



**Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona**

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HYBRID FIBER RADIO NETWORKS: NEW CONCEPTS AND TECHNOLOGIES

Autor: Rosa C. Torres Román

Director: María C. Santos Blanco

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Dedicated to my parents and brothers by always be with me.

To my friends, because our friendship overcame continents.

To the person, who was the most important for me during these two years

and I still love...

Table of contents

1	Introduction	6
1.1	Objectives.....	7
1.2	Project Organization.....	8
2	Converged systems: Fiber and Radio	10
2.1	Working frequencies	10
2.2	Wireless environment	11
2.3	Centralized Structure	12
2.4	Transmission scheme: Radiofrequency over Fiber	13
3	Hybrid Fiber Radio networks.....	18
3.1	Architectural considerations to design HFR network	18
3.1.1	Nature of the topology.....	18
3.1.1.1	Example: Integration GSM in a HFR system	18
3.1.1.1.1	GSM structure	18
3.1.1.1.2	Hybrid GSM- fiber structure.....	19
3.2	HFR topology	20
3.2.1	Broad features of basic topologies.....	21
3.2.1.1	Bus topology.....	22
3.2.1.2	Ring topology.....	23
3.2.1.3	Star topology	23
3.2.1.4	Tree topology	24
3.2.2	HFR access based on mixed topology	25
4	Hybrid Fiber Radio links.....	30
4.1	HFR-link's anatomy.....	32
4.1.1	Modulation.....	34
4.1.1.1	Direct modulation	34
4.1.1.2	External modulation.....	36
4.1.2	Transmission.....	38
4.1.3	Detection	41
4.1.3.1	Non coherent detection	42
4.1.3.2	Coherent detection	43
4.2	SSB+C Modulation scheme to mitigate dispersion's effect.....	46

4.2.1	Double Sideband plus Carrier (DSB+C) modulation	47
4.2.1.1	VPI simulations	48
4.2.2	Single Sideband plus Carrier (SSB+C) modulation.....	50
4.2.2.1	VPI simulations	50
4.2.3	Comparison DSB+C and SSB+C modulation schemes	52
5	Conclusions	54
6	Table of figures.....	55
7	Table of tables	57
8	Bibliographic references	58

1 Introduction

Each of the current network technologies, such as twisted pair, microwave radio links, wireless (fixed / mobile), optical fiber, or coaxial wire, provide different levels of mobility and specific bandwidth to each user, have different techniques for signal generation, transmission and reception as well as different costs of installation, operation, energy consumption and maintenance. But the continuous increase in the demand of broadband and mobile communications with continuous connectivity and high Quality standards, pose a challenge on the network technologies that have to support these new and enhanced services, with feasibility of cost and implementation, because the current networks, either wireless or wired, satisfy just a part of the new demand due to some of their limitations.

Thus taking account the growing requirements and separately the advantages / disadvantages of the basic technologies, there comes the necessity of the implementation of a network in which the limitations of one technology can be overcome via the coexistence with another technology, in the same network. Thus photonics and microwave technologies merge into a new hybrid technology termed as Microwaves Photonics (MWP), in which both technologies are complementary to each other and when are combined together in an adequate sequence allow to overcome separate limitations and to provide new features.

Some MWP applications involve transport of radio signals over fiber, optical generation of radio signals, and control of Phased Array Antennas (PAA) optically, optical processing of radio signals, among others. Nevertheless, one of the major applications of this hybrid technology is

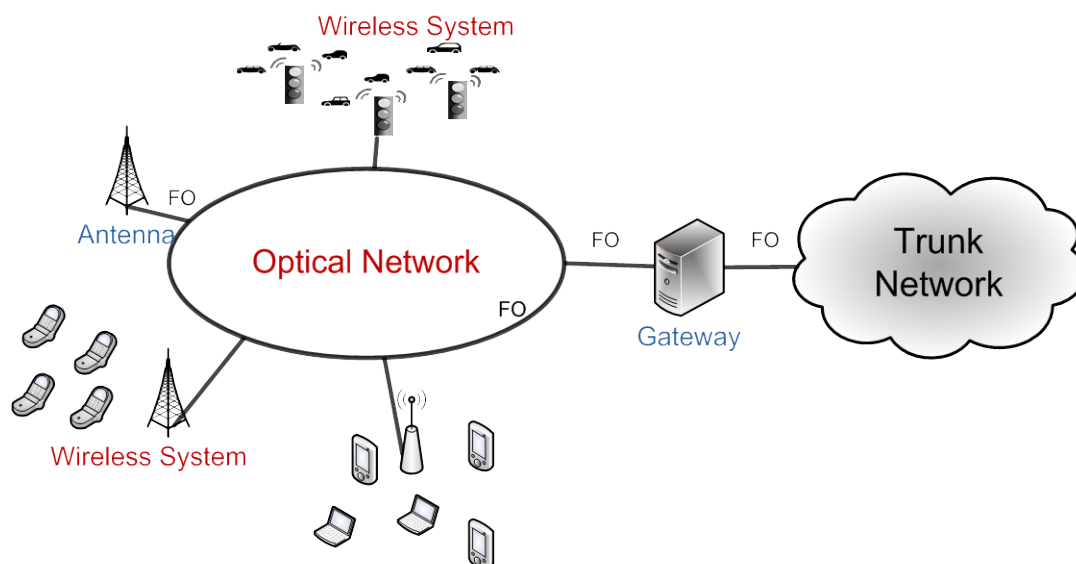


Figure 1.1: Basic diagram of the coexistence of the Wireless and Optical Networks

the implementation of the hybrid wireless-fiber system, also named as Hybrid Fiber-Radio System (HFR) (In remains of this PFC, the terms 'radio' and 'wireless' will be used interchangeably).

Figure 1.1 shows a basic diagram of coexistence of the wireless and fiber technologies, together in the same network. As seen, several wireless systems which may be short-range connectivity to devices (i.e. Bluetooth), systems in buildings, cellular, Hotspots, wireless local area networks (i.e. WLAN), mobile services, among others are interconnected via an optical network, which in turn may be connected with the trunk network via a gateway.

In a HFR system the high bandwidth capacity and low cost of the optical fiber is combined with the flexibility and mobility of wireless access networks and thus it may be used to extend the range and capacity of the wireless networks, represents an enhanced solution for the 'last mile', can be used to implement indoor applications with Distributed Antenna Systems (DAS) to transport radio signals to remote antennas distributed throughout buildings, can be used to implement an interconnection network of multiple antennas with a control center, etc.

1.1 Objectives

- To study the main trends which drive the merging of fiber and wireless technologies in access networks. As the hybrid radio networks constitute a new and emerging field of knowledge it is difficult to get a clear picture of their main building blocks and basic technologies and concepts. Due to the lack of reference texts with a basic entry level, in this PFC we aim at carrying out a thorough study of the related literature in order to establish a clear classification of systems and techniques, to clarify the basic terms and to study the specific transmission characteristics of hybrid radio links, both from a point to point as well as from a networks management perspective.
- Steaming from the above, the main physical effects and phenomena around optical and wireless technologies will be reviewed and the basic analytical as well as computer and simulation tools will be presented along with some simulation examples showing relevant fiber-radio transmission effects and techniques.
- The main driver will be to help newcomers to the field to get a fast understanding of the basic related ideas and analysis techniques for hybrid fiber-radio networks.
- In this regard the key building blocks to implement the HFR's networks will be identified. These should include underlying concepts such as working frequencies, general structure for the coexistence of wireless and fiber technologies, the network components and topologies proposed, as well as the hybrid link's features, characterizing parameters and main impairments that degrade the quality of transmission.

1.2 Project Organization

This study has been carried out in five chapters, which include:

Chapter 2 Converged systems: Fiber and Radio

This chapter provides a description of the main functional features of the Hybrid Fiber- Radio Networks such as working frequencies, wireless environment, the consequent requirement of centralized structure and the transmission scheme that enables it. Also the interior structure of the optical portion and its border components is described.

Chapter 3 Hybrid Fiber Radio networks

Within this chapter, a study about the nature of the hybrid topology is developed based on the migration process from the structure of the GSM service. Moreover, the description of basic optical topologies and proposed HFR's mixed topologies is carried out.

Chapter 4 Hybrid Fiber Radio links

This chapter is dedicated to the description of the hybrid fiber- radio links, considering the options for source modulation and detection techniques.

Chapter 5 Conclusions

There is the valuation of the reach and utility of the investigation about the HFR networks carried out in this PFC. Moreover, there are commented the major features of the HFR's network that both have been corroborated and also deduced.

2 Converged systems: Fiber and Radio

The use of wireless networks has been extending because they bring mobility, have easy and fast implementation, offer greater coverage area, reaching zones where the wired networks can't or the monetary inversion may be expensive, or where its implementation may be economically impractical such as for reduced environments. But the increasing demand for broadband services poses the requirement of wireless systems with increased network capacity, operating at higher carrier frequencies, and providing services to a large density of users. These requirements lead to several issues that increase the cost of installation and maintenance of those radio systems. In this chapter these issues will be studied and how the use of optical fiber tackles them.

2.1 Working frequencies

The typical wireless systems currently have a limited spectral bandwidth they because operate at low frequencies, where there is spectral congestion produced by the large number of services assigned there. Because the provision of broadband applications and high data rates is restricted in these frequencies; there is a growing interest in working at higher frequencies, where it is possible to provide higher data rates and large bandwidth.

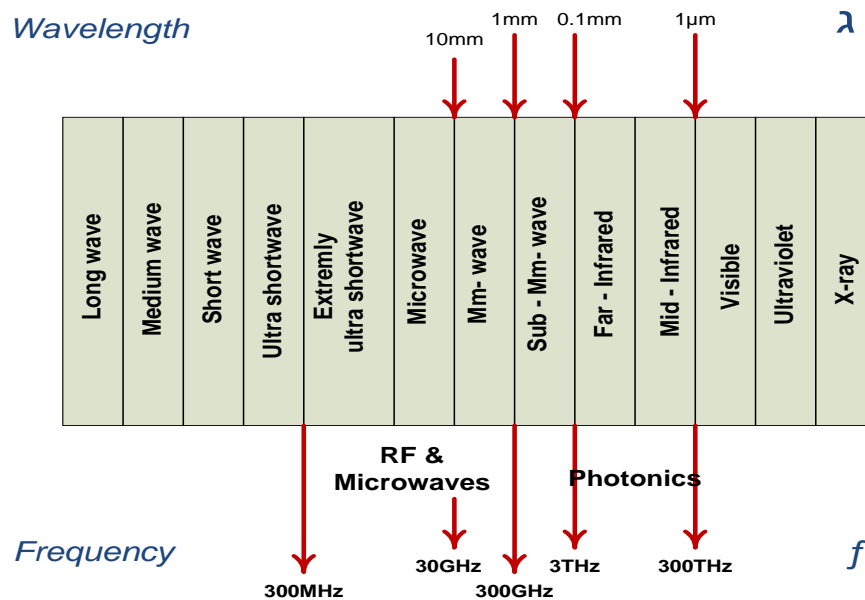


Figure 2.1: Electromagnetic spectrum distribution

In order to provide broadband services the working frequency is moving up to the Millimeter band (MMW), at which there is huge bandwidth available and the consequent provision of high data rates in the Gigabit/seg range to the MMW-HFR systems (i.e. on the 60GHz band the

bandwidth allocated is 7GHz that spans between 57 – 64 GHz (Nan Guo, September 2006) (Chong, 2006)).

On the other hand, it is important to remark that there is no consensus about the distribution of the frequency bands in the electromagnetic spectrum. There are different frequencies ranges assigned to both MW and MMW bands, even the term: 'Microwave', is usually used to refer to either both bands or the radio signals in general. In order to avoid this inaccuracy, in this PFC the distribution of electromagnetic spectrum shown in the **Figure 2.1** will be used. This shows that the Extremely Ultra shortwave, Microwave and Millimeter bands are grouped in a band named as 'RF & Microwaves', also it is seen that the MMW band corresponds to the frequencies from 30GHz to 300GHz and the photonics frequencies correspond to the band from 3THz to 300THz. Unless otherwise specified, in this work any transmitted signals in wireless communication will be named 'radio signal'.

2.2 Wireless environment

Despite the fact that the large bandwidth and the high data rates are translated in a high potential of capacity and flexibility, MMW signals suffer of large atmospheric attenuation and divergence at space that occur at these higher frequencies due to the selective molecular absorption; these effects in turn are translated into higher path loss.

These impairments lead to a considerably reduction of the Signal to Noise Rate (SNR) at the receiver as transmission distance increases; by which, the wireless coverage must be reduced down to micro cells (Michael Sauer, 2007).

Microcellular system

A microcellular system obtains milder propagation characteristics than with greater radio coverage (200- 2000Km) and is capable to allow broadband transmissions with smaller cell coverage and low transmission power. This is an efficient way to increase the capacity because it allows to accommodate more subscribers per unit service than macrocells and can support heaviest traffic; also, the reduced coverage enables the use of efficient radio frequency-reuse schemes, which in turn increase the network throughput, though the radio resource management becomes more difficult and the system becomes highly limited by interference and more sensitive to traffic variations or growth of the radio network.

In order to provide a wide geographical coverage a large number of cells will be required; which leads to increments in the installation and maintenance costs. The use of optical fiber allows to overcome these limitations, because of the optical medium isn't affected by the

interference, is capable to manage high density of traffic and its variations, and also allows the interconnection of several remote locations with increased capacity and reduced cost.

2.3 Centralized Structure

The use of radio transmission at the final portion of the MMW-HFR network (**Figure 1.1**), provides flexibility to end users, and thus they may have mobility and, roaming; but the HFR's challenge is the interconnection of a large number of users with low cost and in efficient way. This is possible via an Interconnection Network that provides centralized and remote management of the resources, and also an efficient configuration of the hardware within each cell to reduce the complexity and costs of each remote unit.

The centralized structure of the HFR system provides the reduction of the system complexity by the simplification of the management of the radio network as well as the provision of transparency to upgrades and updates because these can be carried out at the central location (i.e. Central Office). This feature is achieved by moving as many tasks, hardware and intelligence as possible to the centralized location, Central Office (CO), thus all the routing, switching and processing functionalities are processed there and the Remote Base Stations (BS) are as simpler as possible.

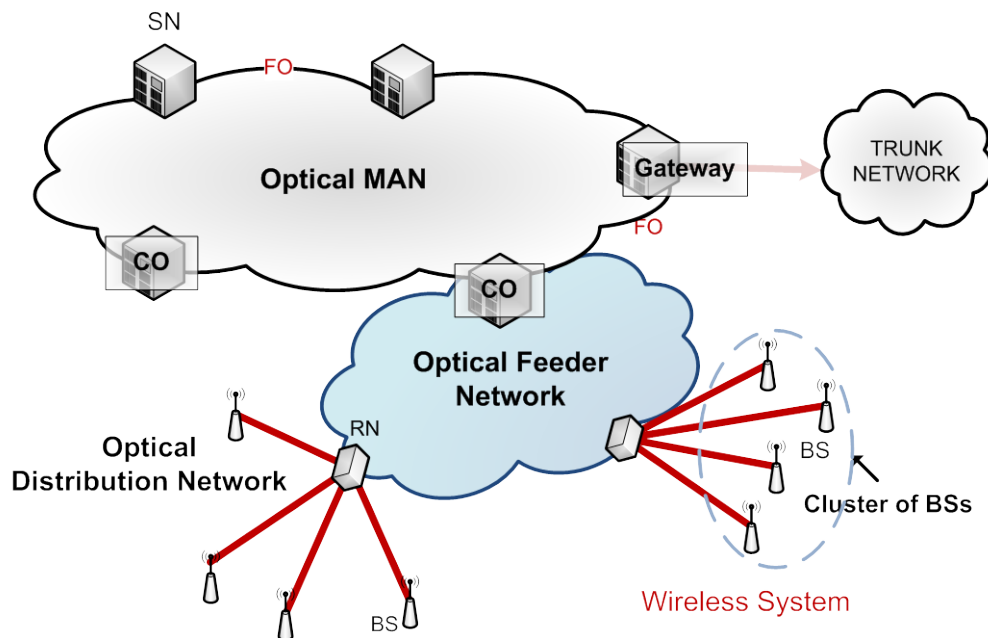


Figure 2.2: General diagram of a HFR system exhibiting the concept of centralized structure

Figure 2.2 shows the basic structure of a MMW- HFR system. BSs are grouped in clusters and interconnected with an intermediate optical node named Remote Node (RN), which will help

to manage the radio resources for each cluster; this first optical portion is the Optical Distribution Network (ODN). The RNs are interconnected with the centralized node: CO, constituting the Optical Feeder Network (OFN). In conjunct, both ODN and OFN form the HFR Access Network or also called as Optical Interconnection Network (OIN).

On the other hand, in order to provide metropolitan coverage, several COs with additional functionalities (Switching Nodes, SN) are interconnected via an Optical MAN which allows connection with other networks or the trunk network when one of the SNs also acts as a Gateway.

2.4 Transmission scheme: Radiofrequency over Fiber

In order to enable a cost effective design of a HFR system according to provided wireless application, it is necessary to choose a suitable transmission scheme for both uplink and downlink. This scheme should be compatible with the kind of transmission (half duplex/full duplex), modulation scheme, bandwidth required, data rate, environment (indoor/outdoor), etc.; because these considerations will determine the configuration of the network components (BS, CO, RN). The centralized structure of the MMW-HFR systems implies to have simpler BS, and therefore the transmission scheme should enable this requirement. (Lee, 2007)

The HFR radio signal transmission schemes, as shown in **Figure 2.3**, may be:

- Radiofrequency over Fiber (RF over Fiber - RoF)
- Intermediate frequency over Fiber (IF over Fiber)
- Baseband over Fiber (Baseband over Fiber)

The transmission scheme ultimately determines the complexity and costs. The radio signal at the input of the optical link depends both on the HFR technology and the functionality desired, and the radio signal generated must be in agreement with the specifications set by the wireless application provided by the wireless system.

