UNIVERSIDADE DE SÃO PAULO
ESCOLA DE ENGENHARIA DE SÃO CARLOS
DEPARTAMENTO DE ENGENHARIA ELÉTRICA E COMPUTAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA ELÉTRICA

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**Topologias WDM-PON utilizando Auto-Alimentação com
Dupla Cavidade Óptica para *Fronthaul* Analógico de
Redes 5G**

SÃO CARLOS – SP

2018

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Redes 5G**

Dissertação de mestrado apresentada
ao Programa de Engenharia Elétrica
da Escola de Engenharia de São
Carlos como parte dos requisitos para
a obtenção do título de Mestre em
Ciências.

Área de Concentração:
Telecomunicações

Orientador: Murilo Araujo Romero

SÃO CARLOS – SP

2018

Trata-se da versão corrigida da dissertação. A versão original encontra-se disponível na EESC/USP que aloja o Programa de Pós-Graduação em Engenharia Elétrica.

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Marques de Souza, Adelcio

M228e Topologias WDM-PON utilizando Auto-Alimentação com Dupla
Cavidade Óptica para Fronthaul Analógico de Redes 5G /
Adelcio Marques de Souza; orientador Murilo Araújo
Romero. São Carlos, 2018.

Dissertação (Mestrado) - Programa
de Pós-Graduação em Engenharia
Elétrica e Área de Concentração em
Telecomunicações -- Escola de
Engenharia de São Carlos da
Universidade de São Paulo, 2018.

1. WDM-PON. 2. Self-Seeding. 3. Radio-over-Fiber.
4. Analog Fronthaul. I. Título.

FOLHA DE JULGAMENTO

Candidato: Bacharel **ADÉLCIO MARQUES DE SOUZA**.

Título da dissertação: "Topologias WDM-PON utilizando auto-alimentação com dupla cavidade óptica para fronthaul analógico de redes 5G".

Data da defesa: 10/09/2018.

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*Dedico o presente trabalho de mestrado à
memória do amigo e colega pesquisador
Wander Henrique Machado Freitas.*

Agradecimentos

Agradeço primeiramente aos meus pais, Antonio Santana de Souza e Marieta Santos de Souza, pelo incondicional apoio e amor que sempre me proveram. Sem essa base familiar fundamental, nenhuma dessas conquistas teria sido possível.

Agradeço às pessoas que estiveram diretamente envolvidas nesse trabalho de mestrado e foram fundamentais para o desenvolvimento dele: meu orientador, Dr. Murilo Araujo Romero, pelos ensinamentos e conselhos; o doutorando Daniel Ricardo Celino, pelas contribuições no processo de simulação das topologias e discussões acerca deste trabalho, e o Dr. Ulysses Rondina Duarte, pelos esclarecimentos prestados.

Agradeço aos professores Dr. Arismar Cerqueira Sodré Jr e M.Sc. Antônio Alves Ferreira Jr pelas indicações, conselhos e orientações quando decidi me candidatar ao Programa de Mestrado.

Agradeço aos amigos e familiares que me apoiaram e acompanharam durante esses dois anos: Marco Antonio de Moraes, Benedito Marques dos Santos, Daniel Ricardo Celino, Johnata Cavalcanti Fonseca, Rafael Seiji Ishibe, Rafael Fachinetti, Yuri Barduchi Robin, Wesley Vieira, Ariana Ramos Tiburcio, Luanna de Luna Sena, Sâmara Chebli Baptista e Tahiana Menin Proença. A presença de vocês em diversos momentos e de diversas formas foi essencial para que eu superasse as adversidades e encontrasse motivação para continuar essa caminhada.

Por fim, agradeço o apoio financeiro da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). Espero que futuramente eu possa retribuir de alguma forma esse débito com muitos cidadãos, que talvez nunca tiveram a oportunidade de educação em nível superior.

Adelcio Marques de Souza

"Failure is not an option."

Gene Kranz (Apollo 13, 1995)

Resumo

SOUZA, A. M. **Topologias WDM-PON utilizando Auto-Alimentação com Dupla Cavidade Óptica para Fronthaul Analógico de Redes 5G**. 2018. 116 f. Dissertação de Mestrado – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2018.

As futuras redes de acesso sem-fio, como a quinta geração de telefonia celular (5G), estão introduzindo e consolidando diversas tecnologias, tais como a operação em ondas milimétricas, picocélulas e o emprego massivo de antenas para diversidade espacial e temporal. Todas essas mudanças trazem desafios para a capacidade dos enlaces presentes nessas redes, como o *backhaul* e *fronthaul*. Nas últimas gerações, o *fronthaul* tem utilizado Rádio-sobre-Fibra Digital (D-RoF, *Digital Radio-over Fiber*). Entretanto, neste novo paradigma, o processo de digitalização pode vir a consumir uma largura de banda excessiva e a transmissão analógica dos sinais de RF sobre a fibra se torna uma solução mais atrativa.

Ao mesmo tempo, WDM-PON (*Wavelength-Division-Multiplexing Passive-Optical-Network*) é uma proeminente alternativa para o futuro das PONs, especialmente considerando o seu emprego como fronthaul. Para reduzir a necessidade de diversos transmissores diferentes, várias técnicas de auto-alimentação para obtenção de fontes ópticas agnósticas em comprimento de onda têm sido propostas.

O presente trabalho faz um estudo de topologias de auto-alimentação com dupla cavidade para operarem como fronthaul analógico nas futuras redes de acesso sem-fio. Simulações numéricas utilizando o software Optisystem demonstram a viabilidade destas topologias em diversos cenários previstos para estas redes de acesso, especialmente considerando a operação em ondas milimétricas. Transmissões bem sucedidas foram obtidas para sinais ASK, M-PSK e M-QAM em frequências de microondas (1,25, 2,5 e 5 GHz) e ondas milimétricas (38 e 60 GHz) com vazões de 155 Mbps a 10 Gbps utilizando modulação direta e modulação externa.

Palavras-chave: 5G, auto-alimentação, ondas milimétricas, redes de acesso, rádio-sobre-fibra, WDM-PON.

Abstract

SOUZA, A. M. **Double-Cavity Self-Seeding WDM-PON Topologies as 5G Networks Analog Fronthaul**. 2018. 116 p. M.Sc. Dissertation – Sao Carlos School of Engineering, University of Sao Paulo, Sao Carlos, 2018.

Future radio access networks, such as the fifth generation mobile network (5G), are introducing and consolidating disruptive technologies, such as millimeter wave operation, dense picocell coverage and massive use of antennas for spatial and temporal diversity. These new technologies present a challenge for the capacity of the links that are present on these networks, including backhaul and fronthaul. In the latest cellular network generations, the fronthaul was typically implemented by Digital Radio-over-Fiber (D-RoF) technique. However, in this future context, the digitalization process would require a prohibitive bandwidth and the analog transmission of RF signals over the fiber can be a more attractive solution when compared to D-RoF.

At the same time, Wavelength-Division-Multiplexing PON (WDM-PON) is prominent alternative for the future of PONs, especially considering its use as fronthaul. In order to avoid employing numerous distinct transmitters, several self-seeding techniques have been proposed to achieve colorless optical sources.

This dissertation presents a numerical study of double-cavity self-seeding topologies to serve as analog fronthaul for future radio access networks. Numerical simulations using the software Optisystem demonstrate the feasibility of these topologies in various scenarios envisioned for these access networks, especially considering operation in millimeter waves. Successful transmission was achieved for ASK, M-PSK and M-QAM signals at microwave (1.25, 2.5 and 5 GHz) and millimeter wave (38 and 60 GHz) frequencies with throughput of 155 Mbps to 10 Gbps using direct and external modulation.

Keywords: 5G, access networks, millimeter waves, radio-over-fiber, self-seeding, WDM-PON.

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List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
A/D	Analog/Digital
ADSL	Asymmetrical Digital Subscriber Line
AM	Amplitude Modulation
AMPS	Advanced Mobile Phone System
A-RoF	Analog Radio over Fiber
ASE	Amplified Spontaneous Emission
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
Aux	Auxiliary
AWG	Arrayed Waveguide Gratings
BBU	Base Band Unit
BER	Bit Error Rate
BLS	Broadband Light Source
BPON	Broadband Passive Optical Network
BWA	Broadband Wireless Access
CATV	Cable Television
CN	Core Network
CO	Central Office
CoMP	Coordinated Multi-Point transmission/reception
CPRI	Common Public Radio Interface
C-RAN	Centralized/Cloud Radio Access Network
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
DAMPS	Digital Advanced Mobile Phone Service
DAS	Distributed Antenna System
DBA	Dynamic Bandwidth Allocation
DBR	Distributed Bragg Reflector
DCF	Dispersion Compensation Fiber
Demux	Demultiplexer
DFB	Distributed Feedback
DL	Downlink
DPD	Digital Pre-Distortion
D-RoF	Digital Radio over Fiber
EAM	Electroabsorption Modulation

eCPRI	evolved Common Public Radio Interface
EDFA	Erbium Doped Fiber Amplifier
EDGE	Enhanced Data rates for GSM Evolution
eNodeB	evolved NodeB
EPON	Ethernet Passive Optical Network
ER	Extinction Ratio
ETSI	European Telecommunications Standards Institute
EVM	Error Vector Magnitude
FBG	Fiber Bragg Grating
FBG-DC	Fiber Bragg Grating Dispersion Compensator
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FP-LD	Fabry Perot Laser Diode
FR	Faraday Rotator
FRM	Faraday Rotator Mirror
FS	Functional Split
FSO	Free Space Optics
FTTB	Fiber To The Building
FTTC	Fiber To The Curb
FTTH	Fiber To The Home
FTTx	Fiber To The x
GEM	GPON Encapsulation Method
GFDM	Generalized Frequency Division Multiplexing
GPON	Gigabit Passive Optical Network
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HD	High Definition
HetNet	Heterogeneous Networks
HFC	Hybrid Fiber Cable
HM	Horizontal Mode
HSPA	High Speed Packet Access
HWP	Half Wave Plate
IEEE	Institute of Electrical and Electronics Engineers
IFoF	Intermediate Frequency over Fiber
IM-DD	Intensity Modulation Direct Detection
IoT	Internet of Things
IP	Internet Protocol
ISM	Industrial Scientific Medical
ITU	International Telecommunications Union
LAN	Local Area Network
LED	Light Emission Diode
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced

MAC	Media Access Control
MAN	Metropolitan Area Network
MIMO	Multiple Input Multiple Output
MPLS	Multi-Protocol Label Switching
MPN	Mode Partition Noise
MQW	Multi-Quantum Wells
MtM	Machine to Machine
Mux	Multiplexer
MWP	Microwave Photonics
MZM	Mach Zehnder Modulator
NFV	Network Functions Virtualization
NGPON	Next Generation Passive Optical Network
NLOS	Non-Line Of Sight
NLSE	Nonlinear Schrodinger Equation
NR	New Radio
NRZ	Non Return to Zero
OBSAI	Open Base Station Architecture Initiative
OCS	Optical Carrier Suppression
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Termination
ONT	Optical Node Termination
ORI	Open Radio equipment Interface
OSSB	Optical Single Side Band
PBS	Polarization Beam Splitter
PDG	Polarization Dependent Gain
PF	Polarization Filter
PLS	Physical Layer Split
PON	Passive Optical Network
PRBS	Pseudo Random Bit Sequence
PSK	Phase Shift Keying
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
RAU	Radio Access Unit
RE	Radio Equipment
REC	Radio Equipment Control
RF	Radio Frequency
RFoF	Radio Frequency over Fiber
RN	Remote Node
RoF	Radio over Fiber
RRC	Radio Resource Control
RRH	Remote Radio Head
RSOA	Reflective Semiconductor Optical Amplifier
RU	Radio Unit
Rx	Receiver

SFDR	Spurious-Free Dynamic Range
SDH	Synchronous Digital Hierarchy
SDN	Software Defined Network
SOA	Semiconductor Optical Amplifier
Sonet	Synchronous Optical Network
SoP	State of Polarization
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TIA	Trans Impedance Amplifier
TWDM	Time Wavelength Division Multiplexing
Tx	Transmitter
UAV	Unmanned Aerial Vehicles
UF-OFDM	Universal Filtered Orthogonal Frequency Division Multiplexing
UL	Uplink
UMTS	Universal Mobile Telecommunication System
UTRAN	UMTS Terrestrial Radio Access Network
VCSEL	Vertical Cavity Surface Emitting Laser
VDSL	Very High Digital Subscriber Line
VM	Vertical Mode
VR	Virtual Reality
W-CDMA	Wide-Band Code-Division Multiple Access
WDM	Wavelength Division Multiplexing
WECA	Wireless Ethernet Compatibility Alliance
Wi-Fi	Wireless Fidelity
WiGig	Wireless Gigabit
WiMAX	Worldwide Interoperability for Microwave Access
WPAN	Wireless Personal Area Network
DSL	Digital Subscriber Line
XGPON	10-Gigabit-capable Passive Optical Network

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Introduction

1.1 – Outlook on data traffic

According to the Mobility Report published by Ericsson [1] in June 2018, smartphones world data traffic is expected to increase from 14,872 PB/month in 2017 to 106,535 PB/month in 2022, as shown in Fig. 1. Considering only 2017, world data traffic increased around 68%, boosted by the proliferation of video-on-demand streaming. The outlook for 2023 is that video applications will consume up to 73% of mobile networks data resources, as displayed in Fig. 2. Since there is a tendency to offer these services in high quality, it is imperative that the new standards for mobile networks must offer increasingly higher data rates. Currently, for instance, the entertainment company Netflix recommends a connection of at least 25 Mbps for an Ultra HD video-on-demand streaming using their services [2].

Figure 1 – The latest Mobility Report published by Ericsson [1] in June 2018 indicates an exponential growth on the mobile data traffic through smartphones for the next few years.

The Cisco Visual Networking Index white paper [3], published in June 2017, points to an increase of wired IP traffic from 88853 PB/month in 2016 to approximately 229838 PB/month in 2021, as appointed in Fig. 3. This includes fixed Internet costumers, corporate traffic and TV/media transport. It is worth noticing that wireless and mobile devices will account for 63 percent of general IP traffic in 2021, accordingly to their report, especially considering the IoT (Internet of Things) forthcoming scenario.

Besides, most mobile traffic will eventually use a wired transport network to reach the core network, which also increases the data flow in wired networks.

