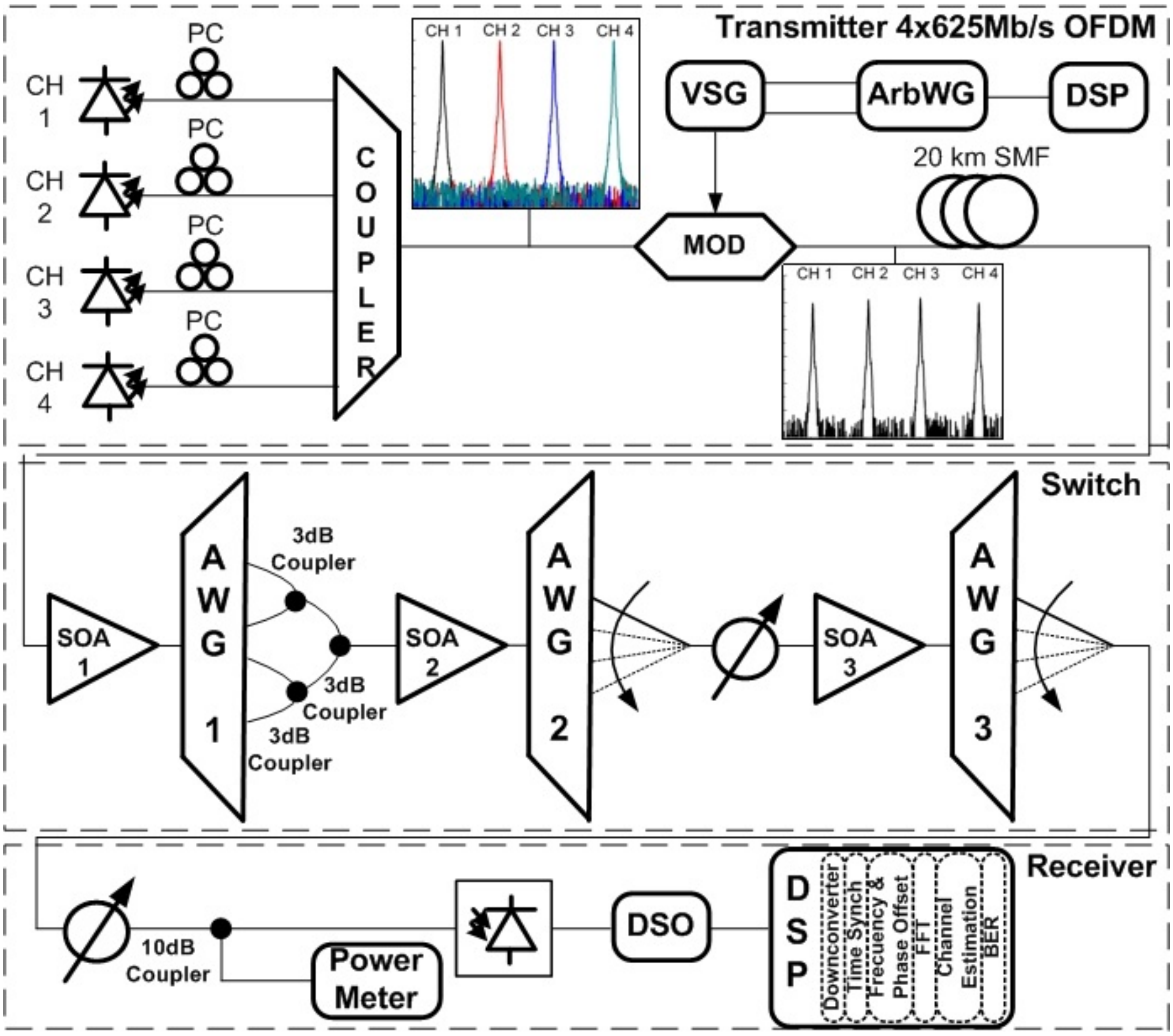


Figure 4.2. Experimental setup and two optical spectra of the signal. Channel (CH). Polarization controller (PC). Vector Signal Generator (VSG). Arbitrary Waveform Generator (ArbWG). Digital Signal Processor (DSP). Modulator (MOD). Single Mode Fiber (SMF). Digital Sampling Oscilloscope (DSO). Fast Fourier Transform (FFT).

To emulate four channels we operated four lasers with different wavelengths: λ1=1547.65 nm, λ2=1548.48 nm, λ3=1549.27 nm, and λ4=1550.12 nm for the respective channels: CH1, CH2, CH3 and CH4. The continuous waves were modulated using a MZM, set at 4.3 V bias voltage, by the electrical signal from a VSG. The VSG was driven by an ArbWG, set with a sample rate of 1.25 GSa/s. It generated an OFDM 4QAM and it was fully computer controlled. The VSG was set to operate at 5 GHz with a bit rate of 625 Mbit/s and an output signal of +19 dBm. The modulator used was a Mach-Zehnder modulator (MZM) with a bandwidth of 10 GHz and Vpi of 8 V.