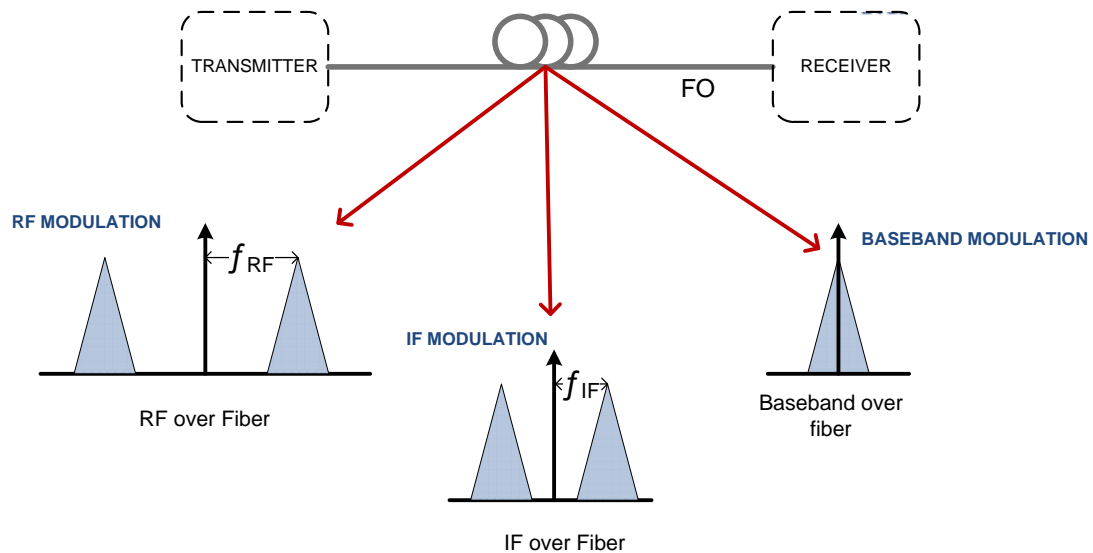


Figure 2.3: HFR Technologies

Radio over fiber

In this scheme, the MMW radio signals are transported directly over the fiber at the MMW radio carrier frequency. It enables the design of simpler remote BS architectures because it doesn't require any frequency conversion at the BS and the greater part of processing and frequency conversions are realized at the CO.

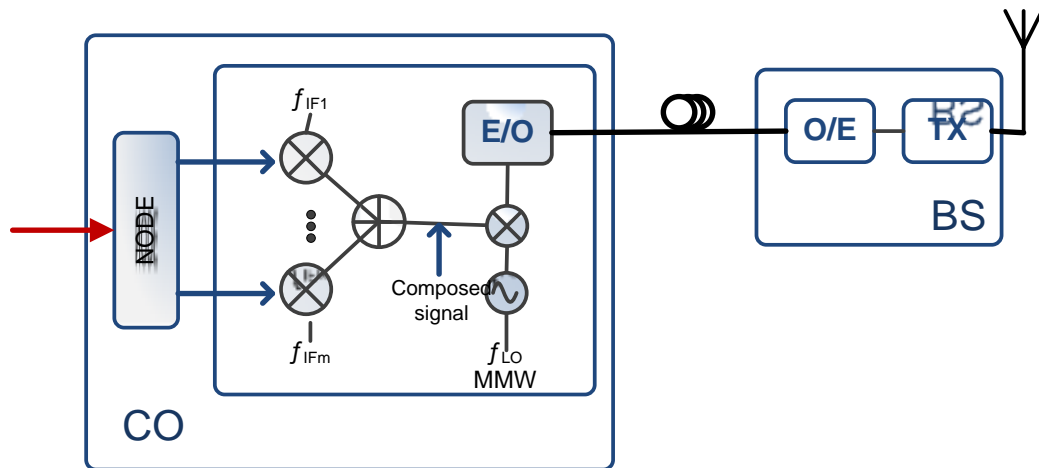


Figure 2.4: Scheme of the basic hardware required for the downstream transmission via Radio over Fiber scheme

As seen in **Figure 2.4**, the data from the trunk network is modulated onto a number of lower intermediate frequency carriers, and then these signals are combined into another signal. This last is up-converted to the MMW-radio frequency using a LO source at the CO, and after the

E/O conversion, the MMW optical modulated signal is transported over the optical fiber upon the Remote BS. Here, the signal is converted to the electric domain and without the need for any subsequent up- or down- conversion; this is directed to the antenna to be transmitted to the space. For upstream transmission at the BS the MMW-radio signal is modulated onto the optical carrier and then transmitted over the fiber to the CO, where the signal is photodetected.

In case of IF over fiber scheme (**Figure 2.5**), because the MMW radio signal is transported over the optical fiber at IF frequencies, at the BS an optical mixer is required for up and down frequency conversion respectively for up- down- stream transmission.

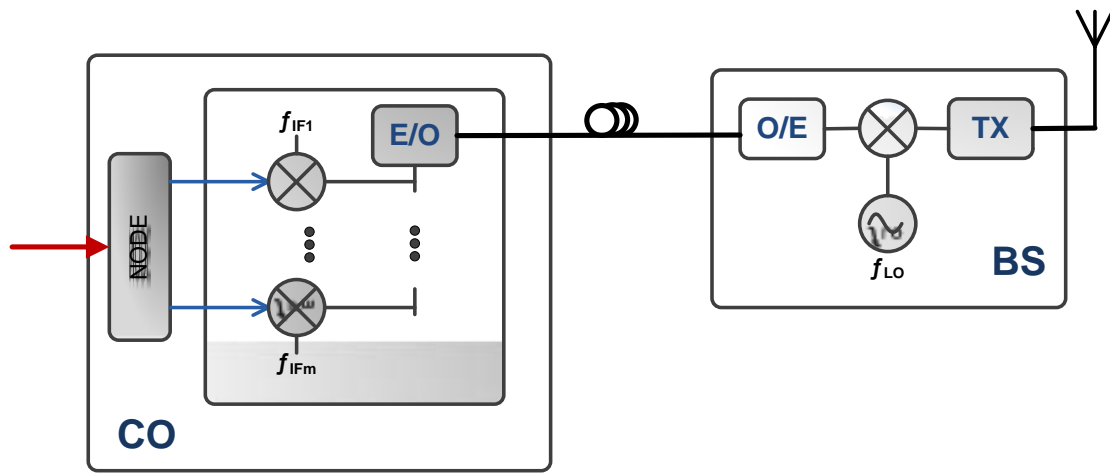


Figure 2.5: Scheme of the basic hardware required for the downstream transmission via Intermediate over Fiber scheme

In the case of Baseband over fiber (**Figure 2.6**), the information is transported up to the BS as a multiplexed data stream. For downstream direction the individual data channels are demultiplexed, up-converted to IFs, before undergoing an additional frequency up-conversion to the required MMW frequency; for upstream direction, at the BS the MMW received radio signal is down converted to baseband before the transmission back to the CO.

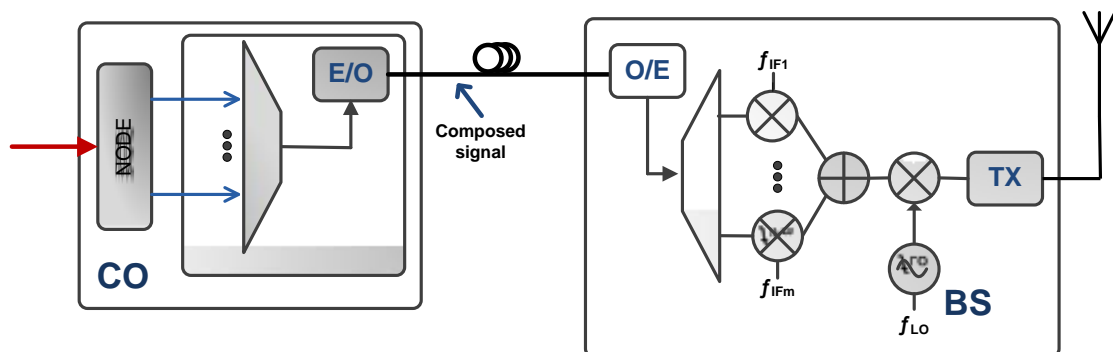


Figure 2.6: Scheme of the basic hardware required for the downstream transmission via Baseband over Fiber scheme

In short, RoF is the most suitable transmission scheme for design the MMW-HFR links due to its simplicity and lessening the cost and complexity of the simpler remote BS. Moreover usually these initials (RoF) and HFR are used interchangeably to reference hybrid fiber-wireless system because this is the scheme most commonly commercially used, on the other hand also due to the same reason, usually this technology is considered the HFR technology to use by default.

3 Hybrid Fiber Radio networks

3.1 Architectural considerations to design HFR network

Usually the terms: 'topology' and 'architecture' are used interchangeably, although within this work they will be differentiated considering that the architecture of a network is a term more general because it defines network characteristics, such as the access method, protocols used, method of distribution of signals, signaling and even the topology, between others. And on the other side the topology indicates how the network components are linked and define the network structure.

3.1.1 Nature of the topology

The HFR network's topology is designed according to the wireless application. For this reason it is necessary to know the wireless structure in order to define the limits between the portion that will remain wireless and that which will be optically implemented

3.1.1.1 Example: Integration GSM in a HFR system

For example in the case of a GSM service, it is useful to know that this system is structured in functional units and interfaces that act as border limits between the basic units.

3.1.1.1.1 GSM structure

As shown **Figure 3.1**, the GSM's topology has three functional subsystems: MS (Mobile Subsystem), BSS (Base Station Subsystem) and NSS (Network Switching Subsystem).

The components used by the service subscriber and MT (Mobile Terminal) are housed into the MS; the mobile stations can be cell phones, laptops, devices in cars, etc.

The BSS contains the infrastructure of the radio aspects to the GSM system. It is composed of the BTS (Base Transceiver Station) and BSC (Base Station Controller); several BTS are connected to one BSC. The BTS is known as BS (Base Station) and is responsible of the transmission and reception of the radio signals. The BSC manages the radio resources and makes the 'handover'.

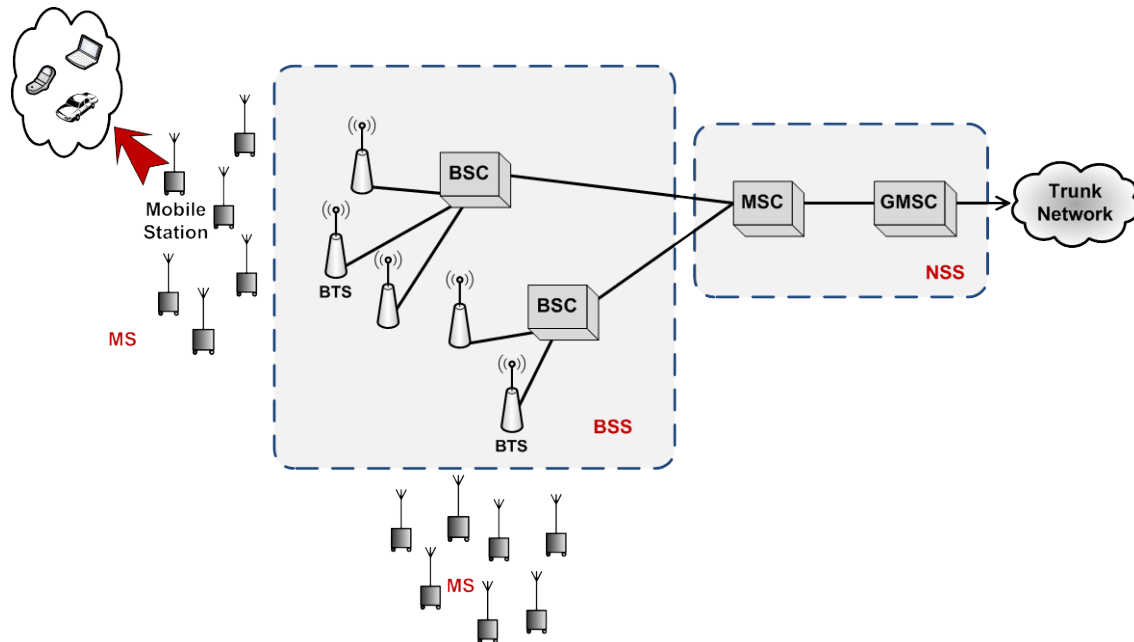


Figure 3.1: GSM topology

The NSS is responsible of the switching and routing of the calls, management of databases containing subscribers information. There are two elements: MSC (Mobile Switching Center) and GMSC (Gateway Mobile Switching Center). MSC is an interior element switching of the GSM network. On the other hand, the GMSC is an element used for the interconnection with others networks (GSM and fixed). When an external user tries to call to a GSM user, the GMSC looks for the MSC provider of the mobile service.

3.1.1.1.2 Hybrid GSM- fiber structure

Once the wireless application is known, the limits between the wireless and wired portion may be established; and thus also, the tasks that the border components will carry out in order to achieve the seamless interconnection of both portions.

As seen in **Figure 3.2**, for a GSM application, a centralized Switching Node (SN) will take care of the MSC tasks and the BTS will remain the Base Station (BS). The transmissions will remain wireless from the BS to MT, but the connections up to the gateway or centralized control point will be via optical links. The Gateway- MSC tasks (GMSC) will be realized by a SN that will act as gateway and take on tasks that allow the connection with the trunk network or other networks. All the optical links between the BS and the CO/gateway form an Interconnection Network (IN) will be optical.

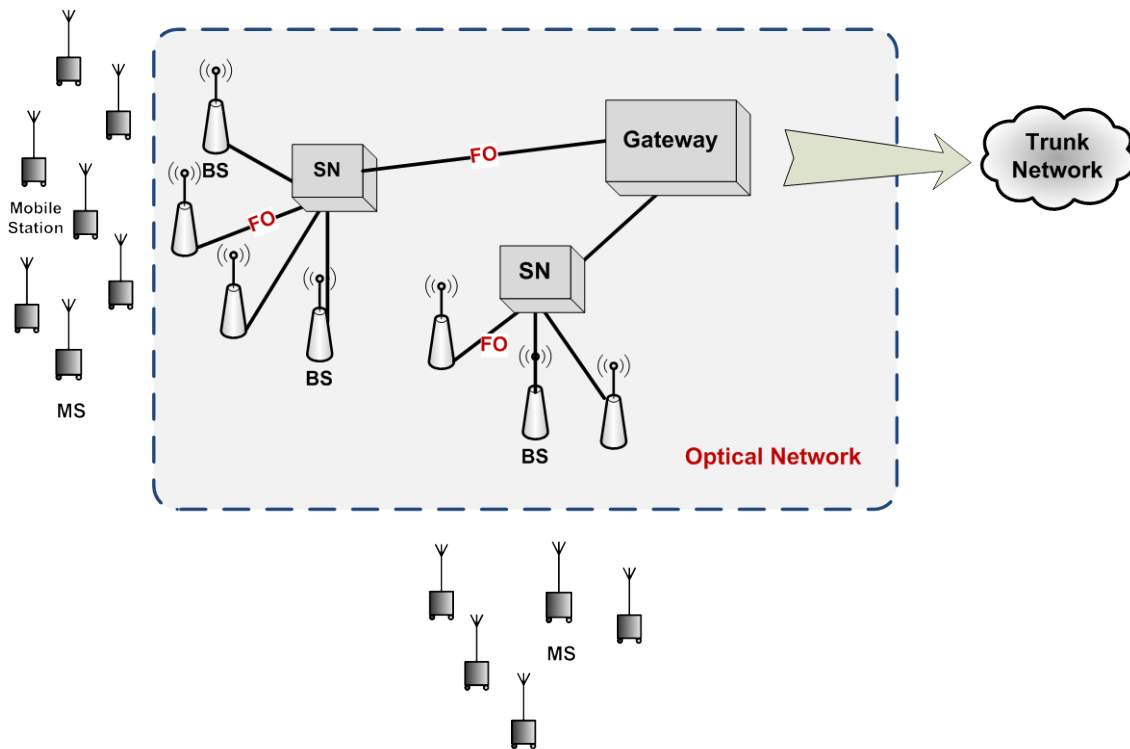


Figure 3.2: HFR topology with GSM service

As seen the wireless application's structure helps to establish the portions that will remain wireless and the portion that will be replaced by an optical infrastructure. Thus this process needs to be particularized to each wireless system. Nevertheless because the current wireless structure commonly has some modules which centralize tasks and there are hierarchies of those modules with assigned tasks depending on the level within the hierarchy; it is possible to propose a common basic structure of the HFR network, which is in concordance with the centralized structure mentioned (2.3); within this structure the border between the wireless and wired portions is the same: the BS, but taking into account that apart from the typical conversions (E/O, O/E), up- or down- frequency conversion or DEMUXs processes; also the BSs will assume additional tasks and particular functions according to each wireless application.

3.2 HFR topology

Typically the metropolitan coverage is given by a MAN ring of SNs. In this PFC we will mainly concerned with the HFR access network design, and not so much about the MAN. Thus, the next topic is related to the possible topology of both ODN and OFN (Sivarajan, 2002). Different combinations of network topologies for both sub networks are possible to implement the HFR access (**Figure 3.3**).