Figure 2 – In 2022, video applications will consume up to 73% of mobile networks data resources, which means that the upcoming technologies must be able to meet the high speed connections demands of this type of application [1].

Figure 3 – The Cisco Visual Networking Index white paper [3] published in June 2017 indicates an almost linear growth on the wired IP data traffic for the next few years.

To prepare for these forecast scenarios, telecommunication companies and organizations are always working on new technologies and standards for wired, wireless and mobile networks. Here, we will be dealing with access networks, the connection between subscribers and service providers. In the next sections, we will discuss two specific segments of access networks and their interplay: wireless/mobile networks, especially the upcoming fifth generation standard, and passive optical networks.

1.2 – Wireless/Mobile access networks

A telecommunication system is generally composed by core, metro or aggregation and access networks. Core and metro or aggregation networks are high speed dense traffic connections among cities or local regions. Optical fibers are widely used in these scenarios with technologies such as Wavelength Division Multiplexing (WDM), Synchronous Digital Hierarchy (SDH) and Synchronous Optical Networking (SONET). Access networks are connections between these high speed backbones and end users. These *last mile* connections can be either wired or wireless. For the wireless scenario, we are going to focus our discussion on *Wireless Fidelity* (Wi-Fi), Worldwide Interoperability for Microwave Access (WiMAX) and the evolution of mobile networks.

1.2.1 – Wi-Fi (IEEE 802.11)

In 1999, a research group called Wireless Ethernet Compatibility Alliance (WECA) was formed by an association of telecommunications companies to define a wireless network standard. The result was the Wi-Fi technology, specified in the IEEE802.11 standards family [4], as a wireless Local Area Network (LAN). They were expected to have a maximum reach of 100 meters and operate in the 2.4 and/or 5 GHz unlicensed Industrial, Scientific and Medical (ISM) bands. Wi-Fi is usually used for short range connections, such as the distribution of Internet over a house, a building and a university campus, thus it can be considered a complement to access networks. IEEE802.11 standards, their respective operation frequencies and data rates are summarized in Table 1.

Table 1 – IEEE802.11 standards.

Standard	Frequency	Maximum Data Rate
IEEE802.11	2.4 GHz	2 Mbps
IEEE802.11a	5 GHz	54 Mbps
IEEE802.11b	2.4 GHz	11 Mbps
IEEE802.11g	2.4 GHz	54 Mbps
IEEE802.11n	2.4/5 GHz	600 Mbps
IEEE802.11ac	5 GHz	3.4 Gbps
IEEE802.11ad	60 GHz	6.7 Gbps

1.2.2 – WiMAX (IEEE 802.16)

In order to extend the physical reach of wireless networks and the throughput capacity, an association of telecommunications companies organized the WiMAX Forum to discuss a new technology to serve as a wireless Metropolitan Area Network (MAN). The WiMAX standard, under IEEE802.16 family [5], was defined as a Broadband Wireless Access (BWA) system. As will be discussed later, WiMAX is one of the main options for mobile backhauling, along with optical fibers. It is capable to cover distances up to 50 km and it usually operates on the 2.5, 3.5 and 5 GHz frequency bands. With IEEE802.16e and IEEE802.16m, WiMAX added some features to also support mobile users. Table 2 shows the operation frequency range and the maximum data rates for the main WiMAX standards.

Table 2 – IEEE802.16 standards.

Protocol	Frequency Range	Maximum Data Rate
IEEE802.16	10-66 GHz	134 Mbps
IEEE802.16a	2-11 GHz	75 Mbps
IEEE802.16e	2-6 GHz	15 Mbps (mobile)
IEEE802.16m	2-6 GHz	100 Mbps (mobile) 1 Gbps (fixed)

1.2.3 – Mobile networks

A mobile network, also known as cellular network, provides radio coverage over a group of land areas called cells. Within a cell, a user can be served with voice and data services, while he is in movement. So far, mobile networks have evolved through four generations, about a decade apart, going from simple analog voice transmission to broadband data connection [6].

In the early 80's, the First Generation (1G) was introduced, bringing mobile analog voice service. In the US, the first mobile standard was called Advanced Mobile Phone System (AMPS) and was developed by Bell Labs [7]. Since it uses Frequency-Division Multiple Access (FDMA), it required one frequency channel for each connection and consumes a high bandwidth to serve all users. However, it was the main mobile protocol in the world until the consolidation of digital voice transmission in the late 90's.

A decade later, the Second Generation (2G) switched to digital voice transmission, popularizing cell phones for the general public. It includes a digitized version of AMPS (DAMPS) and the Global System for Mobile Communications (GSM) standard developed by the European Telecommunications Standards Institute (ETSI). It uses Time-Division Multiple Access (TDMA) along with FDMA to optimize the sharing of spectral resources and it was the most ubiquitous mobile technology until 2010. The support for data services was first introduced as an extension of GSM, with technologies such as General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE), establishing a bridge for the next generation. However, these initial technologies only support low data rates, up to 40 kbps (GPRS) and 384 kbps (EDGE) [8].

With the Third Generation (3G), mobile networks were optimized to the broadband data services. The technologies includes Universal Mobile Telecommunications System (UMTS), an evolution of GSM that uses Wideband Code-Division Multiple Access (W-CDMA), High Speed Packet Access (HSPA) and HSPA+, with data rates that can reach 42 Mbps [9]. These technologies, along with the introduction of the smartphone, led to a rapid increase of broadband mobile data demand and the proliferation of triple play services (voice, video and data), requiring high speed connections and low latency.

Fourth Generation (4G) has been expanding the connectivity to better and faster mobile broadband access. Introduced in 2009, Long Term Evolution (LTE) has been consolidated as the most successful 4G standard, although there are controversies of whether it meets the criteria established for the fourth generation [10]. Its evolution, LTE Advanced (LTE-A), however, is a truly 4G network technology, in which the nominal data rate can reach up to 1 Gbps [6] [11].

Although LTE coverage has been growing exponentially over the last five years, becoming the dominant mobile technology in 2018, 3rd Generation Partnership Project (3GPP) is already developing a Fifth Generation (5G) standard. Besides improving the user broadband experience, 5G is expected to handle applications such as Machine-to-Machine (MtM) communication, Internet of Things (IoT), Virtual Reality (VR), industrial control, Unmanned Aerial Vehicle (UAV) control, tactile Internet, etc. These applications are driving the 5G requirements, especially for high data rates and low

latency, as presented by 3GPP on the *TS22.261: Service requirements for the 5G system* document [12]. As was pointed out before, video streaming is one the driven applications for higher data rates. Other applications like tactile interactions, for instance, require latencies as low as 0.5 ms. Table 3 presents the requirements for some of these 5G applications.

Table 3 – Some 5G scenarios/applications and their requirements [12].

Scenario / Application	Requirement
Urban coverage	50 Mbps (DL), 25 Mbps (UL)
Dense urban coverage	300 Mbps (DL), 50 Mbps (UL)
Rural coverage	50 Mbps (DL), 25 Mbps (UL)
Indoor coverage	1 Gbps (DL), 500 Mbps (UL)
High-speed train coverage (up to 500 km/h)	50 Mbps (DL), 25 Mbps (UL)
Discrete automation control	1 ms end-to-end latency
Automation for high voltage electricity distribution	5 ms end-to-end latency
Intelligent transport systems	10 ms end-to-end latency
Tactile interaction	0.5 ms end-to-end latency

1.2.4 – Millimeter waves communications

One of the main challenges to meet 5G requirements is to fit broadband data flow in the already crowded microwave region between 700 and 2500 MHz, where most mobile networks operate nowadays. Over the years, this challenge has been addressed with advanced modulation techniques and strategic ways to increase the spectral efficiency. However, these improvements are reaching a saturation point and new portions of the electromagnetic spectrum are being considered.

The millimeter waves region is a strong candidate for the next generations of wireless and mobile access networks [13]. Formally, it is defined as the spectral portion between 30 and 300 GHz. The first two bands of interest are the 28 (26 in some cases) and 38 GHz bands and the other one is around 60 GHz. In the US, for instance, the Federal Communication Commission (FCC) reserves the 57-64 GHz band for non-licensed applications [14]. The Institute of Electrical and Electronics Engineers (IEEE) also defines the 802.15.3C standard, the first one with a wireless capacity over 1 Gbps, as a Wireless Personal Area Network (WPAN) in 60 GHz. It also defines the WiGig standard, IEEE802.11ad, as a wireless LAN in the same region. Therefore, although the

use of millimeter waves is an innovation to mobile networks, the features and drawbacks of operating in this region are well known to the research community.

One of the main properties of millimeter waves links is high attenuation. Oxygen absorption in the 60 GHz band creates an attenuation of about 15 dB/km and free space attenuation is about 30 dB higher than in the microwave region below 5 GHz. Besides, the signal has small penetrability and is easily absorbed by walls or blocked by obstacles like the human body [15]. Consequently, the range of a cell in these frequencies is limited to a few meters, which makes it more suitable for indoor environments. A group of picocells, with a range of little more than 100 meters or femtocells, with a range of less than 10 meters, are optimal choices for signal coverage in these scenarios. They would be capable to deliver very high speed data with low interference, using high directivity antennas operating in the millimeter waves.

Therefore, 5G radio access networks should be able to coordinate a large number of high speed cells and handle signal processing in very high frequencies. One prominent interdisciplinary field that offers a lot of solutions for these problems is Microwave Photonics (MWP) [16]. For instance, by merging high frequency electrical signals with optical processing, it is possible to easily control the beamforming of millimeter wave antennas, which would require high speed A/D converters and phase shifters in an all-electrical solution. The overall processing of millimeter waves is highly facilitated with the aid of microwave photonics techniques. Moreover, their transport can also benefit by Radio-over-Fiber (RoF) techniques that allow the distribution of radio signals over optical links, enjoying all the advantages of optical fibers.

Optical fibers have already been used in 3G and 4G mobile networks in two different scenarios, as shown in Fig. 4. The first one, known as backhaul, is the connection between the mobile access and core networks. The other one is present in an architecture called Centralized Radio Access Network (C-RAN). In this architecture, all the base band processing is removed from the cell site and Base Band Units (BBUs) are grouped in a Central Office (CO), leaving just the Remote Radio Heads (RRHs) close to the user. The link between the centralized BBUs and RRHs is called fronthaul and can be implemented using optical fibers. In most applications, the signal is digitalized under a protocol called Common Public Radio Interface (CPRI) [17] and I/Q samples are sent

through the optical link. However, as we will further discuss in Chapter 3, a digital solution imposes several challenges for the upcoming high speed access networks. Therefore, Analog Radio-over-Fiber (A-RoF) techniques have been proposed as fronthaul solutions to future access networks [18].

Figure 4 – Mobile access network in the C-RAN architecture. The BBUs are all stored inside the central office and the cell sites are left with the RRHs. An optical network can be used as backhaul and/or fronthaul, employing radio-over-fiber techniques.

1.3 – Passive Optical Networks

1.3.1 – Optical fibers in *last mile*

Traditionally, the wired *last mile* was served by telephone and cable TV companies. The first uses twisted-pair cables to transmit analog or digital voice signals along with digital data, using a technology family called Digital Subscriber Line (xDSL). The different signals are separated in frequency, with the higher ones reserved for upstream/downstream data. Since the attenuation in these cables increases with frequency, the transmission is limited on bandwidth and distance. The maximum performance for Asynchronous DSL (ADSL) is 8 Mbps (downstream) and 5.5 km reach. Even with the newest Very-high-bit-rate DSL 2 (VDSL2), it does not reach a much higher bitrate, serving about 50 Mbps up to a maximum of 1.2 km [19].

TV companies use coaxial cables to delivery analog video signals and digital data services to the end user. In fact, this is a Hybrid Fiber Coax (HFC) system that uses optical fibers to transport signal up to remote nodes and posteriorly employs coaxial cables to distribute to the end users. For this technology, the downstream data rate can reach 2 Mbps per user with a cooper cable link of a maximum of 0.5 km [20]. With the increasing demand for broadband access in the *last mile*, these metallic wire links became the bottleneck of the telecommunication systems in the late 90's, when fibers started to get progressively closer to the end user, giving rise to the optical access networks.

It was well known that optical fibers have virtually unlimited bandwidth and very low attenuation, when compared to metallic cables. But, up to late 90's, it was unnecessary and costly to have an optical access network. When the driver applications started to payoff, internet providers extended their services to the so called Fiber-To-The- x (FTTx), where x can stand for home (FTTH), building (FTTB), curb (FTTC), etc. To provide these services, the companies developed a series of standards based on the concept of Passive Optical Network (PON), a point-to-multipoint network with no active elements between the service provider and the end user or distribution facility. This reduces operation costs and maintenance for the provider and it enables the delivery of high speed data to the users.

1.3.2 – PON structure

The basic structure of a generic PON is shown in Fig. 5. It contains the following elements:

- **Central Office (CO)** – the network switching facility that interconnects subscribers and also serves as a gateway to the core network.
- **Optical Line Terminal (OLT)** – located inside the central office, it contains the transceivers and the active modules.
- **Feed Fiber** – connects the central office to an optical remote node.
- **Remote Node (RN)** – contains the passive optical splitter that distributes and collects the user's signals.
- **Distribution Fiber** – connects the remote node to end users or to some local facility.

- **Optical Network Unit (ONU)** – transceiver located at some facility besides the user home. It can be a cabinet located in a curb, for example. Beyond this point, the signal can be delivered by a metallic cable.
- **Optical Network Terminal (ONT)** – transceiver located at the user's home.

Figure 5 – Basic structure of a generic PON.

In the case of Time Division Multiplexed PONs (TDM-PONs), which are the most commonly implemented networks, the remote node is composed by power splitters/combiners and a single pair of wavelengths is shared by a group of ONUs. The downstream data flow occurs in broadcast, i.e., the OLT sends the information to all ONUs through the power splitter and each one is responsible for filtering their addressed packages. For upstream, since there is only one available channel for a group of ONUs, they send their data on predefined time windows, with synchronization provided by the OLT. A Coarse WDM (CWDM) coupler separates upstream and downstream data flow in the OLT.

1.3.3 – PON standards

In order to create a standard, seven telecommunications companies united in 1995 to found the Full Task Access Network (FSAN) working group. Later, the International Telecommunication Union (ITU-T) and IEEE standardized different generations of PONs.

