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**EXPERIMENTAL ASSESSMENT OF NOMA-CAP
WAVEFORMS FOR BEYOND 5G OPTICAL FRONTHAUL
APPLICATIONS**

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Abstract

The constant growth of traffic demands caused by IoT, cloud computing and streaming services on personal devices, requires changes in architecture and more sophisticated schemes by pushing forward 5G optical fronthaul applications. An experimental assessment of NOMA CAP modulation is performed to foresee as technique for fronthaul setups concerning the 5G and beyond paradigms. NOMA CAP has been measured in scenarios with IM-DD systems. The transmitter is staged: on one side, a DML with a RayCan™ 1550 nm (VCSEL); on the other hand, an EML based on TLS and modulated by MZM. In addition, the receivers proposed are based on PIN (-13 dBm) and APD (-25 dBm) with a maximum data rate 14 Gbps over 50km of SSMF. Moreover, a practical approach for APD is validated with the comparison between the block (EDFA-Filter-PIN) and an SFP transceiver (APD included), the results in terms of sensitivity show a 0.1 dB to 0.5 dB difference.

Key words:

NOMA CAP, fronthaul, 5G, VCSEL, APD, vertical cavity surface emitting laser, avalanche photo diode.

Dedication

The achievement of this thesis is dedicated to my little Emilio. You are the reason to keep fighting and to go ahead. Every time I was losing the energies, I thought in the example I wanted to give you. You will never walk alone; you can do more than you can imagine. Never give up of your dreams, if you can breathe still there is hope. I love you my son. WE DID IT!

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I love you.

VICO

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Table of contents

Abstract	ii
Dedication	iii
Acknowledgements	iv
Revision history and approval record.....	v
Table of contents	vi
List of Figures	ix
List of Tables	xiv
1. Introduction.....	1
1.1. Scenario	3
2. State of the art.....	6
2.1. Modulation Formats.....	6
2.1.1. On-off Keying (OOK)	7
2.1.2. Phase Amplitude Modulation (PAM)	8
2.1.3. Quadrature Amplitude Modulation (QAM).....	8
2.1.4. Orthogonal Frequency Division Multiplexing (OFDM)	9
2.1.5. Non-Orthogonal Multiple Access (NOMA)	10
2.1.6. Carrierless Amplitude Phase (CAP).....	11
2.1.7. Non-Orthogonal Multiple Access with Multi-Band Carrierless Amplitude Phase Modulation (NOMA-CAP)	11
2.2. Signal Generation.....	12
2.2.1. Signal Transmitted.....	13
2.2.2. Signal Recovered	14
2.2.3. Transmission Laser Modulation Techniques.....	16
2.2.3.1. DML (Direct Modulated Laser).....	17
2.2.3.2. EML (External Modulated Laser)	21
2.3. Detection Schemes	23
2.3.1. Direct Detection.....	23
2.3.1.1. PIN Photodetector	24
2.3.1.2. Avalanche Photo Diode (APD)	25
3. Methodology	28

3.1.	Calibration System	28
3.1.1.	Power ratio between users: Strong and Weak	29
3.1.1.1.	4-QAM NOMA per both users.....	29
3.1.1.2.	16-QAM NOMA for users Strong and Weak	29
3.1.1.3.	4-QAM NOMA and 16-QAM NOMA and combinations	30
3.1.1.4.	Power ratio contour	31
3.1.2.	CAP filter <i>N_{sym}</i> variable in the Tx	31
3.1.3.	Decision Feedback Equalizer (DFE): <i>numFBT</i> & <i>numFFT</i>	32
3.1.3.1.	The <i>numFBT</i> fixed and the <i>numFFT</i> variable.....	32
3.1.3.2.	The <i>numFFT</i> fixed and the <i>numFBT</i> variable.....	33
3.1.4.	The <i>numFFT</i> and <i>numFBT</i> are variable	34
4.	Experimental Measurements and Results.....	36
4.1.	Experimental Setup Description.....	36
4.1.1.	Physical Setup Description	36
4.1.2.	Data Rate examination	38
4.1.2.1.	BandCAP width 1 GHz	38
4.1.2.2.	BandCAP width 500 MHz.....	40
4.1.2.3.	Binary Regime Calculation	45
4.2.	Receptor: PIN.....	47
4.2.1.	Downlink Transmitter Mach-Zehnder Modulator with PIN	48
4.2.1.1.	Adding Fiber optics cable to Downlink	49
4.2.2.	Uplink Transmitter Vertical Cavity Surface Emitting Laser with PIN	52
4.2.2.1.	Adding Fiber optics cable to Uplink	54
4.3.	Emulated Receptor APD.....	57
4.3.1.	Downlink Transmitter Mach-Zehnder Modulator with Emulated APD	57
4.3.1.1.	Evaluation of Cable fibers addition for Downlink	59
4.3.2.	Uplink Transmitter Vertical Cavity Surface Emitting Laser with APD.....	61
4.3.2.1.	Evaluation of Cable fibers addition for Uplink	62
4.4.	Comparison of Systems and Discussion.....	64
4.4.1.	PIN Receiver for Uplink and Downlink Transmitters.....	64
4.4.2.	APD Receiver for Uplink and Downlink Transmitters	65
5.	Budget.....	66
5.1.	Available Resources.....	66
5.2.	Budget.....	69

6. Conclusions and Future Works.....	70
7. Bibliography.....	73
Appendices.....	78
Appendix A: Temperature Controller Thorlabs TED200C	78
Appendix B: Laser Diode Controller Thorlabs LDC200C.....	80
Appendix C: Arbitrary Wave Generator TEKTRONIX (AWG 70002A).....	82
Appendix D: Vertical Cavity Surface Emitting Laser VCSEL RayCan™ RC33xxxI-FFAmt 1550nm	85
Appendix E: TEKTRONIX Mixed Signal Oscilloscope (MSO 70804C)	86
Appendix F: EXFO Optical Spectrum Analyzer FTB-2	88
Appendix G: EXFO Variable Optical Attenuator FVA 600	89
Glossary	90

List of Figures

Figure 1-1. Flexible 5G Metro-Access Network scenario. Inlet: considered flexible ultra-dense WDM frequency slot division [3]	2
Figure 1-2. High-layer split DWDM-PON-based fronthaul solution. Inset: Proposed flexible full-duplex DWDM division [14].	4
Figure 1-3 NOMA-CAP multiplexing scenario to be implemented.	5
Figure 2-1. OOK modulation unipolar (a) Constellation (b) Signal.....	7
Figure 2-2 OOK modulation bipolar (a) Constellation (b) Signal.....	7
Figure 2-3 Baseband 4-PAM (a) constellation (b) signal.	8
Figure 2-4. Baseband 4-QAM (a) constellation (b) signal.....	9
Figure 2-5. Subdivision of the channel bandwidth W into narrowband subchannels of equal width Δf [13].	9
Figure 2-6. OFDM frequency distribution.[22]	10
Figure 2-7. NOMA with Strong and Weak Users (a) 4-QAM NOMA both users (b) Weights per user (c) Resultant Constellation.....	10
Figure 2-8. CAP transmitter filters for channels I (top) and Q (button) [8].	11
Figure 2-9. Power multiplexing using NOMA and multiCAP: (a) NOMA multiplexing of two users employing all multiCAP bands, (b) multiple users are multiplexed employing NOMA and multiCAP [9].	12
Figure 2-10. Principle of operation of a MultiCAP system. [8]	12
Figure 2-11. DSP diagram of the digital transmitter (DTX) from [9]	13
Figure 2-12. Resultant constellation for one bandCAP (transmitted)	14
Figure 2-13. DSP diagram for the digital transmitter (DRX) from [9].	15
Figure 2-14. Resultant constellations for one bandCAP (received) (a) Normal (b) With Rotation.....	15
Figure 2-15. Structures for Fabry Perot, DFB and VCSEL lasers. [25]	16
Figure 2-16 Typical light–current characteristic for a laser diode [25].	17
Figure 2-17 Direct modulation scheme using Bias tee	18
Figure 2-18 VCSEL’s structure [22]	19
Figure 2-19 VCSEL RayCan™ up to 1550 nm (footprint)	20
Figure 2-20. Scheme used for VCSEL RayCan™ (Source and Temp Controller included).	20
Figure 2-21. Wavelength and optical power from VCSEL measured by OSA.	21
Figure 2-22. External modulator based on Pockel’s effect [22]	21
Figure 2-23 Mach–Zehnder modulator transfer characteristic. [25]	22
Figure 2-24. Configuration for MZM used.	23

Figure 2-25 Photodiode transfer characteristic [25].....	24
Figure 2-26 Example p-i-n photodiode. (a) Diode structure. (b) Doping profile. (c) Charge profile. (d) Energy-band diagram. (e) Electric field profile. [30].....	25
Figure 2-27. Example of an avalanche photodiode (APD). (a) Diode structure. (b) Doping profile. (c) Charge profile. (d) Energy-band diagram. (e) Electric field.....	26
Figure 2-28 Relation BER and Received Power for SFP APD & Proposed Scheme.....	27
Figure 3-1. Transmitter and Receiver Scheme.....	28
Figure 3-2. $\log_{10}(BER)$ vs Power relation rP. Primary modulation format 4-QAM NOMA	29
Figure 3-3. $\log_{10}(BER)$ vs Power relation rP. Primary modulation format 16-QAM NOMA	30
Figure 3-4. $\log_{10}(BER)$ vs Power relation rP. (a) 4-16 QAM NOMA (b) 16-4 QAM NOMA.	30
Figure 3-5. Power relation between users weak and strong vs. Power received considering $\log_{10}(BER)$ for 4-QAM NOMA. (a) Strong User (b) Weak User.....	31
Figure 3-6. Weak user performance when N_{sym} in CAP filter is variable	31
Figure 3-7. Strong user performance when N_{sym} in CAP filter is variable	32
Figure 3-8. Relation between BER and Received Power for NOMA weak user fixing num_{FBT}	33
Figure 3-9. Relation between BER and Received Power for NOMA strong user while num_{FBT} is fixed.	33
Figure 3-10. Relation between BER and Received Power for NOMA weak user for fixed num_{FFT} values.	34
Figure 3-11. Relation between BER and Received Power for NOMA strong user while the value of num_{FFT} is fixed.	34
Figure 3-12. Relation between BER and Received Power for NOMA weak user considering the variation of num_{FFT} and num_{FBT} in the same proportion.	35
Figure 3-13. Relation between BER and Received Power for NOMA strong user.....	35
Figure 4-1. Complete Experimental Setup description	36
Figure 4-2. Relation between BER and Received Power for: (a) One Band (b) Two bands (1 GHz per band).....	38
Figure 4-3. Transmitted and received NOMA-CAP spectra for: (a) One Band (b) Two bands (1 GHz per bandCAP).....	39
Figure 4-4. Relation between BER and Received Power for: (a) Three Bands (b) Four bands (1 GHz per band)	39
Figure 4-5. Transmitted and received NOMA-CAP spectra for: (a) Three Bands (b) Four bands (1 GHz per band)	40
Figure 4-6. Relation between BER and Received Power for: (a) One Band (b) Two bands (0.5 GHz per band)	40

Figure 4-7. Transmitted and received NOMA-CAP spectra for: (a) One Band (b) Two bands (0.5 GHz per band)	41
Figure 4-8. Relation between BER and Received Power for: (a) Four Bands (b) Six bands (0.5 GHz per band)	41
Figure 4-9. Transmitted and received NOMA-CAP spectra for: (a) Four Band (b) Six bands (0.5 GHz per band)	42
Figure 4-10. Relation between BER and Received Power for: (a) Seven Bands (b) Eight bands (0.5 GHz per band)	42
Figure 4-11. Transmitted and received NOMA-CAP spectra for: (a) Seven Band (b) Eight bands (0.5 GHz per band)	43
Figure 4-12. BER vs. Received Power for different setups with strong and weak NOMA levels for different number of bands for 1 GHz (Average)	43
Figure 4-13. BER vs. received power for different setups with strong and weak NOMA levels for different number of bands for 0.5 GHz (Average)	44
Figure 4-14. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Three Bands and 1 GHz split.....	45
Figure 4-15. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Four Bands and 1 GHz split. (Aliasing effect)	45
Figure 4-16. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Seven Bands and 1 GHz split	46
Figure 4-17. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Eight Bands and 0.5 GHz split (Aliasing effect).....	46
Figure 4-18. Scheme for PIN Receiver in cases of Uplink and Downlink.....	47
Figure 4-19. Scheme for PIN Receiver signal transmitted using Match-Zehnder Modulator (Downlink)	48
Figure 4-20. Physical Implementation Setup for PIN Receiver signal transmitted using Match-Zehnder Modulator (Downlink).....	48
Figure 4-21. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink).....	49
Figure 4-22. Physical spool fiber cable used. SSMF G652.	50
Figure 4-23. BER vs. received power for strong and weak NOMA levels for seven bands (0.5 GHz) adding 25 km fiber cable. (Downlink).....	50
Figure 4-24. BER vs. received power for strong and weak NOMA levels for seven bands (0.5 GHz) adding 50 km fiber cable. (Downlink).....	51
Figure 4-25. BER vs. received power for strong and weak NOMA levels for seven bands (0.5 GHz) for 0/25/50 km (Average-Downlink)	51
Figure 4-26. Set of connections for Vertical Cavity Surface Emitting Laser (VCSEL RayCan™ 1550nm)	52
Figure 4-27. Scheme for PIN Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)	52

Figure 4-28. Physical Implementation Setup for PIN Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)	53
Figure 4-29. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink)	54
Figure 4-30. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) adding 25 km fiber cable. (Uplink)	54
Figure 4-31. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) adding 50 km fiber cable. (Uplink)	55
Figure 4-32. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) for 0/25/50 km (Average-Uplink)	55
Figure 4-33. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) for 0/25/50 Km (Average-VCSEL+EDFA+PIN) Chirp Effect.....	56
Figure 4-34. Power Spectra for strong and weak NOMA levels for Seven bands (0.5 GHz) for 0/25/50/75/100 km (VCSEL+EDFA+PIN) Chirp Effect	56
Figure 4-35. Scheme for APD Receiver in cases of Uplink and Downlink	57
Figure 4-36. Scheme for APD Receiver signal transmitted using Match-Zehnder Modulator (Downlink)	58
Figure 4-37. Physical Implementation Setup for APD Receiver signal transmitted using Match-Zehnder Modulator (Downlink)	58
Figure 4-38. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink) for APD Receiver	59
Figure 4-39. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink) for APD Receiver adding 25 km SSMF	59
Figure 4-40. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink) for APD Receiver adding 50 km SSMF	60
Figure 4-41. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz). (Downlink) for APD Receiver (0/25/50) km SSMF (Averages)	60
Figure 4-42. Scheme for APD Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)	61
Figure 4-43. Physical Implementation Setup for APD Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)	61
Figure 4-44. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink) for APD Receiver	62
Figure 4-45. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink) for APD Receiver adding 25 km SSMF	63
Figure 4-46. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink) for APD Receiver adding 25 km SSMF	63

Figure 4-47. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz). (Uplink) for APD Receiver (0/25/50) km SSMF (Averages).....	64
Figure 4-48. BER vs. received power for Seven bands (0.5 GHz) (Uplink vs Downlink) for PIN receiver (a) Strong NOMA users (b) Weak NOMA users	64
Figure 4-49. BER vs. received power for Seven bands (0.5 GHz) (Uplink vs Downlink) for APD receiver (a) Strong NOMA users (b) Weak NOMA users	65
Figure A- 1. Front panel Thorlabs TED200C [32].....	78
Figure A- 2 Front panel Thorlabs TED200C [32].....	79
Figure A- 3 Pin Out Connector Thorlabs TED200C [32].....	79
Figure B- 1 Front panel Thorlabs LDC200C [33].....	80
Figure B- 2 Rear panel Thorlabs LDC200C [33]	81
Figure B- 3. Pin assignment LD OUT jack Thorlabs LDC200C [33]	81
Figure C- 1 Front Panel AWG Tektronix 70002A [34]	82
Figure C- 2 Rear Panel AWG Tektronix 70002A [34].....	83
Figure C- 3 Screen functionalities AWG Tektronix 70002A [34]	84
Figure D- 1 RayCan™ VCSEL Pin Out / Dimensions [38]	85
Figure E- 1. Front Panel MSO Tektronix 70804C [35].....	86
Figure E- 2 Rear Panel MSO Tektronix 70804C [35]	87
Figure F- 1 EXFO Optical Spectrum Analyzer FTB-2 [35].....	88
Figure G- 1 EXFO Variable Optical Attenuator FVA 600 [36]	89