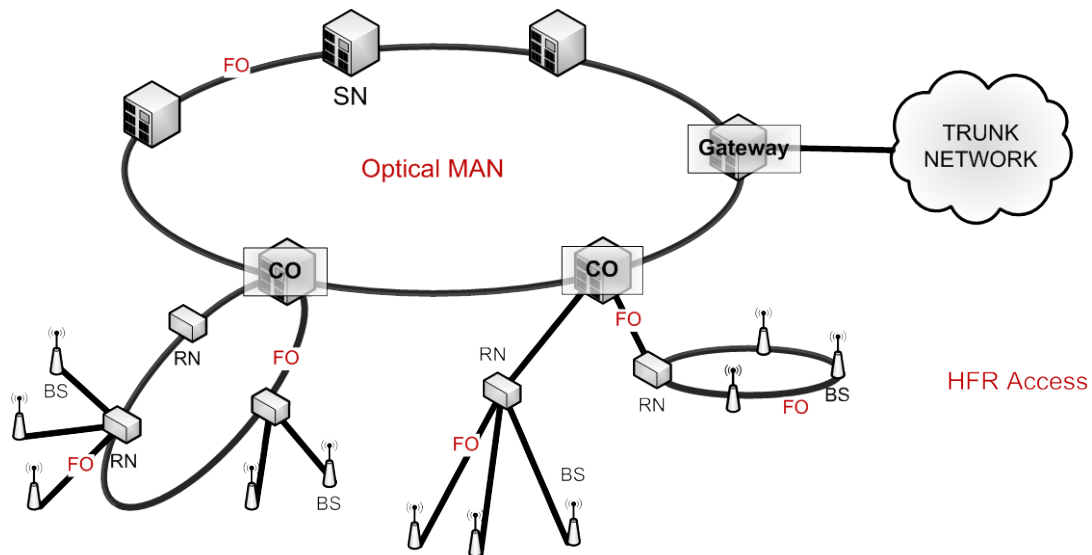


Figure 3.3: HFR system exhibiting different topologies for each optical sub network

3.2.1 Broad features of basic topologies

The OFN can be implemented via topologies that assign each RN its own bandwidth (Dedicated Bandwidth) via for example assigning fixed resources to each one; or on the other hand the topology can use shared bandwidth techniques.

The ODN that is most related with the service provided by the access network, it may be implemented via a topologies wherein which each RN broadcasts the information received from the CO through the OFN to the all its BSs, or else, via topologies where the RNs processes the incoming data and sends it to the addressed BSs only by switching. (Table 3.1)

Distribution Network	Feeder Network	
	Bandwidth shared	Bandwidth dedicated
Broadcast	x	x
Switched	x	x

Table 3.1: Classification of different combinations to Access Networks

Thus each one of the typical topologies (**Figure 3.4**) has different features due to its broadcast or switched nature and treatment of the bandwidth, and also additionally of the number of nodes that it can support, capability to be extended, or survivability (R.Randhawa, 2009) (Prat,

2008). According on the features of the service provided, there will be different combinations of those options to support these requirements.

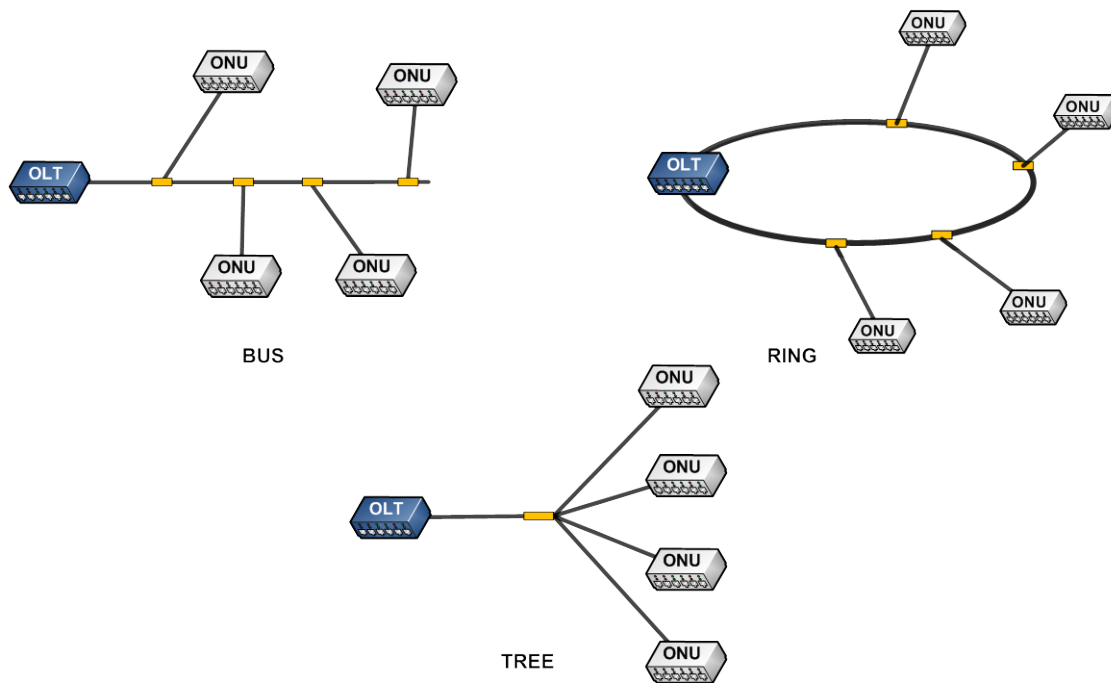


Figure 3.4: Different optical topologies

3.2.1.1 Bus topology

In this case, each node sends the information in broadcasting through the distribution fiber up to the destiny node and there could be collisions when two nodes try to transmit at the same time by which makes the use of schemes of collision handling or collision avoidance on the network a necessity; even more if large number of BSs is to be interconnected, because this schemes should be highly efficient to handle the high probability of instantaneous communications request.

In the event of a node failure said node is isolated from the communication but the rest of the network can still operate, whereas if there is a problem in some portion of the distribution fiber then the complete network goes down; thus doesn't provide survivability and the identification of failures is harder and slower than others topologies.

Moreover as the nodes are passive and don't amplify the signal and the quality of transmission is degraded when traveling long distances. Even if amplifiers are places at the start of each fiber segment, there are power penalties and the signal isn't recovered efficiently. (R.Randhawa, 2009)

On the other hand also the performance of the network will degrade as either the number of BSs or the length of the fiber trunk, increase. In addition, because bandwidth is shared among the nodes and because this topology doesn't support the transmission of heavy traffic due to the collisions management, the requirement of high bandwidth to broadband applications is limited. And, because the information is heard by all nodes the possibility to intercept the information by unauthorized users is greater.

3.2.1.2 Ring topology

This topology provides reliable networks because it may be implemented using one or more rings to add redundancy. This topology has different configurations, which are differentiated by the initials: "M x N", which means that there are M protection rings to support the N working rings; the protection rings may either be idle or active. The idle protection rings are activated only when some working protection ring falls, unlike the active protection rings can be directly connected to the working rings or the network components. This last is used in critical environments and the flow of traffic may pass transparently through both kinds of ring.

Also there are ring topologies that include the self-healing capacity, named Self Healing Ring (SHR), which besides to offer bandwidth sharing, also offer the self healing capability to mitigate network failures via different techniques, for example: reconfiguration of the interconnections between the internal switches of the nodes. The capacity offered by a SHR depends on the number of nodes in the network and the traffic demand, and the number of fiber cable demanded depends on the number of nodes.

The information is passed of one node to its adjacent node, in each one there is an Optical Add/Drop Multiplexer (OADM) which adds or drops sets of wavelengths channels, when the transmission is running; and each node acts as a repeater, from this manner the quality of the signal improves in each node and this doesn't arrive weakly to its destiny, to improve the quality factor of the network and connection to greater number of nodes (R.Randhawa, 2009).

In short, as the quality of the signal is improved with the increasing of the number of nodes and this allows to use more number of channels to up and downstream directions in a optical ring network; and there is the possibility of to add the self-healing and redundancy capabilities; this topology has been considered as a cost-effective survivable network topology (Ding-Zhu, 2007).

3.2.1.3 Star topology

This topology is centralized and of easy installation. Any node may communicate with all the other nodes; first, the information is conducted toward the central node, in which it is retransmitted to final destiny. The transmission is quick because the information doesn't travel

toward unnecessary nodes, which keeps the quality of the signal at every node though the number of nodes increases (R.Randhawa, 2009). However, due to each node is connected by point-to-point optical links (P2P), if there is large number of them, such as the case of the HFR network, the cost of the system is more expensive than using bus or ring topologies. Also, due to that the bandwidth is shared among the links, this limits the provision of high bandwidth applications.

The central node may be passive or active, in the first case, this node doesn't enable to respond to incidents related with echo of transmissions; otherwise, and the active node tolerates and responds the echo. In both cases, the central node is the weakest point of the network because if this fails then the entire network is broken; but if any another node fails or the fiber that connects it with the central node, only this node is not able to receive or send information, but all the rest of the network is not affected. Thus this topology isn't reliable because the main point of resources management is the major weak of the network and as all the information passes through the central node, the bottlenecks may arise if a wide volume of this is transmitted. On the other hand, this topology shows greater characteristics of the input signal than at bus topology nodes. The quality of the signal doesn't decrease or increase even if the number of nodes increases and there is a little tolerance to timing errors (R.Randhawa, 2009).

3.2.1.4 Tree topology

This is a topology that follows a hierarchical pattern, sometimes, it is known as an Expanded-Star topology because contains multiple star networks combined together, the central hubs of each one of these are connected to the trunk cable of the network and it is the mean communication with the central node.

It is a good option for branched out networks, because the groups of nodes may be configured in star topology and may be connected to the backbone, after. Also, it is of easy growth, since the nodes may be added or removed easily and the quality of the signals improves as the number of nodes increases (R.Randhawa, 2009). However, the trunk cable and the central node are the main weak points of the network because if anyone fails then the entire network is broken, unlike if there is some failure in some star network then a node can be isolated or in the worst case this star network is going off. Also, it is difficult to manage, configure and wire than other topologies; and if a link fails there isn't an alternative route.

3.2.2 HFR access based on mixed topology

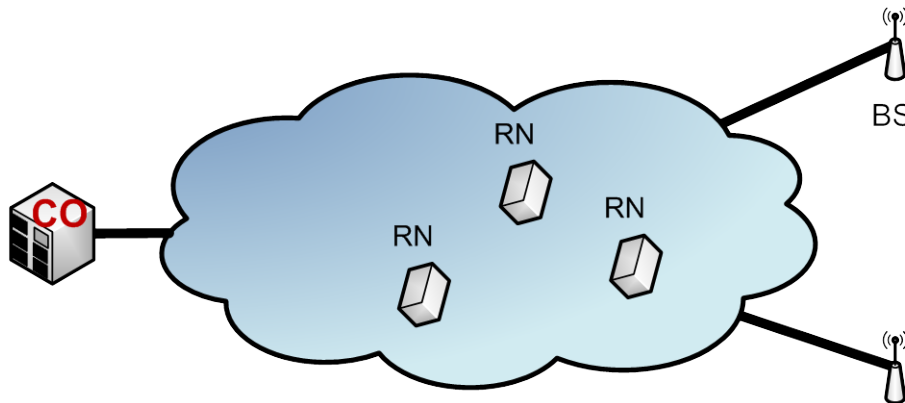


Figure 3.5: Optical access HFR network

As seen there isn't an absolute winner topology with totally optimal characteristics to implement the HFR's network; therefore mixed topology where two or three topologies are merged to overcome some limitations and to offer enhanced features for the implementation of the HFR network is what it is usually found.

In **Figure 3.7**, the cloud that represents the optical access network may be replaced by mixed topologies such as: Star- Ring, Star- Ring, Star-Bus-Ring, Star- Tree, Bus (Zhang, y otros), among others. (Zhang, y otros, 2005) (Peng-Chun Peng, 2007). According to the chosen mixed topology, there will be a different performance of the signal transmission and distribution signals.

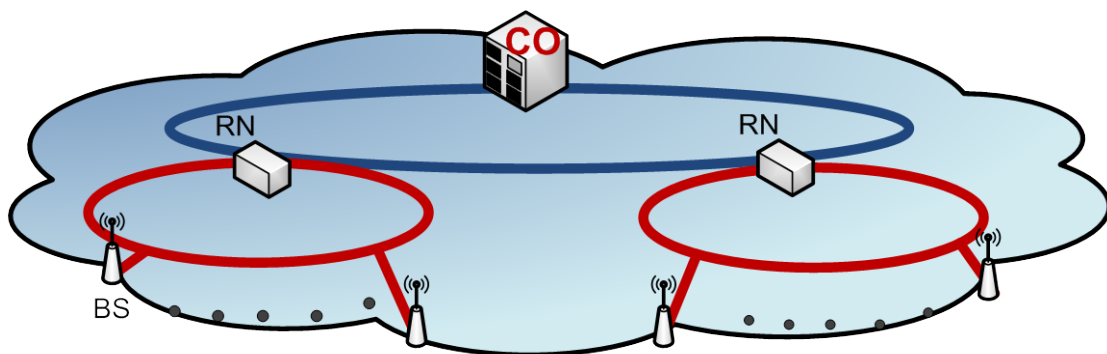


Figure 3.6: HFR access based on Ring- Ring topology

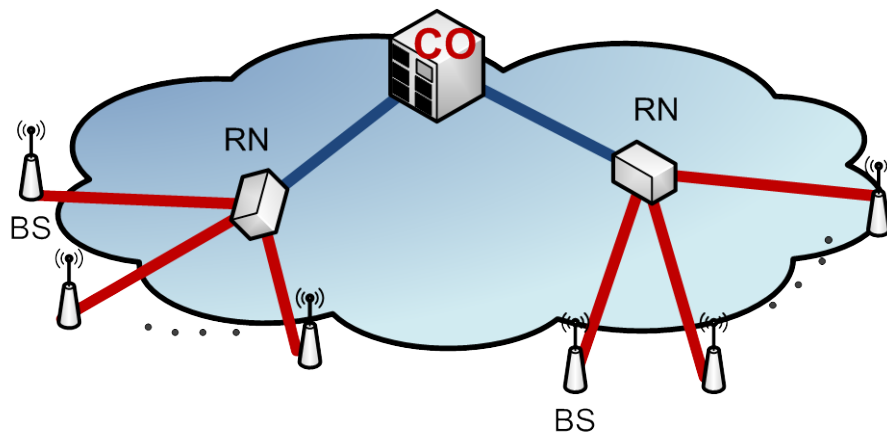


Figure 3.7: HFR access based on Star- Tree topology

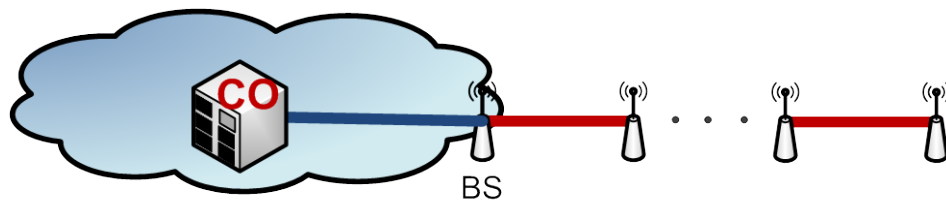


Figure 3.8: HFR access based Bus topology

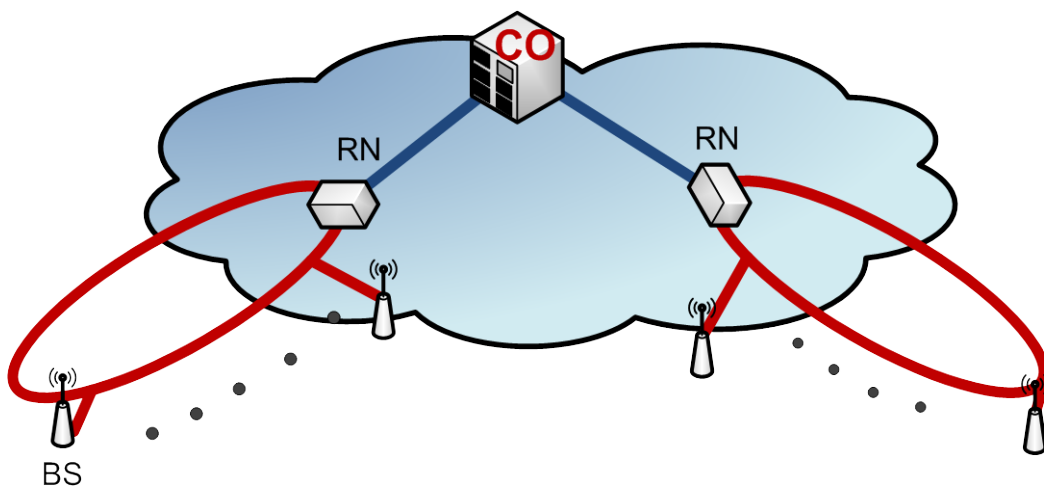


Figure 3.9: HFR access based Star- Ring topology

These mixed topologies are some physical topologies of the networks that are part of the named ngPON (Next-generation PON) or also known as Converged Networks.