The first standard by ITU-T was the G.983.x family [21], known as Broadband PON (BPON) or ATM-PON, since it uses Asynchronous Transfer Mode (ATM) for data framing. It has nominal data rates of 155, 622 and 1244 Mbps, with symmetric and asymmetric configurations and a maximum reach of 20 km. Downstream transmission is done over the 1480-1580 nm window and upstream transmission is done over the 1260-1360 nm window.

The next standard presented by ITU-T was the G.984.x family [22], called Gigabit PON (GPON), because it is capable to deliver 2.4 Gbps in downstream direction and 1.2 or 2.4 Gbps in upstream direction with maximum reach of 20 km. For data framing, it uses GPON Encapsulation Method (GEM) to provide flexible transport of various services, which was generally maintained in the following standards, with some improvements. GPON found commercial success in America and Europe, while Japan and South Korea preferred to implement its IEEE equivalent, IEEE802.3ah [23] or Ethernet PON (EPON), which, as the name indicates, uses Ethernet for data framing. However, for our purposes, we chose to focus on ITU-T standards and we will not further discuss the Ethernet-based standards.

Afterward, the ITU.T increased the data rate provided to the end user with the G.984.x series [24], denominated XGPON. XGPON operates with 10 Gbps downstream and 2.5 Gbps upstream, while XSGPON operates with 10 Gbps on both directions. This series is also known as Next Generation PON 1 (NGPON1).

Up to this point, all standards employed TDM for data multiplexing and CWDM to separate upstream and downstream data flow. TDM has a major data rate limitation since it shares the overall bandwidth by all users. Therefore, for the next standard, ITU-T chose Time-Wavelength Division Multiplexing (TWDM) as the multiplexing protocol, maintaining the capability with previous standards. The new standard, G.989.x [25], is referred to as NGPON2 and it has a nominal capacity of 40 Gbps in downstream direction and 10 Gbps in upstream direction.

In a future outlook, GPON is expected to dominate the home users market for the next few years, since it is perfectly able to meet the current demands and the migration for the newest standards are still costly. NGPON1 is expected to fulfill the demands for business applications and coexist with GPON. However, driving applications such as future mobile access networks backhaul and fronthaul are boosting the interest for

NGPON2 and even a still hypothetical NGPON3 [26]. Along with Orthogonal Frequency Division Multiplexing PON (OFDM-PON) and Coherent-PON, WDM-PON is one of the prominent options for a future generation of passive optical networks [27]. In fact, WDM-PON was already considered by FSAN in the development of NGPON2 [28] and it has been intensively studied since the early 90's [29].

Unlike traditional Time-Division Multiplexing PON (TDM-PON), a WDM-PON assigns a unique wavelength to each user and there is no resource sharing, providing a higher individual bandwidth. However, one of the main issues that have been appointed since the beginning of WDM-PON is the need for different transmitters for each wavelength, which increases inventory and operational costs. Although tunable lasers could be an immediate solution for this problem, they may still be too expensive for a PON application.

In order to solve this problem in a cost-effective way, colorless sources relying on self-seeding technique were proposed [30], [31]. In this technique, an active optical component generates an optical signal that is self-tunable to the designated channel in the remote node. Therefore, a single and inexpensive type of transmitter can be employed for all users, regardless of their wavelength. A review of the main techniques and the research developed by our group regarding self-seeding will be presented in Chapter 2.

1.4 – Dissertation overview

Throughout Chapter 1, it was presented an increasing demand for high speed fixed and mobile data services, driven by new applications such as high quality video streaming. In order to meet this demand, the telecommunication industry is working on new standards and technologies for mobile and optical networks. In the mobile world, 5G and millimeter wave communications represent trends. On the other hand, PON market is currently evaluating WDM-PON as one of the possible solutions for NGPON3. In both areas, there are still open questions such as the inventory problem related to dedicated wavelength assignment in WDM-PON and future of mobile fronthauls in the upcoming mobile networks. Following up the research done by our group at the University of Sao Paulo on self-seeding techniques, this dissertation proposes the use of a double-cavity self-seeded WDM-PON topology as an analog mobile fronthaul.

In Chapter 2, we will briefly discuss the evolution of colorless sources, in particular the self-seeding techniques. A combined self-seeding and wavelength reuse topology will be presented with a further improvement employing two reflective transmitters to form a double-cavity scheme. An overview on the use of self-seeded WDM-PONs as mobile fronthaul will also be presented.

Chapter 3 will be dedicated to a discussion on the future of C-RAN architecture. Digital Radio-over-fiber techniques are already in use on the current mobile fronthaul. However, with the ambitious 5G requirements and need for further centralization in access networks, an analog RoF alternative is promising to bring a new perspective to the future mobile fronthaul.

In Chapter 4, the simulation results of the proposed topologies will be presented. It will start with an overview of the calibration process, used to obtain a reliable simulation setup based on our previous experimental investigations. In sequence, we will present simulations on direct and external modulation topologies operating at various data rates, modulation formats and frequencies bands, especially in millimeter waves.

Concluding, Chapter 5 summarizes our key results, contributions and suggestions on research directions for future works in this area.

Chapter 2

Self-Seeding

2.1 – WDM-PON structure

As stated earlier, in a WDM-PON architecture, each user has, in principle, a dedicated wavelength for data transmission and reception. The general structure of a WDM-PON topology is illustrated at Fig. 6. It comprises the following elements:

- **OLT:** n downstream Transmitters (Tx) and n upstream Receivers (Rx), where n corresponds to the number of users, each one in a different wavelength, a Multiplexer (Mux) and a Demultiplexer (Demux), usually implemented with an Arrayed Waveguide Grating (AWG), and an optical circulator, responsible for the upstream/downstream signal routing.
- **RN:** a Mux/Demux system. Responsible for channel aggregation/separation.
- **ONU or ONT:** an upstream transmitter and a downstream receiver. They can share the same wavelength or be in different optical bands, depending on how the WDM system is implemented.

Figure 6 – Basic WDM-PON structure.

A downstream data flow is generated by each transmitter at the OLT and is multiplexed to a common port along with the other $n-1$ signals by the AWG. The optical circulator routes signals to the distribution fiber. At the remote node, each channel is filtered and directed to the respective receiver at the ONU by the feed fibers. For the upstream direction, the signal goes through the reverse path, with the optical circulator

at the OLT routing them to the AWG connected to the respective receivers. The upstream and downstream transmissions can occur in the same wavelength for each user, in which the ONU would also have an optical circulator, or in different bands, being separated by C/O band filter, for instance. The C-band corresponds to the 1530-1565 nm wavelengths and is commonly used for downstream. The O-band corresponds to the 1260-1360 nm region and is reserved for upstream. Other possible WDM-PONs configurations with power splitters/combiners, active elements and cascaded AWGs were presented earlier in the literature [32], but they will not be explored in this work.

Since there is no time sharing, each ONT can send and receive signals at any time, regardless of others users. Thus, the available bitrate for each user depends only on the transmitter capacity and defined optical bandwidth. Furthermore, this feature also allows for a gradual expansion on the network capacity.

It is clear the one of the main features of WDM architecture is that each pair of transmitter and receiver must operate at a defined wavelength, which means, at first, that each user must have different optical devices. This is not very attractive in terms of operational costs, since the network manager must have a large number of transmission devices on inventory. It would be better if all transmitters were the same, with a tunable operation wavelength. This is a well-studied problem in WDM-PON research that has been addressed with the concept of colorless sources, optical transmission devices that are wavelength-insensitive, i.e., the same hardware can be employed for any wavelength in a given range [33].

In the following sections, we will provide a brief overview on the evolution of colorless sources and the self-seeding technique. Following, the previous work carried out by our group regarding this subject will be presented, providing the background for the proposal of this dissertation. Finally, we will comment on the use of self-seeding WDM-PON as mobile fronthauls, since this is the application of interest in this work.

2.2 – Colorless sources

2.2.1 – Tunable lasers

A first approach to colorless sources is to employ tunable lasers. In general, laser tunability can be achieved by means of electronic, thermal or mechanical control [34]. There are several architectures; most of them are based on variations of Distributed

Bragg Reflection (DBR) lasers and Vertical Cavity Surface Emitting Lasers (VCSEL) [34]. Although they can be considered a promising solution in a long term future, tunable lasers are still too expensive, narrowband and complex for most commercial applications. There are some works exploring WDM-PON with tunable lasers, regarding a trade-off between admissible traffic and tunable range [34] and cost effective implementations [35]. However, they still require sophisticated technology to deal with high traffic, which implies high cost, and the economic feasibility comes with the expense of relaxation in the performance parameters.

2.2.2 – Spectral slicing

An alternative to tunable lasers is to employ a spectral slicing technique in a broadband source. Examples of these sources are supercontinuum sources [36], Light Emitting Diodes (LEDs) [37][38] and Amplified Spontaneous Emission (ASE) of optical amplifiers like Erbium Doped Fiber Amplifier (EDFA) [39] and Semiconductor Optical Amplifiers (SOA) [40]. A simple method of spectral slicing is illustrated in Fig. 7. The broadband source is connected to an AWG port, which is essentially an optical filter, and a portion of the broadband spectrum is selected accordingly to the channel wavelength. Therefore, a single source can be used for a wide range of channels and the system is self-tunable. In the case of LEDs, direct modulation can be employed. For ASE or supercontinuum slicing, however, this scheme requires an external modulator.

Figure 7 – Example of spectral slicing technique. In this scheme, a broadband source is connected to the AWG common port and the n outputs can be used as optical carriers to external modulators.

One of the main drawbacks of spectrum slicing is that, since only a portion of the spectrum is used, there is a high power penalty that usually requires the use of optical amplifiers, which is not attractive in a PON scenario. Besides, noise sources like Mode Partition Noise (MPN), intensity noise and optical beat noise are inherent properties of a sliced broadband source and impose a limit to the modulation speed [41].

2.2.3 – Reflection mode transmitters

The spectral slicing technique can be improved if the resulting narrow band signal is used as an optical seed for a reflective transmitter. The general scheme is presented in Fig. 8. As explained before, a narrow band signal can be obtained by slicing a BLS spectrum using an AWG, the colorless part. However, the resultant signal has low power and is noisy. In this example, the BLS signal comes from the OLT and it is sliced at the AWG. Each narrow band signal is inserted into an optical transmitter working on reflection mode, like a Reflective Semiconductor Optical Amplifiers (RSOA) [42]. The signal, denoted as optical seed, goes through the transmitter active medium twice and is modulated with data in this process. With this technique, the optical signal is amplified and noise is suppressed.

Figure 8 – Reflection mode transmitter technique. The sliced BLS is used as seed to the RSOA transmitter. As an alternative, a FP-LD can also be employed with OIL.

Besides RSOAs, Fabry-Perot Laser Diodes (FP-LD) are also usually employed in a similar scheme [43]. Working as a resonant cavity, FP-LD is essentially a multimode laser. However, with the injection of an optical seed with central wavelength close to one of the FP-LD resonant modes, the other lateral modes are suppressed and device operates as a single mode laser. This technique is known as Optical Injection Locking (OIL).

Although the use of reflective mode transmitters is an improvement over simple spectral slicing, there is still one problem that persists over these topologies: a failure of the broadband source shuts down the whole system. A second broadband source could be used to add redundancy to the system. However, this comes with an increase in the

networks cost. A more attractive solution is to use a seed generated by the reflective transmitter itself in a feedback scheme.

2.2.4 – Self-seeding

In a self-seeding scheme, the transmitter feeds itself with its own sliced ASE, eliminating the need for a centralized broadband source. One of the first efforts to develop such an autonomous colorless transmitter was attempted in 2005 [44]. In this work, the upstream signal generated by a FP-LD was fed back to the FP-LD itself using a Fiber Bragg Grating (FBG) in the RN. The operation wavelength was determined by the FBG, therefore it is colorless, and a process of self-injection occurs, selecting one of the FP-LD resonant modes. However, as pointed out by Wong et al. in 2007 [31], although this scheme successfully overpass the need for a centralized broadband source, it still does not tolerate a wavelength drift between FP-LD, FBG and AWG. Besides, the number of users is limited to the number of resonant modes in the FP-LD, which are about 10 for this particular experiment. Wong et al. propose the first self-seeding scheme employing RSOAs, as depicted in Fig. 9.

Figure 9 – Self-seeding scheme proposed by Wong et al. [31].

The broadband ASE spectrum emitted by the RSOA is sliced by the AWG and fed back by a passive optical path. In this example, the reflective system is composed by an optical circulator and a band-pass filter with about the same pass-band provided by the AWG in order to avoid the need for temperature tracking. In the experimental demonstration, they also used an EDFA to compensate for the lack of high gain RSOAs. A power coupler guarantees that a portion of the signal is sent for upstream detection.

The portion of the signal is used as a seed to the RSOA, which modulates the optical carrier with upstream data. After reaching a dynamic equilibrium, this process occurs continuously, constituting a self-seeded colorless optical transmitter. The signal characteristics depend on the gain profile, output power and ASE profile of the RSOA and the insertion losses produced by the cavity, as well as by the slicing process. Also, compared to the slicing technique, self-seeding mechanism is able to produce carriers with a narrower linewidth, being more robust to chromatic dispersion effects.

There are two main requirements for the RSOA to work in a self-seeding scheme. The first one is to work in the saturation region, since the RSOA needs to erase the data of the reflected seed on the cavity and insert the new bit sequence to be sent to the upstream receiver [45]. A RSOA generic gain curve is depicted of Fig. 10. If a binary signal is inserted in the saturation region, the gain over the logical level 1 is smaller than the gain over the logical level 0, inducing a compression on the signal. The result is a very low ER signal, almost a Continuous Wave (CW) carrier. Since the Extinction Ratio (ER) is directly related to the detection quality and inversed related to the data erasure, there is an optimum value of ER. In addition, the self-seeding quality is directly related to the seed power. Therefore, the RSOA must have high gain and saturation power in order to be efficient in the data erasing process.

Figure 10 – RSOA gain curve. The input optical data can be erased by gain compression in the saturation region.