The generated optical signals were launched through 20 km standard SMF, with a core size of 8 μm and cladding diameter of 125 μm. In order to utilize the best conditions of the SOAs, they were set at 1.8 V bias voltage, which caused 30 mA of current consumption. In the first AWG (AWG 1) were used four outputs with channel spacing of 100 GHz. These outputs were combined by three couplers. However, only one output of AWG 2 and AWG 3 was used. The arrows drawn in the outputs of the AWG 2 and AWG 3 represent the possibility to have up to 16 different ways, because of lacking of devices in the laboratory, this experiment was done for only 4 outputs.

In the receiver part, the optical signal was attenuated to regulate the input power to the photodiode. Furthermore, a 10 dB coupler was introduced to monitor the power of the signal in the input of the photodiode. Then, the signal was detected by a P-I-N photodiode. After the photodiode, the electrical signal was sent to the DSO to storage the samples. Finally, the samples of the signal were demodulated by DSP routines.

4.2 Characterization of the active components

In this subsection the characterization of the active components, optical modulator and SOAs, used in the experiment are given. The characterization was required to know the optimum operating point of these active components.

4.2.1 Optical modulator

In this experiment, a MZM was used to modulate the RF signal with the beam of light from the lasers. It converts the electrical signal and its information from electrical to optical.

Internally a MZM operates as follows: a beam splitter divides the laser light into two paths, one of which has a phase modulator. Then the beams are recombined. Changing the electric field on the phase modulating path, the two beams will interfere constructively or destructively at the output, and thereby control the amplitude or intensity of the exiting light.

One of the modulator parameter is the bias voltage; it determines the voltage applied to the semiconductor material inside the modulator. This voltage controls the differences of phase between “0” and “1” of the modulator. The characterization of this parameter is shown in Figure 4.3.

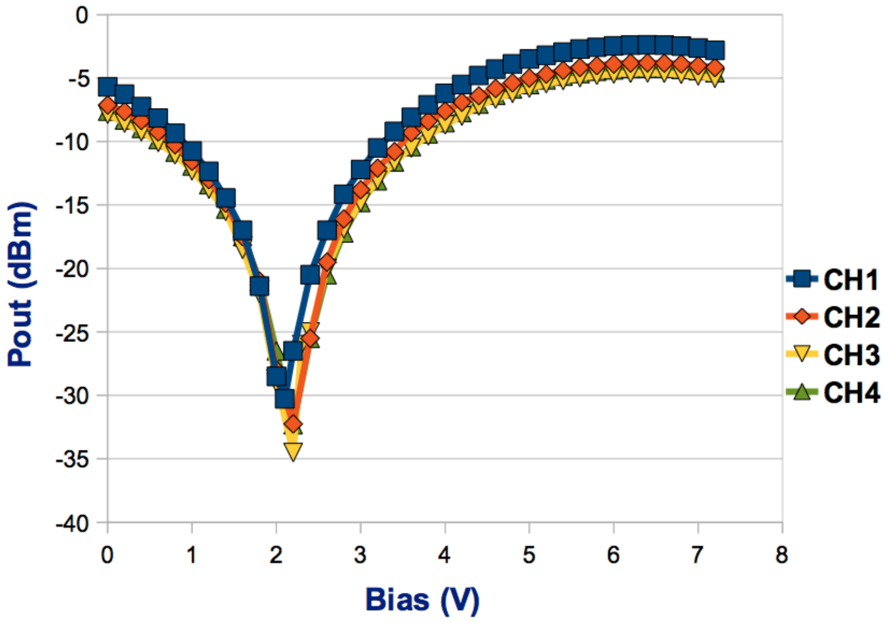


Figure 4.3. Characterization of the modulator for the different channels.

Figure 4.3 shows the output power as a function of the bias voltage applied to the optical modulator for each wavelength. The range of the bias voltage was from 0 to 7.2 V, which is a typical range for modulators. The optical input power was set to be 3 dBm, which provided an optical output power ranging from -2.81 to -34.5 dBm. In order to maximize the modulation depth over the optical carrier, the bias voltage needs to be chosen in the middle of the slop. Furthermore, it needs to be chosen to operate on the positive slop of the transfer function, hence assuring a positive increase on the electrical signal will be converted into a positive increase of the optical signal at the output port, and vice versa. The operating bias was then selected to be 4.3 V, which ensures a large swing between the “0”s and the “1”s values.

4.2.2 Semiconductor optical amplifiers

SOAs are amplifiers which use a semiconductor to provide the gain medium. These SOAs need an external electrical source which is called bias voltage. As in section 4.1.1 with the modulator, the characterization of the SOAs, used in the experiment, is done in order to find the individual operation points.

Despite the fact that the SOAs used in the setup have the same characteristics, usually there are some variations in its properties due to manufacturing process. For this reason it is required to analyze the three SOAs. Figure 4.4 shows the results of characterizations of the output power as a function of the bias voltage applied to SOAs.