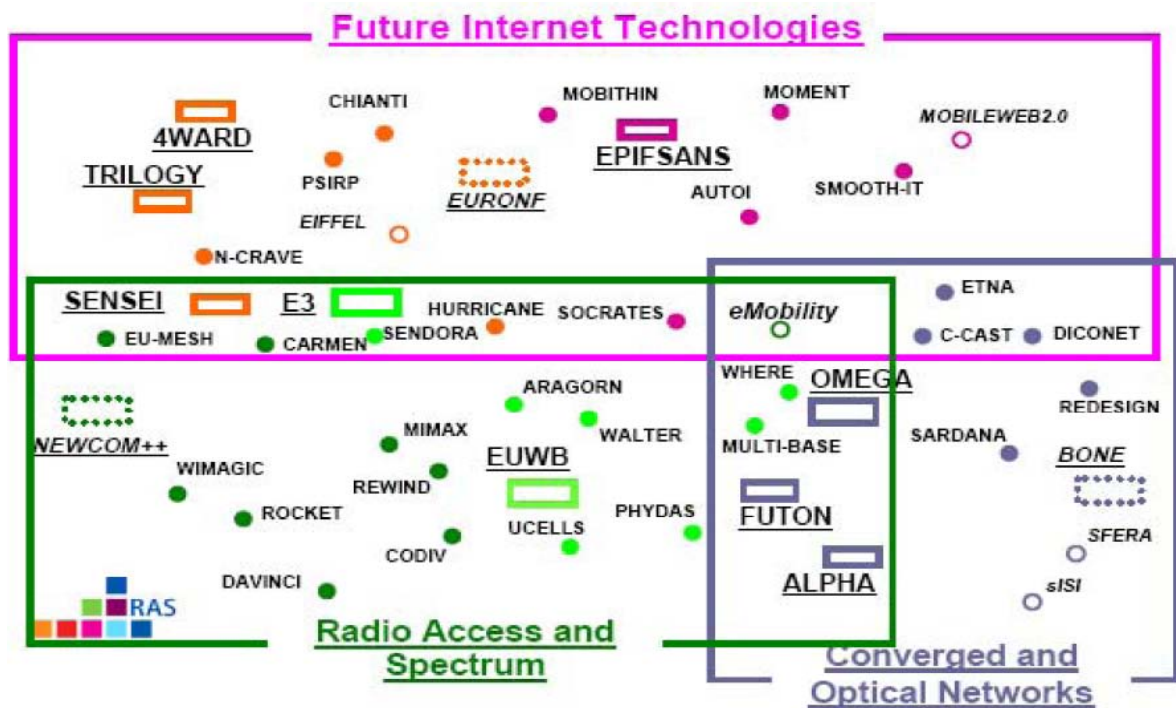


Figure 3.10: Future Networks Project Portfolio and Clustering, from (Peter Stuckmann, 2009)

The topologies of Converged networks are part of an upgrade process that looks into obtaining much higher capacity architectures to satisfy the increasing demand. The goal is to allow upgrades to bandwidth, Services and reach while keeping the existing service and equipment infrastructure. In order to achieve these challenges, a combination of the basic PON multiplexing techniques (PON) such as SCM (Subcarrier Multiplexing), WDM (Wavelength Division Multiplexing) and TDM (Time Division Multiplexing) should be required.

As known, by using SCM a frequency subcarrier is assigned to each ONU; with WDM typically each ONU is assigned two wavelengths unique for downstream and upstream transmission; and finally by using TDM, each ONU has a preassigned Time Slot (TS). In all these cases, the resources are allocated by the CO.

For example, currently there is the ongoing SARDANA Research Project, which is a consortium of research institutes from Spain, France, Finland, Greece, Portugal and Italy and is headed by UPC (Spain). The project aims at defining and developing a WDM/ TDM hybrid solution focused on an extended PON based on WDM technologies **Figure 3.11**. This is part of the first phase of the Seventh Framework Program (FP7) of the European commission Research, whose project portfolio of future networks is sketched in **Figure 3.10**. As seen, there are three clusters: Future Internet, Radio Access and Spectrum, and Converged and Optical Networks; Sardana is part of this last cluster

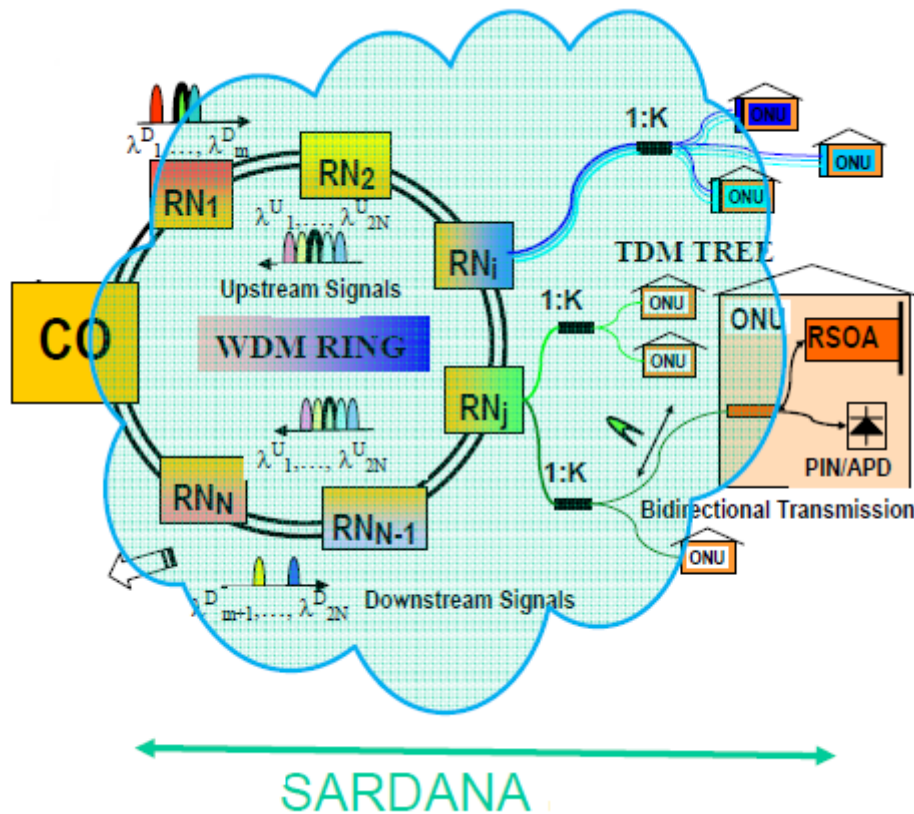


Figure 3.11: SARDANA architecture, from (FP7, 2008)

The WDM/TDM overlay consists in multiple TDM networks combined over a common WDM infrastructure. This approach reduces the implementation cost and provides higher bandwidth capability to end users, scalability and shared use of a common infrastructure by WDM. Thus SARDANA project is based on a Ring- Tree mixed topology, where in a feeder WDM ring network several RNs are connected with a CO and each RN feeds several TDMs trees at different wavelengths.

Sardana is in its third and final year and is close to completion; meanwhile in the 5th step of the same FP7, the development of the new Accordance project: “A converged copper-optical-radio OFDMA-based access network with high capacity and flexibility”, has recently begun as of January 2010 with UPC as a partner.

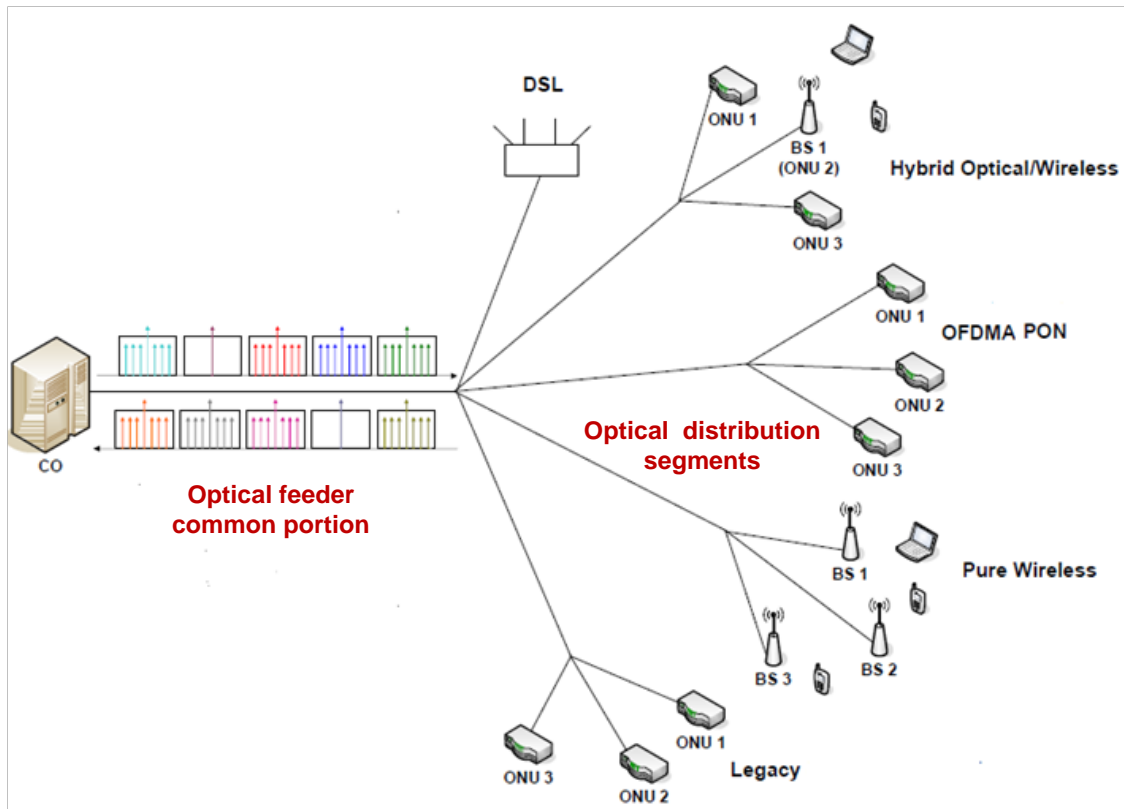


Figure 3.12: Proposed architecture converged copper-optical-radio OFDM-based access network, from (FP7, 2010)

Figure 3.12 sketches the basic goal architecture of the Accordance Network; as seen there, the challenge is the simultaneous feeding of both cable-based and wireless systems through a common fiber infrastructure. This is achieved by introducing OFDMA-based technology and protocols (Physical and Medium Access Control layer) to provide a variety of desirable characteristics, such as increased aggregate bandwidth and scalability, enhanced resource allocation flexibility, longer reach, lower equipment cost/complexity and lower power consumption, while also supporting multi-wavelength operation.

4 Hybrid Fiber Radio links

The majority of optical links for telecommunication applications are digital because the data arrives to the input of the link in digital format and this is regenerated in the same format; but the increasing requirement about high bit rates implies to apply analog techniques to design optical components with features that support this new requirements, such as high-speed lasers, optical modulators and photodetectors. This coupled with the HFR-links' feature to operate with radio signals at both the input and the output interface, usually leads to name them: Hybrid Analog optical links.

These Hybrid Analog optical links may be implemented to carry out either only transmission or else, to incorporate also Signal Processing Functions. When the only function is the signal transmission, the links are transparent and the signals remain unaltered as they cross the fiber; on the other hand when the signal is intentionally altered by the link, this adds functionalities and enables new applications

Thus those multifunctional links have capabilities such as:

- Transportation and distribution of radio signals over optical fiber
- Filtering, processing and data modulation of radio signals in the optical domain
- Generation and frequency conversion (up-down) of radio signals using photonics techniques,

however in this PFC, the focus is about the transport and distribution of the MMW-radio signals over optical fiber and therefore we won't be concerned about these multifunctional links, the interested reader is directed to Bo, 1998.

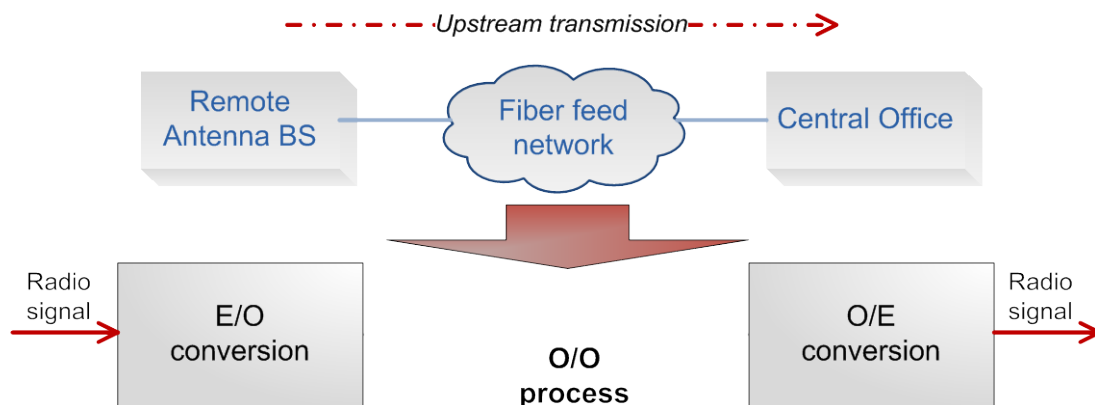


Figure 4.1: Point to point HFR links: scheme of radio signal transmission

The most straightforward implementation of the hybrid analog optical link in a HFR system consists of a P2P (Point to Point) connection between a remote user location (BS) and the centralized location (CO) for control and processing.

Figure 4.1 sketches the broad processing for the hybrid wireless-fiber transmission. As seen, this basically requires:

- Hardware to inject to RF signal onto the optical carrier (E/O)
- Hardware to recover the information from the optical carrier (O/E)
- Transmission media to couple the end devices, optical fiber (O/O)

As **Figure 4.1** shows, for upstream transmission, once the mm-wave radio signal is received by the antenna in the BS, it is subject to electro-optical conversion process (E/O) to propagate the information over the fiber (O/O). Finally in the CO the signal is detected and converted to electric domain again (E/O).

On the other hand, when the signal is transported over the optical fiber, it is important to consider features and properties of both components at the link end as well as the optical fiber, because some of them may highly affect the signal and in consequence also the link performance.

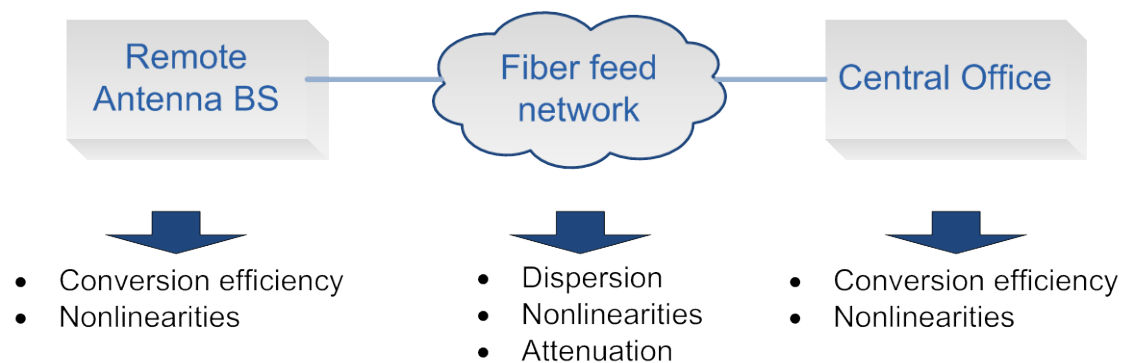


Figure 4.2: Location of impairments in a P2P HFR transmission

Figure 4.2 shows the location of impairments in a P2P-HFR transmission. As seen, it is important to consider the conversion efficiency of both E/O and O/E, the level of the nonlinearities of the processes and the devices at both BS and the CO; and also the properties of the fiber (O/O), that most likely to affect the link performance such as its dispersion, nonlinearities and attenuation.

Due to those impairments, the quality of the signal may decrease and this may produce a degradation of the overall system performance. Thus a challenge in the design of a HFR network consists in the use of schemes and the implementation of strategies in order to overcome these limitations and to allow efficient transmission of the MMW-radio over optical

fiber because the limits on the performance of the links also impact on the device design (C. H. Cox, 2006).

For example, to carry analog signals requires high values of Signal to Noise ratio (SNR), by which there is a need for higher average optical power than in typical digital links; meanwhile the analog optical links also demand High Linearity when receiving those High Optical Powers. Moreover, due to the High Data Rate required by the Broadband applications a High Bandwidth capability is required in devices; and in order to achieve High Conversion Efficiency, there comes the need for High Responsivity values at photodetector. As seen the combination of some requirements may impose some additional tradeoffs. See **Table 4.1**.

High Optical Power	High Responsivity : High conversion efficiency
	High Linearity : Overcome Nonlinearities arisen at High Optical Power
	High Bandwidth : High Data rates

Table 4.1: Analog optical link requirements

4.1 HFR-link's anatomy

The transport of the radio signals over the optical fiber first requires the realization of the process of conversion from electrical to optical domain that consists in the modulation of the radio signal at MMW frequency (w_m) onto an optical carrier (w_0). Considering the electric field generated by a monochromatic laser (ideal condition) as $E(t) = E_0 \cdot e^{j \cdot (w_0 \cdot t + \phi_0)}$, it is possible to modulate either its intensity ($|E_0|^2$), frequency (w_0) or phase (ϕ_0). The typical modulation is Intensity Modulation (IM) and this can be achieved either directly or externally. As **Figure 4.3** shows in the former the MMW radio signal is applied directly to the optical source whereas the latter requires an optical source and an external modulator, and also provides phase and frequency modulation.

The photodetection process consists in the O/E conversion of the incoming modulated optical signal; specifically in a MMW-HFR system, this consists in the recovery of the MMW radio signal. This may be achieved via Non-coherent or Coherent techniques. Also as seen in **Figure 4.3**, the Non-coherent detection also known as Direct Detection (DD), consists just in verifying the presence or absence of the carrier without considering the frequency or any phase information. Conversely, the coherent detectors have the same capacity to detect the intensity (amplitude) but also frequency or phase of incoming signal such as the majority of the radio detectors. On the downside though require an additional optical carrier source at the photodetection side.