The second main requirement is polarization stability. Every semiconductor optical amplifier has a Polarization Dependent Gain (PDG). Therefore, for a high gain, the seed must enter the RSOA in the correct State of Polarization (SoP). However, the light propagation in the feed-fiber and the AWG randomly alters the SoP of the seed,

implying instability in the process of remodulation. In order to solve this problem, Presi et al. propose a new topology using a Faraday Rotator Mirror (FRM) to achieve higher polarization stability [46], as shown in Fig. 11. Since the round-trip time is much shorter than the polarization fluctuations, the use of a FRM guarantees that every two round-trips the light re-enters the cavity in an orthogonal polarization state. As a result, the cavity doubles its effective length. However, these solutions still require low PDG RSOAs, which were already available at the time, but are more expensive than high PDG RSOAs. Later on, a combination of FRM and Faraday Rotator (FR) improved the polarization control, allowing the use of high PDG RSOAs [47].

Figure 11 – Self-seeding scheme proposed by Presi et al. [46]. The use of a FRM as the optical mirror provides polarization stability to the external cavity.

2.3 – Combined self-seeding and carrier remodulation scheme

The previously mentioned topology presented by Prezi et al. is the base topology for the works of our group from University of São Paulo. So far, the colorless schemes, such as self-seeding, were mostly carried out at the ONT side, which implies on a cavity length as long as the feed fiber length. They also usually employed two different optical bands for upstream and downstream. In 2013, our group proposed a WDM-PON topology, in which a self-seeding scheme was employed on the OLT, to generate the signals for downstream direction, and carrier remodulation was performed in the ONT, to erase the downstream data and re-use the same carrier for upstream transmission [48].

The basic setup is illustrated on Fig. 12. At the OLT, an RSOA generates the ASE spectrum to be sliced and reflected back by a FRM to be used as a seed. After dynamic

stabilization, the downstream signal modulates the carrier in the RSOA and a 10/90 power coupler assures that 10% of the signal is injected in the distribution fiber. In the RN, one particular channel is selected and goes to the feed fiber. At the ONU, a 10/90 power coupler sends 10% of the signal to be detected in the downstream receiver and the remaining 90% to be re-modulated in the upstream transmitter. An identical RSOA also working in saturation condition erases the downstream data and inserts the upstream data in the carrier. Therefore, the same wavelength is used for data flow on both ways with a single optical source located at the OLT.

Figure 12 – Combined self-seeding and carrier reuse topology proposed by Duarte et al. [48].

Remodulation schemes were previously explored for WDM-PON in the literature [49][50]. However, their downstream signal was generated by Distributed Feedback (DFB) lasers or slicing techniques, which are not attractive for these applications, as discussed before. The highlighted features of this topology over previous works on self-seeding and carrier reuse are [51]:

- Better spectral allocation, since it works on a single band for data flow on both directions.
- Use of the same reflective transmitter in the whole topology.
- No broadband source sharing in the upstream and robustness to broadband source failure.
- Energy consumption reduction in the OLT with the elimination of a high power broadband source.

2.4 – Double-cavity self-seeding scheme

In order to reinforce the data erasure and simultaneously provide SoP maintenance in the self-seeding topology, our group later proposed the use of a second RSOA in the OLT, forming a double-cavity scheme [52]. The basic setup is demonstrated in Fig. 13. The first RSOA is responsible for the data modulation, so is called RSOA Tx (transmitter). The second RSOA, polarized with a higher current level, improves the data erasure, therefore is called RSOA Aux (auxiliary). The key element for this topology is the Polarization Beam Splitter (PBS) located between both RSOAs and the AWG. Both RSOAs have the same characteristics and, therefore, their high gain modes are the same. A Half-Wave Plate (HWP) positioned in front of the RSOA Aux rotates the SoP in 90°. Therefore, the PBS is aligned with the perpendicular high gain profiles of both RSOAs, forming two orthogonal cavities.

Figure 13 – Double-cavity self-seeding technique proposed by Celino [52].

A closer view on the self-seeding process highlighting the states of polarization is shown in Fig. 14. After dynamic stabilization, the modulated optical signal generated by RSOA Tx goes through the PBS and emerges polarized on Vertical Mode (VM). The AWG selects the designated wavelength and 90% is directed to the FRM by the optical coupler. At the FRM, the signal polarization is reversed to Horizontal Mode (HM) and returns to the PBS common port, being directed to the RSOA Aux on VM by the HWP. This closes the circulation path of the first cavity.

Figure 14 – Double-cavity self-seeding transmitter with highlighted polarization modes.

At the RSOA Aux, the downstream extinction ratio (ER_D) of the incoming signal is suppressed and optical carrier is sent back to the FRM on HM by the HWP. Again, the signal polarization is reversed to VM in the FRM and is reflected back to RSOA TX, closing the circulation path of the second cavity. The remaining 10% signal at the power coupler output is sent to ONT to be detected and later used for re-modulation. A Polarization Filter (PF) assures that only the modulated signal is transmitted, reducing unwanted noise.

In 2015, Parolari et al. proposed a similar topology employing two RSOAs with a duo-binary modulation, i. e., with both working as transmitters [53]. As they pointed out, a double-cavity system with a PBS provides higher polarization stability, allowing the use of cheaper high PDG RSOAs. However, their self-seeding scheme was carried out on the ONT side and the cavity can be a few kilometers long, increasing the polarization fluctuations effects. By performing the self-seeding on the OLT side, the cavity is a few centimeters long and is more robust to polarization changes. Besides, by using the second RSOA for optical erasure only, with a higher current level, the overall performance is better and the use of an expensive EDFA to compensate the losses can be avoided.

2.5 – Self-seeding WDM-PON for fronthaul applications

Up to this point, the main concern was to address the inventory problem and works regarding self-seeding techniques were transmitting baseband data, aiming services like high speed internet access to home users. However, as mentioned earlier,

mobile fronthauls are the main driver application for the future of PONs. Currently, most fronthauls are implemented with point-to-point fiber connections or CWDM links, to reduce the number of fibers. There are some proposals on the use of TDM-PON with low-latency bandwidth allocation, jitter reducing techniques and bandwidth compression [54]–[56]. Nevertheless, with the mobile coverage switching from sparse macrocells to a high number of microcells and picocells in 5G, a large number of links will be required. Therefore, current TWDM-PON and future *dense* WDM-PON are more suitable options for future mobile fronthauls [57].

In the last decade, there were a few proposals on self-seeding WDM-PONs working as fronthaul solutions [58]–[64]. Specially, Saliou et al. [59] and Ma et al. [60] demonstrated successful transmissions of LTE signals using self-seeded WDM PONs in commercial environments. Parolari et al. [58] demonstrated a topology employing high PDG RSOAs that can reach up to 10 Gbps and can be used for fiber-to-the-antenna applications. However, these works deal with the baseband transport of digitalized RF signals under the CPRI. As will be discussed later, although it is the main available solution today, D-RoF may not be suitable for the strict 5G requirements.

To the best of our knowledge, the only alternative to D-RoF in a self-seeding WDM-PON fronthaul is a Pulse-Width Modulation (PWM) transmission proposed by Parolari, Gatto et al. in 2016 [61], [62]. In the uplink, the received RF signals are down-converted to an intermediate frequency, sampled and encoded in the PWM format to be sent over the fiber. Although, as they pointed out, this technique is more robust to distortions and other link impairments than pure analog transmission, there is the need of down-conversion and PWM encoding processing on the antenna site, which opposes the C-RAN simplification advantage, as will be discussed in the next chapter.

Therefore, as an alternative to current studies, we propose the use of a double-cavity self-seeding WDM-PON as an analog mobile fronthaul. The RF signals are readily transported by the fibers and can be sent to the antenna with as little processing as possible. The aspects of future mobile fronthaul will be discussed in the next chapter.

Mobile System Architectures

3.1 – Mobile Radio Access Network

Mobile networks are also known as cellular networks because their coverage area is divided into cells. Each cell is served by a base station with multiple connected mobile users. The base station is the main component of the Radio Access Network (RAN), the bridge between the mobile user and the Core Network (CN). In the third generation UMTS system, for example, the UMTS Terrestrial Radio Access Network (UTRAN) is composed of base stations elements, called Node B, and control nodes, called Radio Network Controller (RNC). In the fourth generation, the Evolved Node B (eNodeB) is its own control system, eliminating the need for a separated controller.

Figure 15 – Traditional Radio Access Network example. BBU and RU are both located on the cell site.

The base station can be divided into Base Band Unit (BBU), responsible for all baseband processing, such as Radio Resource Control (RRC), Media Access Control (MAC), channel coding, modulation, etc., and Radio Unit (RU), responsible of all RF processing, such as frequency filtering, amplification and signal transmission. In the traditional distributed RAN architecture, both BBU and RU are located at the cell site.

BBUs are connected to the core network by a physical link called backhaul and among them by a logical interface called X2. The connection between the radio modules and the antennas are usually implemented with coaxial cables or optical fibers, being only a few meters long. An example of this architecture is illustrated in Fig. 15.

3.1.1 – Centralized Radio Access Network

As an alternative to the traditional distributed architecture, the Centralized Radio Access Network separates the baseband and radio functions, placing multiple BBUs in a centralized location, usually the operator's Central Office, and leaving the cell site with little to no baseband processing. In this case, the RU is known as Remote Radio Head (RRH). This concept is demonstrated on Fig 16. The physical link between the BBUs and the RRHs is known as fronthaul and it is usually implemented using Digital Radio-over-Fiber, although it can also be wireless. In this technique, the radio signals to be transmitted by the radio element are sampled and digitalized into In-Phase and Quadrature data and transmitted over high speed links. Therefore, the RRH still must perform digital to analog conversion and some baseband processing before the RF filtering, amplification and transmission.

Figure 16 – Centralized Radio Access Network architecture. The BBUs are grouped at the central office, leaving the cells sites only with RRHs.

From the CO, one BBU can serve a single or multiple RRHs. Accordingly to [57], the BBUs can be grouped in different ways:

- BBU hotel: they are located at the same facility, but remain separated and serving individual RRHs.
- BBU pool: they cooperate with each other, share hardware resources and can serve multiple RRHs.
- BBU cloud: they are virtualized into cloud computer services.

This last case is the reason why C-RAN is also sometimes referred as Cloud-RAN. It is also aligned with two trend concepts, the Network Function Virtualization (NFV) and Software Defined Network (SDN), which are pointed out among the biggest advances in mobile communication in the last 20 years [65].

Some of the main advantages of C-RAN over the distributed architecture are [66]:

- Due to the use of a simplified radio unit, the cell site consumes less energy, is easy to install and maintain and the need for air-cooling can be eliminated.
- The network expansion in cell sites with limited space becomes feasible.
- In the case of BBU pool and BBU cloud, a cluster of BBUs can serve a cluster of RRHs accordingly to the traffic need, reducing operational costs.
- In the case of Cloud-RAN, the adaptation to non-uniform traffic and the efficient utilization of resources is also enabled.
- Since the BBUs are located in the same facility and even sharing the same hardware or cloud service, they can communicate with lower delay and facilitate cooperation mechanisms, like CoMP (Coordinate Multi-Point), that was already introduced in LTE-A.
- The heterogeneous networks and services can largely benefit from resource and information sharing.

3.1.2 – Backhaul and fronthaul physical links

As mentioned before, a backhaul is the connection between a single BBU in the distributed architecture or a group of BBUs in the centralized architecture and the core network. It transports both user and management/control data and it is usually

implemented over Ethernet, IP and Multi-Protocol Label Switching (MPLS) networks in the regional, metro and access domains [57]. Since 5G is expected to largely increase the backhaul data traffic when compared to current technologies, WDM-PON can also be interesting as a backhaul solution. However, the mobile backhaul is outside of the scope for this dissertation.

The fronthaul segment, introduced with the C-RAN concept, requires a high speed, low latency and low jitter transport link to support the radio network and digital transport needs. These characteristics make optical fibers a very adequate solution, although millimeter waves and Free Space Optics (FSO) are also considered for fronthaul/backhaul cost effective links for short distances [67], [68]. Point-to-point single fibers connections are an immediate and simple option for these connections. However, with the increasing number of cells and antennas per cell which need to be served, the number of fibers can become prohibitive. In scenarios with few cells and low traffic, TDM-PONs can also be used as fronthaul alternatives, as mentioned in the previous chapter, as long as the latency and jitter problems are suppressed. Coarse WDM is another option, although the number of channels might still be limited, especially considering the upcoming 5G or even 4G network expansion scenarios.

The TWDM technology introduced with NG-PON2 is the latest PON standard and it can support up to 8 channels with 10 Gbps each. It can be considered an adequate solution for scenarios where multiple low-traffic cells or sectors can share a single 10 Gbps wavelength channel, which is the case for most of the current LTE coverage. For these applications, however, the Dynamic Bandwidth Assignment (DBA) feature must be turned off in order to guarantee fixed bandwidth to each channel and avoid exceeding jitter when using CPRI [57]. Some options to overcome this limitation have been discussed [69].

Since it can provide numerous logical links, WDM-PON is a more adequate solution for future fronthaul applications, in which very dense coverage with massive antennas and very high bitrates are envisioned, as long as is cost-effective for network operators. As explored in the last chapter, one of the main cost problems is the inventory problem, which has been ultimately addressed with numerous colorless sources techniques. Besides, the large number of channels can also be shared among different network operators and different services, supporting the cost for the

implementation of a new structure. As pointed out in the outlook for the future of PON [26], mobile fronthaul is the main driver for upcoming standards. Therefore, future standardization process will probably address this type of requirements to provide a cost-effective solution.

3.1.3 – Radio interface protocols

The RF digitalization and transmission over optical fibers is usually performed under the Common Public Radio Interface (CPRI) protocol. This protocol is not a standard, but the result of an industry cooperation to define a specification to the interface between the BBU and RU, first released in 2003 [17]. Although it was originally designed to specify the copper wire connection between the BBU at the bottom and the RRU at the top of the tower, it has been adapted for longer optical fronthaul links. Its main characteristics are constant bitrate, accurate synchronization requirements and latency control.

CPRI defines two entities: the Radio Equipment Control (REC), which is the BBU in the C-RAN definition, and the Radio Equipment (RE), the RRH. Both are responsible for digitalization of RF signals into IQ samples. Therefore, the effective transmission of the radio signals over the fiber is at the baseband, not at a RF carrier. It also defines three different logical links between REC and RE: user data plane, management/control plane and timing/synchronization plane. They are all time-multiplexed in a serial flow of constant data rate.