List of Tables

Table 1. Pin configuration VCSEL RayCan™.....	20
Table 2 Parameters used for CAP filter and DFE.....	35
Table 3. Summary of Sensitivities (S) of strong NOMA levels for different number of bandCAPs.	44
Table 4. Summary of Sensitivities (S) of weak NOMA levels for different number of bandCAPs.	44
Table 5. Summary of Data Rates (Gbps) transmitted for different number of bands.	47
Table 6. Elements disposition in the physical implementation for Downlink transmitter using PIN receiver.....	49
Table 7. Elements disposition in the physical implementation for uplink transmitter using PIN receiver.....	53
Table 8. Elements disposition in the physical implementation for Downlink transmitter using APD receiver	58
Table 9. Elements disposition in the physical implementation for uplink transmitter using PIN receiver.....	62
Table 10 Summary of Resources have been used during the project. From: [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42]	69
Table 11. Front Panel Description Thorlabs TED200C [32].....	78
Table 12. Rear Panel Description Thorlabs TED200C [32]	79
Table 13. Pin Out Description for connector Thorlabs TED200C [32]	79
Table 14 Front panel description Thorlabs LDC200C [33]	80
Table 15 Rear panel description Thorlabs LDC200C [33]	81
Table 16 Pin assignment LD OUT jack Thorlabs LDC200C [33]	81
Table 17 Front Panel description AWG Tektronix 70002A [34]	82
Table 18 Rear Panel description AWG Tektronix 70002A [34].....	83
Table 19 Functions AWG Tektronix 70002A [34]	84
Table 20. RayCan™ VCSEL Pin Out Description [38].....	85
Table 21 Front Panel Description MSO Tektronix 70804C [35].....	86
Table 22 Rear Panel MSO description Tektronix 70804C [35].....	87
Table 23 EXFO Optical Spectrum Analyzer FTB-2 Description [35].....	88
Table 24 EXFO Variable Optical Attenuator FVA 600 Description [36]	89

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1. Introduction

Lightwave systems are named thus to distinguish them from microwave systems, mostly the difference due to the carrier frequency they manage. While microwaves work at frequencies around gigahertz (GHz) range, optical (lightwave) communication systems use high carrier frequencies (around 100 terahertz [THz]). [1]

The Lightwave technologies include fiber optic communications systems where the information transmission is performed by optical fiber links. Since the mid-1970s with the first commercial generation, better and more complex modulation schemes are being developed continuously to take advantage of this field, taking advantage to the new optical sources and receivers, and optic fiber as the communication channel.

Some ideas about this continuous evolution are mentioned in [1], main advances are taking place, for instance:

- The fabrication of optical sources and sensors from semiconductors is not anymore fully dedicated to telecommunications applications, they are exploring other alternative purposes such as medicine and national security projects.
- The transoceanic submarine optical networks that permits fully communication to all continents around the world, searching for innovative and ultrahigh capacity systems to be implemented, also regarding the environmental impact it could have during the installation, operation and maintenance.
- The wavelength division multiplexing (WDM) technique in lightwave systems has been considerably studied, this system increased optic-fiber communication channel capacity, and many others like the appearance Space division multiplexing (SDM) based on multicore fiber (MCF) as a promising approach to increasing the transmission capacity (power) of fiber [2].

From the beginning of the 21st century, the traffic demand is growing exponentially due to cloud computing-based services, the Internet of Things (IoT), demanding the convergence between wireless and optical communications in the new 5G paradigm.

One practical and promising solution is the use of ultra-dense wavelength division multiplexing (uDWDM) metro access networks using coherent detection (see Figure 1-1) However, cost-effective transmitters need to be investigated and designed in order to make economically affordable these new networks [3] [4].

Achieving these new capabilities requires changes at the optical networks to enable a scalable growth in traffic volume, while supporting a high level of dynamic connectivity, full network flexibility, reduced end-to-end delay and improved energy-efficiency [5].

Figure 1-1. Flexible 5G Metro-Access Network scenario. Inlet: considered flexible ultra-dense WDM frequency slot division [3]

Consequently, many possibilities of modulation formats have been deployed and experimentally tested through the years, mainly based on the amplitude modulation such as: On-Off Keying, 4-PAM, and quadrature amplitude modulation formats with the N-QAM variety. Nowadays, Orthogonal frequency division multiplexing (OFDM) has been widely foresaw as a potential candidate for future short range transmission applications such as 5G mobile fronthaul, data center interconnect (DCI) and beyond 5G fronthaul optical applications.

Concerning to the numerous benefits it has, such as high spectral efficiency, high resilience to chromatic dispersion, and efficient/flexible resource management [6]. Nonetheless, the most considerable drawback of OFDM is its high computational complexity [7]. To overcome this problem, multi-band carrierless amplitude phase (multi-CAP) modulation has been proposed [9].

As considered in [10], this technique is based on a quadrature amplitude modulation (QAM) using a low frequency carrier where the modulated signal is generated by merging two PAM signals filtered through two specifically designed filters, being not necessary to modulate two orthogonal carriers (quadrature carriers) with the baseband signal using the discrete Fourier transform (DFT).

Moreover, non-orthogonal multiple access (NOMA) concept multiplexes two different signals in the power/amplitude domain by adding the tributary signals and allows combination with time or frequency multiplexing.

For NOMA, successive interference cancellation (SIC) idea must be employed to recover the contributing signals and demultiplex each NOMA signal [11]. NOMA and multi-CAP working in tandem have been reported in [9], proving a maximum total aggregated capacity of 30 Gb/s and an excellent capability to increase the spectral efficiency.

The aim of this project is to evaluate a transmission system similarly to [5], where the sensitivity performance of a NOMA-CAP system with a PIN-based receiver is experimentally assessed for short range transmission applications and different aggregated bit rates. And contemplating some considerations from [12] where experimental assessment proposing for downstream in broadband passive optical networks, the results obtained over 50km of Standard Single Mode Fiber SSMF at 5 (10) Gbps.

Nevertheless, the current work will focus in the consecution of an experimental Assessment of NOMA-CAP Waveforms for beyond 5G Optical Fronthaul Applications, including two proposed alternatives for upstream and downstream Optical Line Terminal (OLT-TX) and alternatives regarding the receiver Optical Network Unit (ONU) as well.

As a first part of the work, basic concepts related with modulation formats, constellations and digital communications [13] and the state of the art and a short discussion of the concepts of non-orthogonal multiple access (NOMA) and carrierless amplitude phase modulation (CAP) before discussing their combination into NOMA-CAP as proposed in [9]. Reviewing the implementation of an OLT-Tx based on a Mach-Zehnder Modulator (MZM), and its configuration and performance based on the information provided in [14], furthermore, the proposed transmitter will include a Vertical Cavity Surface Emitting Laser (VCSEL) as considered in [1] y [3]. Moreover, the reception method is contemplated in this section as well, direct detection based on a PIN photodetector on one side and evaluating the usage of an Avalanche Photodetector APD on the other side. The chapter 2 contains the explanation mentioned before.

A brief description of the methodology for the present work is in chapter 3, here, the stages of the calibration, analysis and practical optimization of the system Transmission-Reception is fully developed. The first experiments and configurations has been included to clarify certain values and requirements established in previously proposed schemes.

The results are exposed and justified in the chapter 4, mainly there is a summary of the all measurements have placed during the period of experimentation, being relevant the different responses in terms of Sensitivity, power received, spectrum efficiency and their performances through the different OLT-TX and ONU-RX possible combinations over three scenarios: back to back, 25 km and 50 km of SSMF.

Chapter 5 gathers the main concepts, insights and conclusions once the experimental assessment has been completed, also describes the future suggested topics and works, based on the results plenty analyzed. Future works are related with the possibility of coherent reception applications out of the scope of the present project.

Finally, a list of materials, devices and elements this thesis worked with, and the list of terminology commonly used through this document, supported by a set of appendices also included.

1.1. Scenario

In consideration with the objective of this study, the physical scenario will be described through the complete setup proposed and depicted in the corresponding chapter, taking some alternatives studied in [12], where small cell based mobile networks are considered as the most promising solution for fronthaul applications. Nonetheless, for this implementation large number of smart cells must be deployed to provide wide coverage, here the cost budget would be an important factor in design. This makes it particularly important to simplify remote cell sites to reduce cost and increase energy efficiency. In [15], [16] as hopeful network architecture solution, cloud access radio networks (C-RANs) have been proposed.

The division of the traditional base station is considered in this solution, all the functionalities of radio and baseband processing will be integrated, into several only-transmitting simple and cheap remote radio heads (RRHs), and a complex processing is

centralized in a single cloud-hub base band unit (BBU) located at the central office (CO) [12].

A new connectivity segment named fronthaul is deployed between the multiple distributed RRHs and the centralized BBU. As it is suggested in [17], currently fronthaul vendors are using the known common public radio interface (CPRI) as most common standard. The digitalized baseband signal transmission over fiber (DBBoF) technique is applied, where the base band IQ samples are digitalized and serially transmitted at a constant bit rate. As a result, CPRI transmission needs huge bandwidth.

Alternatively, radio-over-fiber (RoF) technology has recently gained more and more attention [18] [19], the interfaces of both BBUs and RRHs have been simplified and the bandwidth is saved, the RoF-based fronthaul just needs 2.4 GHz of bandwidth [19]. It is reflected a 30 times reduction regarding to CPRI when the OOK modulation format is used.

In addition, massive small cell deployment will increase the number of optical fibers required. To overcome that issue, as it has been proposed in [20], the high-layer split dense wavelength multiplexing passive optical network (DWDM-PON)-based fronthaul is considered in [14] the scenario depicted in Figure 1-2.

Figure 1-2. High-layer split DWDM-PON-based fronthaul solution. Inset: Proposed flexible full-duplex DWDM division [14].

In this scenario, u-DWDM is accomplished by dividing each WDM channel into two sub-channels, one for up-link and other for down-link, where different user demands can be allocated (see Figure 1-2). The same DWDM channel share a PON and all the antennas are connected. According to [21], similar performances to standard dual fiber networks are provided, this architecture includes the coexistence of different natures and polices, low congestion at the access nodes, and compatibility with systems and industrial temperature ranges [12].

The proposed scenario for this thesis involves a transmission-reception system, including an Optical Line Terminal Transmitter (OLT-TX) located in a Central Office (CO) and an Optical Network Unit Receiver (ONU-RX) sited in the Remote Radio Head (RRH). In details the chapter 4 will depict the fully compacted setup.

For the transmitter there will be two schemes for uplink and downlink, on one side, downlink is based on an external cavity Tunable Laser Source (TLS) modulated by Mach-Zehnder Modulator biased in quadrature point and thermally controlled to ensure its

stability similar to [12]. On the other hand, uplink will use a Vertical Cavity Surface Emitting Laser (VCSEL) directly modulated through a bias tee and direct current similarly to [22].

The receiver to be proposed will contemplate two alternatives as a detector, firstly, a PIN photodetector will be included, secondly, the Avalanche photo detector (APD) option will take place. Here, according to [9], the scenario will be completed considering the idea of only two users at different distances to the base station (BS), to do so, a high capacity link will be assigned to each by means of sharing all multiCAP bands using NOMA multiplexing. Then, NOMA levels will be defined as strong and weak as it is shown in Figure 1-3.

Figure 1-3 NOMA-CAP multiplexing scenario to be implemented.

2. State of the art

Incoming chapter consists in a brief review of the framework in which this project is based on. Optical systems became an interesting topic in the communications field since 1980 when it started revolutionizing the telecommunications' field and continues to do so until now [1]. It is necessary to overview some knowledge of basic concepts of digital communications, transmission systems, modulation formats, and so on. In addition, also it is interesting to have a background on the elements related to the referenced topics and their application to lead the continuous progress the beyond 5G paradigms in telecommunications implies.

A short summary about the different modulation formats that abound in digital data transmission [13], [23]. Regarding phase and amplitude modulations (OOK, PAM, QAM), Orthogonal Frequency Division Multiplexing (OFDM) as implemented in [14], and a short discussion of the concepts of non-orthogonal multiple access (NOMA) and carrierless amplitude phase modulation (CAP), and finally their combination into NOMA-CAP as proposed in [9].

It will be exposed shortly the most common techniques of laser modulation, there are two solutions to achieve the modulation of the output optical beam emitted by a laser: DML (Direct Modulated Laser) and EML (External Modulated Laser) [22] [24] [25], with VCSEL (Vertical Cavity Surface Emitting Laser) and (MZM) Mach-Zehnder Modulator, respectively.

Moreover, the detection concepts to be applied in the reception schemes will be described, firstly, the direct detection performed, on one side by the PIN photodetector, and on the other hand the Avalanche photodetector (APD). Secondly, a brief revision of the coherent detection technique, in despite of it is out of the scope for the present project, it is a proposal to the future works based on the results obtained.

A comprehensive reading of the literature and a background is required; it is known as state of the art including relevant research oriented to the investigation line referenced.

2.1. Modulation Formats

The digital data is composed by a stream of binary data, i.e., a sequence of 0s and 1s. Regardless of whether these data are inherently digital (for instance, the output of a computer terminal generating ASCII code) or the result of analog-to-digital conversion of an analog source (for instance, digital audio and video), the goal is to reliably transmit these data to the destination by using the given communication channel [13].

In the present project, the nature of the communication channel is fiber optics, it is known the data can suffer channel impairments including noise, attenuation, distortion, and so on. To transmit the binary stream over the communication channel, it is needed to generate a signal that represents the binary data stream and matches the characteristics of the channel. This signal should represent the binary data, meaning that after a digital signal processing, it should be able to retrieve the binary stream from the received signal.

Since different channels cause different types of impairments, signals designed for these channels can be drastically different. The process of mapping a digital sequence to signals for transmission over a communication channel is called digital modulation or digital signaling. [13]

For the modulation process, the signals are generally bandpass signals suitable for transmission and the bandwidth provided by the channel. This section is devoted to study the most commonly used modulation schemes and their properties in terms of power energy efficiency.

2.1.1. On-off Keying (OOK)

On-off Keying, used in direct-detection optical data transmission, as well as in “gate-to-gate” transmission in most digital circuits, uses the same basis function as bipolar transmission [13].

OOK implies the simplest representation of amplitude-shift keying (ASK) modulation, which means digital data at the presence or absence of a carrier wave. In other words, the presence of a carrier for a specific duration represents a binary one, meanwhile its absence for the same duration represents a binary zero.

In the Figure 2-1 (a), it is shown the constellation for this modulation format, where one symbol is zero (0), and the other is one (1) with the amplitude value. In Figure 2-1 (b), it is depicted the signal generated with a random sequence of binary numbers.

The signal waveform representation would be as follows:

$$x(t) = \begin{cases} 0 & \text{if } x_Q = 0 \\ 1 & \text{if } x_Q = A \end{cases}$$

Figure 2-1. OOK modulation unipolar (a) Constellation (b) Signal.

Similarly, in the Figure 2-2 (a), the constellation and the signal waveform have been depicted for the following representation:

$$x(t) = \begin{cases} 0 & \text{if } x_Q = -A/2 \\ 1 & \text{if } x_Q = A/2 \end{cases}$$

Figure 2-2 OOK modulation bipolar (a) Constellation (b) Signal.