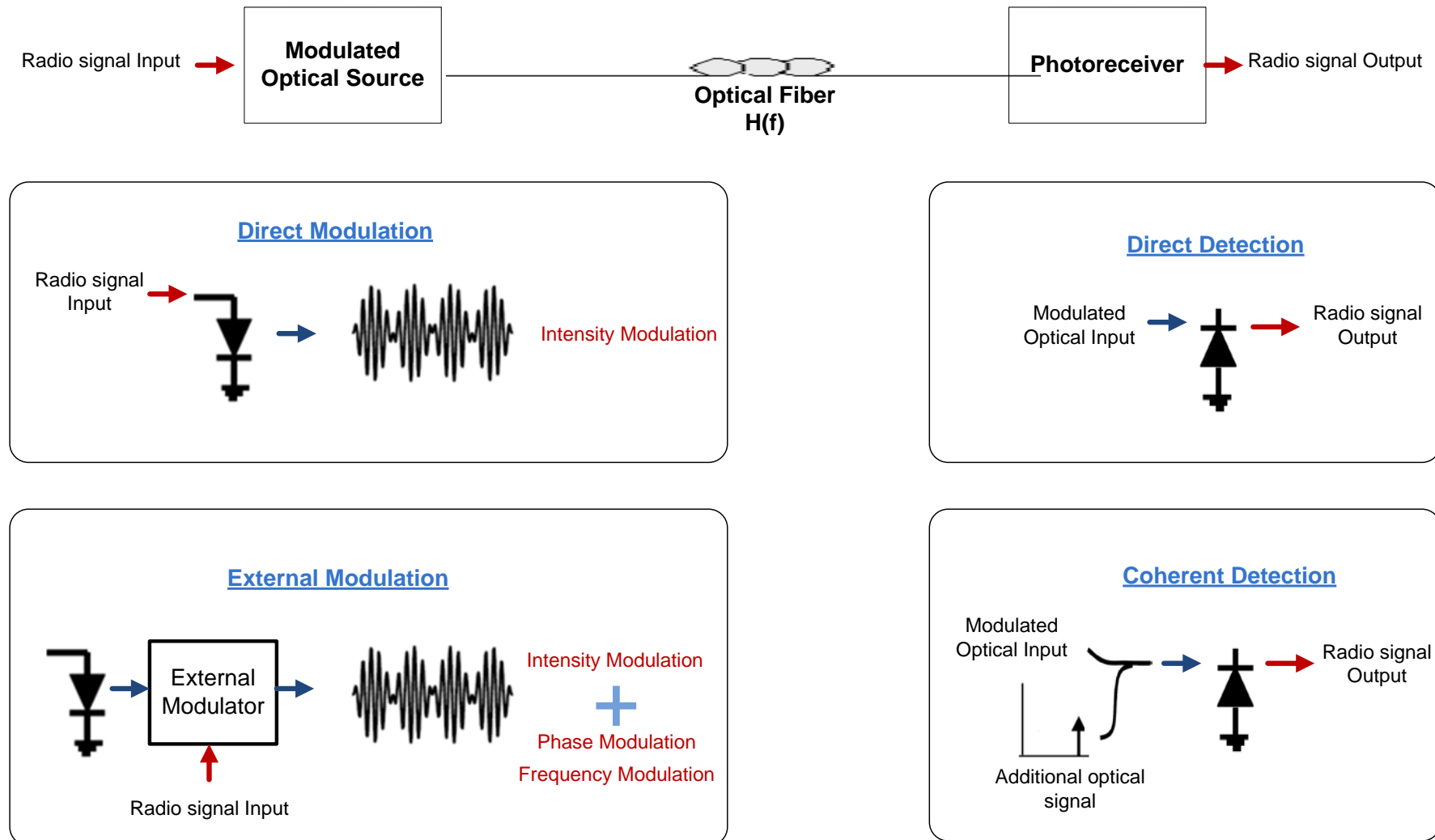


Figure 4.3: HFR link architectures for direct and external modulation, and for direct and coherent detection (Iezekiel, 2009)

The differences between the links based on coherent or non-coherent techniques, basically lie in the role of the modulator in the transmission, if it just realizes E/O conversion or also additional functionalities; and in the detection, if it just consists on the verification of the presence or absence of the optical carrier or also additional conversions. Thus, in the remainder of this chapter the focus is placed on the description of the features of the optical modulation, transmission and photodetection.

4.1.1 Modulation

Due to the IM, the optical modulated signal generated contains a carrier at the central optical frequency (w_0) and multiple sidebands at $w_0 \pm n \cdot w_m$ frequencies, being w_m the MMW frequency and n an integer number. Sometimes this modulation is also termed as Amplitude Modulation (AM), although this latest just produces two sidebands at either side of the carrier. This interchange only is right if the index of modulation (m) is as low that the sidebands of greater order of the IM signal are negligible and its spectrum has approximately the same bandwidth that to AM signal.

4.1.1.1 Direct modulation

This type of modulation requires the use of Directly Modulated Laser (DML) such as Distributed Feedback (DFB) or Fabry Perot (FP), because a drive current (I_L) is directly applied to the entry of the laser to modulate the optical carrier and thus generate the optical output power (P_{OPT}); in this case the MMW radio signal will be the drive current, see **Figure 4.4**.

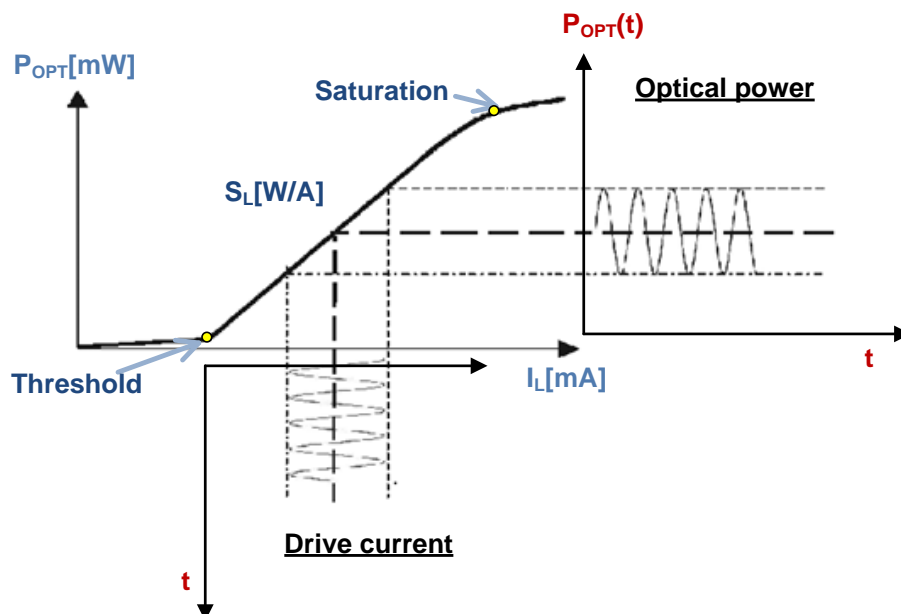


Figure 4.4: Transfer function and operation principle of Direct Intensity modulation

The operation principle is termed as Current Driving because the optical power follows the drive current via the tracking of the changes produced by the variation in the time added to the current. Provided the values of I_L doesn't go below threshold or into saturation, the characteristic Light–Current (L-I) for the laser may be approximated by a straight line curve whose slope is the slope efficiency, S_L , expressed in W/A (See **Figure 4.4**)

The maximum modulation bandwidth, BW_{mod} , is defined according to the design of the laser, because the frequency response of the laser gives a resonance peak at a frequency termed as Relaxation frequency (f_{relax}), which determines the maximum modulation bandwidth of the laser. Commonly the resonance peak is located 3dB over the response at small signal, by which f_{relax} is lesser than the frequency at which is given the BW_{3dB} .

$$f_{relax} \propto \frac{1}{\sqrt{\tau_p \cdot \tau_n}} \quad \text{Equation 4.1}$$

The value of f_{relax} (Equation 4.1) is inversely proportional to the geometric mean of the lifetime of both the photons (τ_p) and the carriers (τ_n). The increment of the incident current reduces both lifetimes and it increases f_{relax} ; this is the nature of the relation between f_{relax} and P_{OPT} , which is:

$$f_{relax} \propto \sqrt{P_{OPT}} \quad \text{Equation 4.2}$$

As seen in Equation 4.2, the f_{relax} is proportional to the square root of the average optical power (P_{OPT}) (Charles H. Cox, 2006); thus in order to obtain higher frequency response, the laser must operate at a drive current several times greater than the threshold current ($I_L \gg I_{TH}$); but to achieve further bandwidth increases via simple increases of the optical power will be difficult due to the laser heating at the higher bias current (drive current). (Charles Cox III, 1997).

, (The most important and limiting factor as compared with external modulation is the Chirp effect. Which is an inadvertent modulation of the optical frequencies that happens while the drive current is being modulated, and that combined with the CD lead to important signal degradation because the portions of the optical signal that are 'chirped' (distorted), are also advanced or retarded by the dispersive effect of the optical fiber, this results in both pulse distortion, residual Phase Modulation (PM) and Intersymbol Interference (ISI). (Asier Villafranca, 2007)

In spite of impairments produced by DM's device limitations and the inherent defects (C. H. Cox, 2006), there is a growing interest to use DMLs in Cost-sensitive and the Optical Access Networks, because of their low cost and compact size compared with external modulation

4.1.1.2; therefore there are several proposed approaches looking into different ways to overcome those limitations. (Zhensheng Jia, 2007)

4.1.1.2 External modulation

Figure 4.5 shows the typical characteristic of the most popular types of external modulators: Electroabsorption (EMM) and Mach-Zehnder (MZM), 'Voltage-driven' devices. As shown the basic setup for both has both an electrical and an optical input; the MMW signal will be applied to the first; an optical signal from a Continuous Wave laser (CW) will be applied.

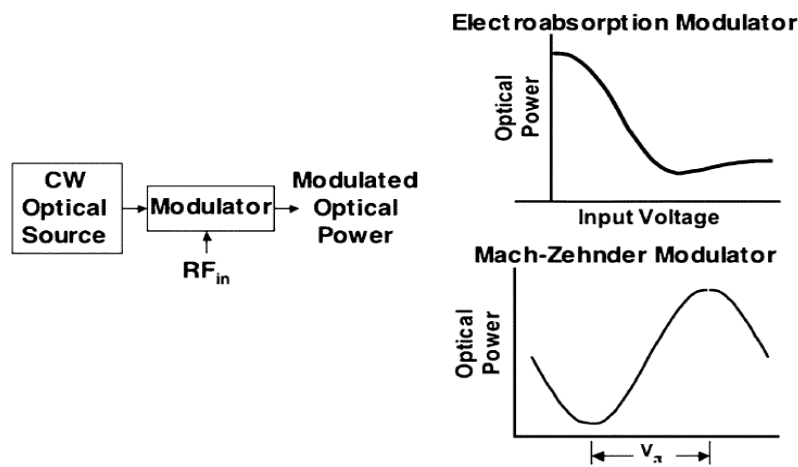


Figure 4.5: External modulation basic setup. Typical characteristics: Electroabsorption and Mach-Zehnder external modulators, from (Richard Williamson, 2008)

MZM is an interferometric modulator that has been the most highly developed and commonly commercially used. Its operation principle is based on the linear electro-optical effect, typical phenomenon of the Lithium Niobate ($LiNbO_3$) crystals with which this modulator is made, and that implies the travelling signal is sensible to the media's refraction index that varies according to the applied electrical field. As seen in **Figure 4.6**, the MZM has two optical branches or interferometric arms, at which a radio signal and a bias voltage at V_{rf} and V_{dc} , are applied respectively.

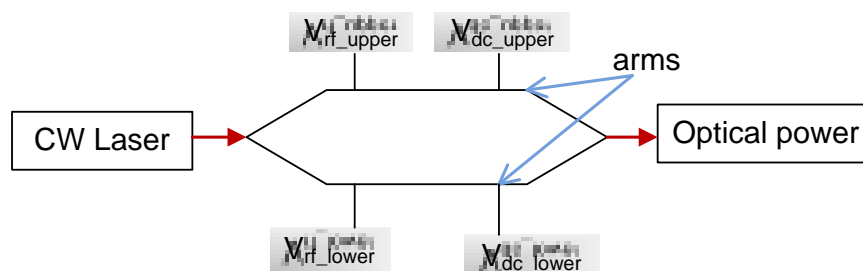


Figure 4.6: Mach-Zehnder external modulator

The principle of operation is as follows the propagated signals get phase-modulated by the electric field applied to the electrodes, and finally the combination of these two signals produces an amplitude modulation at the output.

The **Figure 4.7** sketches the MZM transfer function. In the y-axis there is the ratio of optical power (P_0) to the power supplied by the CW laser source (P_i); and in the x-axis there is the ratio between the drive voltage (V_m) to V_π . The voltage sensitivity of the electrodes that is a property of the modulator and represents the minimum voltage required for a phase shift of π between the two modulator branches, may be considered as analogous to I_{TH} (threshold current) in a laser diode, is represented by V_π .

About the slope efficiency (S), unlike DM, where S_L is a device parameter; for an external modulator, S is a derived parameter. For the MZM, S_{MZ} depends on the Bias point, P_i and V_π , and the external CW laser will act as a external control parameter: 'bias' to control S_{MZ} , because an increase of the CW laser power increases S_{MZ} .

The Bias point is set by the continuous voltage (V_b) at any of its possible operation points: Quadrature Point (QP), Minimum Transmission Point (mTP) and Maximum Transmission Point (MTP). The bias required for small-signal linear modulation, i. e. IM, due to the periodic transfer characteristic, may be located at any multiple of $V_\pi/2$ with alternating slope signs; in Figure 4.7 it has been located at $3V_\pi/2$ where the slope is positive

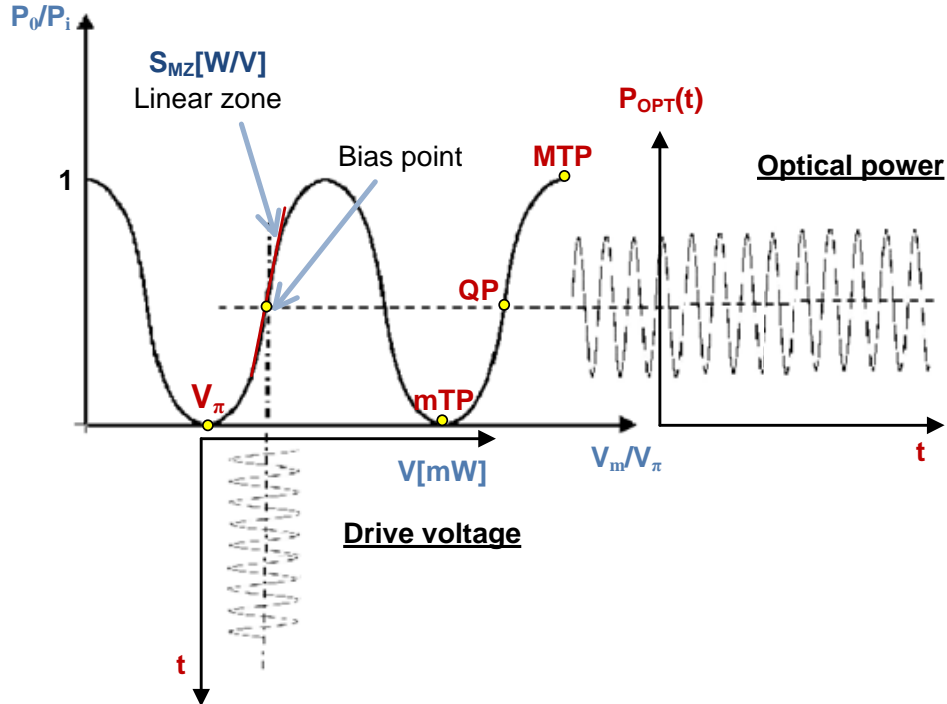


Figure 4.7: MZM transfer function and operation principle

In order to obtain an IM signal as same in DM case, MZM must be in QP. Thus the generated signal also w typically are only a few hundred KHzill be constituted by one optical carrier at w_0 and multiple sidebands at ' $w_0 \pm n \cdot w_m$ ' frequencies. However, unlike DML that provides limited transmission distance due to the interaction between the light chirping with CD, there are external modulation schemes, which may provide far better chirp behavior and thus improves the reach of the link (Graham H. Smith, 1997) (A. H. Gnauck, 1998) (C. H. Cox, 2006)

4.1.2 Transmission

The large bandwidth of the optical fiber is a major driver for using it as a transmission media for the access in the HFR network. The characterization of this O/O process is important in order to know the implications and requirements over the modulation and the photodetection processes.

The majority of the HFR systems reported in the literature and in most wireless standards (GSM, WiFi, 802.11 a/b/g, UMTS, or WiMAX) prefer to use Single Mode fiber (SMF) (Mohammad Shaifur Rahman, 2009), mainly due to the fact that being free from intermodulation dispersion it allows transmission over much more longer distances than multimode fiber. SM in addition features low transmission losses (0.2 dB/km at 1550 nm,,), engineering simplicity and low cost. Among the fiber's effects that affect the HFR transmission mentioned before (**Figure 4.2**), the most relevant is the Chromatic Dispersion (CD). (Charles H. Cox, 2006)

The IM signal has several harmonics and when this is transported over the fiber all its spectral components are affected by the CD and each one experiences a different phase shift which results in radio power penalties after the detection due to the pulse broadening. After sufficient fiber length the reconstructed signal will be a distorted copy of the original and the acceptable tolerance of the CD's effect will be drastically reduced,

Equation 4.3 shows the expression that corresponds to the CD factor, there is seen, the relation that exists between the spreading suffered by the transmitted pulse $\Delta\tau_g$ and the fiber's dispersion. In addition, it helps us to indicate the typical units to express the chromatic dispersion: $ps/nm \cdot Km$ (pulse delay in picoseconds, $\Delta\lambda$ (wave length spectral width) in nanometers and fiber's length in kilometers).

$$D = \frac{\Delta\tau_g}{z\Delta\lambda} \quad \text{Equation 4.3,}$$

There will be frequencies at which there will be complete extinction of the recovered MMW signal and this will limit the transmission distance, because of CD's effect increases as the frequency offset between the sidebands, relative to the carrier, increases. In this section the dispersion induced penalty (See 4.1.3.1). To evaluate the dispersion induced penalty, the fiber

is modeled as a band-pass filter with flat amplitude response and linear group. The low-pass equivalent transfer function of the fiber is given by:

$$H(f) = e^{-j\phi(f)} = e^{-j\alpha f_m^2} \quad \text{Equation 4.4}$$

$$\alpha = \frac{\pi \cdot D \cdot \lambda_0^2 \cdot L}{c} \quad \text{Equation 4.5,}$$

where the MMW frequency modulation will be represented by f_m , the optical carrier wavelength is λ_0 , the CD factor is D , the velocity of light in vacuum is c and fiber's phase is $\phi(f)$.