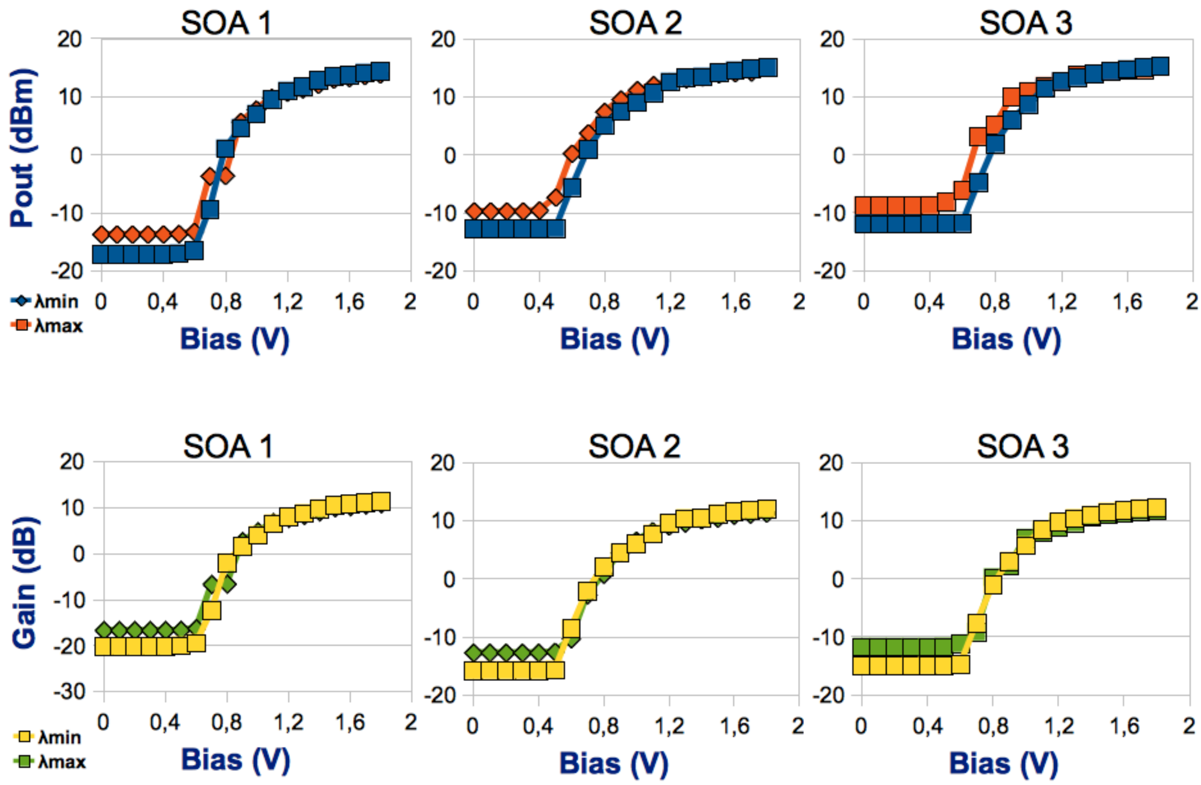


Figure 4.4. Upper row: characterization of the SOAs. Lower row: gain of the SOAs.

The upper row in Figure 4.4 shows the output power as a function of the bias voltage applied to SOAs. Two different wavelengths were used in the input of the SOAs for the characterization: λmin=1546.8 nm and λmax=1555.7 nm. Both, λmin and λmax are the minimum and maximum value respectively, in which the AWG works properly. The wavelengths chosen for each channel of the experiment were between λmin and λmax values. The range of bias voltage was chosen to be from 0 to 1.8 V, because in this range the three states of the SOA (attenuation, linear and saturation) are defined. The optical input power of the λmin and λmax was set to be 3 dBm, which provided an optical output power ranging from -17.2 to 15.21 dBm.

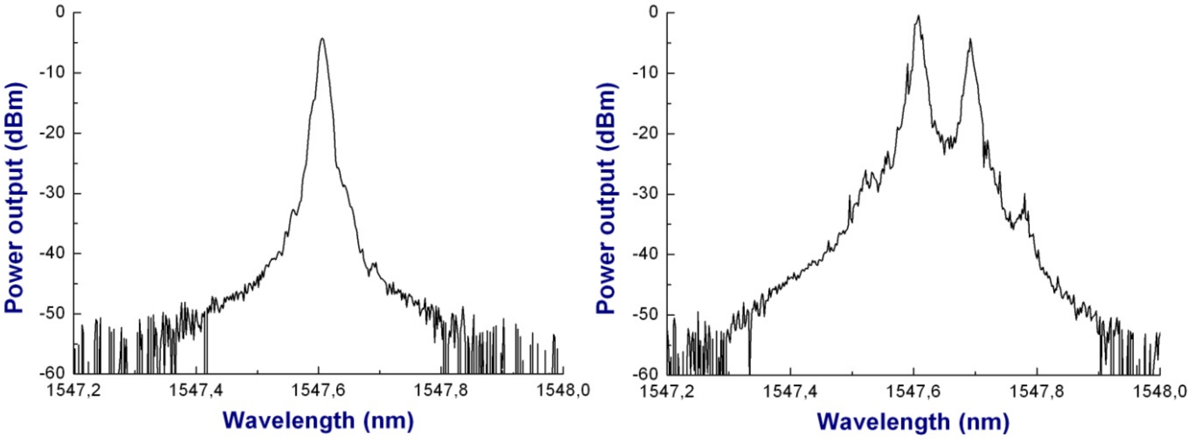
The lower row in Figure 4.4 shows the gain of the SOAs as a function of the bias voltage applied to the SOAs. λmin and λmax were again the wavelength used in the input of the SOAs. The range of bias voltage was the same, from 0 to 1.8 V, which provided a gain ranging from -20.2 to 12.21 dB. It's observed that these graphs have the same form. This is because the gain is obtained by subtracting the input power (3 dBm) to the output power.