OOK is more spectrally efficient than frequency-shift keying. For a given data rate, the bandwidth of a BPSK (Binary Phase Shift keying) signal and the bandwidth of OOK signal are equal. In addition to RF carrier waves, OOK is also used in optical communication systems (e.g. IrDA).

2.1.2. Phase Amplitude Modulation (PAM)

For the case of digital PAM, the signal waveforms may be represented as:

$$S_m(t) = A_m p(t), \quad \text{with } 1 \leq m \leq M \quad \text{Eq. 2.2}$$

Where:

$p(t)$ is a pulse of duration T and $\{A_m, 1 \leq m \leq M\}$ symbolizes the set of M possible amplitudes corresponding to $M = 2^k$ possible k -bit blocks of symbols.

Usually, the signal amplitudes A_m take discrete values [13]. For instance, in the Figure 2-3, it is illustrated a four-amplitude level baseband PAM signal.

The amplitudes are +1, -1, +3, -3.

Figure 2-3 Baseband 4-PAM (a) constellation (b) signal.

2.1.3. Quadrature Amplitude Modulation (QAM)

The bandwidth efficiency of PAM/SSB can be obtained by simultaneously impressing two separate k -bit symbols from the information sequence on two quadrature carriers such as $\cos 2\pi f_c t$ and $\sin 2\pi f_c t$. According with [13], this subsequent modulation technique is named Quadrature amplitude modulation, and the corresponding signal is represented as:

$$S_m(t) = A_{mi} g(t) \cos 2\pi f_c t - A_{mq} g(t) \sin 2\pi f_c t \quad \text{with } m = 1, 2, \dots, M \quad \text{Eq. 2.3}$$

Where A_{mi} and A_{mq} are the information-bearing signals amplitudes of the quadrature carriers, and $g(t)$ is the signal pulse.

In the Figure 2-4, it is exemplified the 4-QAM base band signal.

Figure 2-4. Baseband 4-QAM (a) constellation (b) signal

2.1.4. Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal Frequency Division Multiplexing is a special type of multicarrier modulation, this technique is based on encoding digital data on multiple carrier frequencies and it is consisted in dividing the spectrum in sub-carriers that are spaced with a fixed frequency gap [22].

Figure 2-5. Subdivision of the channel bandwidth W into narrowband subchannels of equal width Δf [13].

The subcarriers are mutually orthogonal, hence, the intersymbol interference is negligible, each subcarrier is associated to a sinusoidal carrier signal of the form:

$$S_k(t) = \cos 2\pi f_k t \quad \text{with } k = 1, 2, \dots, N - 1 \quad \text{Eq. 2.4}$$

where f_k is the mid frequency in the k th sub-channel. By selecting the symbol rate $1/T$ in each of the subchannels to be equal to the frequency separation Δf of the adjacent subcarriers, the subcarriers are orthogonal over the symbol interval T , independent of the relative phase relationship between subcarriers [13].

In the Figure 2-6, it is depicted the frequency distribution in an OFDM modulation, considering a frequency separation Δf as expected.

Figure 2-6. OFDM frequency distribution.[22]

2.1.5. Non-Orthogonal Multiple Access (NOMA)

The Non-Orthogonal multiple access technique is based on multiplexing the data of several users in the power domain by combining the contributing signals and it is fully compatible with time or frequency multiplexing [9]. Moreover, in the terminal units in order to recover the transmitted signals and their contributors and thus demultiplex the different NOMA Users data, it is performed a Successive Interference cancellation (SIC).

For the two users NOMA power multiplexing applied at the symbol level, the constellation is obtained by assigning different weights to the user symbols before directly adding them, as follows:

$$x_{NOMA} = w_1 x_1 + x_2 w_2 \quad \text{Eq. 2.5}$$

Where:

- x_{NOMA} is the multiplexed signal for two NOMA users
- x_1, x_2 are the symbols for close user and far user, respectively.
- w_1, w_2 are the weights for close user and far user, respectively.

The weights are calculated according to the desired power ratio r_p between users in the multiplexed signal.

$$r_p = 20 \log \left(\frac{w_2}{w_1} \right) \quad \text{Eq. 2.6}$$

The concept of r_p will be considered in the calibration stage developed in chapter 3.

In the Figure 2-7, it is illustrated the NOMA signal generation, the resultant is generated by two users (Strong NOMA and Weak NOMA) with 4-QAM signals.

Figure 2-7. NOMA with Strong and Weak Users (a) 4-QAM NOMA both users (b) Weights per user (c) Resultant Constellation

Nowadays, in wireless communications NOMA technique is used to exploit the near-far effect, it will cause asymmetrical channel gains between the users [9].

2.1.6. Carrierless Amplitude Phase (CAP)

Carrierless Amplitude Phase (CAP) is a method that, similarly to quadrature modulation (QAM), can transmit two streams of data separately by means of two orthogonal signals, namely the in-phase (I) and quadrature (Q) components [9]. In contrast to QAM, however, CAP does not rely on a carrier, but uses filters with orthogonal waveforms to separate the different data streams [8]. These filters are the result of the time-domain multiplication of the pulse shaping function and two orthogonal carriers [9]. Moreover, especial feature is the use of a pulse shaping function to considerably improve the spectral efficiency of the system.

Figure 2-8. CAP transmitter filters for channels I (top) and Q (bottom) [8].

CAP modulation as many other modulation systems, requires a flat frequency response of the transmission link to ensure good performance. Agreeing with [9], to alleviate this constraint, the multiband CAP (multiCAP) has been proposed for wireless and optical links, achieving high spectral efficiency over large bandwidths.

Once the spectrum has been split into sub-bands, multiCAP modulation allows the use of bit- and power-loading techniques for each band independently [8].

2.1.7. Non-Orthogonal Multiple Access with Multi-Band Carrierless Amplitude Phase Modulation (NOMA-CAP)

Regarding the previous work developed in [9], the combination of NOMA and multiCAP allows a dynamic assignment of the resources to fulfill the user demands. NOMA power multiplexing is merged with multiCAP modulation, to enhance the capacity and flexibility of the RAN.

The system capacity is improved by the benefits of multiCAP, optimizing the signal to channel conditions. Meanwhile, multiCAP and NOMA provide themselves ideally to flexible and adaptive user provisioning.

Figure 2-9. Power multiplexing using NOMA and multiCAP: (a) NOMA multiplexing of two users employing all multiCAP bands, (b) multiple users are multiplexed employing NOMA and multiCAP [9].

Respecting this project, on one side, at the proposed transmitted NOMA power multiplexing is performed in the constellation level for each multiCAP band independently and before the generation of the multiCAP signal [8] [9]. On the other hand, NOMA-CAP reception will remove each multiCAP band, by operating the inverted matched filters. Final step is to extract the signal desired computing SIC. In addition, if several NOMA users have been multiplexed, the SIC process will be applied iteratively after multiCAP demultiplexing [9].

Figure 2-10. Principle of operation of a MultiCAP system. [8]

One of the drawbacks of using CAP signals is that the reduction in the horizontal eye opening due to not having a carrier to transport the data, since there is no down-conversion to baseband, the process of demodulation takes place in pass-band, and hence the closed horizontal eye opening. [8]

In the corresponding chapter, a NOMA-CAP system employing two levels of NOMA (strong and weak) with QAM signals and up to eight (four) 0.5 (1) GHz multiCAP bands is proposed and discussed.

2.2. Signal Generation

The aim of this work is to evaluate the experimental assessment using the proposed resultant waveform NOMA-CAP (multiCAP), facing the beyond 5G fronthaul optical applications, and foreseeing solutions for the challenges to cope with the growing data transmission capacity demands. Therefore, increasing effort is now put into the possibility of exploiting higher order modulation formats with increased spectral efficiency and reduced optical transceiver complexity [8].

In particular, this section is devoted to explaining the process of the generation of the transmitted signal, as well as the data signal processing (off-line), implemented for the

reception block and the recovery of the signal. Moreover, the computation of the Bit Error Rate of all the bandCAPs will be required, to illustrate the performances of all proposed schemes, in terms of the relation with the power received PRx.

2.2.1. Signal Transmitted

DTX stage is the responsible of the NOMA-CAP generation, the block is mainly based of three processes: Mapping, up-sampling and filtering. The Digital signal processing (DSP) architecture for NOMA-CAP generation is depicted in the Figure 2-11. DSP diagram of the digital transmitter (DTX) from [9] Here, the data of each NOMA level among all the multi-CAP bands and mapped them to quadrature phase shift keying (QPSK) symbols [9]. The two NOMA levels are named “weak NOMA” and “strong NOMA”.

Once defined the systems, the parameters in the generation of the signal appear, based on the scheme depicted.

Figure 2-11. DSP diagram of the digital transmitter (DTX) from [9]

Figure 2-11 depicts the principle of operation of a conventional CAP system. In the current proposal, Data 1.1 (multiCAP band 1) is made of a stream of data generated from a pseudo random bit sequence (PRBS), originally MATLAB function, the length is $2^{11} - 1$ bits. Once generated the PRBS, it is encoded into a M-QAM constellation (firstly $M=4$) through gray coding. The number of samples per symbol in transmission is equal to the ratio between the sampling given by the AWG, and the symbol rate. The parameter $F_{AWG} = 8 \text{ GSa/s}$ and the symbol rate was the bandCAP width and considered equal to R_s .

Latterly the binary sequence has been mapped into the QAM NOMA constellation, the real and imaginary part of this signal will provide the I and Q channels. The orthogonal filtering will take place as the next step. The CAP filter proposed is composed by the time domain multiplication of a root raise cosine (RRC) and the sine and cosine for I and Q channels respectively.

There will be several parameters such as: roll-off factor fixed of (0.05), the filter length defined as number of symbols N_{sym} for the filter, which is experimentally established in the calibration stage in chapter 3, the sine and cosine frequencies. The sine/cosine frequency is determined by the bandCAP frequency.

Figure 2-12. Resultant constellation for one bandCAP (transmitted)

In the DTX planned, the RRC bandpass filter is configured with a bandwidth of $(1 + \text{roll-off factor})$ times the baud rate used. The study of the system response against RRC parameters was plenty analyzed in [8], and the value of roll-off factor was the same as used in [9]. Concerning the idea, while closer roll-off factor approaches to zero, the closer the frequency response of the RRC can be approximated to a $\text{rect}(\cdot)$ function and the bandwidth is most efficiently utilized [27].

The signal generation was developed in a script in MATLAB. Parameters have been defined in advance, and the result exported in text file. The following step is to send the signals using the Arbitrary Waveform generator (Tektronix AWG 70002A).

2.2.2. Signal Recovered

In addition, as explained in the previous section with the TRX, the DRX stage has been illustrated in the Figure 2-13. Here, the DSP (off-line) for the reception developed contains some parameters to be optimized and the Successive Interference Cancellation (SIC) concept is applied. The signal has been captured through the digital sampling oscilloscope Tektronix MSO 70804C, regarding the appendix DSO sampling rate is $F_S = 25 \text{ GSa/s}$ and the bandwidth 8 GHz.

The DSO is managed by a script in MATLAB. The script uses a TCP/IP socket and connects directly the device from the computer, matching the IP address, MAC address and special commands. There are options implemented, for instance, instead of the use of auto-set for the scale, an extra MATLAB loop has been included, with the versatility of measuring the maximum value from the frame captured and then the scale value can be re-established through the special commands. In addition, it is important to verify if the buffer length is enough. Another extra option was to define the number of captures, and then the computation of the average can be done. However, the number of captures has been fixed in one (1) and the buffer length up to 10MSa.

Once the signal is captured, the information is collected in a file .mat, and subsequently the information will be required to compute the BER and finally the results will be saved in a *.xls (Excel file) in order to be imported later for the plots creation.

Figure 2-13. DSP diagram for the digital transmitter (DRX) from [9]

In the DRX, firstly a low pass filter is configured, it has been considered because of the frequency of the Digital Sampling Oscilloscope is 8 GHz and the bandwidth to be used is 4 GHz. Then, inverted matched filters (CAP filters) separate the two channels (I and Q), and the orthogonal signals can be recovered by Successive Interference cancellation (SIC), which means that, for two users, the base station should decode first the data of the strong NOMA user, cancels it from the data (SIC) and finally decode the data of the weak NOMA user [27]. In addition, the sampling frequency of transmission and reception is not the same, it is known the Tektronix AWG 70002A sampling rate is $F_{AWG} = 8 \text{ GSa/s}$ and $F_S = 25 \text{ GSa/s}$. Hence, the signals will require a down-sampling process concerning the ratio between sampling rates.

Figure 2-14. Resultant constellations for one bandCAP (received) (a) Normal (b) With Rotation

In the Figure 2-14, the resultant received constellations are depicted, on one side in (a) the constellation did not suffer any disturbance, on the other hand in (b) a rotation affecting the constellation is depicted. Base on that, a decision feedback equalizer (DFE) has been designed, the function of DFE has been equalizing the signals correcting the eventual phase rotation.

DFE has been defined with the function from MATLAB, DFE is created with a fractionally spaced forward filter. There are several parameters to be considered such as: Number of weights in the forward filter and the feedback filter, for the simulations named *numFBT* & *numFFT*, respectively. The number of weights in the forward filter must be at least 1. In the corresponding section of chapter 3, these values have been evaluated in order to define the optimal system configuration.

After the DFE result, the demodulation of the first signal is performed. The following step to be implemented is Successive Interference Cancellation (SIC), as explained before decodes firstly the strong NOMA user and finally the weak NOMA user. The generalization of this idea in the case of n users is that base station decodes the users from the strongest to the weakest, doing SIC at each iteration [27].

The calculation of the centroid of the symbols will have place. Then, the energy of the first signal is analyzed as noise and removed according the centroid value. So then, a second DFE will be used, and finally, the second signal is demodulated.

The explained process corresponds to a single bandCAP, in order to decode all the transmitted signal, an iterative loop is implemented, and the BER will be computed for strong NOMA and weak NOMA users, and lastly the results are stored in a file.

2.2.3. Transmission Laser Modulation Techniques

In this section a brief description of devices which are available to provide the basic functions of Electric to Optics conversion (E/O) will take place. Regarding intensity modulation concept, there are two ways to be achieved: directly or externally to be analyzed. On one side, direct modulation of a laser simply means adding a time-varying current which results in the intensity (i.e. optical power) tracking changes in the current. On the other hand, an external modulation will be performed, this technique has been implemented by voltage-driven devices and have larger modulation bandwidths [25]. In addition, those elements can provide further modulation formats as phase and frequency.

Laser diodes according to device structure can be categorized in three main types, Fabry-Perot, distributed feedback (DFB) and vertical surface emitting laser (VCSEL), the different structures are summarized in Figure 2-15. In despite of that categorization, the present work will emphasize in the usage and comparison between DFB and VCSEL, regarding the devices available in the optical communications laboratory and the scheme proposed.

Figure 2-15. Structures for Fabry Perot, DFB and VCSEL lasers. [25]

2.2.3.1. DML (Direct Modulated Laser)

The laser diodes have been studied constantly, among the modulation techniques direct modulation has been researched, the main advantages are that they are compact and only require a low value of mA of drive current in order to be operated. Moreover, it also offers a potential route to monolithic integration with a variety of other electronic and photonic structures on the same chip. [25]

Figure 2-16 Typical light–current characteristic for a laser diode [25]

In the Figure 2-16 it is presented a laser diode directly modulated, the drive current I_L is given by the expression:

$$I_L = I_B [1 + m \cos(\omega_m t + \phi_m)] \quad \text{Eq. 2.7}$$

Where:

I_B is the bias current

m is the modulation index

In the Eq. 2.8, the electric field emitted by the laser has been defined, if the chirp effect is neglected.

$$E(t) = E_0 \sqrt{1 + m \cos(\omega_m t)} \exp(j[\omega_0 t + \phi_0]) \quad \text{Eq. 2.8}$$

The output power P_L will be given by the square of the electric field, and the corresponding representation is:

$$P_L = P_0 (1 + m(\cos \omega_m t + \theta_m)) \quad \text{Eq. 2.9}$$

Where:

P_0 is the average power

ω_m is the modulation frequency

θ_m is the phase

The light–current (L–I) characteristic is plotted in the Figure 2-16, a relation between optical output power and the drive current is shown. This seems like the DC piecewise-linear I–V characteristic of a diode [25]. Here, threshold and saturation operation regions

can be clearly identified. This curve is important in order to determine the minimum threshold value of I_B . In addition, the bias point of the laser must be chosen accurately, because the quality of signal could drastically change with a wrong choice and clipping effect could appear, this effect causes the laser's switching off.