The $\phi(f)$ introduces a phase change on each sideband, and a complete extinction happens when the difference of sideband phases is π . Moreover because the dispersion effect exhibits a cyclic behavior, there is a period length (ΔL) at which there will be minima of the detected signal. (U. Gliese, 1996)

$$\Delta L = \frac{c}{D \cdot \lambda^2 \cdot f^2} \quad \text{for } \phi(f) = \pi \quad \text{Equation 4.6}$$

Figure 4.8 shows the mentioned cycling of the CD's fading effect over the detected amplitude, comparing it for two carrier frequencies: 60GHz and 30GHz. The curves correspond to both MMW carriers being transmitted under the same conditions ($\lambda = 1550\text{nm}$, SMF with $D=17\text{ps/km} \cdot \text{nm}$). It is seen that the first fading occurs for the carrier of 30GHz around 4Km of transmission distance, while for the carrier at 60 GHz one has a 1dB of penalty induced around 500m and a complete extinction at 1Km.

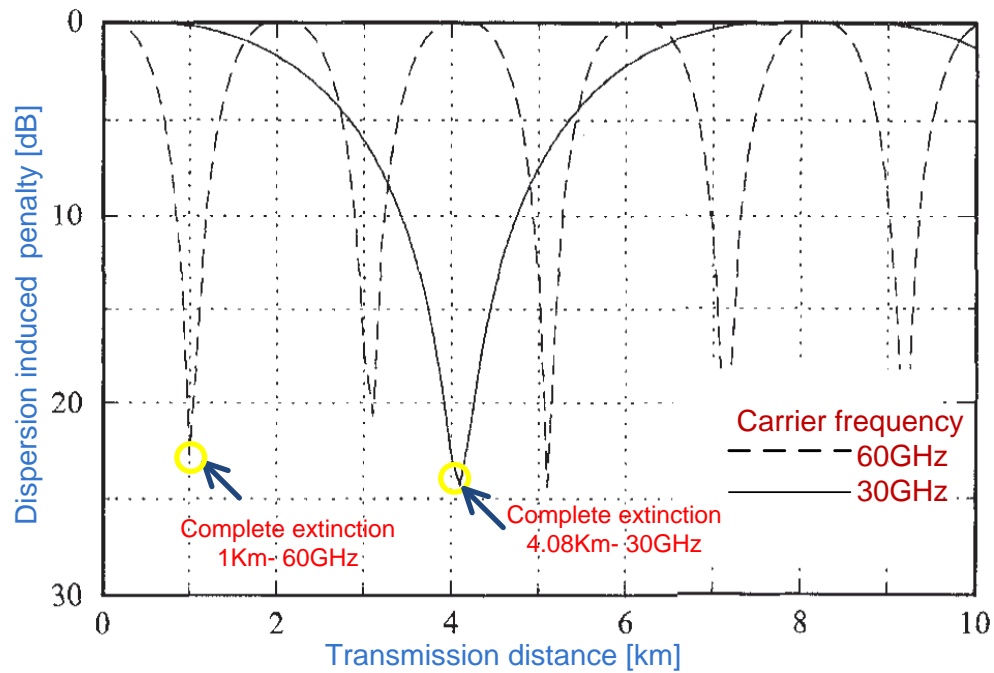
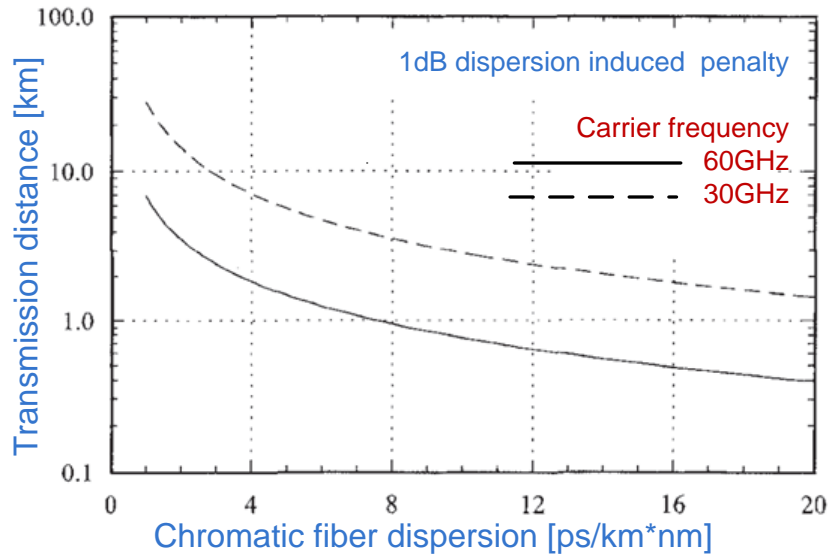


Figure 4.8: Dispersion induced CNR penalty as a function of the transmission distance with carrier frequency as parameter, from (U. Gliese, 1996)

As seen from Equation 4.6, the transmission distance (L) has a $1/D$ dependence on D and a $1/f^2$ dependence on the MMW carrier frequency (f). **Figure 4.9** shows these dependences, considering a tolerable penalty of 1dB; **Figure 4.9.a** shows a fall of the transmission distance curve as D increases due to the $1/D$ dependence, also L is less at 60GHz than at 30GHz for the same values of D which confirms the expectation of shortest transmission distance at higher frequencies; on the other hand **Figure 4.9.b** shows that the transmission distance curve has a faster falling slope as the carrier frequencies increase due to the $1/f^2$ dependence, also at the same values of carrier frequency L is shorter for greater values of D .

a)



b)

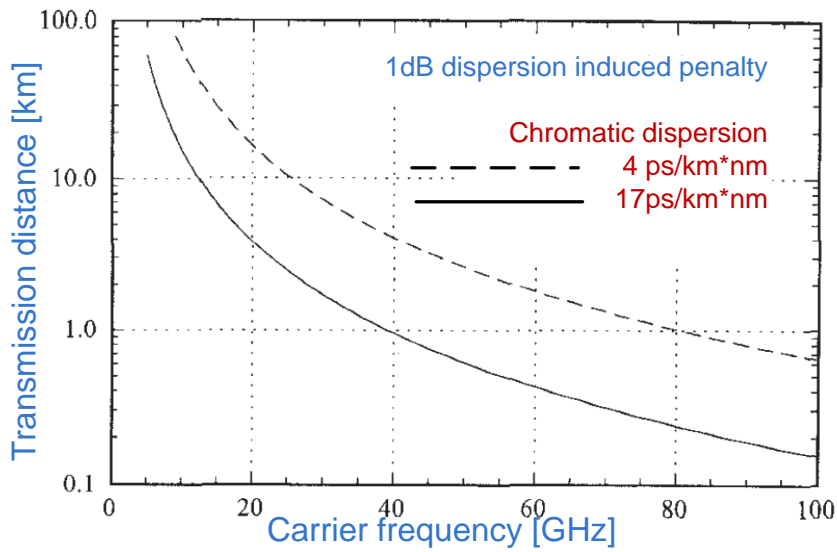


Figure 4.9: Dependence transmission distance on (a) Chromatic fiber dispersion and (b) Carrier frequency, from (U. Gliese, 1996)

4.1.3 Detection

The photodetector should show high bandwidth, conversion efficiency, and saturation power, in order to enable HFR links to have higher link gain, lower noise and wider SFDR. This high bandwidth required implies that the photodetector must operate at high-frequencies, for the case of MMW-HFR links in the MMW band. The conversion efficiency refers to the

photodiode's Responsivity (R) it is expressed in $[\text{mA/mW}]$ units and indicates which portion of the incident optical power (P_I, mW) is absorbed to generate the photocurrent (I_p, mA). Thus due to the linear dependence between R and P_I , in order to generate a high-power MMW signal, the photodetector should exhibit a High Responsivity and to allow high values of optical power incident at the photodetector via a large Saturation photocurrent.

Since R is frequency dependent, $R(j\omega) = I_p(j\omega)/P_I(j\omega)$, there will be a high quality of the detection if R has a fairly flat frequency response, which means an invariant behavior even if the frequency increases (Charles H. Cox, 2006). This is important due to the impairments that arise from some devices when their working frequency increases. The DC component of R is given by the slope of the characteristic curve of the Photodetector Transfer Function (Optical Power-Photocurrent), which is the straight line shown in the **Figure 4.10**.

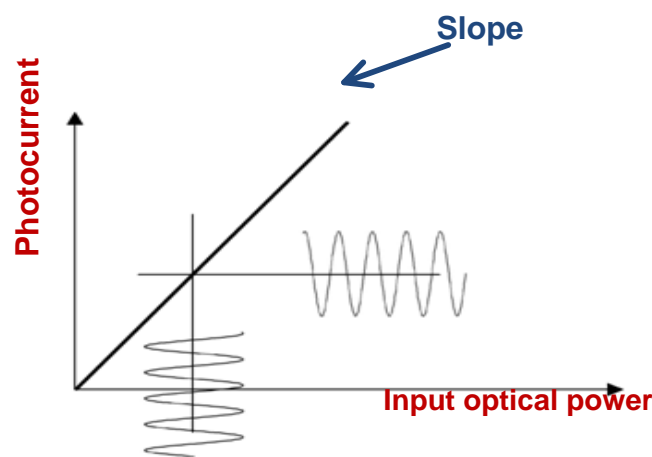


Figure 4.10: Photodetector transfer characteristic

In general the photodetector should provide a high frequency performance at MMW frequencies in order to provide an efficient detection of the MMW optical modulated signals. There are different types of high-frequency photodetector designed to be used in applications for wireless broadband communication and allowing to work at the multi-GHz frequencies or even THz. (Andreas Stöhr, 2001; Charles Cox III, 1997) (Iezekiel, 2009)

4.1.3.1 Non coherent detection

This detection is similar to the typical DD of radio signals although with a little more complexity in the optical domain. It consists of verifying the presence or absence of the carrier thus it is technologically simpler as compared with Coherent detection which detects both the intensity and the frequency or phase information.

Since the photocurrent (I_D) is directly proportional to the square of the magnitude of the incident optical field ($|E(t)|$), and also linearly dependent on R it is also referred to as a Square-law process.

$$I_D = R \cdot |E(t)|^2 \quad \text{Equation 4.7}$$

As the photodiode just responds to the intensity of the optical field it only recovers intensity modulated signals, and all frequency and phase information of the carrier is lost. Hence the DD just can be combined with Intensity Modulation (IM) and the links based on this are termed IM/DD. **Figure 4.12** shows the scheme of the IM/DD links, where the input signal is intensity modulated onto the optical carrier and then it is recovered by DD in a photodiode.

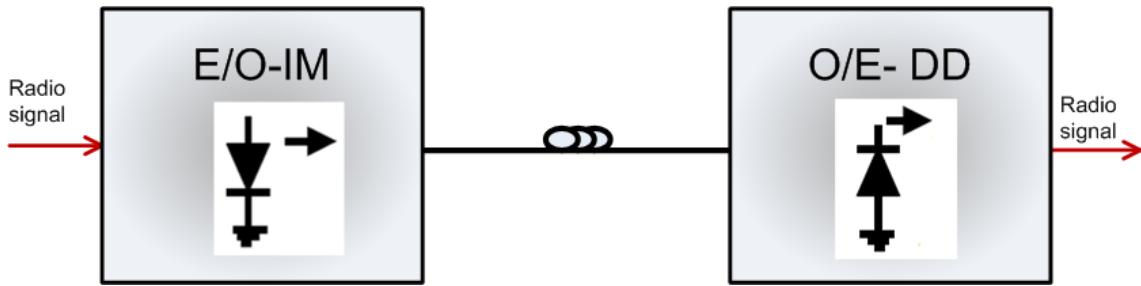


Figure 4.11: IM/DD link

In DD the R is limited by the quantum limit that is a parameter related to the probability of detecting a number of photons and the corresponding probability of error. This limit is scarcely reached by DD links and it is further away for higher working frequencies because of the mentioned frequency dependence of R . Unlike Coherent detection-based links, which provide values nearly to or even exceeding the quantum limit for the DD links; thus the Coherent Detection may provide greater efficiency of detection at higher frequencies (Charles Cox III, 1997).

On other hand, as it has been described in 4.1.2, the CD becomes an important limiting factor for the transmission distance of HFR- IM/DD links when the radio signals are in MMW frequency band (MMW-HFR links) because of the CD's effect increases as the carrier frequency increases.

4.1.3.2 Coherent detection

The coherent detection allows to demodulate the optical carrier modulated either in intensity, frequency or phase, without losing the information of frequency or phase. Its principle of operation consists in the interaction between two laser signals at the photodetector via

heterodyning or homodyning. The generated photocurrent $i(t)$ is obtained as in Equation 4.8 ; where R is the responsivity of the photodetector, the product of the instantaneous powers of the optical modulated signal and the additional optical signal ($P_1 \cdot P_2$) is P , the difference between the instantaneous values of frequencies ($w_1 - w_2$) is w_{IF} , and the difference of instantaneous values of phases ($\phi_1 - \phi_2$) is $\Delta\phi$.

The term ' w_{IF} ' represents the value of the frequency offset that exist between the two optical signals and it is named Intermediate Frequency. The detection process is termed as Homodyne detection if w_{IF} is equal to zero. Whereas if w_{IF} is a radio carrier frequency, the detection is Heterodyne, by which, this last technique is used in the implementation of the detection for the hybrid MMW-HFR links and w_{IF} will be the desired MMW-frequency (Companies, McGraw- Hill, 2002)

$$i(t) = 2R\sqrt{P} \cdot \cos(w_{IF}t + \Delta\phi) \quad \text{Equation 4.8}$$

The heterodyne detection in turn may be implemented via either locally (Local Heterodyne Detection, LHD) or remotely (Remote Heterodyne Detection, RHD). In the RHD links both signals are generated at the transmitter end of the link whereas LHD links require an optical local oscillator to generate the additional signal at the end of the link; both principles of operation are showed in **Figure 4.12** and **Figure 4.13**.

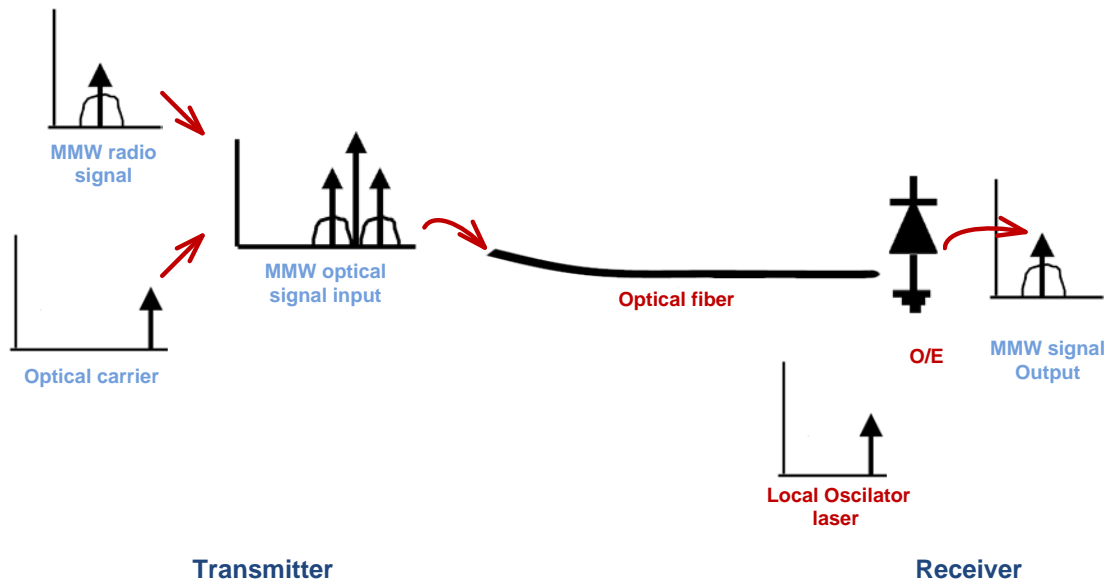


Figure 4.12: Principle of operation Local Heterodyne Detection

From Equation 4.8 the current at the output of the photodetector is maximized for highly correlated laser signals. Thus given that the principle of operation of RHD links (**Figure 4.13**) implies generation of two correlated optical carriers having a frequency offset equal to the desired MMW-frequency, there is more stability to manage and to preserve the parameters of the optical signals as compare using the LHD technique; because in that case both modulated signal and carrier can be extracted from a highly correlated source whereas LHD imply using different sources for modulated signal and carrier whose correlation characteristics are difficult to control.