In order to maximize the amplification over the optical carrier, a bias voltage needs to be chosen in the saturation part of the slop, hence assuring a high gain and a stable amplification at the output port. Moreover, it is recommended to choose the bias voltage at the beginning of the saturation part, where the amplification gain is almost constant, furthermore, with a lower bias voltage the consumption is lower and the devices are protected. In the experiment, the operating bias voltage of the all SOAs was selected to be 1.8 V, which ensured a good amplification.

4.3 Non-linear effects due to power saturation at the SOA

At relatively low light intensities that normally occur in nature, the optical properties of materials are independent of the intensity of illumination. When light waves pass through a medium, there is no interaction between the waves. However, if the optical power is high enough, the optical properties of the medium begin to depend on the intensity and other characteristics of the light [28]. For example, the refractive index "n" of the medium is changed by an amount $\Delta n = n_2 * I$, where "I" is the optical intensity and "n_2" is the nonlinear refraction coefficient.

The semiconductor optical amplifier (SOA) is highly nonlinear in its optical properties. It tends to introduce unwanted effects (such as frequency chirping and interchannel crosstalk) in optical communications systems. For this reason, the non-linear effects due to power saturation at the SOA are examined in Figure 4.5.



(a) (b)

Figure 4.5. Left side: wavelength spectrum with -11.45 dBm input power. Right side: wavelength spectrum with -1.49 dBm input power.

Figure 4.5 shows the output spectra of SOA 3 for two different power inputs. The range of wavelength was chosen to be from 1547.2 to 1548 nm, because in this range is defined the signal. The optical input power of the left graph was set to be -11.45 dBm, which provided an optical output power ranging from -60 to -4.19 dBm. The peak of -4.19 dBm is located at 1547.606 nm. The optical input power of the right graph was set to be 10 dBm higher (-1.49 dBm), which provided an optical output power ranging from -60 to -0.425

dBm. In this case, the peak happened at 1547.606 nm followed by another of -4.194 dBm at 1547.692 nm.

Figure 4.5 gives a good representation of what happens when the input power increase and the non-linear effects appear. In Figure 4.5 (a), a single peak shows up. In contrast in Figure 4.5 (b), a high and two small new peaks appear. These new peaks are produced by the high input power into the SOA. When it happens the SOA starts to generate some non-linear effects. In this experiment, the most relevant was the cross-phase modulation (XPM) which is the responsible for the appearance of the peaks.

The intensity dependence of the refractive index can lead to a nonlinear phenomenon known as XPM. It occurs when two or more channels are transmitted at the same time inside an optical fiber using WDM technique. The nonlinear phase shift for a specific channel depends not only on the power of that channel but also on the power of other channels [29].

In order to obtain the best amplification in addition to prevent the non-linear effects at the output port, a correct input power value needs to be chosen. For the reasons previously given, the operating input power was selected to be equal to -11.45 dBm, which ensures a good amplification without non-linear effects.

5

Experimental Results

This chapter presents the results achieved during the experiment. The chapter starts presenting the plots of the optical spectra of the switched signals for the channels. Then, constellation diagrams of each channel are represented for different output powers, allowing to estimate the minimum output power to recover the signal error free. Finally, in the last section of this chapter a further explanation of the bit error rate measurement and the calculated BER curves is given.

5.1 *Optical spectra of switched signals*

The optical switch used in this experiment comprises three AWGs and three SOAs in cascade. In order to know the quality of the optical signal after the second AWG, in this section, the three possible scenarios for the output signal are analyzed at the output of AWG 2.

In the first scenario, SOA 2 is OFF (bias=0 V) and only one channel is ON. In the second, SOA 2 is ON and only one channel is ON. In the last scenario, the four channels and SOA2 are ON. The four channels were analyzed for the three scenarios to ensure proper operation of the all system. Table 5.1 summarizes the parameters used in each scenario.

SCENARIOS		
	SOA 2	CHANNELS ON
1º	OFF	1
2º	ON	1
3º	ON	4

Table 5.1. Parameter of the three scenarios analyzed .

Figure 5.1 shows the AWG 2 output spectra in the first scenario when SOA 2 is OFF (bias=0 V) and only the channel under test in ON.