Figure 2-17 Direct modulation scheme using Bias tee

The direct modulation laser principle is depicted in the Figure 2-17, on the left, it is shown the bias current I_B , which feeds the inductance by a current source. On the top the RF signal is connected to the capacitance. The role of the capacitance and the inductance present in the scheme is to isolate the input. In DC, the inductance is acting as a short circuit, and the capacitance is having the opposite function.

Direct Modulation has a sort of limitations, including the mentioned in [22]:

- An unintentional modulation of wavelength (the chirp effect mentioned), when combined with the inclusion of fiber cable (dispersion effect) will imply signal degradation.
- Nonlinearity, when the resonance frequency occurs can be considered as significant.
- Multiple-sideband modulation, power fading effect could take place depending on the fiber length and the laser wavelength conditions.
- A relative intensity noise (RIN), the overall noise figure performance can be affected.
- E/O conversion losses, if the differential quantum efficiency obtained is less than the unity.
- Finally, the most important, the lower bandwidth compared with the EML.

In spite of the stated limitations, the main advantages are the simplicity and relatively low cost of direct modulation, thanks to that still they are very attractive for many applications, for instance, a fronthaul transmitter proposed in the current project based on a VCSEL.

Vertical Cavity Surface Emitting Laser (VCSEL)

The proposed scheme for an uplink transmitter is based on direct modulation laser (DML), and VCSEL has been selected as the laser, regarding their low cost and due to the fact VCSEL can be easily modulated by a bias current as studied in the previous section.

In terms of structure, VCSEL are normally fabricated based on GaAs/AlGaAs with emission wavelengths in the range between 750-980nm. Years ago, VCSELs have been widely used in simple applications like lidar, mouse, laser printers, or very-short applications, including intra-datacenter connections, local area networks and storage area networks [22].

Laser diode and VCSEL can be compared respect to costs, and a huge difference can be realized. However, for years the drawback was the difficulty to achieve the emission in the long-wavelength range. Nonetheless, nowadays many breakthroughs have been developed by researchers worldwide, being possible to build VCSELs capable to emit in the region between 1200 nm and 1600 nm [22]. This was successfully completed after diluted nitrides (GaInNAs quantum wells on GaAs) in the know devices made of (GaAs/AlGaAs), this accomplishment has become as very useful tool for PON applications.

Figure 2-18 VCSEL's structure [22]

Respect to Figure 2-18, about the VCSEL's structure, the diameter of the circular emitting surface is considerable small, thus very small threshold value is obtained. The emission direction in VCSEL is vertical and it has a short cavity. These features have occasioned that the single longitudinal mode is achievable more easily. Moreover, the VCSEL gain is very low as consequence of the short length of the active medium. This gain limitation has been overcome by using reflection mirrors in the optical cavity. [28]

Main advantages of VCSEL can be summarized:

- The emission wavelength can be managed by temperature tuning, key idea to be taken in to account during the current work, considering the bandgap will be managed by temperature.
- VCSELs emit vertically with a very small cavity: thus, the single longitudinal mode can be obtained more easily with respect to a traditional DFB laser [28]
- A lower threshold value can be easily reached, and the VCSEL can be fed using a current source through the bias tee.
- A slope-efficiency up to 50% has been demonstrated, concerning [28]

The scheme has considered as an optical source the RayCan™ 1550 nm SM-VCSEL (see the appendix for details), and a footprint previously designed in [1]. There, some features had been specified:

- Data rate up to 10 Gbps
- Cylindrical transistor outline (TO) package with *single-mode* fiber pigtail.
- Enclosed thermistor and thermoelectric cooler (TEC, also known as Peltier device)

Concerning the behavior of VCSELs respect to temperature, due to the temperature dependence of the refractive index, the resonant wavelength can be affected. Moreover, as a consequence of the thermal expansion the length of the cavity will be modified. In addition, the peak of the optical gain decreases and red-shifts towards longer wavelength when the temperature grows. The cavity resonance moves with a different rate, so the cavity mode can match or not the gain maximum. [29]

In the Figure 2-19 VCSEL RayCan™ up to 1550 nm (footprint)Figure 2-19, it is shown the footprint for the used VCSEL, including the terminals available for being connected to the temperature controller Thorlabs TED200C (TEC+, TEC-, TH1, TH2, see the Table 1, and the SMA connector for the source current for the bias current I_B , it has been fed by the Thorlabs LDC206, which provides up to 20 mA.

Pin Out	Function
1	TEC cathode (-) for cool device
2	Thermistor
3	NA
4	VCSEL cathode / mPD anode
5	TEC anode (+) for cool device
6	Thermistor
7	mPD cathode
8	VCSEL anode

Table 1. Pin configuration VCSEL RayCan™

Figure 2-19 VCSEL RayCan™ up to 1550 nm (footprint)

The VCSEL performance mainly can be managed by the temperature, regarding the results have been obtained in [3], the emitted wavelength can be tuned maintaining a constant optical power. Therefore, the emitted wavelength and optical power of the VCSEL can be tuned adjusting both the temperature and the bias current. In the Figure 2-20 the scheme used is depicted.

Figure 2-20. Scheme used for VCSEL RayCan™ (Source and Temp Controller included).

As a result of the configuration explained before, the emitted wavelength and the optical power output of the VCSEL has been measured using an Optical Spectrum Analyzer OSA (EXFO FTB-2), the results are shown in the Figure 2-21.

Figure 2-21. Wavelength and optical power from VCSEL measured by OSA.

2.2.3.2. EML (External Modulated Laser)

At the transmitter point, an optical source has been set up on a desired wavelength, and a analogue signal has been modulated on the optical carrier. In external modulated lasers scheme, there are two separated devices: Laser (light source) and external device capable to manage the power of the laser.

A very popular external modulator is based on the Pockel's effect. The Pockel's effect is a second order optical non-linear effect typical of some no centrosymmetric materials. In some of these materials the change in refractive index depends linearly on the strength of the applied electric field [22]. In the Figure 2-22 is referred an external modulator based in Pockel's effect.

Figure 2-22. External modulator based on Pockel's effect [22]

The performance of an external modulation link can be improved, when the optical power supplied to the modulator is increased (up to the maximum power that the modulator or detector can handle). The optical source does not have to be a semiconductor laser designed for high-frequency direct modulation; a semiconductor laser designed for high-power CW output can be chosen [28].

Concerning Pockel's effect, Firstly, the voltage $V(t)$ is composed by the RF signal, that is applied directly to the non-linear material. Because of that, the material changes its refraction index linearly with the RF input signal. The input light field E_{in} , is received from the laser and it is in CW, furthermore, it is divided equally on the two interferometric arms.

On the right arm, the refractive index is maintained as a constant, thus the light does not change its phase. On the left arm, the refractive index changes proportionally to the RF signal, thus also the phase can be changed according with the value of the refractive index. The output light in both arms have interfered each other, hence an amplitude proportional to the phase difference is obtained in the output light field E_{out} . Like the phase on right arm is constant, the output amplitude of the light will follow the trend of the input signal. Finally, the laser is modulated [22].

Mach-Zehnder Modulator

The Mach-Zehnder interferometer (MZM), has been developed as application of the Pockel's effect. The MZM structure is constituted generally by LiNbO₃.

The transfer function for external modulator is illustrated in the Figure 2-23. Here, a relation between the power ratio P_o/P_i and the bias voltage V .

MZM has been studied, and the advantages can be considered are:

- Optical power level P_o depends not only on the modulator but also on the power supplied by the CW laser source (P_i)
- The ratio V_M/V_π between the drive voltage V_M , and the voltage required for a phase shift of π between the two modulator arms V_π .
- From the Figure 2-23, the optimum bias point can be identified easily, for the maximum efficiency can be located at any odd multiple of $V_\pi/2$ [25].

Figure 2-23 Mach-Zehnder modulator transfer characteristic. [25]

The mathematical representation for the transfer characteristic for the MZM is given by the Eq. 2.10

$$\frac{P_o}{P_i} = \frac{T_{ff}}{2} \left[1 + \cos \left(\frac{\pi V_m}{V_\pi} \right) \right] \quad \text{Eq. 2.10}$$

Where:

T_{ff} is the typical insertion loss of the modulator (e.g at zero volt)

If the applied voltage $V_m = nV_\pi/2$, the expression can be replaced by:

$$\frac{P_o}{P_i} = \frac{T_{ff}}{2} \left[1 + \cos \left(\frac{\pi(V_B + v_m(t))}{V_\pi} \right) \right] \approx \frac{T_{ff}}{2} \left(1 \pm \frac{\pi v_m(t)}{V_\pi} \right) \quad \text{Eq. 2.11}$$

Once the expressions have been defined, in the Figure 2-24 is shown the configuration for the MZM. The external modulation system is based on an external cavity, 100 kHz linewidth, Tunable laser source (TLS), Agilent HP 81640A (see appendix), modulated by a Mach-Zehnder Modulator. The MZM is biased at its quadrature point, according to [9] 2.2 V, and thermally controlled to ensure the stability at 50°C, by the temperature controller Thorlabs TEC200C. Nonetheless, for MZM the temperature has been measured by the sensor AD590.

Figure 2-24. Configuration for MZM used.

2.3. Detection Schemes

2.3.1. Direct Detection

Concerning to the direct detection scheme, in [25], the process has been explained, a photon incident upon a photodetector has a probability of a valence-band electron would be excited to a higher-energy conduction band. Therefore, a response from the photodetector is obtained respecting the incident photon intensity, such that a proportional modulation of output photocurrent has appeared.

The incident optical field E can be represented by the equation 2.12

$$E = E_0 e^{j(2\pi\nu t + \theta)} \quad \text{Eq. 2.12}$$

Where:

E_0 is the amplitude,

ν is the frequency,

θ is the phase of the light.

The result of a direct detection has been defined as photocurrent I_D and given by the equation 2.13:

$$I_D = r_d |E|^2 = r_d E_0^2 \quad \text{Eq. 2.13}$$

From eq. 2.13, a proportionality constant has been considered, r_d is known as the detector responsivity and represents the relation between current and optical power. In addition, the current has not been affected by the optical field, because is calculated based on the square of its amplitude.

Figure 2-25 Photodiode transfer characteristic [25].

Most of photodetectors can absorb photons over a very broad range of optical wavelengths and therefore direct detection is not a viable option for recovering a signal that is modulating the optical frequency; direct detection of optical phase modulation is also implausible. [25]

2.3.1.1. PIN Photodetector

The most commonly used device, for photonic applications is the PIN constituted by a simple structure. It is a junction diode with an intrinsic layer between doped p and n layers, hence the name PIN [25].

PIN has been studied, and its structure and associated bias current have been illustrated in the Figure 2-26, where the doping profile, the charge profile, the energy bands diagram and the electric field profile are depicted.

The simplest PIN is a vertically illuminated structure in which light enters the upper layers of the device and is absorbed as it travels through the structure, generating electron-hole pairs in the depletion region. The depletion region extends mostly over the intrinsic region, being formed by a reverse bias voltage. The generated electron-hole pairs are then swept by the bias electric field to the device contacts to produce a photocurrent. One advantage of the vertical illumination scheme (also known as surface illumination) is the ease with which light can be coupled into the device. A disadvantage is the trade-off between conversion efficiency and transit-time limited microwave performance. [28]

Figure 2-26 Example p-i-n photodiode. (a) Diode structure. (b) Doping profile. (c) Charge profile. (d) Energy-band diagram. (e) Electric field profile. [30]

The transit time has been defined as the time taken for the photogenerated carriers to reach the device contacts, and it is determined by the saturation velocity in the semiconductor material and the width of the active absorption region.

The absorbed optical power can be determined by thickness of the active region, and given by the equation 2.14

$$P(d) = P_0(1 - e^{-\alpha(\lambda)d}) \quad \text{Eq. 2.14}$$

In the present project, one of the receptors proposed has been based on a PIN photodetector (see the model), with a maximum input power of 10mW, it is known that due to the small signal output has been needed to use an additional electrical amplifier in the output, previous to connect the oscilloscope channel input.

2.3.1.2. Avalanche Photo Diode (APD)

A different type of photodetector is known as avalanche photodiode (APD). Unlike conventional p-n or p-i-n photodiodes that generate a single electron-hole pair in response to the absorption of a photon. In APDs, many electron-hole pairs can be generated from a single absorbed photon. This internal "gain" makes APDs attractive for use in constructing sensitive receivers. [30]

In Figure 2-27, the APD structure has been illustrated. In addition, the doping profile, the charge profile, the energy bands diagram and the electric field are depicted.

Figure 2-27. Example of an avalanche photodiode (APD). (a) Diode structure. (b) Doping profile. (c) Charge profile. (d) Energy-band diagram. (e) Electric field.

Two principal breakdown mechanisms can be resultant when a p-n junction is subjected to a high reverse bias. Firstly, the atoms are directly ionized by the applied field, generally used to develop voltage regulating diodes, this mechanism is known as zener breakdown. Secondly, a called avalanche breakdown, with the APDs are based on, and it is caused by high velocity carriers causing impact ionizations within the semiconductor that generate additional carriers. [30]

As it is depicted in the Figure 2-27, in the absorption region in (e), photons are absorbed in the lightly doped semiconductor material, causing electron-hole pairs to form. Moreover, the carriers have been quickly transported by the applied electric field to the edges of the absorption region. Besides, carriers that reach the gain region are further accelerated by an even higher electric field. As they can reach enough velocity increasing a lot their kinetic energy, are capable to exceed the bandgap energy of the material and the carriers can actually "kick" additional electrons out of the valence band and up into the conduction band, causing the formation of additional electron-hole pairs. [30]

In addition to the known advantages for APDs, for high enough multiplication factors (i.e. gain) there is an improvement in the signal-to-noise ratio (SNR) that becomes shot-noise limited provided there is little excess noise [25]. Nonetheless, one limitation of APDs is that there is a fixed gain-bandwidth product resulting from the fact that for higher multiplication factors there is an increased time required for the avalanche to build up within the photodiode structure. Moreover, the APD structure is considerable for temperature sensitivity and the avalanche gain process requires higher operating voltages compared to photodiodes without internal gain. [25]

Practical APD Approach

In order to generate important conclusions from the comparison between PIN detector and APD, and since an APD in terms of cost had not been available in the optical communications laboratory. A practical approach has been designed, as the main advantage of the APD is the high sensitivity value, the inclusion of an EDFA has been considered, and because of the signal to noise ratio effect an optical filter will be connected as well.

The set up configured to demonstrate the approximation was constituted by a signal generator for OOK signal, and two receivers, Firstly, a commercial small form pluggable transceiver SFP including an APD detector (Edge 1550 1.25G) was used, it has a sensitivity value of -28 dBm. Secondly, the proposed block must be located as a receiver in the same conditions of transmitted signal, to achieve the results in terms of sensitivity and response to NRZ modulation formats. NRZ (OOK) signals have been transmitted as the SFP only can manage this kind of signals and not more complex formats as NOMA-CAP. However, as the results illustrated in Figure 2-28, the sensitivity and the curves are considerably similar between APD SFP and the proposed scheme (EDFA-Filter-PIN), demonstrating this scheme can be used in the project as an APD, in the range of BER between 10^{-2} and 10^{-5} , where the differences in sensitivity of 0.5 to 0.1 dB can be achieved.