There are other two less used radio interface protocols: Open Base Station Architecture Initiative (OBSAI), another industry cooperation initiative [70] and Open Radio equipment Interface (ORI), an European Telecommunications Standards Institute (ETSI) effort to develop a standard [71]. The main characteristic of OBSAI when contrasted to CPRI is the use of packet-based interface instead of constant data flow. However, the mapping methods of CPRI are more efficient, being one of the main reasons for its use [72].

3.2 – 5G radio access network features

In the 2014 paper called “What will 5G be?” [65], the authors have already indicated that 5G will not be just an incremental advance of 4G. Indeed, in December of 2017, 3GPP completed the first release on 5G New Radio (NR), specifying the air

interface operation characteristics [73]. This first released refers to non-standalone operation, relying on LTE for initial access and mobility. The standalone operation document was frozen in June 2018, at the time of writing of this dissertation, together with the final Release 15. It has been already anticipated that 5G will support operation up to 52.6 GHz from the start, both on licensed and unlicensed frequency bands, along with another key features such as flexible numerology, latency-optimized frame structure, massive Multiple-Input Multiple-Output (MIMO), interworking between macro and small cells and ultra-lean transmissions.

In order to improve the spectral efficiency, current technologies have already been introducing higher order complex modulation formats, MIMO techniques, advanced channel coding, etc. However, for future wireless and mobile networks, these resources will not be enough to satisfy the broadband requirements, especially in the limited microwave portion of the spectrum below 6 GHz. Alternatives like refarming parts of this spectrum region and also techniques such as cognitive radio were proposed to share the spectral resources in a more effective way. Another interesting solution is to explore the millimeter wave bands. Many bands are being considered, like the 24-29 and 37-39 GHz bands, the license-free band at 60 GHz, and even the bands at 71–76 GHz, 81–86 GHz, and 92–95 GHz [65].

As discussed earlier, although there is plenty available bandwidth, millimeter waves suffer from very high propagation loss and material absorption. These characteristics make them more suitable for the low-range and high-speed small cell coverage scenario. There are several challenges to enable millimeter wave cells, such as operation on Non-Line-of-Sight (NLOS), shadowing, rapid-channel fluctuations, etc. [74]. These issues have been partially addressed with MIMO techniques, beamforming, novel millimeter wave antenna arrays and Distributed Antenna Systems (DAS) [75]–[79]. From the point of view of access networks, this also implies on more traffic over the backhaul/fronthaul link to serve a single cell.

In previous mobile generations, the network coverage was mainly provided by macrocells. As discussed by Ge et al. [80], the density of macrocells is about 4 to 5 base stations per km^2 in the third generation technologies. For 4G, small cells were introduced to provide high speed coverage in high demanding areas, with a concentration of about 8 to 10 base stations per km^2 . 5G, on the other hand, is

anticipated to be an ultra-dense small-cell network, with up to 40-50 base stations per km^2 .

There are two main benefits in small cell coverage: the larger reuse of spectral frequencies over a geographic area, which enhances the coverage capacity, and the reduction in the number of users sharing the same base station resources [65]. Thus, the small cells, operating in millimeter waves, can offload the macrocells, operating in lower frequencies, leaving them mostly with the control plane communication. The larger cells are still crucial to provide ubiquitous coverage and this architecture is often called Heterogeneous Network (HetNet).

One of the main challenges for the dense deployment of small cells is to deal with cell interference and the worsened performance in the cell edges. However, techniques like Coordinate Multi-Point (CoMP) have been envisioned to mitigate these problems. In CoMP, the user communicates with multiple base stations which cooperate to provide the best coverage even in the cell edge [81]. This is possible only with a dynamic and accurate control of multiple RRHs by collaborative BBUs, yet another driver application for C-RAN architecture. Furthermore, a dense coverage with high speed cells and large number of antennas implies significant traffic over many fronthaul/backhaul links, which can also justify the use of a high capacity WDM-PON solution.

Regarding the newest applications demands presented in Chapter 1, 5G is expected to have very high aggregate rates and very low latency. Still, these requirements are not expected to be fulfilled at the same time. The 5G RAN will be device-centric instead of base-station-centric, as in the previous technologies [82]. That means that network resources will be adapted to better serve the applications, accordingly to their needs, in a concept of network slicing. Once again, this novel coverage design can greatly benefit from the Cloud RAN architecture.

3.3 – Future mobile fronthaul

The 5G features presented in the last section pose many challenges to the future fronthaul link. There are some key features that must be considered, summarized as follows:

- The link capacity must support the very high 5G bit rates.

- There are strict requirements on latency and jitter. Therefore, the link must reduce all processing to a minimum.
- Ultra-dense small-cell coverage with multiple antennas on each cell will require a large number of logical connections.
- The use of millimeter wave processing and the large number of RF equipment can be expensive. Simplification of the RRH and aid from MWP can help to reduce costs. Also, A/D e D/A conversion must be avoided on very high frequencies due to device cost and complexity.
- Techniques like CoMP, MIMO and the coordination of HetNets will require centralization, cooperation and cloud processing from the BBUs.

When considering the current digital RoF fronthaul technology based on CPRI, some problems arise. The first one is the enormous fixed bandwidth that CPRI requires. The CPRI data rate R for a single sector is based on [72]

$$R = M \times S_R \times N \times 2 \times C_W \times C, \quad (1)$$

where M is the number of antennas per sector, S_R is the sampling rate, N is the number of bits per sample, 2 is a multiplication factor related to the separate processing of In-Phase and Quadrature data, C_W is the CPRI overhead factor and C is the line coding factor. Examples of practical data rates calculations found in literature are:

- Considering S_R of 15.36 MHz per 10 MHz radio channel bandwidth, 15 bits per sample, 16/15 overhead factor and 8b/10b line coding, a LTE scenario with a single sector, 2x2 MIMO and a 20 MHz channel would require a 2.458 Gbps fronthaul link [72].
- Considering the same CPRI parameters, a LTE-A scenario supporting downlink peak data rates of 1 Gbps with 3 sectors, 8 antennas per sector and a 100 MHz channel would require 147.456 Gbps fronthaul link [57].
- Considering the same CPRI parameters, a potential 5G scenario with 3 sectors, 64x64 MIMO and a 200 MHz channel bandwidth is expected to require a 2.359 Tbps fronthaul link [83]. It is worth noting that the authors made an assumption based on current LTE channel configuration, but the real figures will probably not be far from that.

From these examples, it is clear that current CPRI is very inefficient for a 5G fronthaul solution and it would require unaffordable high-speed optical links. Various techniques to reduce the sample rate such as non-linear quantization IQ data compression have been proposed [66], but there is a trade-off between the compression ratio and signal distortion, limiting their efficiency. More complex techniques have also been proposed recently [84], [85], based on sub-Nyquist sampling and fast-statistical estimation, but they also come with the expense of additional complexity and computational power.

Besides being insufficient for most applications, the extra processing to reduce the sample rate will inevitably introduce more latency and jitter to the link. Xiang Liu and Frank Effenberger state in [83] that, considering the 1 ms end-to-end latency requirement, the latency allowed in the fronthaul is about $200\mu\text{s}$, which imposes that the overall processing can be only a very small fraction of the fiber propagation for a link of up to 20 km. Therefore, fronthaul excess processing must be avoided.

Another trend to overcome the CPRI high data rate is the Functional-Split (FS) between BBU and RRH, as presented by 3GPP in [86]. In this architecture, part of the MAC-layer and the PHY-layer functions are transferred from the BBU to the RRH, reducing the data exchanged between them. The amount and type of functions that are transferred varies accordingly to the implementation option. The newest evolved-CPRI (eCPRI) employs such resources to reduce the data rates up to ten times [87]. However, besides re-introducing complexity to the RRH, Mu Xu et al. also points out that this type of solution may be an obstacle for some 5G features such as CoMP, MIMO and the device centric coverage [85]. Since eCPRI was introduced so recently at the time of writing of this dissertation, its features, capabilities and drawbacks regarding the 5G requirements are still unexplored in literature and no further details are available.

3.3.1 – Analog Radio over Fiber Fronthaul

As an alternative to digital mobile fronthaul, Analog RoF is a strong candidate for future fronthaul links. Following the terminology adopted in [18], the RRH of C-RAN architecture is replaced by a Radio Access Unit (RAU). The RAU differs from the RRH primarily by removing the A/D and D/A converter, leaving only the electro-optical (E/O) and optical-electrical (O/E) converters and the essential RF equipment. The A-RoF fronthaul architecture is presented in Fig. 17.

In this A-RoF architecture, mobile signals are transmitted over the fiber in their original analog waveforms modulated over an electrical carrier frequency, regardless if the modulation format is analog, such as Amplitude Modulation (AM), or digital, including ASK (Amplitude Shift Keying). The carrier frequency can be the wireless radio frequency, in which case the technique can be referred as Radio Frequency over Fiber (RFoF), or an Intermediate Frequency (IF), the so called IFoF. This last is often employed to avoid fiber impairments that are more severe as the signal frequency increases. However, a RF mixer on the RAU or an up-conversion photonic technique must be employed to adequate the received signal to the wireless frequency.

Figure 17 – Analog Radio over Fiber fronthaul. The RRH is replaced by a RAU, comprising only E/O and O/E converters and basic RF processing such as amplifiers, diplexers and frequency filters.

In terms of optical transmitter, there are also two options to modulate the electrical signal into the optical carrier. The first option is to add the RF signal to the bias current that feeds the laser, in a direct modulation scheme. Although it is a simple and very common technique for baseband applications, limited cutoff frequency and chirp problems might limit its use for RoF transmission, especially at higher frequencies. The other option is to employ an external modulator, like an Electrical Absorption Modulator (EAM) or different types of Mach-Zehnder Modulators (MZM). Self-seeding techniques can be applied for both cases, either working as a directed

modulated laser or a CW laser that feeds the external modulator, as will be demonstrated later.

Analog RoF has already been employed on investigations involving the transmission of novel 5G candidate waveforms both on IF and millimeter waves. At reference [88], Delmade et al. analyzed the performance of a simultaneous IFoF transmission of both 4G and 5G signals. Seventy five bands of LTE signal and 10 bands of Universally Filtered OFDM (UF-OFDM), a 5G candidate waveform, were successfully transmitted over a 25 km fiber link. Since they used direct modulation, the IF frequency was limited to 2.4 GHz, the bandwidth of the laser. In another recent publication [89], Borges et al. also experimentally demonstrated a successful A-RoF transmission of 5G signals over a G-PON link. The electrical signals were generated by a Generalized Frequency Division Multiplexing (GFDM) transceiver, another promising solution for 5G. They integrate signals on both 735 MHz and 26 GHz bands aiming a HetNet coverage scenario. For this proposal, a dual-drive MZM was employed for external modulation and a Digital Pre-Distortion (DPD) scheme mitigated the nonlinearities impairments.

When compared to CPRI-based D-RoF, the main advantages of A-RoF as a future fronthaul solution are:

- The further simplification of the RRH into a RAU with basic RF reduces costs and complexity for the mobile network, especially considering the dense cell coverage with multiple antennas.
- By avoiding the digitalization process, the overall data rate can be reduced to the effective mobile rate without the aid of complex compression techniques. Also, when compared to the functional split solution, ARoF offers higher bandwidth efficiency and it can benefit novel techniques such as CoMP.
- In the case of millimeter wave cells, the digitalization process would require very high speed A/D and D/A converters. By using A-RoF, this complexity is eliminated. Furthermore, the analog transmission of millimeter waves can largely benefit from various microwave photonics techniques such as heterodyne detection [90].

- Since there is no processing in the fronthaul link for analog transmission, the overall latency is determined only by the fiber link length.
- In terms of costs, a comparative study between CPRI, A-RoF and a functional split solution called Physical Layer Split (PLS) was recently published by Ranaweera et al. [91]. They demonstrated that PLS and ARoF both satisfy the primary requirements of 5G and the deployment costs are reduced when compared to the traditional CPRI-based C-RAN. The study was based on an optimization framework to plan a cost-optimal 5G network and it was applied to different deployment scenarios in a suburban area of Australia.
- A-RoF also enables multi-band, multi-service and multi-operator coexistence in a shared infrastructure [18]. The analog transmission of various wireless and wired technologies such as WiFi, WiMAX, Cable Television (CATV), FTTx services and mobile access over a single PON structure has been extensively researched in last two decades [92]–[95] and the convergence of access networks is a key feature to provide seamless coverage in a future scenario.

The main drawback of analog transmission over a fiber link is the higher susceptibility to chromatic dispersion and nonlinearities on optical components such as external modulators, which reduces the Spurious-Free Dynamic Range (SFDR). Regarding chromatic dispersion, the main constraint is the fading effect where the beating of the signal side-bands leads to periodic destructive interference [96]. Since this effect increases with the signal frequency, it can be especially harmful for millimeter wave transmission. However, this problem has been addressed with chromatic dispersion compensation, zero dispersion fibers and techniques such as Optical Single Side Band (OSSB) and Optical Carrier Suppression (OCS) modulation formats [97]. The recent interest on A-RoF for mobile fronthaul has also boosted the investigation in various nonlinearities mitigation techniques [98], [99].

3.4 – Double-Cavity Self-Seeding WDM-PON as A-RoF Fronthaul

Concluding the discussions on Chapters II and III, we propose the use of a WDM-PON as fronthaul for future mobile networks, as illustrated in Fig. 18. The WDM-PON topology integrates a double-cavity self-seeding scheme at the OLT and carrier reuse at

the ONT. The fronthaul structure is based on Analog Radio-over-Fiber and is able to accommodate both microwave and millimeter wave transmission.

Figure 18 – Double-Cavity Self-Seeding WDM-PON as A-RoF Fronthaul.

The main features and advantages of our topology are summarized as follows:

- Passive Optical Networks for fronthaul and backhaul has the all advantages of optical fibers, such as low loss and high bandwidth, and is a cost effective solution due to the low cost of its passive components. It also reduces the number of fibers when compared to traditional point-to-point links.
- Wavelength Division Multiplexing allows serving a large number of small cells with dedicated high bandwidth channels on a single fiber. It also avoids the issues with time-sharing induced jitter and latency that is introduced with the TDM and TWDM solutions.
- Self-seeding at the OLT and carrier-reuse at the ONT provides colorless transmitters that solve the inventory problem and represent an improvement over traditional self-seeding schemes [51].
- The double-cavity scheme improves the optical erasure in the self-seeding scheme and provides a systematic gain over the single-cavity topology [52].
- Analog Radio-over-Fiber transmission avoids the prohibitive bandwidth consumption when compared to current fronthaul solutions and complies

with several requirements of future mobile networks, such as millimeter wave transmission, low latency links, antenna site simplification, CoMP, massive MIMO, convergence, etc. It is also a cost effective alternative, along with PLS, when contrasted with CPRI.