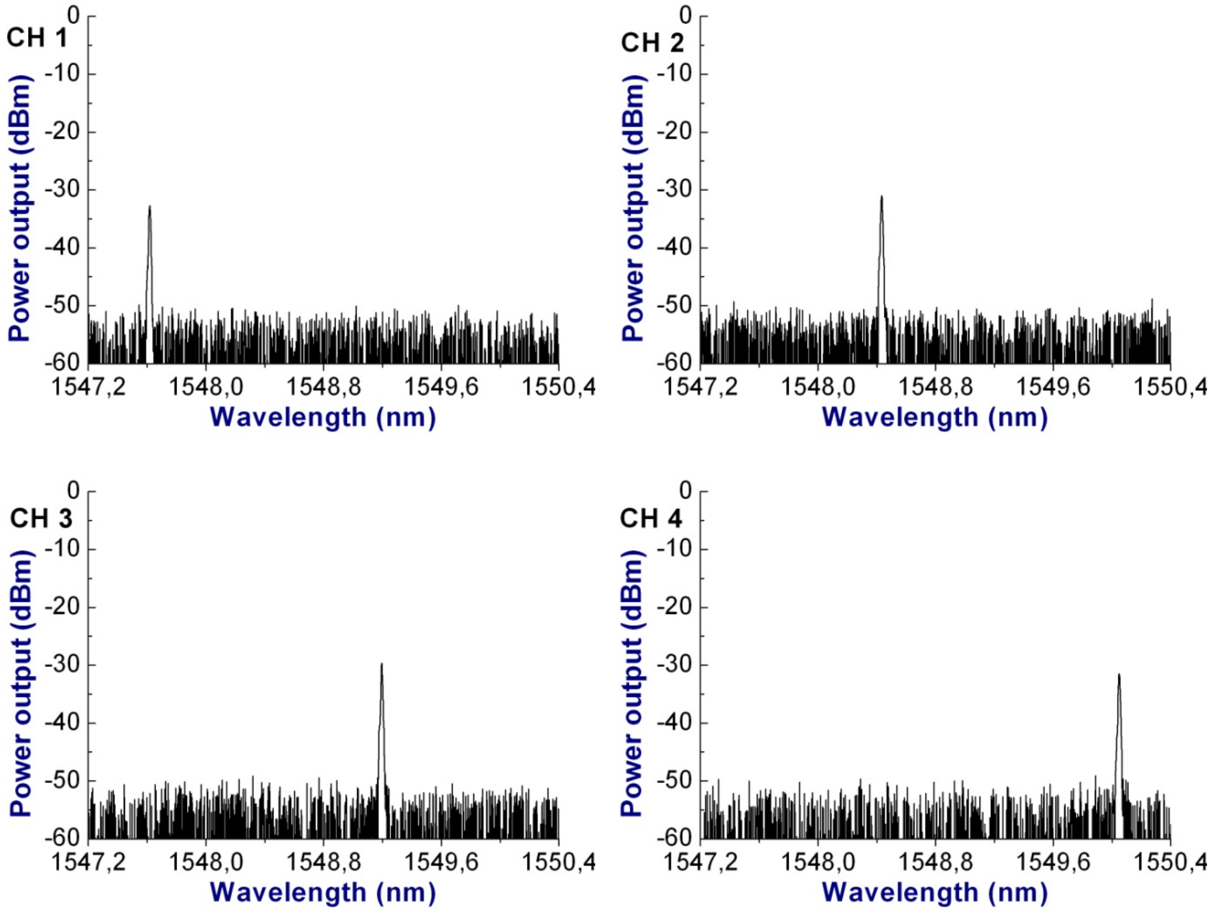


Figure 5.1. Output power spectra after AWG 2 for CH 1, CH 2, CH 3 and CH 4.

The top left graphic in Figure 5.1, corresponds to CH 1 and the top right graph to CH 2. In the lower row, the left graph corresponds to CH 3 and the right graph to CH 4.

The range of wavelength was chosen to be from 1547.2 to 1550.4 nm. The input powers at SOA 2 were -12.5, -10.89, -10.95, -11.77 dBm and the optical output powers after AWG 2 were -32.68, -30.99, -29.67, -31.48 dBm for CH1, CH2, CH3 and CH4 respectively. Therefore, when SOA 2 is in off state, it works like an attenuator of 20 dB. These signals are so low that SOA 2 can be also considered as noise.

Combining this case when the bias is set to 0 V and the case from section 4.2.2 when the bias of SOAs are set to 1.8 V, is observed a functioning of the SOAs as a gate. With 0 V it is open gate and with 1.8 V it is close gate.

Next, the second and third scenario are analyzed at the same time. In the second scenario, only one channel is ON and the third, all channels are ON. This time SOA 2 is always ON. The comparison between the output power of these two scenarios is shown in Figure 5.2.