Figure 2-28 Relation BER and Received Power for SFP APD & Proposed Scheme

3. Methodology

In order to get the results through the current project, many experiments have been proposed, and some measurements have been obtained such as Bit Error Rate (BER), in terms of Received Power, using several configurations and Set Ups.

In the following stage the setting up of parameters will be performed, the signal to be transmitted as it was described in the previous chapter would be NOMA-CAP, the information has been coded using a script in MATLAB. The study of the effects of the Non-Orthogonal Multiple Access signals in different set ups will be reached with two stages: Direct Detection. Firstly, a receptor using PIN photodetector, secondly, a receptor based on an Avalanche photo diode (APD).

To achieve those results, certain steps need to be placed in action:

1. Calibration System, maximizing and optimizing the parameters of the systems in TX stage, according to their practical performance.
2. Configurations of Receiver and Transmitter, to be performed must be fully defined.
3. Measurements of parameters such as: Optical Power received, Bit Error Rate, Sensitivity.

3.1. Calibration System

The experimental set up for the first stage is depicted in Figure 3-1. Here, the optical Transmitter (Tx) was based on a (TLS) Tunable Laser Source, Hewlett Packard 8168A, modulated by a (MZM) Mach-Zehnder Modulator, MZM was biased and its quadrature point, as recommended in [5]. However, in the current configuration the MZM was driven with an arbitrary waveform generator (AWG), Tektronix AWG70002A, with 8 GHz and 3dB electrical bandwidth, generating the NOMA-CAP modulation (as main signal). After, this modulated signal was amplified at the TX output with an Erbium-doped optical amplifier (EDFA), with the mission to emulate the standard TX output signal levels in commercial integrated vector modulators.

As it is shown in the Figure 3-1, the optical receiver (Rx) was based on a single PIN photodetector combined with an electrical amplifier. Finally, the detected signal was digitalized with a 25GSa/s real time oscilloscope (DSO) with 25 GHz of electrical bandwidth (see Appendix: Tektronix MSO 70804C) and processed off-line. For the first experiments this configuration would be fixed, which means one (1) bandCAP. Then, sometimes the detector would use: Avalanche Photo Detector (APD).

Figure 3-1. Transmitter and Receiver Scheme

(more details of the configuration in the next section)

3.1.1. Power ratio between users: Strong and Weak

The first test suggested from the set of tests proposed was modifying the values of power ratio (r_p) between the users: strong and weak, when r_p is power weighted and defined as the relation between the two NOMA levels, ($r_p = 20 \log_{10} w_2/w_1$) .

The values which provide BER under the limitation of $2,2 * 10^{-3}$ have been evaluated and represented in the plot of the $\log_{10}(BER)$, and its value is -2,657. This BER limit corresponds to a 7% forward error corrections (FEC) overhead [31].

Since the set up consists in a real TX and RX complete systems, there is the possibility of managing several combinations of primary modulation formats between users. It means, from 4-QAM NOMA for both users up to 16-QAM NOMA for both, passing through the combinations.

3.1.1.1. 4–QAM NOMA per both users

Figure 3-2. $\log_{10}(BER)$ vs Power relation rP . Primary modulation format 4-QAM NOMA

The results in the Figure 3-2 were obtained after setting a single bandCAP, and 4-QAM format in both users. In addition, some parameters have been considered, explained in the previous section and more detailed in [9]. The restriction of the $\log_{10}(BER)$ values for weak and strong have been contemplated, as consequence of that the possible relations in dB are in the range of 5-6 [dB], the selected power relation is the $r_p = 6$ [dB], it will be fixed as optimal for the following measurements.

3.1.1.2. 16–QAM NOMA for users Strong and Weak

As explained before, the transmitter system is capable to provide also 16-QAM NOMA primary format for users strong and weak. Moreover, in the Figure 3-3 is shown the result of the variation of the power ratio r_p , between strong NOMA and weak NOMA, and the response of the system has been plotted in terms of $\log_{10}(BER)$.

Figure 3-3. $\log_{10}(\text{BER})$ vs Power relation rP . Primary modulation format 16-QAM NOMA

From the Figure 3-3, the strong user is represented by the curve in blue and it has accomplished the BER restriction considered as a limit. Nevertheless, the weak user is also plotted in red, it has never reached the minimum value of BER defined. In fact, weak user is not even asymptotic to the limit. As conclusion from this experiment, this configuration is not possible to implement in the system, the current offline data signal processing has not enough features in order to perform more complex primary modulation formats.

3.1.1.3. 4-QAM NOMA and 16-QAM NOMA and combinations

As studied in the previous experiment a generation of 16 – QAM NOMA in both users is not feasible. There is the possibility of generating 4 and 16 QAM signal, it can be done by the combination in NOMA users, and it is still subject to be demonstrated or discarded. As explained in the signal generation section many configurations would be proposed.

Figure 3-4. $\log_{10}(\text{BER})$ vs Power relation rP . (a) 4-16 QAM NOMA (b) 16-4 QAM NOMA.

In the Figure 3-4, regarding (a) and (b), the limit of 7% FEC has been reached by the strong users. However, the weak users have not complied the restriction, in fact, the

exaggerated value of $r_p = 20$ [dB] had been considered for the experiments, despite of that in real terms of manufacture, the cost of developing this r_p is not feasible.

3.1.1.4. Power ratio contour

A deep analysis has been performed and the results are shown in the Figure 3-5. Here a contour curve has been created based on the different values of relation power r_p , the BER values obtained and the received power.

Figure 3-5. Power relation between users weak and strong vs. Power received considering $\log_{10}(BER)$ for 4-QAM NOMA. (a) Strong User (b) Weak User.

3.1.2. CAP filter N_{sym} variable in the Tx

The CAP filter used in the Tx signal generation DTx considers many parameters, such as the variable N_{sym} , as it was explained in the chapter 2 corresponds to the filter length, and it has been determined as a critical parameter due to performance and complexity of the system. The lower the length of the filter, the simpler [8]. Regarding the study previously analyzed, the current experiment will be performed in order to get experimentally the optimal value of N_{sym} .

Figure 3-6. Weak user performance when N_{sym} in CAP filter is variable

Figure 3-7. Strong user performance when N_{sym} in CAP filter is variable

After the experiment, the results have been obtained with the variation of BER using several N_{sym} . It is demonstrated that there is not significant difference in terms of sensitivity values (see Figure 3-6 and Figure 3-7), since all the curves are really close each other. In fact, the optimal value is $N_{sym} = 25$ (depicted in black). Nevertheless, this behavior is quite similar from $N_{sym} = 20$ until $N_{sym} = 60$. From now the value is $N_{sym} = 20$ will be selected, after an analysis of implementation have been done. The resources to build a commercial system with more symbols in each filter will increase considerably, and hence the sensitivity is similar between them, is not needed to develop a filter using large number of symbols without a substantial change in sensitivity.

3.1.3. Decision Feedback Equalizer (DFE): *numFBT* & *numFFT*

As explained in the previous chapter, the Decision Feedback Equalizer (DFE) has in its setting up two filter sections. The parameters backward and forward taps numbers have been studied. In the current project the variables assigned to these parameters are: *numFBT* and *numFFT* respectively.

In order to visualize the trend and behavior of these parameters, the following experiments were designed.

3.1.3.1. The *numFBT* fixed and the *numFFT* variable

Taking into consideration the values configured experimentally in [5], the first experiment has consisted in fixing the Backward *numFBT* = 20 and exploring the variation of *numFFT* from 10 to 60. At the end, the plot obtained shows the dependence of $\log_{10}(BER)$ in terms of Received Power PRx, for the weak and strong users.

According with Figure 3-8 and Figure 3-9, the curves have been depicted and it is shown that the same pattern is maintained. Moreover, when the value *numFFT* = 30, the curve has reached the maximum value of Sensitivity, defined as the minimal power required to achieve the FEC limit (of $BER = 2,2 \cdot 10^{-3}$) described in the plots.

Figure 3-8. Relation between BER and Received Power for NOMA weak user fixing $numFBT$

Figure 3-9. Relation between BER and Received Power for NOMA strong user while $numFBT$ is fixed.

3.1.3.2. The $numFFT$ fixed and the $numFBT$ variable.

Regarding the values considered experimentally in [5], is time to explore the variation of $numFBT$ while fixing $numFFT$, thus the plots resultant will show the dependence of $\log_{10}(BER)$ in terms of Power Received PRx , in the weak and strong users, and then the optimal value would be chosen.

In the plots shown in Figure 3-10 and Figure 3-11, the trend has been examined. The highest value in terms of sensitivity has been obtained when the value $numFBT = 20$. In addition, the performances for the remaining values have not experimented a considerable improvement. Hence, the optimal value can be selected regarding the complexity of the development of a system.

Figure 3-10. Relation between BER and Received Power for NOMA weak user for fixed $numFFT$ values.

Figure 3-11. Relation between BER and Received Power for NOMA strong user while the value of $numFFT$ is fixed.

3.1.4. The $numFFT$ and $numFBT$ are variable

Another proposed experiment has consisted in to vary the values of $numFFT$ and $numFBT$ in the same proportion. The results have been depicted in the Figure 3-12 and Figure 3-13. Here, it is experimentally demonstrated the optimal values are $numFFT = 30$ and $numFBT = 20$. The values have been changed in the same proportion in order to get more insights. Nonetheless, the curves have proved the chosen combination of values is the optimal. In terms of sensitivity, complexity and computational cost.

The set of proposed experiments have validated the configurations and parameters considered in [5], and the parameters have demonstrated the optimal values to achieve good responses when the signal is recovered by direct detections schemes.

Figure 3-12. Relation between BER and Received Power for NOMA weak user considering the variation of $numFFT$ and $numFBT$ in the same proportion.

Figure 3-13. Relation between BER and Received Power for NOMA strong user

The experiments performed have provided the expected results, the values for the critical parameters for the DTX and DRX blocks, with CAP filter in transmitter and DFE in the receiver respectively. Moreover, the values considered optimal and the implemented are summarized in the table X. Here, the justification implies the trade-off between a small value (less computational cost and complexity) and the sensitivity (the values chosen less than 1 dB difference) in terms of transmission systems. Nonetheless, an additional analysis can be proposed as future work, if the values can be reduced to the minimum and to validate if the changes in terms of sensitivity are considerable when kilometers of fiber cable are physically added.

Parameter	Optimal	Implemented
N_{sym}	25	20
$numFFT$	30	30
$numFBT$	20	20

Table 2 Parameters used for CAP filter and DFE.

4. Experimental Measurements and Results

In the current chapter the results of this master thesis are presented, issues and solutions are given through the development of the project, with the correspondent justification for the success or failure of the achievements. Here, there will be four defined sections: First, the description of experimental setup to be implemented, where the different schemes are depicted showing the configurations, and the practical-mathematical analysis for getting the maximum binary regime, and transmission capable to be received and decoded with the corresponding BER limitations mentioned before. This BER limit corresponds to a 7% forward error corrections (FEC) overhead [31]. Second, once defined all the configurations, the idea would be with the Downlink/Uplink transmitter to evaluate the advantages, pros and cons of the receiver, to do so the PIN Photodetector will be used. Third, furthermore of PIN receiver the idea of increasing the power budget and sensitivity has motivated to explore the fact of using a block proposed as: EDFA, BPF and PIN, in order to verify if its function could be performed as an Avalanche Photo Detector (APD). Finally, with the results obtained, a comparison would be presented showing some conclusions and moreover clarifying if their use as receiver is justified.

4.1. Experimental Setup Description

4.1.1. Physical Setup Description

Figure 4-1. Complete Experimental Setup description

Where:

OLT-TX:	Optical Line Terminal	ONU-RX:	Optical Network Unit Receiver
AWG:	Arbitrary Waveform Generator	VDC:	Voltage Direct Current Source
TIA:	Trans Impedance Amplifier	TLS:	Tunable Laser Source
MZM:	Mach-Zehnder Modulator	EDFA:	Erbium Doped Fiber Amplifier
BPF:	Band Pass Filter	VOA:	Variable Optical Attenuator
OPM:	Optical Power Meter	PIN:	PIN Photodetector
DSO:	Digital Sampling Oscilloscope	VCSEL:	Vertical Cavity Surface Emitting Laser
IDC:	Intensity Direct Current Source	DTx:	Digital Transmitter
DRx:	Digital Receiver	SSMF:	Standard Single Mode Fiber
APD:	Avalanche Photodetector		

The complete experimental setup is depicted in the Figure 4-1. Here, the scheme is separated in stages TX and RX, as explained in the chapter 2, where it was defined the scenario to be analyzed. Regarding ONU/OLT, there are Uplink ONU-TX and Downlink OLT-TX transmitters.

Downlink transmitter is based on an external cavity tunable laser source (TLS), Hewlett Packard 8168A, with a wavelength of 1545 nm, modulated by a Mach-Zehnder Modulator (MZM), this one biased at its quadrature point, and thermally controlled to ensure its stability [12], using a digital transmitter (DTx), where similar to [9], the block diagram signal generation for the NOMA-CAP signal will be shown in the next figure. First the data the user is generated by a data-pseudo random bit sequences (PRBSs) of length of $2^{12} - 1$, with different seed values for each multiCAP band, and they are QPSK mapped for each NOMA level. As reviewed in the chapter before the two NOMA levels are power weighted and added for each multiCAP band before the band signals are upsampled and filtered using a pair of bands specific multiCAP orthogonal filters. [9] Then the bandCAP width will be determined in order to maximize the data transmission rate, suggesting 1GHz and 500 MHz. Then, the signal is generated with an arbitrary waveform generator (AWG) with 4 GHz-bandwidth, set at 8 GSa/s. Finally, the modulated optical signal is amplified to obtain 0 dBm power output as in typical Tx systems [9], by an erbium-doped fiber optical amplifier (EDFA). The optical signal-to-noise ratio (OSNR) is then at 41 dB.

A second transmitter is also considered, as an Uplink possibility, based on a Vertical cavity surface emitting laser (VCSEL) (see model and type), the specifications and more details are shown in Appendix. In this setup, as previously detailed in [3] the static and dynamic (frequency chirp) parameters of a commercially available VCSEL from Raycan™ with thermal stabilization had been measured, giving the chance to directly modulate the VCSEL using a bias current based on the maximum value of 15mA, and connected with a bias tee as explained in the previous section. The RF signal and the bias current mixed together and are sent to the arbitrary waveform generator (AWG) used for Downlink transmitter. Is important to consider the temperature control used through the THORLABS device (See the model), which recognizes the type of temperature sensor (thermocouple) and uses a Proportional Integral Derivative PID controller, synchronizing the wavelength and will maintain as a stable value.

In both cases, as uplink and downlink transmitter, the optical signal is launched into 25 km and 50 km of standard single-mode fiber (SSMF) G652, as the results will show later.

For the ONU-RX, two different cost-effective optical receivers are considered for comparing some characteristics, differences and capabilities, both in Direct Detection. The first one, a receptor simply based on a PIN photodetector, combined with an electrical amplifier, to be finally connected to de Digital Sampling Oscilloscope (DSO) and then to the DRx (data processing off-line). Second one, according with the study was made before between a commercial APD and the combination of EDFA, BPF and PIN, would be considered as similar performance. So, here, the idea is reproducing this experiment and using the block as receiver and capturing the data with de DSO as expected before.

The results will include a relation between the Power Received PRx, and the calculation of Bit Error Rate after recovering the signal transmitted using data processing, for the several frames captured, the idea is including a Variable Optical attenuator (VOA) and a splitter with 90/10. This means a relation of 9.54 dB difference for the values measured from the optical power meter (OPM).