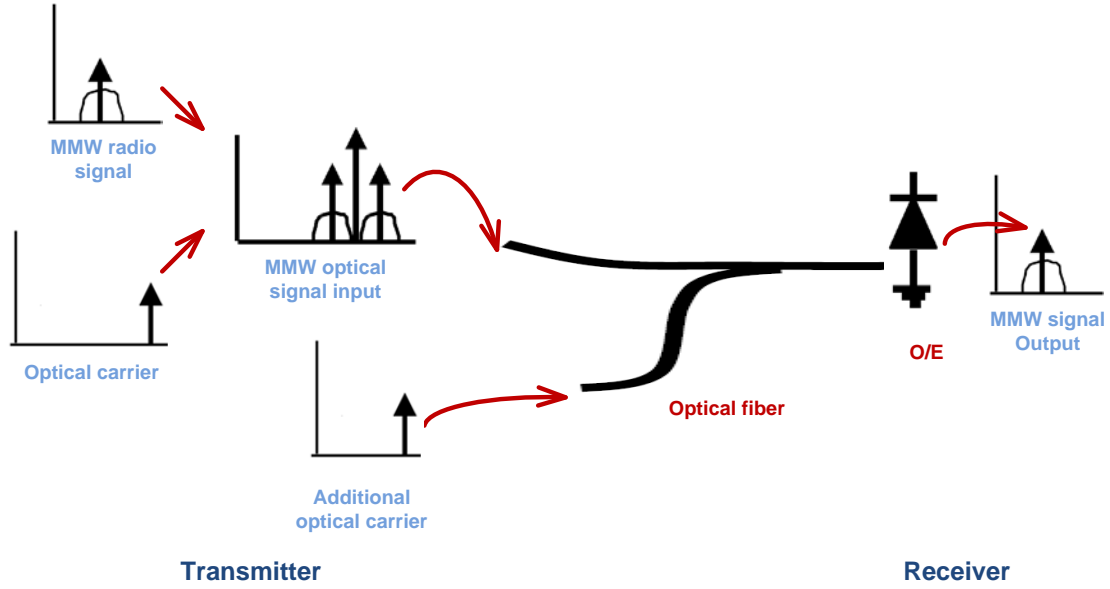


Figure 4.13: Principle of operation of Remote Heterodyne Detection

On the other hand, in RHD although the signals are generated in correlation to preserve the parameters of the optical signals, both could not be phase-correlated at the remote detector due to a differential propagation delay ($\Delta\tau$). This effect is sum of a differential delay produced by the CD when they travel together in the fiber ($\Delta\tau_{disp}$) and other produced by the path imbalance ($\Delta\tau_{path}$) in the emitter:

$$\Delta\tau = \Delta\tau_{disp} + \Delta\tau_{path} \quad \text{Equation 4.9}$$

$$\Delta\tau_{disp} = \frac{D \cdot L \cdot \lambda^2 \cdot f}{c} \quad \text{Equation 4.10}$$

$$\tau_{path} = \pm \frac{\Delta L_{path} \cdot n}{c} \quad \text{Equation 4.11}$$

The differential dispersion delay $\Delta\tau_{disp}$ (Equation 4.10) is produced by the differential propagation delay that the signals experience while traveling inside the fiber and it depends on L, λ, f (MMW carrier frequency) and D . Moreover because of the signals may be propagated via different paths, which are not perfectly balanced, the signals also experience a differential path delay $\Delta\tau_{path}$ (Equation 4.11), that depends on the difference in path length ΔL_{path} and a refractive index ' n '.

For small values of $\Delta\tau$ the signals remain correlated; but as $\Delta\tau$ increases the correlation diminishes. Thus there will be $\Delta\tau$ values to which there will be obtainable transmission distance (L) with acceptable penalties and others where L will be limited. In this sense, the coherent principle states that the sum of optical laser signal linewidths must be much less than the receiver linewidth or both must have very narrow linewidths; thus this scheme of detection allows to transmit over long distances with reduced linewidth of the source (U. Gliese, 1996). On another hand, because the majority of optical sources with reduced linewidth cannot be directly modulated at high frequencies the HD should be combined with the External modulation in the MMW-HFR links. (Nan Guo, September 2006)

On the other hand, as is seen in Equation 4.8 any change in some parameter of these optical signals produces a proportional variation in the output signal; this allows to implement signal processing in the optical domain, which isn't possible in Non-coherent links, and offers high flexibility in terms of multiple link functionalities. In this regard, by using a Dual frequency laser transmitter in a RHD link, two phase-correlated signals are generated which can be individually processed. Thus, as seen in Figure 4.13, the principle of operation of the RHD detection, one of these optical carriers is modulated by the MMW radio signal to then be transmitted with the other optical signal together through the FO to the photodetector; where they are heterodyned and the intermediate frequency equal to the MMW frequency is generated.

In short, despite the RHD detection requires more hardware and it is more complex than DD because it implies greater control over the relationship between the frequencies and phases of the lasers; it is more convenient because provides high-quality detection (greater CNR- less phase noise) and they allow great reach at MMW frequencies because they are inherently less sensitive to fiber dispersion and it allows for impairments correction in the electrical domain (Iezekiel, 2009) (Companies, McGraw- Hill, 2002).

4.2 SSB+C Modulation scheme to mitigate dispersion's effect

As afore mentioned in 4.1.2, CD may severely limits the maximum transmission distance of DD-based links. These penalties can be mitigated via different techniques such as advanced modulation schemes chirped fiber gratings, phase conjugation, etc. The most frequently used

technique consists in the generation of another signal format different from the typical IM DSB+C (Double sideband plus Carrier) format, such as SSB+C (Single Sideband plus Carrier). This scheme allows to overcome the dispersion induced radio power fading along the fiber and also to implement other techniques to improve the transmission and distribution of the MMW radio signals in the HFR network such as Wavelength Interleaving (WI) scheme for efficient multiplexing of the signal (J. J. Vegas Olmos, 2008) (M. Bakaul, 2005), Simultaneous multiplexing demultiplexing (Masduzzaman Bakaul, 2006), Wavelength Reuse for improved optical spectral efficiency usage (Ampalavanapillai Nirmalathas, 2001), reduction of the complexity and cost of the BS (Zhensheng Jia, 2007), etc.

In section 4.1.1.2 we focused in the application of the external modulator to the generation of IM modulation. Here we will see that the MZM is a flexible device which allows for generation of other kinds of modulation. Following there is a description and comparison between the fading performance of both DSB+C and SSB+C signals transmitted under the same conditions using the VPI Simulation Tool, in order to show the improved performance obtained by using SSB+C modulation.

4.2.1 Double Sideband plus Carrier (DSB+C) modulation

In order to obtain an optical modulated signal with DSB format, it is necessary to reduce at negligible levels the harmonics of greater order so that we are left with only the first upper and lower sideband. In this chapter, this is accomplished by means of external modulation with a MZM biased at quadrature ($V_\pi/2$). Thus as illustrated in **Figure 4.15**, it is generated an optical field whose spectrum consists of an optical carrier at w_0 frequency with the upper and lower sidebands located at $w_0 + w_m$ and $w_0 - w_m$ frequencies, respectively; where w_m corresponds to the MMW radio modulation frequency.

When the DSB+C signal is transported over the fiber, due to the CD, the optical carrier and the two sidebands travel at different velocities which causes time lag between them, which in turn leads that each sideband to experience different phases changes relative to the optical carrier. Upon photodetection, the square-law process (DD) generates two beat components at the MMW frequency, which have a relative phase difference between them due to the phase shifts of the sidebands; as a result of this phase distortion, there is an alteration of the power of the MMW radio signal recovered.

The fading performance occurs along the fiber due to cancellation of the beat signal between the upper sideband and the carrier and the beat signal between the lower sideband and the carrier. When the phase difference is π (Direct Detection, $\phi = \pi$), a destructive interference between sidebands leads to the MMW radio signal cancellation at regular intervals along the transmission distance. This is in accordance with what we saw in section 4.1.2, where also is mentioned the $1/f^2$ dependence on the MMW frequency modulation (f_m), thus there will be most power impairment and in consequence more limited transmission distance at higher frequencies.

4.2.1.1 VPI simulations

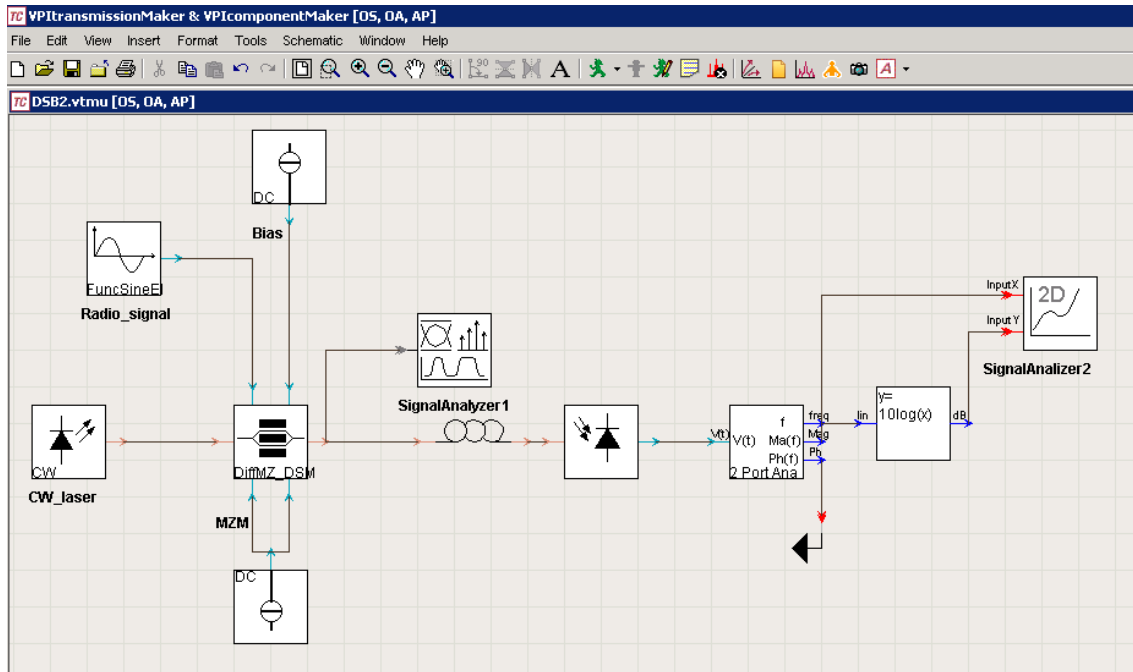


Figure 4.14: Simulation setup for DSB+C modulation implemented via using a MZM biased at quadrature ($V_{\pi}/2$) with a phase and a phase shift of π .

Figure 4.14 sketches the simulation setup for this modulation. There, in order to make DSB+C modulation (Figure 4.15), the MZM is biased at quadrature with a $V_{\pi} = 8.2V$ and a DC bias of 4.1V; and both MMW radio signal and the Bias current are applied to both electrodes of only a branch, meanwhile those of another branch are grounded. On the other hand, to show the behavior of the power impairments over the MMW radio signal recovered after the photodetection while the frequency of modulation is modified, there is a Sweep control of the MMW radio frequency from 0.1GHz to 20GHz with a step width of 0.2GHz.

Figure 4.16 shows via the outcome of the second signal analyzer after the photodetector, the predicted cyclic behavior of the CD power penalties over the MMW radio signal power received after a transmission over 80Km of SMF D= 16 ps/nm/km and a increasing frequency modulation from 0.1GHz to 20GHz .

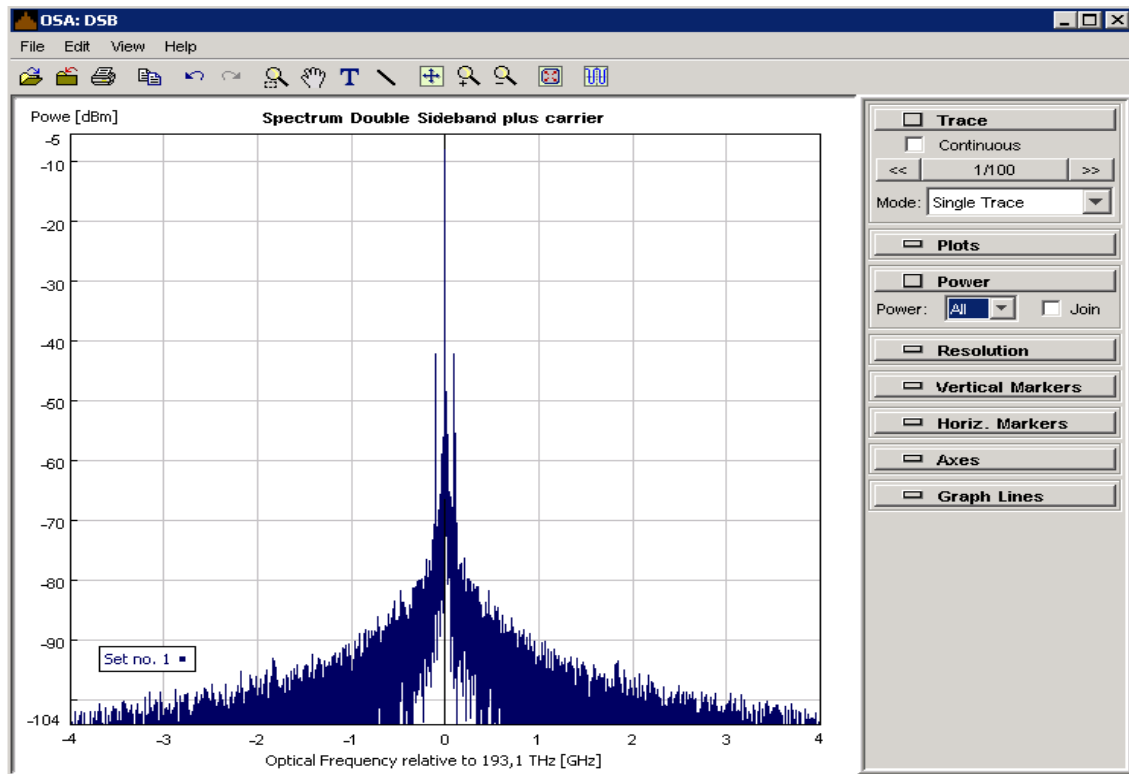


Figure 4.15: Spectrum of the MMW optical modulated signal with DSB+C format obtained with the signal analyzer 1

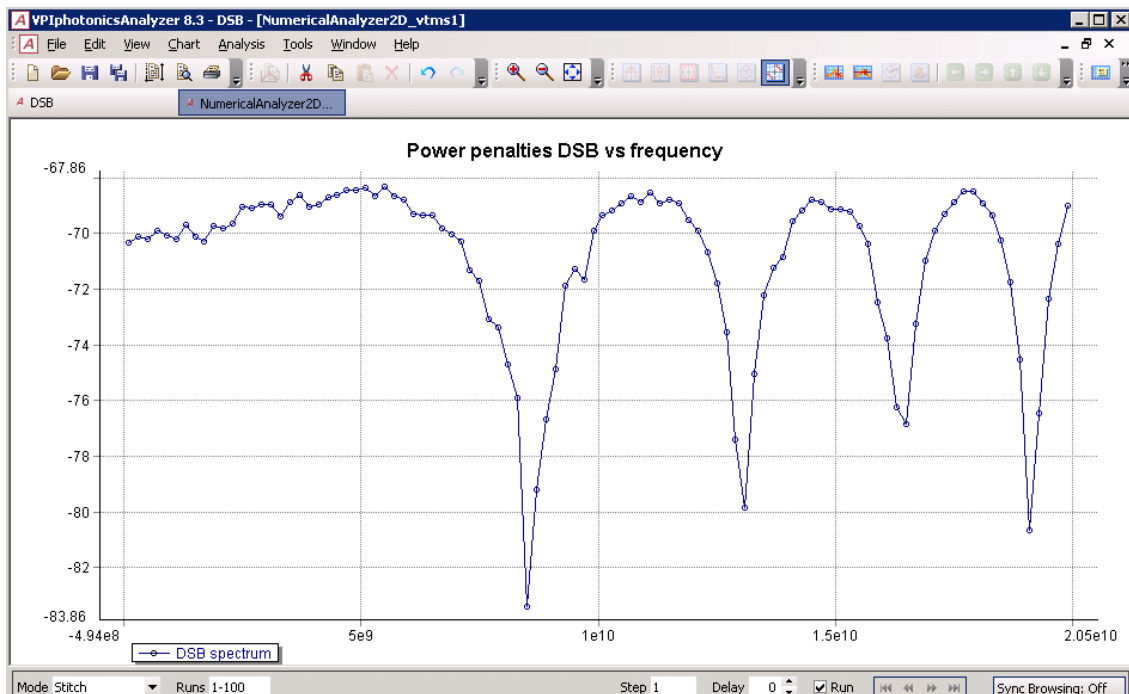


Figure 4.16: Measured power of the MMW radio signal recovered for a MMW optical modulated signal with DSB+C scheme after being transmitted over 80km of SMF with $D= 16$ ps/nm/km

4.2.2 Single Sideband plus Carrier (SSB+C) modulation

As has been mentioned, the dispersion effects may be reduced by the elimination of one of the sidebands of the DSB+C typical signal. Added features of this transmission format are the enabling of techniques for spectral efficiency such as, wavelength reuse, wavelength interleaving, efficient Dense Wavelength Division Multiplexing, among others. There are different approaches to achieve the SSB+C modulation, one of these implies the generation of the typical DSB+C signal and the subsequent suppression of one sideband via optical. Another approach implies the optical generation of the signal with this format directly at the output of the modulator, which means to suppress a sideband while the optical carrier is modulated. This method allows for greater flexibility and transparency and it will be the one used in our simulations. As seen in Figure, light from a CW laser source is modulated with a MZM biased at quadrature ($V_{\pi}/2$) and with a phase shift of $\pm\pi/2$ applied to its two RF electrodes.

4.2.2.1 VPI simulations

The simulation setup for the SSB+C modulation is shown in **Figure 4.17**. It comprises a MZM biased at quadrature ($V_{\pi} = 8.2V$, DC bias of 4.1V), in which the MMW-radio signal is applied to its two RF-electrodes with $\pi/2$ electrical phase difference between them. As in the case of the DSB+C modulation, also in this setup there is a Sweep control to the frequency of the MMW-radio signal from 0.1GHz to 20GHz with a step width of 0.2GHz. **Figure 4.18** depicts the spectrum of MMW-radio optical modulated signal obtained with the first signal analyzer.