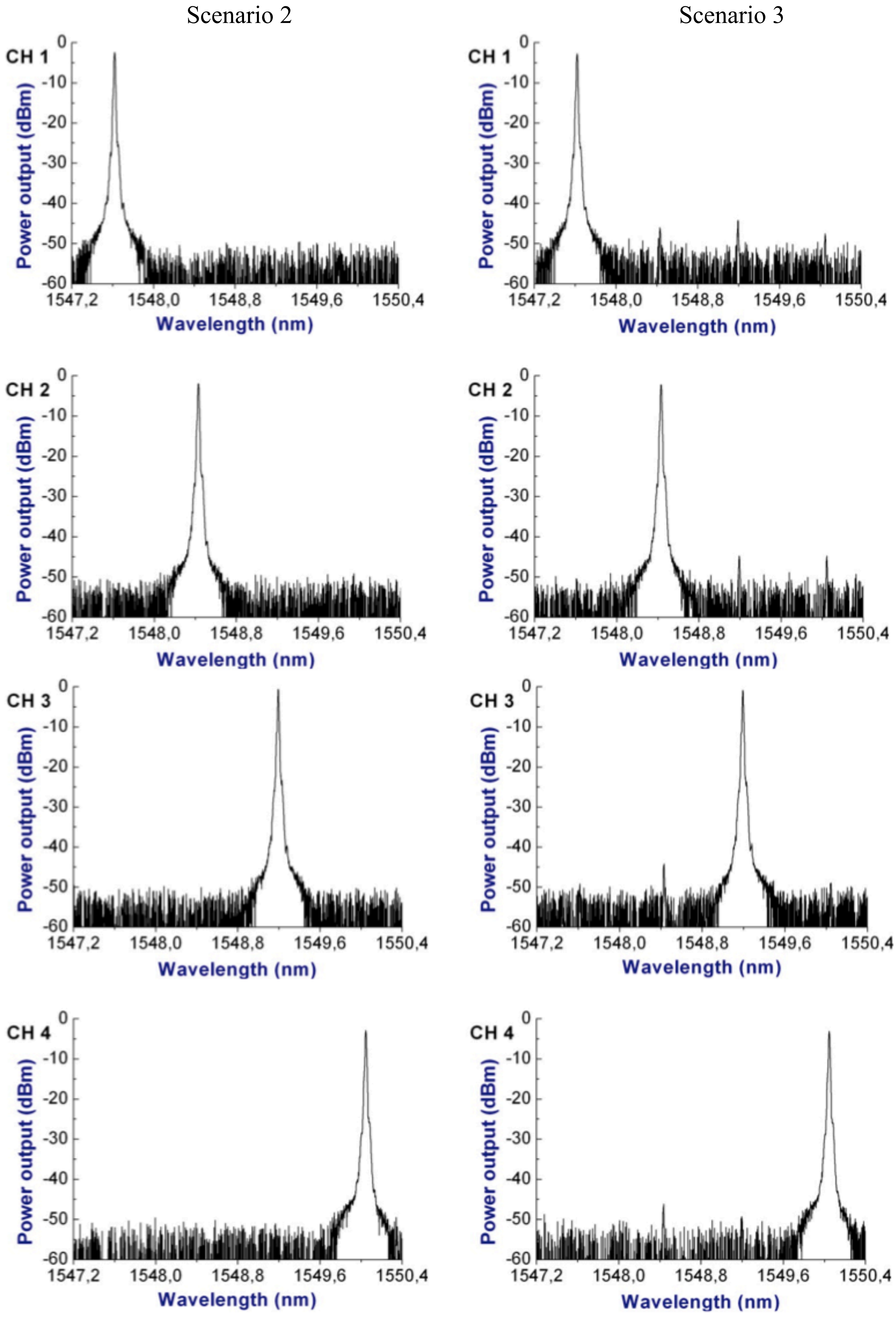


Figure 5.2. Output power spectra after AWG 2 for CH 1, CH 2, CH 3 and CH 4.

The graphs in left column of Figure 5.2 correspond to the output power to each channel when the others are OFF. The graphs in right column correspond to each channel when the others are ON.

The range of wavelength was chosen to be from 1547.2 to 1550.4 nm. The input powers at SOA 2 were -12.5, -10.89, -10.95, -11.77 dBm and the optical output powers after AWG 2, with only the channel under test ON (scenario 2) were -2.39, -1.95, -0.61, -2.88 dBm for CH1, CH2, CH3 and CH4 respectively.

In scenario 3, the input powers in each channel were the same than scenario 2, and the optical output powers after AWG 2 with all channels ON were -2.75, -2.17, -0.9, -3.13 dBm for CH1, CH2, CH3 and CH4 respectively. Therefore, there is an amplification around 9 dB per channel.

Comparing the two scenarios, there are 0.3 dB losses between the signals with only one channel ON and the signals with all the channels ON. In addition, low peaks appeared with an optical output power of -45 dBm in the graphs of scenario 3; however they can be considered negligible because the suppression ratio is 43 dBm, that means the AWG makes a good filter of the undesired signals. These peaks were produced due to the others channels. This phenomenon is called cross-talk.

For all of the reasons mentioned in this section 5.1, it’s possible to conclude that a good transmission without cross-talk can be expected at the receiver, for each channel and in its three possible combinations.

5.2 Constellation diagrams

A constellation diagram is a representation of a signal modulated by a digital modulation scheme such as quadrature amplitude modulation (QAM) or phase-shift keying (PSK). In a more abstract sense, it represents the possible symbols that may be selected by a given modulation scheme as points in the complex plane.

As the symbols are represented as complex numbers, they can be visualized as points on the complex plane. The real and imaginary axes are often called I-axis and Q-axis. Plotting several symbols in a scatter diagram produces the constellation diagram. The points on a constellation diagram are called constellation points. They are a set of modulation symbols, which comprise the modulation alphabet [30].

After the reception of the signal, the demodulator examines the received symbol, which may have been corrupted by the channel of the receiver (e.g. additive white Gaussian noise, distortion, phase noise or interference). It estimates the point closest to the received symbol. Thus will demodulate incorrectly if the corruption has caused the received symbol to move closer to another constellation cluster than the transmitted.