4.1.2. Data Rate examination

Once, the system had determined the optimal parameters, and experimentally demonstrated their performance, as it was done in the section 3, the next step is the examination of the maximum Data Rate to be transmitted through the setup, considering any of the laser configuration as transmitter and its characteristics. In order to do that, and based on the expression:

$$\text{Data Rate} = N_{bands} * N_{User-band} * \log_2(M) * R_s \quad \text{Eq. 4.1 [9]}$$

Where:

- N_{bands} Maximum number of bands complying the BER limit restriction
- $N_{User-band}$ As the system has two levels NOMA CAP
- M Modulation format order 4-QAM
- R_s Sample rate per bandCAP

As the modulation format order for this experiment is fixed as 4-QAM, (regarding the possibility was evaluated), the number of NOMA users is fixed and equal to two (Strong NOMA and Weak NOMA), there would be two alternatives: explore the bands number and the value of the width assigned to each bandCAP up to complete the total bandwidth BW=4GHz, in order to make a fair comparison between the VCSEL and MZM, concerning one parameter from VCSEL's datasheet BW is 4 GHz. (For more details see Appendix D).

4.1.2.1. BandCAP width 1 GHz

In the current experiment each bandCAP width is set as 1 GHz value, and the number of bands will be increasing until the maximum bandwidth is reached, in this case, theoretically this number is four.

For generating the curves, the VOA attenuation value is set in steps of 1 dB and every time the frames are captured, is also known the insertion loss value of 1.5 dB from the datasheet description, (for details see the appendix), determining their BER in off-line data processing will consider an initial value of attenuation, then the number of captured frames became 30.

Figure 4-2. Relation between BER and Received Power for: (a) One Band (b) Two bands (1 GHz per band)

The curves in the Figure 4-2 shows the relation between BER and Received Power PRx, but the vertical axis is based on a logarithmic scale, the $\log_{10}(BER)$ is showed as presented in previous plots. Once again, the value of sensitivity is estimated as the value achieves the BER limitation considered in [31], $\log_{10}(2.2 \times 10^{-3})$, corresponding to the 7% forward error correction (FEC).

The power spectral density for one bandCAP and two bandCAPs configuration, is shown in the Figure 4-3, here a comparison between received and transmitted spectra, regarding the maximum bandwidth to be used is 4 GHz.

Figure 4-3. Transmitted and received NOMA-CAP spectra for: (a) One Band (b) Two bands (1 GHz per bandCAP)

When the number of bandCAPs is equal to three, still all the users (Strong NOMA and weak NOMA) achieved the BER limitation, moreover, as demonstrated in Figure 4-4 (b), when the number is four the last bandCAP was not able to achieve the BER desired as maximum.

Figure 4-4. Relation between BER and Received Power for: (a) Three Bands (b) Four bands (1 GHz per band)

Clearly, in the Figure 4-5, the power spectra is depicted, and here the effect of reaching the maximum bandwidth admitted is notable, on one hand when bandCAP number is three, still the spectrum profiles are clean and complete, nonetheless, when is four the last bandCAP is affected and overlapped with a noise, as conclusion is not possible to transmit any information through this band and its users.

Figure 4-5. Transmitted and received NOMA-CAP spectra for: (a) Three Bands (b) Four bands (1 GHz per band)

4.1.2.2. BandCAP width 500 MHz

Once the experiment with a bandCAP width equal to 1 GHz is finished, and meaningful conclusions were obtained, the further step is to evaluate the impact of reducing the width in terms of half of the frequency, to do so the configuration will be modified and in the generation signal process the value of bandCAP is equal to 500 MHz (0.5 GHz).

This value 0.5 GHz will provide the capability to allocate until eight bandCAPs, for practical results, the evaluation included in the current project is calculated and depicted in one, two, four, six, seven and eight different bands.

Figure 4-6. Relation between BER and Received Power for: (a) One Band (b) Two bands (0.5 GHz per band)

Figure 4-7. Transmitted and received NOMA-CAP spectra for: (a) One Band (b) Two bands (0.5 GHz per band)

When the number of bandCAPs is low in this case one and two, all the bandCAPs fitted completely in the power spectrum required, also their sensitivities are high, and separations between bandCAPs are not changed significantly. Despite of those advantages, the maximum data rate is not enough as it will be explained in the binary regime analysis.

Figure 4-8. Relation between BER and Received Power for: (a) Four Bands (b) Six bands (0.5 GHz per band)

The plots placed above are demonstrated that in terms of power spectrum, the bands have been not affected yet by the effect of the noise or aliasing caused by the AWG. In fact, still all the bandCAPs spectrum profiles are well conformed and can be easily identified.

Figure 4-9. Transmitted and received NOMA-CAP spectra for: (a) Four Band (b) Six bands (0.5 GHz per band)

The most helpful comparison is shown in the Figure 4-10. Where, in (a) the seven bandCAPs successfully fitted, and their separation is not relevant. Nonce, in the Figure 4-10 (b) the last bandCAP does not achieve the minimum BER limit required as is depicted in the plot in green color.

Figure 4-10. Relation between BER and Received Power for: (a) Seven Bands (b) Eight bands (0.5 GHz per band)

According to the power spectrum, the situation is similar respecting the bandCAPs, when the maximum bandwidth was reached with bandCAP width equal to 1GHz, which means the last band is overlapped and corrupted by the noise and the aliasing effect. However, results are quite different than the previous ones, because of the amount of information is not capable to transmit at the same data rate. The mathematical analysis will be clarified in the following sections.

Figure 4-11. Transmitted and received NOMA-CAP spectra for: (a) Seven Band (b) Eight bands (0.5 GHz per band)

From the results obtained in the figures, the separation between the first and last bandCAP (for Strong NOMA and Weak NOMA), in terms of power, is less than 2 dBm, in order to provide a comprehensive analysis and future comparisons, the sensitivity will be calculated and represented as the average from all the bands respecting the user type.

Figure 4-12. BER vs. Received Power for different setups with strong and weak NOMA levels for different number of bands for 1 GHz (Average)

Figure 4-13. BER vs. received power for different setups with strong and weak NOMA levels for different number of bands for 0.5 GHz (Average)

Table 3 and Table 4 summarize the sensitivities depicted in Figure 4-12 and Figure 4-13. Considering the different setup configurations when the split is 1 GHz, the maximum number of bands achieved to the BER limitation was three. Meanwhile, for the split 0.5 GHz was seven. This idea will be useful for the next step, consisting in calculation of the binary regime.

NOMA level	Strong														
Num Bands	1		2		3		4		6		7		8		
BandCAP width [GHz]	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	0,5
S [dBm]	-18,5	-19,0	-14,5	-16,1	-14,0	x	**	-14,5	x	-13,3	x	-13,2	x		**

Table 3. Summary of Sensitivities (S) of strong NOMA levels for different number of bandCAPs.

** The sensitivity was not reached in the configuration

NOMA level	Weak														
Num Bands	1		2		3		4		6		7		8		
BandCAP width [GHz]	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	0,5
S [dBm]	-16,0	-16,9	-12,2	14,1	-12,1	x	**	14,0	x	12,8	x	12,7	x		**

Table 4. Summary of Sensitivities (S) of weak NOMA levels for different number of bandCAPs.

** The sensitivity was not reached in the configuration

4.1.2.3. Binary Regime Calculation

Once established the averages for every configuration proposed, it is necessary to evaluate the maximum data rate transmission which accomplishes the BER requirements.

From the expression:

$$Data\ Rate = N_{bands} * N_{User-band} * \log_2(M) * R_s \quad \text{Eq. 4.1 [9]}$$

Where R_s corresponds to the sample rate per band, for simplicity considered and calculated as the frequency width per bandCAP.

According to the Figure 4-14, the power spectrum density demonstrates somehow an aliasing effect appears after the bandwidth used, but still the transmitted signal was recovered without any complication.

Figure 4-14. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Three Bands and 1 GHz split

Nevertheless, regarding to the Figure 4-15 which includes the four bandCAPs setup, after the bandwidth of the transmitted signal and the aliasing effect are combined. It is realized that it is impossible to distinguish the aliasing effect from the transmitted signal.

Figure 4-15. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Four Bands and 1 GHz split. (Aliasing effect)

After the graphical analysis above, the expression mentioned before would be fulfilled as follows:

- For $R_s = 1 \text{ Gbps}$ and maximum number of bands = 3

$$\text{Data Rate} = 3 * 2 * \log_2(4) * 1 \text{ Gbps}$$

$$\text{Data Rate} = 12 \text{ Gbps}$$

For the split of 0.5 GHz, the Figure 4-16 shows the power spectrum of the seven bandCAPs configuration. The signal is easily recognized due to the guard band separation from the aliasing effect, which makes possible to decode the transmitted signal.

Figure 4-16. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Seven Bands and 1 GHz split

Nonetheless, the aliasing effect is more dangerous in the setup of eight bands, as it is shown in the Figure 4-17, where the signal and the last band are corrupted.

Figure 4-17. Power Spectrum density taken from Digital Sample Oscilloscope for Setup: Eight Bands and 0.5 GHz split (Aliasing effect)

- For $R_s = 0.5 \text{ Gbps}$ and maximum number of bands = 7

$$\text{Data Rate} = 7 * 2 * \log_2(4) * 0.5 \text{ Gbps}$$

$$\text{Data Rate} = 14 \text{ Gbps}$$

Considering the Eq. 4.1, the Table 5 summarizes all the possible data rates would be transmitted.

Num bandCAPs	1		2		3		4		6		7		8		
BandCAP width [GHz]	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	1,0	0,5	0,5
Data rate [Gbps]	4	2	8	4	12	6	**	8	x	12	x	14	x	16	**

Table 5. Summary of Data Rates (Gbps) transmitted for different number of bands.

** The sensitivity was not reached in the configuration

Based on the calculations above, the maximum transmission data rate in the configuration corresponds to a bandCAP width of 0.5 GHz and seven bands, the total bandCAP width is up to 3.5 GHz and its data rate is 14 Gbps.

4.2. Receptor: PIN

The first alternative proposed for the Rx is using a PIN photodetector as receiver. Its characteristics are shown in the section of resources used. As expected, it is necessary to use an electrical amplifier, and connect directly its output to the Digital Sampling Oscilloscope Tektronix MSO 70804C input channel, which has a maximum sampling rate of 25 GSa/s and 8 GHz bandwidth. Another consideration is that the sign of the signal captured by the DSO. Since the amplifiers (one at PIN output) will have to be checked in order to compute the BER in the digital signal processing block. Otherwise, full error result would be obtained.

Figure 4-18. Scheme for PIN Receiver in cases of Uplink and Downlink

4.2.1. Downlink Transmitter Mach-Zehnder Modulator with PIN

In the current experiment, the proposed transmitter corresponds to the Downlink, here, the digital signal is generated, and it was sent through the AWG. Next step is to electrically amplify the signal, and to modulate it by a Match-Zehnder Modulator. MZM is thermally controlled by the Thorlabs TED200, which considers the measurements of the temperature using the sensor AD590, this configuration was exposed in the chapter 2. In addition, Tunable Laser source (TLS) (Agilent HP 81640A) is set as 1545 nm and using a non-polarization fiber cable connected to the MZM. The output of the MZM is connected to the EDFA, which emulates typical power outputs from commercial transmitters, around 0 dBm. Later on, a band pass filter (Oz Optics) is also set in same wavelength value. As a final step, variable optical attenuator (VOA) EXFO FVA 600 is connected, with steps of 1 dB attenuation. Details will be described in the following figure and the features about devices are available in appendixes.

Figure 4-19. Scheme for PIN Receiver signal transmitted using Match-Zehnder Modulator (Downlink)

Figure 4-20. Physical Implementation Setup for PIN Receiver signal transmitted using Match-Zehnder Modulator (Downlink)

From the Figure 4-20, the physical disposition of the elements is shown, here the numbers correspond to the following table.

Item	Element
1	Digital Sampling Oscilloscope
2	Mach-Zehnder Modulator
3	Trans Impedance Amplifier
4	Arbitrary Waveform Generator
5	Voltage Direct Current Source
6	Temperature Controller for MZM
7	Band Pass Filter
8	Erbium Doped Fiber Amplifier
9	PIN Photodetector
10	Splitter 90/10
11	Variable Optical Attenuator
12	Optical Power Meter
13	Tunable Laser Source

Table 6. Elements disposition in the physical implementation for Downlink transmitter using PIN receiver

Figure 4-21. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink)

From the Figure 4-21, the main idea obtained is that all the bandCAPs allocated perfectly in the bandwidth assigned, the signals belong to the users are undistorted and free of any interference as noise, overlapping, etc. In fact, all users are achieved the BER limitation established, giving the sensitivity value of -14.1 dBm for the strong NOMA user in the first band. In addition, the distance between first and last band is not considerable. In this case, the possibility of computing an average of the all bandCAPs is still valid, for generating a simple comparison between systems and providing more interesting conclusions.

4.2.1.1. Adding Fiber optics cable to Downlink

The previous experiment was done in Back to Back configuration, for the next step analysis, the idea is adding some distances of fiber (physically in spools). Firstly, the consideration is testing an additional spool of 25 km, then one extra spool will be added which let us to reach 50 km in total.

The cable fiber is a spool made of a length of 25 km standard single mode fiber (SSMF) G652 with acrylate coatings and type SC (square connector) connectors are used. The attenuation factor is 0.22 dB/km, with approximately total attenuation of 5.5 dB.

Figure 4-22. Physical spool fiber cable used. SSMF G652.

The motivation of including physical fiber cable is to analyze the presence of some effects such as: attenuation, dispersion, non-linear effects, etc. from the fiber length. The spools could reflect changes in the curves which represent the relation between received power (PRx) and the Bit Error Rate computed per each bandCAP.

Figure 4-23. BER vs. received power for strong and weak NOMA levels for seven bands (0.5 GHz) adding 25 km fiber cable. (Downlink)

When the second 25 km fiber cable spool is connected, the total length became 50 km, with a total attenuation measured equal to 11.2 dB. It is shown in the Figure 4-23 and Figure 4-24, no special effects are detected in the curves.

Remarkably, the separation between them is increased, even though the computation of the averages of all bandCAPs are good approximation, in order to generate a logic comparison between all the experimented scenarios: Back to back (0 km), 20 km and 50 km fiber.

Figure 4-24. BER vs. received power for strong and weak NOMA levels for seven bands (0.5 GHz) adding 50 km fiber cable. (Downlink)

Once the system was responded in positive way to the effect of adding some kilometers of fiber and taking into account the penalty between bandCAPs is less than 2 dB. The plots will be presented as the average BER of the seven bandCAPs, in terms of PRx, as follows.

Figure 4-25. BER vs. received power for strong and weak NOMA levels for seven bands (0.5 GHz) for 0/25/50 km (Average-Downlink)

4.2.2. Uplink Transmitter Vertical Cavity Surface Emitting Laser with PIN

Regarding to next experiment, the uplink transmitter is proposed as it is depicted in the Figure 4-27. The laser to be used, is a vertical cavity surface emitting laser (VCSEL) from Raycan™ and its bandwidth is 4 GHz (see the appendix for more details). To begin with, it was necessary to check the VCSEL temperature using the Temperature Controller Thorlabs LED200C. Concerning the sensor, TH20K was used as a thermistor and then the bias tee (Microcircuits) is being fed by bias current source, so that it is combined with the RF signal generated by the AWG. This configuration was specified in the chapter 2 and it is shown in the Figure 4-26 where the connections are exposed.

Figure 4-26. Set of connections for Vertical Cavity Surface Emitting Laser (VCSEL RayCan™ 1550nm)

In addition, the VCSEL optical output is equal to -5 dBm, this value corresponds to a previous configuration from [12], there the characterization of the VCSEL was done and the values of current forward intensity I_F is defined to 12 mA, and the temperature set in the controller equal to 50 °C, and taking into account the limit of I_{TEC} , as exposed in the chapter 2, helps to cooling or heating the thermoelectric cooler element inside, and overpassing this value the VCSEL will be damaged. Finally, the optical output is connected directly to the variable optical attenuator EXFO FVA 600, with steps of 1 dB attenuation.

Figure 4-27. Scheme for PIN Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)

The setup shown in the Figure 4-28 and it corresponds to the physical implementation was done in the Optical Communications Laboratory, the devices used are described in the appendix included.