Simulation Framework

In this chapter, we present the simulation framework concerning the Radio-over-Fiber transmission using a double-cavity self-seeding topology. In order to have a reliable simulation framework, we first performed the calibration of our model based on experimental data. The general simulation setup is then described with direct modulation. The external modulation setup is presented later as a variation of this initial description. The numerical analysis and the results of our simulations will be discussed on Chapter 5.

4.1 – Calibration process

In order to evaluate the proposed topologies, we performed numerical simulations using the Optisystem 13.0 software provided by Optiwave [100]. Optisystem is a powerful software design tool to plan, test and simulate optical links. However, as in ever theoretical or numerical analysis, the simulated results can be distinct from experimental results since it is almost impossible to take all relevant system variables into account. In an effort to avoid such discrepancies and obtain reliable results, we calibrated our topologies following the experimental investigation on the combined single cavity self-seeding and carrier reuse topology reported by Duarte et al. on [48], [51]. The detailed calibration process and the overall numerical evaluation for the double-cavity self-seeding topology with carrier reuse can be found on the master's dissertation by Daniel Celino on [52]. Following, we will present the main calibration curves and procedures that provide reliability to our proposed investigations in the present work. The main concerns on these calibrations were to reproduce the RSOAs characteristics and the BER performances on both downstream and upstream direction. Since the present work does not investigate the upstream performance, only the downstream calibration will be presented.

4.1.1 – RSOA calibration

Accordingly to the Optisystem technical manual, the RSOA component simulates a model with bulk material as the active element. This SOA model is based on the numerical solution of a set of coupled differential equations that describe the interaction

between the carrier density and photon rates along the active layer length [101]. The main parameters used for the RSOA model are presented on Table 4, as they are named on the software.

Table 4 – RSOA model parameters.

Parameter	Value	Unit
Input coupling loss	3	dB
Output coupling loss	3	dB
Input facet reflectivity	50×10^{-6}	-
Output facet reflectivity	0.99	-
Length <i>Active region length</i>	0.85	mm
Taper length <i>Taper region length</i>	0.0001	
Width <i>Active region width</i>	0.4	μm
Height <i>Active region thickness</i>	0.4	μm
Optical confinement factor	0.4	-
Recombination coefficient A <i>Linear recombination coefficient</i>	360×10^{-6}	s^{-1}
Recombination coefficient B <i>Bimolecular recombination coefficient</i>	0.56×10^{-15}	m^3/s
Recombination coefficient C <i>Auger recombination coefficient</i>	30×10^{-42}	m^6/s
Group velocity	75×10^6	m/s
Temperature <i>Absolute temperature</i>	300	K
Junction ideality factor	2	-
Material gain <i>Define the approximation used to calculate the material gain coefficient</i>	Lorentzian	-
Gain constant a_0 <i>Differential gain coefficient</i>	0.25×10^{-18}	m^2
Gain constant a_2 <i>Gain constant characterizing the gain-peak shift</i>	0.29×10^{-36}	m^4
Carrier density at transparency <i>Transparent carrier density</i>	1.4×10^{-24}	m^{-3}
Gain peak wavelength <i>Peak wavelength at transparency</i>	1545	nm
Gain bandwidth <i>The 3 dB bandwidth of the linear gain coefficient</i>	123	nm
K_0 <i>Carrier independent absorption loss coefficient</i>	6200	m^{-1}
K_1 <i>Carrier dependent absorption loss coefficient</i>	7.5×10^{-21}	m^2

The calibration was performed by adjusting the ASE central frequency, confinement factor, active length and the carrier dependent (K_o) and independent (K_i) absorption loss coefficients. The approximation used to calculate the material gain coefficient was also switched from default to a Lorentzian approximation [102]. The main goal as to closely approach the gain characteristics of the actual RSOA employed in the experiment. Fig. 19 shows the comparison between the gains curves for the real RSOA and the Optisystem model under 60 and 90 mA biases current, which were the values employed for downstream and upstream in the experiment. As it can be seen, the values differs less than, respectively, 0.3 dB and 1.0 dB from the experimental data. Therefore, we have satisfactory reproduced the optical behavior of the devices operating on DC.

We have also confirmed that the simulated optical spectrum profile after stabilization is very close to the one obtained in the experiments, reaffirming that the RSOA is well calibrated (Fig. 20). The remaining elements present on the cavity also affect the spectrum, but they were detailed on the main text.

Figure 19 – Optical gain curves comparison between simulated curves and experimental data [48].

Figure 20 – Normalized spectrum curves comparison between simulated curves and experimental data [48].

4.1.2 – Downstream calibration

The other important calibration performed on the topology regards the PIN photodetector model. The responsivity and noise characteristics were altered to adjust the BER characteristics in the downstream direction. The main parameters used for the PIN photodiode model are presented on Table 5, as they are named on the software. The simulated BER results are compared to the experimental data on Fig. 21.

Table 5 – PIN photodetector model parameters.

Parameter	Value	Unit
Responsivity type	Constant	-
Responsivity	0.5	A/W
Effective noise bandwidth	1	GHz
Dark current	10	nA
Noise calculation type	Numerical	-
Add signal-ASE noise	Yes	-
Add ASE-ASE noise	Yes	-
Add thermal noise	Yes	-
Thermal power density	100×10^{-24}	W/Hz
Add shot noise	Yes	-
Shot noise distribution	Gaussian	-
<i>Determines the distribution used to generate the shot noise</i>		
Transfer function model	Ideal	-

Figure 21 – BER curves comparison between simulated curves and experimental data [48].

The responsivity type and the transfer function model parameters were kept constant and ideal in order to accommodate different signal frequencies and bandwidths to the same simulation model. Accordingly to the Optisystem technical manual, the noise calculations performed by the software are based on [103]. There is a discrepancy between the curves of no more than 0.5 dB, indicating that the setup configured on the simulator is reliable. The upstream calibration was also performed on [52], yielding very similar PIN diode characteristics. However, the present work does not include carrier reuse and upstream transmission in the simulation setup.

4.2 – General topology description

The main simulation setup for downstream transmission using direct modulation is illustrated at Fig. 22. The Pseudo-Random Bit Sequence (PRBS) is encoded into Non-Return-to-Zero (NRZ) format and it is sent to the electrical modulator. The modulation formats employed for our investigations are ASK, M-PSK and 16 QAM. For the last two, the bits are mapped into signal vectors and modulated by a quadrature modulator. The modulated signal with 48.2 mV peak-to-peak is then added to a 100 mV DC bias voltage and inserted into the RSOA Tx, as shown in Fig. 23. These values were chosen to be the same as the experimental baseband transmission performed in [48]. For the

direct modulation simulations, all transmissions were performed in the wireless frequency, i.e., 1.25, 2.5 and 5 GHz.

Figure 22 – Basic simulation setup for downstream transmission.

Figure 23 – Electrical signal inserted into the RSOA.

As described earlier, the RSOA Tx model main characteristics were calibrated with experimental data. The frequency response, however, was neither available from the experimental information nor can be simulated in the Optisystem. In order to account for a RSOA with a RC frequency response, we considered attenuations of 1.7 dB on the 2.5 GHz input signal and 5.5 dB in the 5 GHz input signal in our simulations, following typical data found in the self-seeding literature [104]. The same parameter values were employed for the RSOA Aux. The bias voltage was set to 125 mV DC to reinforce erasure.

The crucial device to control the polarization and separate the orthogonal cavities is the Polarization Beam Splitter (PBS). This device was emulated at Optisystem using a sub-system which introduces a 25 dB attenuation to the unwanted polarization in each port and adds both polarizations in the common port. The Half-Wave Plate (HWP) was not necessary in the simulation since the RSOA model is polarization insensitive, i.e., it has zero PDG. The Faraday Rotator Mirror was emulated on Optisystem using a 90° Polarization Rotator (PR) and a reflector (or mirror) that reflects 99% of the signal and introduces a 0.5 dB attenuation plus a 90° phase shift. Finally, before being inserted into the fiber, the output signal goes through a Polarization Filter (PF) to reduce noise. This device introduces a 25 dB attenuation in the polarization orthogonal to the one which the signal was modulated by the RSOA Tx.

The AWG at the transmitter side is responsible for the spectral slicing as well as to the multiplexing functions. Since our simulations are performed on a single channel and our main concern is the self-seeding process, the AWG was replaced by an optical filter, which has more configurable parameters. The same was done for the AWG in the receptor and the filters have identical configurations, except where noted in the following sections. The optical filters have 4th order Bessel transfer functions, central frequency of 193.3 THz (or 1550.91 nm), bandwidth of 0.5 nm and 5.5 dB insertion loss. As already demonstrated, these configurations on a single-cavity calibration topology yielded a very close spectral result when compared to experimental data.

To close the transmitter description, the Power Coupler is responsible to direct 90% of the signal for downstream transmission and 10% to the FRM. The insertion loss for this device was set to zero. A bidirectional circulator was also considered in the simulation via an attenuation of 1.8 dB, since it will be present in a bidirectional transmission. The FRM closes the two orthogonal polarization cavities where the self-seeding process occurs.

In order to illustrate the modulation and data erasure that occurs in the self-seeding process, the optical signals at the input and output of both RSOAs are shown on Fig. 24. The RSOA Tx output (a) is the modulated optical signal. After reflection at the FRM, the modulated signal returns to the RSOA Aux (b) and the data is erased by it (c). The output of RSOA Aux is similar to a CW signal and it is used as an input for the RSOA Tx (d).

Figure 24 – The modulation and erasure process inside the cavity. a) RSOA Tx output. b) RSOA Aux input. c) RSOA Aux output. d) RSOA Tx input. The random abrupt peaks that are present in the signals are due to the simulation process and have no physical meaning.

As discussed in [105], the self-seeding process reaches dynamic stabilization after around 100 iterations. Figs. 25 and 26 present the output signal without modulation in the time and spectrum domain, respectively, in the 0th and 100th iterations. Notice that at the 100th iteration the signal linewidth is reduced from 0.5 nm, the bandwidth of the AWG filter, to 0.095 nm. After this dynamic stabilization, the optical carrier is ready to be modulated with data by the RSOA Tx. In practice, this process takes place few milliseconds after the transmitter is turned on.

Figure 25 – Output signal in the time domain in the 0th and 100th iterations.

Figure 26 – Output signal in the spectrum domain in the 0th and 100th iterations.

Following on the simulation setup, the fiber link is composed of a distribution fiber of 15 km and a drop fiber of 5 km. The fiber parameters were based on commercial fibers, such as Corning SMF-28 [106], with 0.22 dB/km attenuation, 17.3 ps/nm/km dispersion parameter and 0.092 ps/nm²/km dispersion slope. Optisystem uses the familiar Split-Step Fourier method to solve the Nonlinear Schrodinger Equation (NLSE) [107]. However, nonlinear effects were turned-off to save computational time after a preliminary investigation demonstrated that they did not significantly affect a single channel transmission.

The effects of chromatic dispersion over the transmission of microwave and millimeter waves in optical fibers are well known, as analyzed in [96]. In the case of Intensity-Modulation Direct-Detection (IM-DD) links, the electrical signals are carried as a lower and upper side band on the optical carrier. Due to their spectral distance and the effect of dispersion, each of these bands experiences a different phase shift. After photodetection, the phase difference will affect the electrical signal amplitude. For instance, if the phase difference between both side bands is π , the signal will be completely extinct. These “nodes” are periodical with link distance, with length period

$$\Delta L = \frac{c}{2D\lambda^2 f_c^2}, \quad (2)$$

where c is the speed of light in vacuum, D is the dispersion parameter, λ is the optical carrier wavelength and f_c is the electrical signal frequency. Fig. 27 illustrates simulated fading nodes in the experimental setup for microwave frequencies.

Figure 27 – Fading nodes for 1.25, 2.5 and 5 GHz transmission.

As indicated by eq. (2) and illustrated on Fig. 20, the penalty is higher with the increase of electrical frequency. Therefore, a millimeter wave transmission is even more affected by dispersion. In order to mitigate this problem, we employed a FBG-DC (Fiber-Bragg-Grating Dispersion Compensator) to compensate the chromatic dispersion of the optical fiber link. The FBG-DC was emulated in the simulation setup by a module which compensates 99% of the total dispersion (342.54 ps/nm) and introduces a 3.5 dB insertion loss. This module was chosen to compensate the dispersion of a single channel after the drop fiber. As an alternative, depending on the application, a Dispersion Compensation Fiber (DCF) could also be employed to pre-compensate all channels.

At the receiver, the PIN photodetector is employed along with an ideal Transimpedance Amplifier (TIA), providing a 15 dB gain. The detected signal is then filtered by an ideal flat-top filter and it is sent for analysis. Error Vector Magnitude (EVM) analysis is performed on the IQ modulation format signals (i.e. BPSK, QPSK, 8PSK and 16QAM) and BER analysis is performed on the ASK signals, after demodulation. It is worth noticing that the signal evaluation is performed before the signal is sent to the wireless transmitter.

4.3 – External modulation topologies description

4.3.1 – External modulation with EAM

RSOA-based self-seeding with direct modulation is limited to a few GHz due to the RSOA limited frequency response [104]. Therefore, to transport millimeter wave signals in an IM-DD scheme, an external modulation is required. EAM presenting electrical bandwidth up to 60 GHz was employed for such applications since the early 2000s by Kitayama's group [108]–[111]. For our self-seeding topology, EAM also presents the advantage of being a semiconductor device that can be integrated to the RSOA, which is not possible for MZM, since it is usually made of Lithium Niobate. On the other hand, external modulation is more expensive than direct modulation, but it might be cost-effective for fronthaul applications since it is a commercial application with very high bandwidth demand.

As stated before, the external modulation topologies will be treated as a variation of the general direct modulation topology. In this case, the RSOA Tx is polarized with a

DC bias current only, to provide only the self-seeded CW signal that will serve as an optical carrier to the external modulator. The DC bias current was kept at 100 mA to maintain the same RSOA characteristics as before. The EAM was inserted in front of the RSOA Tx, as illustrated at Fig. 28:

Figure 28 – External modulation transmitter setup.