In this section, the constellations diagrams of the output powers will be used in order to find until which output power value the received signal remains error free. Five constellation diagrams are show in Figure 5.3.

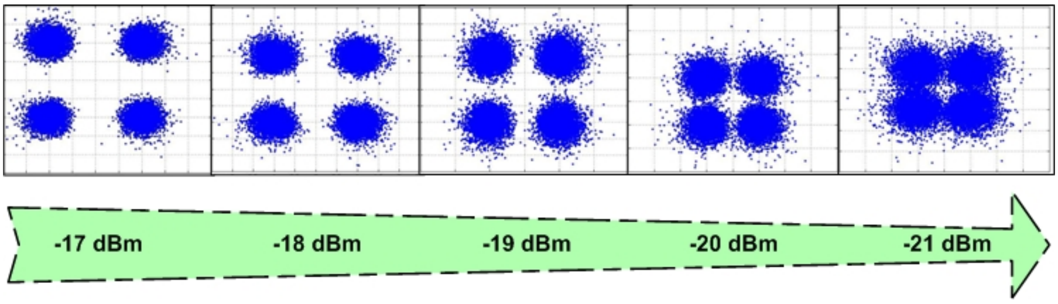


Figure 5.3. Evolution of the constellation diagrams.

Figure 5.3 shows five constellation diagrams from CH 1 when the output power was set at values -17, -18, -19, -20 and -21 dBm. In this range, the evolution of the error detection depends on the output power is shown.

Each cluster represents a symbol of the modulation. A 4-QAM modulation was used for the setup, consequently there are four clusters.

The first diagram at -17 dBm shows clearly four separate different circles, it means, the reception is error free. However, when the output power increases, the circles are closer and it starts to be some errors. Finally, if the power is too low, there is only the four circles collapse one into each other as happens for -21 dBm. Therefore, the signal is impossible to recover.

Furthermore, the minimum output power required to have a perfect transmission without errors is -18 dBm.

5.3 Bit error rate measurements

The bit error rate is the number of errors divided by the total number of transmitted bits during a studied time interval. The errors are the received bits of a data stream over a communication channel that have been altered due to noise, interference, distortion or bit synchronization errors.

In this section, the curves of the BER of all channels are shown and three different situations are analyzed.

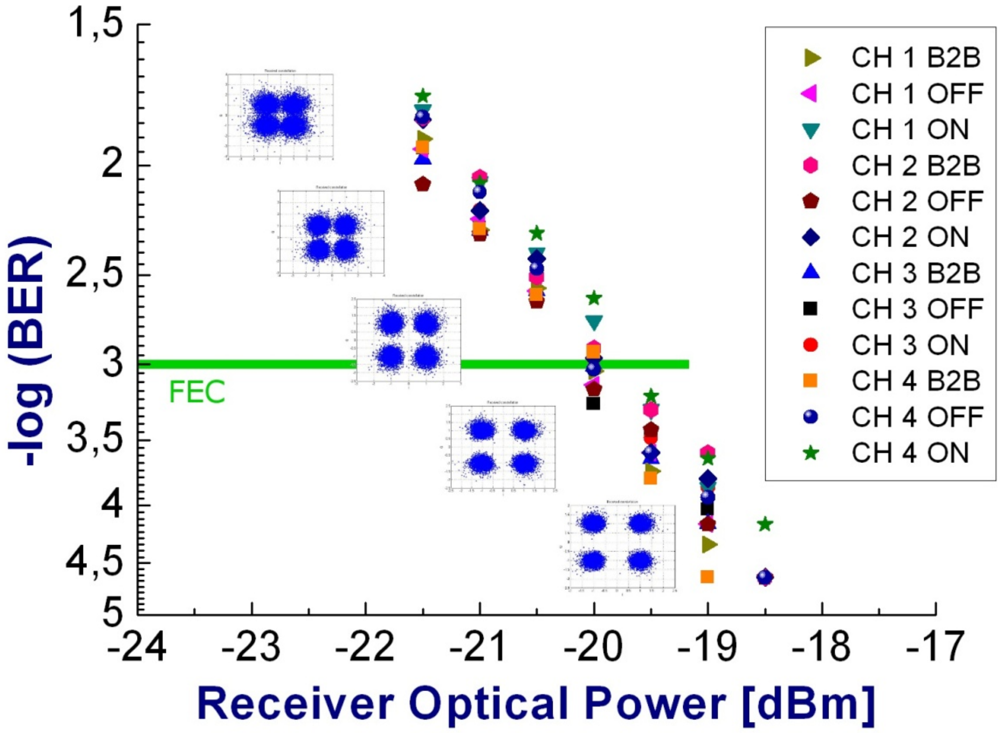


Figure 5.4. Bit error rate curves.

Figure 5.4 shows twelve BER curves. The range of the receiver optical power was chosen between -21.5 and -28.5 dBm. The amount of errors is given depending on the optical power and is represented in a logarithmical scale.

Figure 5.4 presents three situations of transmission: optical back-to-back (B2B) with one channel ON, 20 km of fiber with one ON, and 20 km of fiber with all channels ON. These three situations were analyzed for each channel.