Figure 4-28. Physical Implementation Setup for PIN Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)

From the Figure 4-28, the physical disposition of the elements is shown, here the numbers correspond to the elements listed as follow.

Item	Element
1	Digital Sampling Oscilloscope
2	Trans Impedance Amplifier
3	Arbitrary Waveform Generator
4	VCSEL and Biastee connections
5	Current Direct Source
6	Optical Power Meter
7	Temperature Controller for VCSEL
8	Variable Optical Attenuator
9	Splitter 90/10
10	PIN Photodetector

Table 7. Elements disposition in the physical implementation for uplink transmitter using PIN receiver

From the Figure 4-29, the main difference with the curves using MZM is the distance (separation) between bandCAPs is smaller as before, in fact, is around 1 dB, additionally, all the signals can be differentiated easily, and their information can be detected. The concept used before about computing the BER as the average of all the bandCAPs is valid one more time, the curves of the relation between Power Received and BER in each bandCAP are really close each other, and it will be helpful to the goal to generate a meaningful comparison with the response of the system using MZM as transmitter.

The sensitivity value in this configuration is located in -15 dBm, for the first bandCAP, as mentioned before the separation between bands is not significative, for obtaining a higher value of sensitivity is necessary to explore the proposed scheme using and Avalanche photodetector APD, this analysis will take place in the next section when the receiver block is replaced by a PIN detector, a band pass filter and an EDFA amplifier.

Figure 4-29. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink)

4.2.2.1. Adding Fiber optics cable to Uplink

To evaluate if including physical cable fiber presents some effects in the back to back system response, the next step was connecting in series one 25 km spool as before.

From the Figure 4-30 the changes are enough significant in terms of separation of all curves, despite of this increment still all the bands achieved the BER limitation established.

Figure 4-30. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) adding 25 km fiber cable. (Uplink)

As expected, an effect in the curves appeared when including one spool of fiber, the further step corresponds to add one more spool, and evaluate the consequences behind. The Figure 4-31 shows its effect, here, the bandCAPs have a considerable separation each other, and the sensitivity value will decrease considerably, however for practical effects the average computation will be performed. One possible reason for this effect, is the chirp effect related with the usage of Vertical cavity surface emitting laser, some effects are characterized and evaluated in [3].

Figure 4-31. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) adding 50 km fiber cable. (Uplink)

Finally, the summary of the measurements in this experiment is depicted in the Figure 4-32.

Figure 4-32. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) for 0/25/50 km (Average-Uplink)

In order to get some insights about the chirp effect present in the VCSEL (Uplink) configuration a small experiment was designed, it consists in including an Erbium Doped Fiber Amplifier to the optical output of the laser, then capturing frames and to compute as before the BER for the signal received, once calculated, the curves and the relation between Power Received and BER is generated, in this case, the effect is visible for the length equal to 50 km.

Figure 4-33. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) for 0/25/50 Km (Average-VCSEL+EDFA+PIN) Chirp Effect

Another option is to evaluate the power spectrum changes suffered after including kilometers of fiber cable, being specific the maximum length will be 100 km made of 4 spools of Standard single mode fiber (SSMF) G652 with a total of attenuation of 22 dB.

Figure 4-34. Power Spectra for strong and weak NOMA levels for Seven bands (0.5 GHz) for 0/25/50/75/100 km (VCSEL+EDFA+PIN) Chirp Effect

4.3. Emulated Receptor APD

The second proposed configuration for the ONU-Rx applies the conclusion obtained from the chapter 2, where the experiment demonstrated the similar performance between an Avalanche Photo detector APD from a commercial Small Form-Factor Pluggable (SFP) transceiver (see the appendix for more details), and the block conformed by an EDFA, Band pass filter and PIN detector as compact receiver. All the same as before, the expected result would be an important increment in the value of sensitivity for the system. Once again, the output of the PIN photodetector is connected to an electrical amplifier, and directly connect to the channel 1 input of the Digital Sampling Oscilloscope Tektronix MSO 70804C, which the known maximum sampling rate of 25 GSa/s and 8 GHz bandwidth, still a valid consideration is the sign of the signal captured through the DSO, because of the amplifiers (one at PIN output) will have to be checked in order to compute the BER in the digital signal processing block, otherwise instead of getting a not error result the obtained would be full error.

Figure 4-35. Scheme for APD Receiver in cases of Uplink and Downlink

4.3.1. Downlink Transmitter Mach-Zehnder Modulator with Emulated APD

In accordance with the experiment before, the proposed transmitter for Downlink applications and its digital signal is generated and connected to the AWG, after electrically amplified, and finally modulated by a Match-Zehnder Modulator, being thermally controlled by the Thorlabs TED200C, the temperature is detected by means of a sensor (AD590), this configuration was exposed in the chapter 2.

Respecting the Tunable Laser source (TLS) Agilent HP 81640A, the wavelength is set as 1545 nm as before, and uses a non-polarization fiber cable connected to the MZM, its output is connected to the same Optilab rEDFA as before, in order to emulate typical power outputs from commercial transmitters around 0 dBm. Later, the Oz-Optics band pass filter is configured in the same wavelength value, this output joined to the variable optical attenuator EXFO FVA 600, with steps of 1 dB attenuation for practical purposes.

Figure 4-36. Scheme for APD Receiver signal transmitted using Match-Zehnder Modulator (Downlink)

Figure 4-37. Physical Implementation Setup for APD Receiver signal transmitted using Match-Zehnder Modulator (Downlink)

From the Figure 4-37, the physical disposition of the elements is shown, here the numbers correspond to the following table.

Item	Element
1	Digital Sampling Oscilloscope
2	Mach-Zehnder Modulator
3	Trans Impedance Amplifier
4	Arbitrary Waveform Generator
5	Voltage Direct Current Source
6	Temperature Controller for MZM
7	Band Pass Filter
8	Erbium Doped Fiber Amplifier
9	PIN Photodetector
10	Splitter 90/10
11	Variable Optical Attenuator
12	Optical Power Meter
13	Tunable Laser Source
14	Erbium Doped Fiber Amplifier 2

Table 8. Elements disposition in the physical implementation for Downlink transmitter using APD receiver

From the Figure 4-38, all the bandCAPs allocated fit perfectly in the bandwidth assigned, and the users and their signals are clean and free of any interference as noise, overlapping, etc. The figure shows the signals being transmitted in Back to Back

measurement, and the conclusion as expected is the increasing of the sensitivity caused using an EDFA amplifier, in this case the gain is around 11 dB.

Figure 4-38. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink) for APD Receiver

4.3.1.1. Evaluation of Cable fibers addition for Downlink

In fact, from the previous measurements, in despite of the benefit in terms of sensitivity, the distance difference between the first and the last band is significant, however, for generating a simple comparison including all systems and providing more interesting conclusions the computation of the average BER for all bandCAPs will be performed.

Figure 4-39. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink) for APD Receiver adding 25 km SSMF

The addition of more kilometers of fiber cable did not affect the curves generated, concerning the Figure 4-39 and Figure 4-40, the distances between bandCAPs are not different as the obtained in the Figure 4-38 corresponding to the back to back configuration.

Figure 4-40. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Downlink) for APD Receiver adding 50 km SSMF

Although the separation described before, the Figure 4-41 depicts the average curves completed comparing the scenarios of Back to back (0 km), 25 km and 50 km as a summary of sensitivities.

Figure 4-41. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz). (Downlink) for APD Receiver (0/25/50) km SSMF (Averages)

4.3.2. Uplink Transmitter Vertical Cavity Surface Emitting Laser with APD

As the last proposed configuration, the uplink transmitter is managed by the VCSEL with the connections described previously, using a bias current to turn on the laser and proportionally commanding the power optical output, and the stabilization of the wavelength by the THORLAS LDC200C. All the blocks belonging this scenario are still in operation, which means the signal sent through the AWG connected to the Bias tee and optically modulated by the VCSEL, its output connected to the VOA and finally through a splitter the optical power meter is detecting the Received power changes. Finally, the hint if the sign in the received signal is helpful, because at the starting point of the transmitter there is not an amplifier which would invert the sign of the signal to be transmitted.

Figure 4-42. Scheme for APD Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)

The devices used in the current configuration are shown according to the numbers in the Figure 4-43 and associated with the table below.

Figure 4-43. Physical Implementation Setup for APD Receiver signal transmitted using Vertical Cavity Surface Emitting Laser VCSEL (Uplink)

The physical disposition of the elements listed in the table, as a brief description of their function.

Item	Element
1	Digital Sampling Oscilloscope
2	Trans Impedance Amplifier
3	Arbitrary Waveform Generator
4	VCSEL and Bias tee connections
5	Current Direct Source
6	Optical Power Meter
7	Temperature Controller for VCSEL
8	Variable Optical Attenuator
9	Splitter 90/10
10	PIN Photodetector
11	Erbium Doped Amplifier

Table 9. Elements disposition in the physical implementation for uplink transmitter using PIN receiver

In the Figure 4-44, the curves reflect the advantages of including an APD receiver in the system, however, the chirp effect briefly determined in the previous section is still affecting to the separation of the bandCAPs, in despite of this effect the computation of the BER average will be performed in order to get conclusions in the final discussions. The sensitivity of the first bandCAP gets a value of -25.8 dBm as expected, this is approximately 10 dB greater than the value obtained using a PIN detector only.

Figure 4-44. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink) for APD Receiver

4.3.2.1. Evaluation of Cable fibers addition for Uplink

Once more, the effect of including physical cable fiber will provide valuable ideas, in this first step a 25 km spool is connected in series with the setup, and the curves depicted in the Figure 4-45, is shown the effect of the chirp belonging to the use of the VCSEL. Although, the benefit of the use of an APD receptor is still the high value of sensitivity.

Figure 4-45. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink) for APD Receiver adding 25 km SSMF

When the second spool of fiber cable is connected, which means 50 km and additional attenuation of 11dB, the effect of chirp is more powerful, the Figure 4-46 is clearly demonstrating the considerable separation between bandCAPs, for practical purposes, the average of all bandCAPs will be required.

Figure 4-46. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz) in Back to Back configuration. (Uplink) for APD Receiver adding 25 km SSMF

As summary, the averages of all bandCAPs for all scenarios: back to back, 25 km and 50 km, are shown in the Figure 4-47. Here, the advantage of using APD in terms of sensitivity is valuable, but the separation between curves would be an issue adding some difficulties when the signal is transmitted for higher distances.

Figure 4-47. BER vs. received power for strong and weak NOMA levels for Seven bands (0.5 GHz). (Uplink) for APD Receiver (0/25/50) km SSMF (Averages)

4.4. Comparison of Systems and Discussion

4.4.1. PIN Receiver for Uplink and Downlink Transmitters

Once tested the receiver based on a PIN detector, transmitting the signals through a downlink (Mach-Zehnder Modulator) and uplink (Virtual cavity surface emitting laser), a practical comparison would be obtained.

The Figure 4-48 (a) shows the behavior of the systems for strong NOMA users, there, the response of MZM curves respect to the fiber cable lengths does not include any harmful effect to the signal transmitted, in fact the information of all bandCAPs was recovered completely achieving the BER limitations established in [31]. On the other hand, for the VCSEL obtained curves the existence of a small separation between the bandCAPs is detected, regardless this effect, the BER limits corresponding to the 7% overhead (OH) Forward Error correction estimated in [31] was reached as well.

Figure 4-48. BER vs. received power for Seven bands (0.5 GHz) (Uplink vs Downlink) for PIN receiver (a) Strong NOMA users (b) Weak NOMA users

Moreover, the Figure 4-48 (b) illustrates the weak's NOMA performance reacting to the presence of additional fiber cable distances, in these cases, for the MZM signals the impact of including some kilometers of fiber cable does not affect the sensitivity value, there is not penalty at all. Respecting to the VCSEL measurements, it is reflected a small penalty around 2 dB in terms of sensitivity when the 50 km fiber cable is added to the setup, once again this penalty is negligible because the BER limit is reached.

4.4.2. APD Receiver for Uplink and Downlink Transmitters

Same as before, the implementation of receiver based on APD detector was placed, the comparison to be performed consisted in transmitting the NOMA CAP signals though a downlink (Mach-Zehnder Modulator) and uplink (Virtual cavity surface emitting laser), then using the relation between the Power Received and the BER a practical comparison would be obtained.

The Figure 4-49 (a) and (b) display the Strong and weak NOMA performance respectively, in the first case, in the Strong NOMA, for the MZM, the sensitivity is nearly -25 dBm as expected thanks to the APD configuration, while including distances of fiber cable the value of sensitivity is not being affected. Now, taking into account the VCSEL, there is a considerable penalty due to the chirp effect belonging to the modulator laser, this is a drawback in terms of sensitivity, because the difference between back to back and 50 Km fiber is around 8 dB, if fact is still better than the sensitivity provided by the PIN detector case, but also included a higher budget if the systems are compared. Secondly, with the Weak NOMA the response barely differs from the conclusions obtained in the case of Strong NOMA, is noticed the penalty is nearly 9 dB if compares the back to back and the 50 km SSMF additionally series connected.

Both cases achieved successfully the BER limitation contemplated in [31], however, the consideration to foresee one solution from another will take place in terms of the penalty in sensitivity it has, in other words for VCSEL solution the penalty is higher than the MZM setup. Even though the important advantage of high sensitivity in back to back scheme, with the distance this is becoming as a drawback.

Figure 4-49. BER vs. received power for Seven bands (0.5 GHz) (Uplink vs Downlink) for APD receiver (a) Strong NOMA users (b) Weak NOMA users

5. Budget

The current project has taken place in the Optical Communications Laboratory of UPC's Signal Theory and Communications (TSC) Department. Hence, most of the elements have been available for the project use. Nevertheless, a budget description is required. Based on it, the devices provided by the department will be listed. Furthermore, the budget will be calculated based on the invested time during the consecution of the experiments, measurements, data processing and writing processes.

5.1. Available Resources

In the Table 10, have been summarized all the technical devices and equipment, which belong to Optical Communications Laboratory from UPC, and have been used in order to set up the schemes and any experiment have been proposed in the current project. In addition, a brief summary of the features has been included.