Figure 4.19 shows the spectrum of the MMW-radio signal obtained after the photodetection, this exhibits the predicted reduced effect of the CD effect because this hasn't the same fading performance that the DSB+C signal showed.

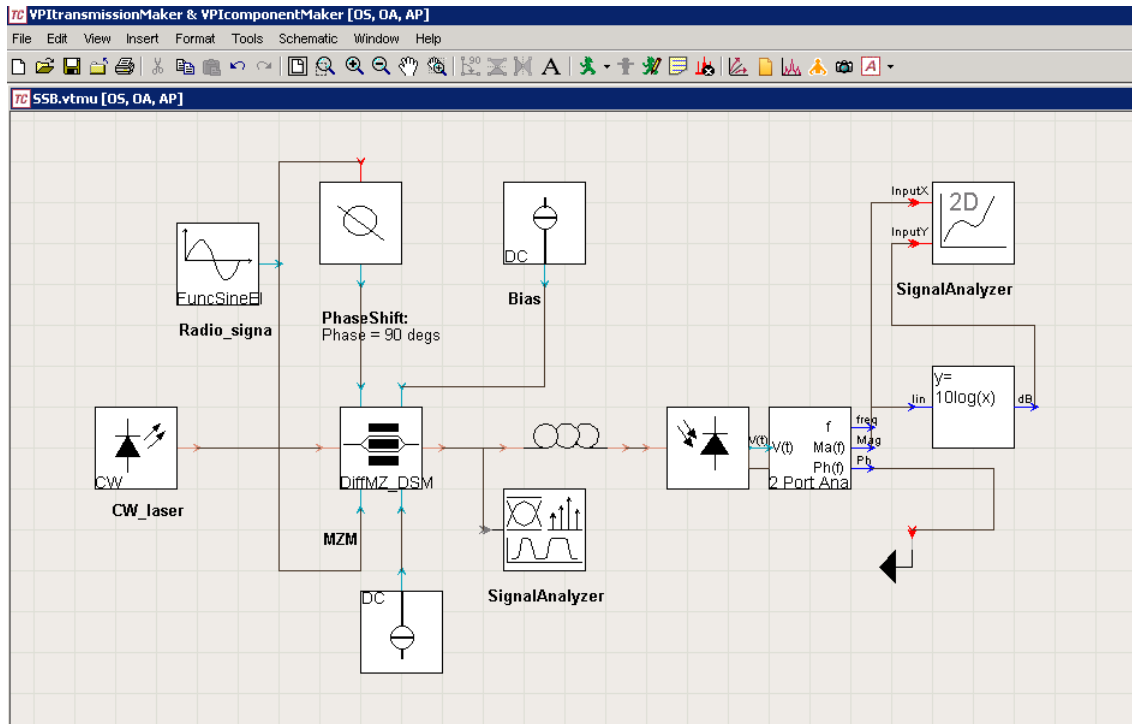


Figure 4.17: Scheme of the SSB+C modulation implemented via using a MZM biased at quadrature ($V_{\pi}/2$) with a phase and a phase shift of $\pi/2$.

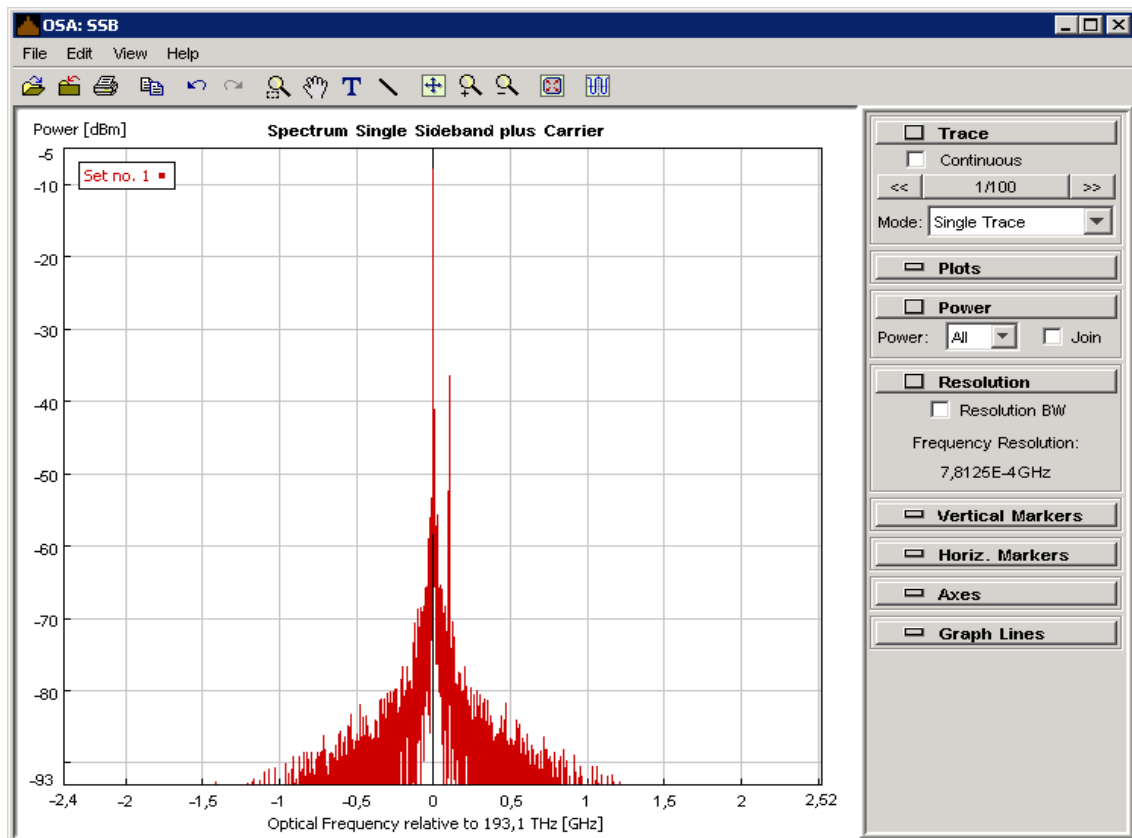


Figure 4.18: Spectrum of the modulated MMW optical signal with SSB+C format obtained with the signal analyzer 1

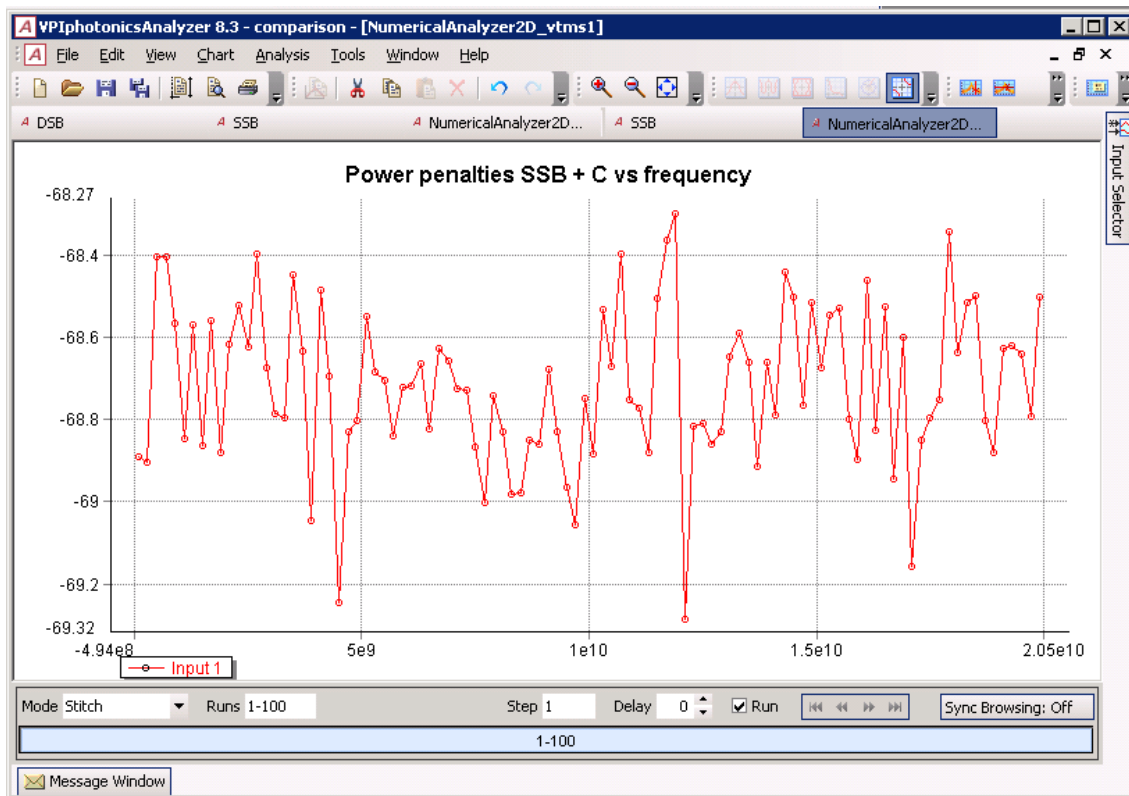


Figure 4.19: Measured MMW-radio signal power for optical SSB modulation after transmission over 80km of SMF with $D= 16$ ps/nm/km

4.2.3 Comparison DSB+C and SSB+C modulation schemes

Both modulation schemes are simulated at the same time under the same transmission conditions (over 80km of SMF with $D= 16$ ps/nm/km) and the MMW radio signals amplitudes recovered are plotted in a signals analyzer with multiple inputs. As seen in **Figure 4.22**, the power received of both signals has an almost linear behavior up to 5GHz. From this frequency up, the DSB signal exhibits a cyclic fading unlike the SSB+C signal, which still has a behavior almost constant even when the frequency increases. From this, at lower frequencies (5GHz, in this case) one may use DSB or SSB+C modulation, because the CD impairments are similar; nevertheless this analysis confirms that SSB enables to overcome the CD effect at higher frequencies and allows to obtain greater transmission distances than the typical DSB signals.

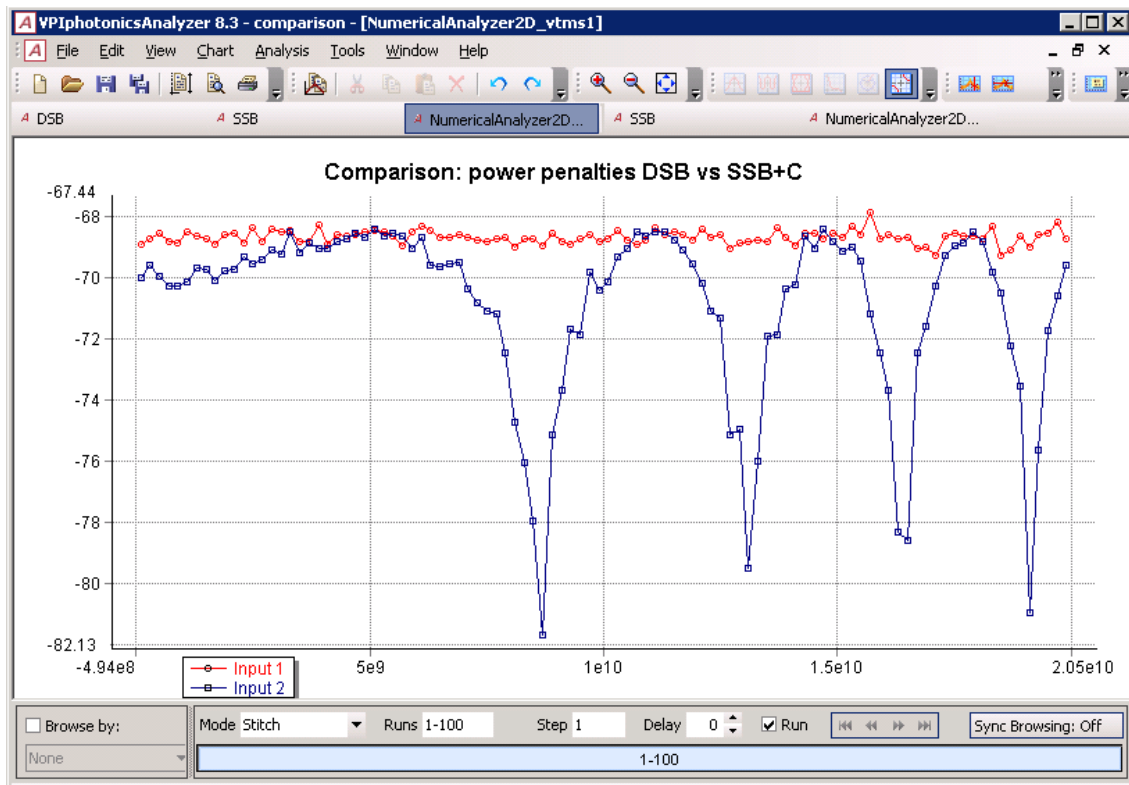


Figure 4.20: Comparison of the behavior of the power penalties between DSB and SSB+C signals

5 Conclusions

Within this PFC a study of the concepts and techniques around the new and emerging field of hybrid fiber-wireless networks has been carried out. This study constitutes a basic reference containing all the concepts that will help beginners to introduce themselves to this new hybrid technology, because it covers the inaccuracies and vacuums that currently exist in the majority of the bibliography related to HFR networks. Thus once known all the context of motivation, nature and structure of the topology, and transmission technologies, it is possible to choose a research line of the great range that exists related to this emergent hybrid technology.

The current network trends and access technologies such as SCM, TDM, WDM or hybrid multiplexing accesses which have been reviewed will support the mixed topology required to implement the HFR networks. The EU-FP7 Sardana and Accordance research projects with UPC leadership and participation respectively have been described as examples of research toward the definition of the hybrid converged networks of the future.

It has been shown that the HFR network topology is inherently related to the structure of the wireless service provided; because this last determines the functionalities that must be carried out by each component and this knowledge allows to define the border network components between the wire and wireless portion as well as to allocate the tasks to CO, RN and BS and the topology that will have the ODN and OFN.

The basic physical phenomena around the processes of signal generation, modulation, transmission and detection have been reviewed, and the main sources for impairments and the basic techniques to counteract them have been studied and analyzed. The potential of VPI as a simulation tool to describe and analyze fiber-radio links has been shown through representative point to point transmission examples.

6 Table of figures

Figure 1.1: Basic diagram of the coexistence of the Wireless and Optical Networks	6
Figure 2.1: Electromagnetic spectrum distribution	10
Figure 2.2: General diagram of a HFR system exhibiting the concept of centralized structure.	12
Figure 2.3: HFR Technologies.....	14
Figure 2.4: Scheme of the basic hardware required for the downstream transmission via Radio over Fiber scheme	14
Figure 2.6: Scheme of the basic hardware required for the downstream transmission via Baseband over Fiber scheme	16
Figure 3.1: GSM topology	19
Figure 3.2: HFR topology with GSM service.....	20
Figure 3.3: HFR system exhibiting different topologies for each optical sub network.....	21
Figure 3.4: Different optical topologies	22
Figure 3.6: HFR access based on Ring- Ring topology.....	25
Figure 3.7: HFR access based on Star- Tree topology	26
Figure 3.8: HFR access based Bus topology	26
Figure 3.9: HFR access based Star- Ring topology	26
Figure 3.10: Future Networks Project Portfolio and Clustering, from (Peter Stuckmann, 2009).....	27
Figure 3.11: SARDANA architecture, from (FP7, 2008).....	28
Figure 3.12: Proposed architecture converged copper-optical-radio OFDM-based access network, from (FP7, 2010)	29
Figure 4.1: Point to point HFR links: scheme of radio signal transmission.....	30
Figure 4.2: Location of impairments in a P2P HFR transmission	31
Figure 4.3: HFR link architectures for direct and external modulation, and for direct and coherent detection (Iezekiel, 2009)	33
Figure 4.4: Transfer function and operation principle of Direct Intensity modulation	34
Figure 4.5: External modulation basic setup. Typical characteristics: Electroabsorption and Mach-Zehnder external modulators, from (Richard Williamson, 2008).....	36
Figure 4.6: Mach –Zehnder external modulator.....	36
Figure 4.8: Dispersion induced CNR penalty as a function of the transmission distance with carrier frequency as parameter, from (U. Gliese, 1996)	40
Figure 4.9: Dependence transmission distance on (a) Chromatic fiber dispersion and.....	41
Figure 4.11: IM/DD link.....	43
Figure 4.12: Principle of operation Local Heterodyne Detection	44
Figure 4.13: Principle of operation of Remote Heterodyne Detection.....	45
Figure 4.14: Simulation setup for DSB+C modulation implemented via using a MZM biased at quadrature ($V_{\pi/2}$) with a phase and a phase shift of π	48
Figure 4.15: Spectrum of the MMW optical modulated signal with DSB+C format obtained with the signal analyzer 1.....	49

Figure 4.16: Measured power of the MMW radio signal recovered for a MMW optical modulated signal with DSB+C scheme after being transmitted over 80km of SMF with $D= 16$ ps/nm/km.....	49
Figure 4.17: Scheme of the SSB+C modulation implemented via using a MZM biased at quadrature ($V_{\pi/2}$) with a phase and a phase shift of $\pi/2$	51
Figure 4.18: Spectrum of the modulated MMW optical signal with SSB+C format obtained with the signal analyzer 1.....	51
Figure 4.19: Measured MMW-radio signal power for optical SSB modulation after transmission over 80km of SMF with $D= 16$ ps/nm/km	52
Figure 4.20: Comparison of the behavior of the power penalties between DSB and SSB+C signals.....	53

7 Table of tables

Table 3.1: Classification of different combinations to Access Networks.....	21
Table 4.1: Analog optical link requirements.....	32

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