For the EAM model, the Optisystem technical manual states that the optical output signal response to an applied voltage is

$$E_{out} = \sqrt{I(V)} e^{\left\{ \frac{j}{2} \int \alpha_m(V) d[\ln I(V)] \right\}}, \quad (3)$$

where $I(V)$ is the voltage-dependent intensity of the signal and $\alpha_m(V)$ is the measured alpha-parameter, provided by Optisystem as an example of a Multiple-Quantum-Well EAM (MQW-EAM), as shown in Fig. 29.

Figure 29 – Dependence of α_m on the applied voltage for an MQW-EAM, as provided by the Optisystem's technical manual.

The applied voltage to the EAM is composed of the input electrical signal plus a bias voltage that can be chosen between 0 and -2 V. The DC bias voltage was set to -0.6

V and the signals amplitude were adjusted to 1.3 V peak-to-peak, since this configuration yielded the best BER results in our investigation (Fig. 30).

Figure 30 – Signal applied to the external modulator without bias voltage.

4.3.2 – External modulation with MZM

As an alternative to the EAM, we also evaluated the use of a MZM to perform frequency multiplication. The motivation behind this proposal is to employ frequency doubling to avoid the need for a high frequency external modulator as well as 60 GHz RF processing in the transmitter. With this technique, a 60 GHz signal transmission requires a MZM operating up to 30 GHz, which can be found commercially [112]. It also requires 30 GHz mixers and amplifiers on the transmitter, instead of 60 GHz ones.

This technique was first introduced by O'Reilly et al. in 1992 [113]. They employed a MZM to generate a very narrow linewidth 36 GHz signal using a 18 GHz tone. Already at that time there were discussions on the application of such technique in future picocellular communications. The main idea is that the mixing of two tones at the photodiode generates sum and difference frequencies signals. Therefore, if two optical signals are 60 GHz apart, for instance, a 60 GHz electrical signal can be generated in the photodetection process.

The optical output of a MZM driven by a sinusoidal signal and a bias voltage, as a function of time, is given by [113]

$$E_{out}(t) = \cos\left\{\frac{\pi}{2}[(1 + \varepsilon) + \alpha \cos(2\pi f_s t)]\right\} \cos(2\pi f_o t), \quad (4)$$

where ε is the bias point normalized to V_π , α is the normalized amplitude of the drive signal, f_s is the signal frequency and f_o is the optical frequency. By expanding (4) in Bessel functions, it can be shown that if the modulator is biased to make $\varepsilon = 0$, the central optical frequency f_o is suppressed along with the even components, leaving strong components centered at f_o and separated by $2f_s$. Therefore, at the photodetector, a $2f_s$ electrical signal is generated.

To emulate a frequency multiplication technique in our topology, we employed the Lithium Niobate Mach-Zehnder Modulator based on measured parameters provided by Optisystem with similar characteristics to the commercial MZM referred in [112]. The main parameters are displayed on Table 6. The device model does not include the frequency response, but, since the operation occurs within the reference's specified bandwidth, we assume that no penalty is imposed. Also, the output power was adjusted to maintain the same circulating power in the cavity as in the experimental reference [48], maintaining the same conditions for the self-seeding process.

Table 6 – Lithium Niobate Mach-Zehnder Modulator model parameters.

Parameter	Value	Unit
Extinction ratio	7	dB
Switching bias voltage <i>DC voltage required to turn the modulator from the OFF state to the ON state, or vice versa</i>	5	V
Switching RF voltage <i>RF voltage required to turn the modulator from the OFF state to the ON state, or vice versa</i>	5	V
Bias voltage1	0	V
Bias voltage2	-5	V
Insertion loss	0	dB
Normalized electrical signal	No	-

The simulation setup for this technique is very similar to the one used for the EAM and it is illustrated in Fig. 31. Notice that the employed modulator is dual-arm MZM. We chose this model since it is the most complete one in terms of configurable parameters. In a real implementation, other types of MZM and optical configurations might yield even better performance. However, our goal here is only to demonstrate the feasibility of a frequency doubling technique in external modulation double-cavity self-seeding topology.

Figure 31 – External modulation transmitter setup using MZM.

Regarding this topology, we performed simulations for 38 and 60 GHz signals, which are candidate operating frequencies for 5G and future wireless access networks. The MZM input signals are at 19 and 30 GHz, respectively, and their amplitudes are set to 1 V peak-to-peak. The comparison between their optical spectra when modulated with the EAM and the MZM is shown in Figs. 32 and 33.

Figure 32 – Comparison between the 38 GHz signal optical spectra with EAM and MZM modulations.

Figure 33 – Comparison between the 60 GHz signal optical spectra with EAM and MZM modulations.

Notice that the carrier is not suppressed as was expected in our previous assumptions. After some investigation, we noticed that this issue was due to the small extinction ratio set in the MZM model parameters. Optisystem default value is 20 dB and the carrier suppression is noticeable with this value. However, our self-seeding process is limited by a capacity of erasing signals with extinction ratio up to about 12 dB and 7 dB was the default value in the reference experiments. Nevertheless, this issue does not affect the frequency doubling, besides the obvious power penalty caused by the presence of the carrier.

4.4 – Global parameters and simulation process

Before starting simulating, Optisystem requires the configuration of global parameters which, besides affecting all components, will also affect the speed, accuracy and memory requirements. These parameters were set as indicated in Table 7. For the choice of these parameters, two main constraints were taken into account:

1. **Limited computation time and memory requirements.** With our available computation hardware, some of the simulations required up to 90 hours to run and 32 GB RAM memory. Therefore, lower resolution was necessary in order to run all the investigations.

2. **Results accuracy and reliability.** On the other hand, better resolution is required in order to achieve the minimum sample rate for high frequency signals and especially to have lower margin of error in the statistical evaluations.

Therefore, preliminary tests were run to find the best trade-off between both. The resolution was progressively increased until it stops affecting the BER and EVM results of similar simulation setups that did not require multiple iterations and, therefore, are faster to run.

Table 7 – Global parameters.

Parameter	Value
Bit Rate	The simulation main bit rate, i. e., 155 Mbps, 622 Mbps, 1.25 Gbps and 10 Gbps.
Sequence length	512 bits for 38/60 GHz simulations, 2048 for 16-QAM simulations and 256 bits for the rest.
Samples per bit	512 samples for 38/60 GHz simulations and 256 for the rest.

In order to further reduce the computation effort, the overall simulation and analysis were also divided in three steps:

1. **CW self-seeding generation.** The RSOAs operate only with the DC bias for 100 iterations (or round-trips) in order to generate a stable CW signal. The RSOA Tx input CW signal in the 100th iteration is then saved to be used on direct and external modulation simulations. Due to the different parameters combinations presented in Table 5, 10 different signals were necessary.
2. **Direct or external modulation transmission.** For this step, the CW signal saved in the previous step is inserted in the RSOA Tx for 3 iterations before any data is modulated. After that, 17 round trips are run with data modulation and the fiber input signal in the 20th is saved.
3. **Link and detection analysis.** The transmission signal saved in the last step is then analyzed with different link and receiver scenarios to evaluate the performance. In this case, there is no need to have multiple iterations since there is no more self-seeding process at this point. However, we averaged the results of 3 iterations to reduce fluctuations on the simulation process.

4.5 – Performance evaluations

4.5.1 – BER evaluation

In the cases of ASK format, we performed BER evaluations to demonstrate the feasibility of our proposed topologies. To do so, the photodetected signal is filtered by a band-pass ideal filter with a bandwidth two times the bitrate of the evaluated signal. Next, the Electrical Amplitude Demodulator with an associated Cosine Roll-Off (roll-off factor of 0.3) Low-Pass Filter demodulates the signal. Examples of signals after filtering and demodulating are presented in Fig. 34:

Figure 34 – Electrical signal after filtering (top) and after demodulation (bottom).

After demodulation, the signal goes through a 3R Regenerator which extracts the bit sequence and the NRZ pulses. These two outputs, along with the input signal, are used for the BER evaluation. The BER Analyzer estimates the error value assuming Gaussian noise distribution with the expression for the error probability given by

$$P_e = \frac{M}{N+M} P_{e0} + \frac{N}{N+M} P_{e1}, \quad (5)$$

where M is the number of samples for the logical 0, N is the number of samples for the logical 1 and P_{ei} ($i = 0,1$) is the error probability for each sample, based on

$$P_{ei} = \frac{1}{2} \operatorname{erfc} \left(\frac{\pm S \mp \mu_i}{\sqrt{2} \sigma_i} \right), \quad (6)$$

where erfc is the complementary error function [103], S is the decision threshold, μ_i is the sample's average value and σ_i is the sample's deviation standard value.

4.5.2 – EVM evaluation

In the cases of IQ modulation formats, we performed EVM evaluations instead of BER measurements, since equations (5) and (6) are restricted to NRZ formats and EVM is commonly used for these types of analysis in the context of wireless networks. For this, the photodetected signal is filtered by a Squared Root Band Pass Raised Cosine Filter with a bandwidth equals to the symbol rate of the evaluated signal and roll-off factor of 1. Next, the Quadrature Demodulator with an associated Cosine Roll-Off (roll-off factor of 0.3) Low-Pass Filter demodulates the signal, which remains encoded in the respective modulation format, i.e., M-PSK or M-QAM mapping. This encoded signal is then evaluated at the Electrical Constellation Visualizer. After normalizing the amplitude and correcting an eventual phase offset in the electrical constellation, the EVM value can be extracted. The software defines the EVM as

$$EVM = \sqrt{\frac{\sum_{l=1, l \neq k}^M d_{kl}^2}{\sum_{k=1}^M d_k^2}}, \quad (7)$$

where M is the number of received symbols, d_k is the distance of the center of the region where the k^{th} symbol was mapped and d_{kl} is the distance between the received symbol and the referred center (see Fig. 35). Therefore, EVM is a measure of how much the received symbols differ from their original constellation mapping.

Figure 35 – Electrical constellation illustrating the relevant distances to the EVM evaluation.

Results and Discussion

In this chapter, we present and discuss the numerical results from based on BER and EVM metrics for various signal formats with bitrates and operational frequencies aiming the applications presented in the previous Chapters. We also included an analysis of multiband transmission to demonstrate a possible application of our topologies as fronthaul for future converged networks and heterogeneous networks, operating on both microwave and millimeter wave frequency bands.

5.1 – Direct modulation analysis

Using our proposed direct modulation double cavity self-seeding topology (Fig. 36), we performed the transmission of ASK format signals over the frequencies of 1.25 GHz, 2.5 GHz and 5 GHz. These values were chosen to be close to the frequencies of commercial wireless and mobile access networks, like LTE, WiFi and WiMAX. The tested bitrates for each frequency were 155 Mbps, 622 Mbps and 1.25 Gbps, which are also commonly used in telecommunications systems. Higher frequencies and higher bitrates were not tested because of limited response of state-of-art RSOAs.

Figure 36 – Direct modulation double cavity self-seeding topology.

As mentioned in the last chapter, although the software does not include a limited frequency response in the RSOA model, we emulated such limitation based on real RSOAs. It is also worth mention that current data transmission over these commercial wireless and mobile access networks is performed with complex techniques, such as OFDM and various codifications, in order to increase spectral efficiency and deal with

wireless transmission impairments. However, Optisystem is not intended for RF design and our main goal with these numerical evaluations is to demonstrate the feasibility of transporting microwave and millimeter wave analog signals over a novel optical network topology.

The directly modulated ASK-format BER analysis over the mentioned frequencies and bitrates are presented in Figs. 37 to 39. All transmitted signals demonstrated successful recovery with an optical received power of -25 dBm when considering a BER Forward Error Correction (FEC) limit of 10^{-3} . The 5 GHz signal reaches a 10^{-9} BER floor even for the low rate 155 Mbps transmission. This is due to the frequency limitation imposed to the RSOAs, especially since the optical power circulating on the cavity decreases at this modulation frequency. The performance also moderately worsens with the increasing bitrate, reaching a 10^{-8} BER floor when transmitting 1.25 Gbps. The curves for 155 Mbps transmission at 1.25 and 2.5 GHz present BER performances beyond the error-free stipulated value of 10^{-12} with no curve floor.

Figure 37 – Directly modulated ASK format signals BER evaluation at a bit rate of 155 Mbps.

Figure 38 – Directly modulated ASK format signals BER evaluation at a bit rate of 622 Mbps.

Figure 39 – Directly modulated ASK format signals BER evaluation at a bit rate of 1.25 Gbps.

The BER Analyzer provides the eye diagram graph for the qualitative evaluation of noise and intersymbol interference. A general example of typical eye diagram resulting from RoF double-cavity self-seeding transmission is provided o Fig. 40. This

result was obtained from a directly-modulated 1.25 Gbps ASK transmission at 1.25 GHz. The optical received power was -26.84 dBm.

Figure 40 – Example of eye diagram resulting from RoF double-cavity self-seeding transmission.

The eye vertical aperture indicates the moderate presence of noise and its horizontal aperture also indicates the moderate presence of jitter. The main sources of noise are the residual noise introduced in the self-seeding cavity due to incomplete data erasure and the noise added by the optical receiver. It is also worth noticing that there is residual dispersion on the link to emulate imprecise dispersion compensation. Moreover, the linewidth of the self-seeding carrier is very large when compared to conventional single-mode lasers ($\Delta\lambda=0.095$ nm at 1550.91 nm), which also accounts for the degradation of optical signals. However, since the eye pattern appears wide open on both dimensions, we assume that the self-seeding process produces a fair signal quality for our applications. Further numerical evaluation of jitter and latency is out of the scope of our present investigation with Optisystem.

For the IQ modulation formats, we performed the transmission of BPSK, QPSK, 8PSK and 16QAM signals at 1.25 GHz with a bit rate of 1.25 Gbps. The EVM evaluations were all performed at a received optical power of -26.84 dBm. 64QAM and higher order modulations were not tested due to computational limitations, since it would require a better resolution to obtain reliable results. The electrical constellations and EVM values are displayed on Fig. 41.

Figure 41 – Directly modulated BPSK, QPSK, 8PSK and 16QAM signals at 1.25 GHz with a bit rate of 1.25 Gbps. The EVM evaluations were all performed at a received optical power of -26.84 dBm.