These three situations help to know two relevant things. The first is to know how many errors introduce the fiber transmission for the same output power value. The bit errors introduced can be calculated by subtracting the bit errors of the output power when only one channel is ON to the bit errors of B2B output power. The second thing is to know how much each channel interferes in the others (cross-talk). It can be calculated by subtracting the bit errors of the output power when only one channel is ON to the bit errors when all channels are ON. In addition, looking the Figure 5.4, a power penalty of 0.5 dB for the first case (B2B-one channel) and around 0 dB for the second case (one channel-all channels) are observed.

In Figure 5.4 is also drawn a horizontal line at 10E-3 of BER, which is the forward error correction (FEC) value. FEC is a technique used for controlling errors in data transmission over unreliable or noisy communication channels. The central idea is that the sender encodes his message in a redundant way by using an error-correction code (ECC). The redundancy allows the receiver to detect a limited number of errors that may occur anywhere in the message, and often to correct these errors without retransmission. Therefore, if this technique is used, it is possible to recover all signal information, as happens when there is error free, until the value 3 in the “Y-axis” [31].

Due to the graphically and numerically analysis done in this section, it is know that the bit errors introduced by the fiber are very few, there is error free transmission until -20 dBm output power using FEC, and the cross-talk is very low.

6

Conclusions

In this thesis, an AON with an optical switch, consisiting of SOAs, dealing with wireless signals was evaluated. The results show a negligible power penalty on each channel over 20 km of fiber, for both the best and the worst case in terms of inter-channel crosstalk. One published paper and other submission under review have resulted while carrying out this thesis.

An experimental validation was conducted; the experiment consisted in the implementation of a four-channel system operating on a WiMax frequency band. The modulation employed was an OFDM 4QAM with 5 GHz and a bit rate of 625 Mbit/s per channel. The transmission of the data used over 20 km of optical fiber, and the active switching was a one-by-sixteen active optical switch.

The system meets the requirements for an AON for wireless-over-fiber for optical access networks and prove the feasibility and attractiveness of optical switching compost of SOAs (OSMOSIS) for providing secure wireless services in RoF technologies.

6.1 Future work

During the development of this project many new issues arose, especially during the experimental phase of the project. At a theoretical level, it seems clear that there is a large pool of switching technologies that need to be assessed in relation to their impact on wireless-over-fiber signals, both theoretically and through numerical simulations. In this project, employment the OSMOSIS switch was a design choice due to the availability of such switch in the laboratory.

The analysis conducted in this thesis mainly focused on evaluating the performance of the switch and its impact on the quality of WiMax-like signals. However, a study on engineering parameters of the optical switching should be conducted. For example, switching time, insertion losses, scalability, cascadability (degradation due to noise accumulation), and other parameters that play a central role when designing an optical system. A more general study should include also a cost analysis and an energy consumption characterization.

WiMax-like signals were chosen for two reasons: first, they have become one of the most widely deployed wireless systems worldwide. Second, it was possible to implement a signal generator, receiver and analyzer in the lab premises. Hence, the results are narrowed down to this specific scenario, while the goal should be a more generic study. The optical switch should be characterized employing higher order modulation formats (i.e. 16-, 32-, 64-QAM) operating at different frequency bands. Ultimately, operability at the E- and W-band bands (>60 GHz) should be assessed, which are considered the next operational bands for mass production wireless systems.

Finally, this thesis dealt with a distribution system. However, actual systems are normally bidirectional. Hence, a smart upstream collection system needs to be studied and designed.

All these follow up activities can be independently taken in the future, and can build on the knowledge generated within this project.

Conclusiones

En esta tesis, se ha evaluado como una red óptica activa (AON) con un conmutador óptico constituido por amplificadores ópticos semiconductores (SOAs), lidia con señales inalámbricas. Los resultados muestran una degradación de la señal imperceptible en cada canal usando 20 km de fibra óptica, para el mejor escenario y el peor en términos de interferencias entre canales. Una publicación y otra bajo revisión han sido el resultado de esta tesis.

El sistema presentado fue realizado en su totalidad en un laboratorio con el fin de llevar a cabo una validación experimental. El experimento consiste en la implementación de un sistema de 4 canales operando en la banda de frecuencia WiMax. La modulación empleada fue OFDM 4QAM con 5 GHz y una velocidad de transmisión de 625 Mbit/s por canal. La transmisión de la información fue a través de 20 km de fibra óptica, y la conmutación activa de la información fue llevada a cabo por un conmutador óptico de 1 entrada y 16 salidas.

El sistema cumple los requerimientos de una red óptica activa, para señales inalámbricas a través de fibra para redes ópticas de acceso. Este trabajo intenta dejar constancia de la viabilidad y del atractivo de los conmutadores ópticos compuestos de SOAs, como proveedores de servicios inalámbricos seguros en las tecnologías radio a través de fibra.

7

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Appendix A
PUBLICATIONS

PAPER 1: G.A. Rodes, J.J. Vegas Olmos, F. Karinou, I. Roudas, L. Deng, X. Pang, and I. Tafur Monroy, “Optical Switching for Dynamic Distribution of Wireless-over-Fiber Signals,” Accepted for publication at the 16th International Conference on Optical Network Design and Modeling, Essex, UK, April 2012.

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