Taking the LTE Technical specification provided by 3GPP as a reference [114], the maximum tolerable EVM for BPSK and QPSK is -15.31 dB (17.5%) and for 16QAM is -18.06 dB (12.5 %). There is no indication for 8PSK. Although it is not the same simulation since the 3GPP specifications refers to IQ modulation within the LTE complex transmission context, it indicates that our results are close to the minimum requirements, with only 16QAM falling short. Another feature that can be noticed on the constellation is a phase offset of little more than 10 degrees on all signals. We believe that this phase rotation is imposed by the transfer functions of the optical filters that emulate the AWGs both on transmission and reception. However, since this deviation is expected to be constant, this can be easily handled with signal processing techniques. Also, the use of optical filters other than the Bessel types might mitigate the impairments over the electrical signal, since we have noticed that the shape of the filter alters the signal quality. In any case, our proposed topologies were simulated based on

the calibration with previous experiment results, not on optimizing the transmission for the RoF performance. Optimized operation conditions can certainly improve these results.

5.2 – External modulation analysis

In the proposed external modulation topology using the EAM (Fig. 42), we initially performed the transmission of ASK format signals over the frequencies of 1.25 GHz, 2.5 GHz and 5 GHz and bit rates of 155 Mbps and 1.25 Gbps.

Figure 42 – External modulation double cavity self-seeding topology.

BER analyses of these signals are shown in Figs. 43 and 44. When compared to the direct modulation transmission (Figs. 37 and 39), BER performance of the 5 GHz signal improved significantly, with error free transmission at 155 Mbps and the noise floor shifted from 10^{-5} to 10^{-9} at 1.25 Gbps. We also performed the transmission of BPSK, QPSK, 8PSK and 16QAM signals at 1.25 GHz with a bit rate of 1.25 Gbps. The electrical constellations and EVM values are displayed on Fig. 45. When compared to the direct modulation transmission, EVM values display an improvement for the BPSK and QPSK modulation formats of about 2 and 1.3 dB, respectively. The EVM values for 8PSK and 16 QAM are about the same. The phase offsets are also very similar for all formats. This indicates that the optical modulation scheme does not affect significantly the IQ transmission for a same frequency and same bitrate, when considering an operation frequency within the RSOA modulation bandwidth.

Figure 43 – Externally modulated ASK format signals BER evaluation at a bit rate of 155 Mbps.

Figure 44 – Externally modulated ASK format signals BER evaluation at a bit rate of 1.25 Gbps.

Figure 45 – Externally modulated BPSK, QPSK, 8PSK and 16QAM signals at 1.25 GHz with a bit rate of 1.25 Gbps. The EVM evaluations were all performed at a received optical power of -26.84 dBm.

Following, we performed the evaluation of 1.25 Gbps IQ modulation format transmissions at 60 GHz. Since we are assuming that the EAM cut-off frequency is above 60 GHz [108]–[111], the process of optical modulation does not affect the performance when increasing the frequency. The optical filters and the residual link dispersion impose severe degradation to the 60 GHz signals, since the sidebands are 120 GHz apart. Therefore, to obtain successful transmission, we reduced the residual link dispersion from 1% to 0.01% (ideal compensation), by improving the dispersion compensator and increasing the reception optical filter (Demux) bandwidth from 0.5 nm to 1.2 nm. The AWG at the transmitter were not altered to keep the same self-seeding conditions, with the penalty of filtering (attenuating) some information at the sidebands. The EVM results for the 60 GHz transmission under these conditions are presented on Fig. 46. Notice that overall results improved when compared to the transmission at 1.25 GHz, except for the BPSK signal. The 16QAM EVM almost meets the minimum EVM

requirements for this case. The imposed phase shift was also altered to about 23 degrees in all transmissions. These results confirm that the IQ transmission can be improved by optimizing the self-seeding process and link conditions.

Figure 46 – Externally modulated BPSK, QPSK, 8PSK and 16QAM signals at 60 GHz with a bit rate of 1.25 Gbps. The EVM evaluations were all performed at a received optical power of -26.84 dBm. The residual link dispersion is 0.01% and the optical filter (Demux) bandwidth is 1.2 nm.

In order to compare the transmission of millimeter wave signals using EAM and MZM with frequency doubling technique, we evaluate the BER for 1.25 Gbps and 10 Gbps ASK format signals at 38 and 60 GHz. The BER results for the signals at 38 GHz are displayed of Fig. 47. All transmitted signals demonstrated successful recovery with an optical received power of -27 dBm when considering a BER FEC-limit of 10^{-3} . The BER results on Fig. 47 demonstrate that the power performance of the MZM modulation is about 2 dB better than the EAM modulation for most of the values. The 10 Gbps EAM modulation also presents a BER floor of about 10^{-7} . The main reason for this improved performance is that MZM-modulated signal is effectively being

transmitted with sidebands separated by half the spectrum distance when compared to the EAM-modulated signal. Therefore, the dispersion and optical filters imposed penalty is less severe. On the other hand, there is received power penalty of about 3 dB for using this particular MZM doubling technique.

Figure 47 – Externally modulated ASK format signals BER evaluation at bitrates of 1.25 and 10 Gbps and operation frequency of 38 GHz.

The BER results for the 1.25 Gbps signals at 60 GHz are displayed in Fig. 48. In this case, the EAM-modulated scheme requires at least -21 dBm for successful transmission and the power performance of the MZM modulation is significantly better. This is because, in order to compare the performances, the link conditions were kept the same. Therefore, the dispersion and narrowband optical filter impairments are way more severe when the sidebands are separated by 120 GHz. By using the MZM doubling technique, the sidebands are separated by only 60 GHz, and a further optimization of the optical link can improve these results even more. Besides, although we are simulating a single channel, reducing the bandwidth occupied by the signal allows for a reduction in the channel spacing on a WDM-PON network, i.e., a fixed operation band can allocate more users.

Figure 48 – Externally modulated ASK format signals BER evaluation at a bit rate of 1.25 and operation frequency of 60 GHz.

The BER results for the 1.25 Gbps signals at 60 GHz are displayed at Fig. 49:

Figure 49 – Externally modulated ASK format signals BER evaluation at a bit rate of 10 Gbps and operation frequency of 60 GHz. The conditions for EAM-modulated transmission were altered to a 0.1% residual link dispersion and 1.2 receiver optical filter bandwidth.

For this case, in order to obtain successful transmission using the EAM, we also reduced the residual link dispersion from 1% to 0.1% (ideal) by improving the dispersion compensator and increased the reception optical filter (Demux) bandwidth

from 0.5 nm to 1.2 nm. The MZM simulation conditions were kept as the default. In this framework, both transmitted signals allowed successful recovery with an optical received power of -27 dBm when considering a BER FEC-limit of 10^{-3} . Still, the MZM-modulated signal demonstrated a better performance, reinforcing that this technique can significantly improve the transmission quality of millimeter waves.

5.3 – Multiband transmission analysis

As a last investigation regarding our self-seeding topology, we have explored the transmission of multiple signals over the same wavelength using the EAM. As explained on reference [108], multiband transmission using a single EAM requires a tedious process of simultaneously adjusting the amplitude of multiple signals and the bias conditions in order to find the best performance. This occurs because the signals interfere with each other in different ways at different bias points. We chose to keep the amplitude of the applied signal to EAM the same as we have employed before, with each signal having amplitude of 0.65 V peak-to-peak, as shown on Fig. 50. The bias voltage was also kept at -0.6 V. This means that, although we have achieved successful transmission, these are possibly not the best conditions for multiband modulation.

Figure 50 – Multiband signal applied to the external modulator without bias voltage.

To demonstrate the feasibility of our external modulation topology as a converged fronthaul solution, we simulated the simultaneous transmission of 5 and 60 GHz. Although a simplified demonstration, this simulation can account for a scenario where the same logical link serves both the small cell and the macrocell or two different

services, like 5G and Wi-Fi. The BER results of 1.25 Gbps signals simultaneous transmission at 5 and 60 GHz are displayed on Fig. 51. For this transmission, the link conditions were also altered to a 0.1% (ideal) residual link dispersion and 1.2 receiver optical filter bandwidth. Successful transmission was obtained for received optical power of -22 dBm for the 60 GHz signal and -27 dBm for the 5 GHz. Both signals were analyzed separately, by using ideal rectangular electrical filters. However, these results indicate that they can be split before the photodetector, leaving more optical power to the 60 GHz receiver. In any case, different bias and amplitude conditions can yield different results, requiring an optimization process. Also, the BER results are better than the individual transmissions presented of EAM-modulated 1.25 GHz and 60 GHz presented earlier. However, the link conditions are different, with less distortion and dispersion being imposed on the simultaneous transmission.

Figure 51 – BER analysis for the simultaneous transmission of 1.25Gbps ASK format signals at 5 and 60 GHz. The link conditions are: 0.1% residual link dispersion and 1.2 receiver optical filter bandwidth. The signals are analyzed separately.

Conclusions and Future Works

6.1 – Conclusions

The increasing demand for high speed data connections, driven specially by video-on-demand, and new applications brought by the proliferation of smartphones are imposing several challenges to the future of access networks. On the mobile/wireless market, telecommunications companies are working on the 5G, the Fifth Generation of mobile networks. This upcoming standard is expected to provide high speed internet access with low latency response to dense coverage environments. In order to meet these challenges, among other features, 5G will operate on the millimeter wave's portion of the electromagnetic spectrum (30-300 GHz). Due to the propagation characteristics on this region, the mobile coverage will be performed by a large number of small cells, referred as picocells, with the aid of the traditional macrocells in Heterogeneous Network (HetNet) architecture. As a consequence, backhaul and fronthaul links, the connections behind the radio network, must be able to handle these new features. However, current fronthauls are implemented using Digital Radio-over-Fiber, which would require a prohibitive bandwidth to serve the 5G mobile network. In this dissertation, we explored the advantages of implementing a Centralized Radio Access Network (C-RAN) architecture using Analog Radio-over-Fiber (A-RoF) techniques in the upcoming 5G scenario.

On the fixed (wired) telecommunications market, the new Passive Optical Network (PON) standard, NGPON2, was recently introduced and it is expected to fulfill the demand for the next few years. However, driven exactly by its application as future backhaul and fronthaul links, the future of PON is already being discussed. Wavelength Division Multiplexing PON (WDM-PON) is one of the strong candidates for the new standard and it was already discussed at the time of NGPON2 standardization. The main advantage of WDM-PON is that each user has a time-dedicated wavelength to transmit. However, this feature imposes the so called inventory problem, since the network provider must have distinct transmitter and receiver devices for each user. In order to address this issue, several colorless sources, i.e., devices that are able to operate over a range of wavelengths were proposed in the last decade. One of the most prominent

proposals are based on self-seeding techniques, where the Amplified Spontaneous Emission (ASE) spectra of an active optical device is sliced in the defined wavelength and used as seed to the device itself. In this dissertation, we studied the use of a double-cavity self-seeding WDM-PON topology based on Reflected Semiconductor Optical Amplifiers (RSOAs) proposed earlier by our group as an analog fronthaul.

In order to demonstrate the feasibility of combining double-cavity self-seeding technique and analog transmission of microwave and millimeter wave signals over a fiber, we proposed three different topologies employing direct modulation and external modulation with Electroabsorption Modulator (EAM) and Mach-Zehnder Modulator (MZM). The latter benefits from a frequency doubling technique to reduce the impact of high frequency transmission in the optical link. All three were numerically evaluated using the simulation software Optisystem. The simulation setups were all calibrated with previous experimental investigations in order to obtain reliable results.

By these means, we demonstrated that our proposed direct modulation topology is capable of successful transporting 155 Mbps, 622 Mbps and 1.25 Gbps data using amplitude modulation and IQ modulation formats at 1.25, 2.5 and 5 GHz. The external modulation topologies provide an overall better performance under these same conditions and it is also suitable for millimeter waves (38 and 60 GHz) transport of 1.25 and 10 Gbps data signals. We also successfully demonstrate the frequency doubling technique using MZM for these same frequencies, employing 19 and 30 GHz electrical carriers. At last, aiming at the benefits of access networks convergence that are currently being discussed by research groups, we also performed an investigation on simultaneous multiband transmission of microwave (5 GHz) and millimeter wave (60 GHz) signals over a single wavelength.

In conclusion, this dissertation demonstrated the feasibility of using a double-cavity self-seeded WDM-PON link as an A-RoF fronthaul in the upcoming 5G scenario concerning the main characteristics of the physical layer. To the best of our knowledge, this is the first investigation regarding the analog transport of signals over a self-seeded WDM-PON, especially employing millimeter waves. It is also the first time that a double-cavity self-seeding scheme is proposed in the context of a WDM-PON serving as a mobile fronthaul. Therefore, these are solid contributions to the converged optical-wireless access networks research field.

6.2 – Future works

Although the main research goals of this dissertation were achieved, further investigation is necessary to validate the simulation setups and explore different directions that can be taken from the present work. Future research topics related to this work are:

- **Optimization of the proposed topologies for the best performance as a mobile fronthaul.** In the present work, we have concentrated our efforts on calibrating the simulation setups as close as possible to the experimental investigations. Therefore, the components and operation conditions were not optimized for the transmission of RF signals and the aimed application. An investigation on this topic can certainly improve the presented results.
- **Further investigation on the simultaneous multiband transmission.** Since there are several discussions on how access networks convergence will be crucial to the future of telecommunications services, there is an opportunity to explore multiband transmission and expand our initial investigation using the proposed double-cavity self-seeding topology.
- **Experimental evaluation of the double-cavity self-seeding technique on both FTTx and mobile fronthaul applications.** In order to validate our numerical evaluations and the feasibility of the proposed topologies, it is imperative to perform experiments in a real 5G network scenario.
- **Investigation of an approach to reduce the linewidth of the carrier generated by the self-seeding process in order to allow heterodyne detection techniques.** One option that was initially explored during the development of our research is to employ heterodyne detection on the transmission of millimeter waves, i.e., beat an optical tone and the baseband signal separated by 38 or 60 GHz in order to perform up-conversion on the photodetector. However, this technique requires high phase coherence between both optical components and a narrow linewidth. A possible future contribution to this research is to investigate an approach to reduce the linewidth of the optical carrier generated by the self-seeding technique. This is also certainly a concern in the FTTx applications of WDM-PON.

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