Device	Features
THORLABS Thermoelectric Temperature Controller (TED 200C)	<p>TEC Current Output Control Range 0 to ± 2 A Compliance Voltage > 6 V Maximum Output Power 12 W Measurement Resolution 1 mA Measurement Accuracy ± 10 mA Noise and Ripple (typ.) < 1 mA</p> <p>TEC Current Limit Setting Range 0 to > 2 A Resolution 1 mA Accuracy ± 20 mA</p> <p>Thermistor Sensors Control Range 10 W to 20 kW 100 W to 200 kW Resolution 1 W 10W Accuracy ± 10 W ± 100 W Supported Sensors AD590, AD592, LM135, LM335 Control Range with AD590, LM135 -45 °C to $+145$ °C Control Range with AD592 -25 °C to $+105$ °C Control Range with LM335 -40 °C to $+100$ °C Resolution 0.01 °C Accuracy ± 0.1 °C</p> <p>See Appendix A</p>
THORLABS Laser Diode Controller (LDC 200CV)	<p>Current Control (Constant Current Mode) Control Range 0 to ± 20 mA Compliance Voltage > 6 V Resolution 1.0 μA Accuracy ± 20 μA Temperature Coefficient < 50 ppm/°C</p> <p>Current Limit Setting Range 0 to > 20 mA Resolution 1 μA Accuracy ± 50 μA</p> <p>See Appendix B</p>
TEKTRONIX Arbitrary Waveform Generator (AWG 70002A)	<p>Analog bandwidth of 14 GHz a Output frequency of 20 GHz Sample rate up to 50 GS/s Record length of 2 giga samples (GSa)</p>

	<p>Range 0.25 Vp-p to 0.5 Vp-p into 50 Ω single-ended 0.5 Vp-p to 1.0 Vp-p into 100 Ω single-ended Resolution 1.0 mV Accuracy $\pm(2\%$ of amplitude + 1 mV) DC accuracy $\pm(2\%$ of amplitude + 1 mV)</p> <p>See Appendix C</p>
RayCan™1550 VCSEL pigtail	<p>Electrical and Optical Characteristics Threshold current I_{th} 2 mA Forward voltage V_f 3 V Series resistance R_s 100 200 Ω Output power P_o 0,5 mW Wavelength λ 1550 nm</p> <p>Absolute maximum ratings ($T = 25^\circ\text{C}$ unless otherwise stated) Forward current I_f 15 mA Reverse voltage V_r 5 V TEC maximum current I_{TEC} 0,7A</p> <p>See Appendix D</p>
TEKTRONIX Mixed Signal Oscilloscope (MSO 70804C)	<p>Four (4) channels Maximum bandwidth of 8 GHz Typical rise time of 50 ps (picoseconds) Sample rate up to 25 Giga samples per second (GS/s), Capable of recording up to 250 million samples at once. Input resistance 100 kΩ $\pm 1.0\%$ Input capacitance 3.0 pF Maximum non-destructive input signal ± 42 V User defined threshold range ± 40 V Minimum detectable pulse width 1 ns Digital channel to digital channel skew 200 ps Probe length 1.3 m (4.27 ft)</p> <p>See Appendix E</p>
EXFO Optical Spectrum Analyzer FTB-2	<p>Calibrated wavelengths (nm): 850, 1300, 1310, 1490, 1550, 1625, 1650 Optional CWDM calibrated wavelengths (nm): 1270, 1290, 1310, 1330, 1350, 1370, 1390, 1410, 1430, 1450, 1470, 1490, 1510, 1530, 1550, 1570, 1590, 1610, 1383, 1625 Power range (dBm) e 27 to -50 Uncertainty (%) e, f $\pm 5\%$ ± 10 nW Display resolution (dB): 0.01 = max to -40 dBm, 0.1 = -40 dBm to -50 dBm</p> <p>See Appendix F</p>
EXFO Variable Optical Attenuator FVA 600	<p>Calibration wavelengths (nm): 1310/1550 Wavelength range (nm): 1250 to 1625 Wavelength increment (nm): 1 Maximum attenuation (dB) 65 IL (dB) b, c, d ≤ 1.5 Resolution (dB): 0.01 Linearity (dB) b, c, e ± 0.1 Repeatability 2σ (dB) c ± 0.1 Optical return loss (dB) f, h, i > 50</p> <p>See Appendix G</p>
EDGE SFP	<p>Media Type: Single-Mode Fiber (SMF) TX Wavelength: 1550 nm RX Wavelength: 1270-1610 nm Minimum Optical Budget: 32 dB Maximum Distance: 120km</p>

	<p>Supported Data Rate: 1.063-1.25Gbps Supported Applications: Gigabit Ethernet (1.25 Gbps), 1G Fiber Channel (1.0625 Gbps) Connectors: Double LC Tx Wavelength Bandwidth: 20nm (1540 – 1560 nm) Rx Wavelength Bandwidth: G.694.2 CWDM Grid (1270-1610nm) Minimum Transmitting Power: 0 dB Maximum Transmitting Power: 5 dB Receiver Sensitivity: -32 dBm Receiver Overload: -7 dBm Dispersion: 2600-2700 ps/nm</p> <p>Transmitter Type: DFB Laser Receiver Type: APD Photodiode Power: +3.3V single power supply</p>
TENMA Digital multimeter 72-7780	<p>0.001 volts precision Max. Voltage 600 volts.</p>
GO4FIBER Power meter GFHS-A	<p>Six (6) calibrated wavelengths Accuracy of $\pm 5\%$ Maxi. Optical Input +10 dBm Scales in dB and mW.</p>
Oz Optical Band Pass Filter	<p>Resolution: Typically, less than 0.1nm Tuning Range: 50nm Wavelength Range: 1520–1570 (C-band), 1570–1620 (L-band) and 1470–1520 (S-band) standard. Other ranges available on request. Linewidth: (FWHM): 1.1 $\pm$ 0.1nm standard.</p> <p>Wavelength/Temperature Sensitivity: Typically less than 0.002nm/°C PDL: Typically less than 0.3dB Insertion Loss: Typically less than 2.5dB for complete device over full tuning range. Power Handling: Up to 200mW for standard package. Response Time: 50nm change in less than 1 sec. 1nm change in less than 0.1 sec.</p>
Agilent HP Tunable Laser Source 81640A	<p>GPIO Interface Front Panel BNC Connectors Tunable Range 1470 to 1580 nm Wavelength Accuracy ± 0.1nm Resolution 0.001nm Front BNC Connectors Mod. Input, Analog Output</p>
Agilent HP 11982A Amplified Lightwave Converter	<p>1200 nm to 1600 nm Bandwidth dc to 15 GHz (optical) (characteristic) dc to 11 GHz (electrical) Full Width Half Maximum 29.4 ps Conversion Gain (dc responsivity)¹ > 200 V/W Noise Equivalent Power² 30 pW/√ Hz Input Return Loss > 23 dB Corrected Freq Response³ 20 to 30°C 0 to 55°C dc – 22 GHz ± 2.2 dB* ± 4.7 dB* Harmonic Distortion > 41 dB* below fundamental Output < -10 dBm Maximum Safe Optical Input Power 10 mW (+10 dBm) (average) Output Voltage Range > 700 mV Output Offset Voltage < 1 mV Output Electrical Return Loss: 0.1 to 12 GHz (characteristic) > 11 dB* ;12 GHz to 22 GHz > 9 dB*</p>

Mini-Circuits Bias-tee ZFBT-4R2GW	Wideband, 0.1 to 4200 MHz Low insertion loss, 0.6 dB typ. Feed through terminal per DC port RF Power 30 dBm max. Voltage at DC port 30 V max. Input Current 500 mA DC resistance from DC to RF&DC port 4.5Ω typ.
Optilab rEDFA Erbium Doped Fiber Amplifier	Operating Wavelength Range 1530 nm to 1565 nm Input Power Range -5 dBm to +7 dBm Output Power Level +17 to +26 dBm Output Power Stability 0.15 dB over 8 hours Number of Output 1 port standard, 2, 4, 8, 16 ports available Optical Return Loss 50 dB min. Input/Output optical Isolation 30 dB min. Polarization Mode Dispersion 1.0 ps max. Polarization Dependent Gain 0.15 dB max. Noise Figure (NF) 5.0 dB max. @ +3 dBm Input Input Output Fiber Type Corning SMF28

Table 10 Summary of Resources have been used during the project. From: [32] [33] [34] [35] [36] [37] [38] [39] [40] [41] [42]

5.2. Budget

The project proposed have been achieved after several hours of dedication. Therefore, the stages accomplished can be defined as follows:

1. Overview the theoretical background (schemes proposed) and defining a project plan.
2. Calibration of the system.
3. Experimental testing for the proposed schemes with NOMA CAP waveforms.
4. Off-line Data Processing and results analysis.
5. Documenting the present thesis.

According with the stages mentioned before, an estimated of nine hundred (900) hours have been devoted. Typically, the minimum value for an hour payment for graduated students has been defined as nine euros (9€). Hence, the calculation will be performed:

$$Total_{\epsilon} = Value_{\epsilon/\text{hour}} * Hours \quad \text{Eq. 5.1}$$

$$Total_{\epsilon} = 9_{\epsilon/\text{hour}} * 900 \text{ hours}$$

$$Total_{\epsilon} = 8100 \text{ €}$$

6. Conclusions and Future Works

The main objective of this thesis was to demonstrate an experimental assessment of NOMA CAP waveforms for beyond 5G optical fronthaul applications. After the present project NOMA-CAP have been foreseen as a technique able to support fronthaul setups concerning the 5G and beyond paradigms in communications transport. NOMA CAP has been measured in the proposed scenarios with an Intensity Modulation and Direct Detection systems. In general, the transmitter was performed by two cases: on one side, Direct Modulator Laser (DML) with a RayCan™ 1550nm Vertical Cavity Surface Emitting Laser (VCSEL). On the other hand, a second transmitter, with External Modulator Laser (EML), based on a Tunable Laser source (TLS) and modulated by a Mach-Zehnder Modulator (MZM). In addition, the receivers have been proposed to analyze the pros and cons between a PIN-based and Avalanche Photo Diode (APD).

The first stage has been defined as the calibration of the Tx/Rx system. Firstly, concerning the generation signal process in DTx block, the parameters of the CAP filter used have been optimized experimentally, for instance: the filter length, named as N_{sym} variable, was established in a value of 20 symbols. The filter length is a critical parameter to both performance and complexity of the system. The lower the length of the filter, the simpler [28]. Secondly, regarding the DRx process, where a decision feedback equalizer (DFE) has been designed, the function of DFE has been equalizing the signals correcting the eventual phase rotation in their constellations. DFE has been defined with a fractionally spaced forward filter. There are two parameters to be considered such as: Number of weights in the forward filter and the feedback filter, for the simulations named $numFBT$ & $numFFT$, respectively. After the experiments, and regarding the trade-off between complication of the signal processing and the cost to implement it. The values considered were $numFBT = 20$, and $numFFT = 30$.

Second stage for the present project is the data binary regime, once the calibration has been completed and the optimal and cost-effective values have been defined. The analysis consisted in the evaluation of the impact of the bandCAPs number and the value of the width assigned to each bandCAP up to complete the total bandwidth BW of 4 GHz (maximum bandwidth for VCSEL). The results have demonstrated that with the configurations: a) seven (7) bandCAPs with a width of 500 MHz each, a total data rate of 14 Gbps was achieved; and b) three (3) bandCAPs with a width of 1 GHz each, a total data rate equal to 12 Gbps was reached. The power spectrum shape was also crucial in the analysis of the fourth bandCAP (1GHz) and eight bandCAP (0.5 GHz). It was clear that due to the effect of aliasing, those bandCAPs were corrupted, and, fourth bandCAP (1GHz) and eight bandCAP (0.5 GHz) could not fit inside the 4GHz available BW due to the required small band guard between bandCAPs, as it was explained in chapter 4.

In order to increase the sensitivity results obtained with a linear PIN detector and, as a linear APD was not available, a practical linear EDFA-Filter-PIN emulator of a linear APD was implemented. A previous comparison between a non-linear APD, available, and the EDFA-Filter-PIN was done for OOK signal to check the adequacy of the emulator. As non-linear APD, a commercial small form pluggable transceiver (SFP) including an APD detector (Edge 1550 1.25G) with a sensitivity value of -28 dBm was used. For the same OOK signal, the resultant value of sensitivity with the EDFA-Filter-PIN differs in 0.1 to 0.5 dB for BER between 10^{-5} to 10^{-2} . Therefore, the proposed block (EDFA-Filter-PIN) was correctly approached as an APD for the following experiments.

A third stage corresponds to the implementation of all scenarios proposed, regarding uplink and downlink transmitters, and the alternatives for receivers based on PIN and the APD with its practical approach described before. Moreover, when the receiver was based on APD, as expected, the sensitivity has gotten an important gain around 11dB (compared with PIN).

Regarding to the uplink transmitter, based on VCSEL, the chirp effect is clear based on the separation between bandCAPs. Firstly, for the PIN receiver: the difference from the first strong NOMA bandCAP user and the last strong NOMA bandCAP user is around 4 dB, for a transmission link of 50 km sensitivity is around -14dBm. Secondly, in APD receiver: the bandCAP separation is considerable ($> 6\text{dBm}$) over 50 km SSMF and a penalty in sensitivity of 4 dB (-26dBm in B2B) was obtained. The VCSEL chirp effect is major limitation in this configuration, an alternative could be to find another laser-based transmitter, which will be capable to avoid these limitations in futures approaches.

In addition, for the downlink transmitter. The MZM and TLS scheme were also implemented to both receivers. Concerning the PIN based receiver, the results were the most stable (around -13dBm sensitivity), over 50 km of SSMF. As the summary has shown the average approximation works perfectly and the drawback is the low value of sensitivity. The separation between bandCAPs had no exceeded 2 dB. Meanwhile, when the downlink transmitter was combined with APD, the highest value of sensitivity was reached for the first bandCAP strong NOMA user (-28dBm). Nonetheless, the bandCAP separation increased considerably over 25/50 km of SSMF (in total 6 dB).

Finally, the average approximation is computed. In a) the PIN based receptor: for the MZM signals the impact of including 50 km of SSMF did not affect the sensitivity value, there was not penalty at all (-13dBm). Respecting to the VCSEL, it is reflected a small penalty around 2 dB (-12.5dBm in B2B) in terms of sensitivity over the 50 km fiber cable. In b) with APD: both transmitters achieved successfully the BER limitation (2.2×10^{-3}). However, the consideration to foresee one solution from another will take place in terms of the penalty in sensitivity. For MZM solution the penalty is less than 1dB (-25dBm in B2B) but in the MZM setup is up to 7 dB (-24.9dBm in B2B). Even though the considerable advantage in sensitivity for back to back scheme, while the distance has increased this became into a drawback.

Based on the obtained results, and once the strengths and drawbacks for different schemes had been evaluated, it is recommended to continue this research by:

- The current project has considered for the receivers' schemes only direct detection, due to the simplicity of the signal processing algorithms implemented and the use of intensity modulation. Hence, a good analysis will consist in the implementation of a higher sensitivity detection (coherent detection) out of the scope for this thesis. In this case, more robust Costas Loop algorithm can be studied as the signal in this case will be not in baseband.
- Additionally, for the coherent detection scheme the presence of the local oscillator is a requirement, here based on the performance of VCSELs, they can be considered as an alternative. During the last part of this thesis a few tests of it were performed, but the results were not included.
- Lastly, an Avalanche Photo Diode (APD) will clarify more in details the results obtained in the present thesis. The practical approach was useful to

get some ideas. It will be interesting an additional comparison with a more robust receiver.

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Appendices

Appendix A: Temperature Controller Thorlabs TED200C

Front Panel:

Figure A- 1. Front panel Thorlabs TED200C [32]

N.	Name	Function
F1	-	5-digit LED display
F2	LED "°C"	Temperature display in C
F3	LED "kΩ"	Resistance display in k
F4	LED "A"	Current display in A
F5	LED "OTP"	Over temperature protection is active
F6	LED "OPEN"	TEC element is not connected or too high resistance
F7	LED "NO SENSOR"	Temperature sensor is wrong or not connected
F8	LED "TEC ON"	TEC output is switched on
F9	Key "TEC ON"	On / Off switch for the TEC output
F10	-	Knob for adjusting the set temperature / resistance
F11	-	Line switch (ON / OFF)
F12	LIM I	Potentiometer for setting the TEC current limit
F13	LED "TACT"	Display shows the actual temperature / resistance
F14	LED "ITEC"	Display shows the TEC current
F15	LED "TSET"	Display shows the set temperature / resistance
F16	LED "ILIM"	Display shows the current limit
F17	Key "DOWN"	Select the parameter to be displayed
F18	Key "UP"	Select the parameter to be displayed
F19	LED "AD590"	Selected sensor is AD 590, AD 592, LM 135 or LM 335
F20	LED "TH 200kΩ"	Selected sensor is thermistor in the 200 kΩ range
F21	LED "TH 20kΩ"	Selected sensor is thermistor in the 20 kΩ range
F22	P	Potentiometer for setting P- (gain) share of control loop
F23	I	Potentiometer for setting I- (integral) share of control loop
F24	D	Potentiometer for setting D- (derivative) share of control loop
F25	Key "SENSOR"	Select sensor / disable I-share (press for more than 1 sec.)

Table 11. Front Panel Description Thorlabs TED200C [32]

Rear Panel:

Figure A- 2 Front panel Thorlabs TED200C [32]

N.	Description
R1	Analog temperature control input "TUNE IN", -10 ... +10 V
R2	Analog temperature control output "CTL OUT", -10 ... +10 V
R3	Fan
R4	4 mm banana jack for chassis ground
R5	15-pin D-SUB jack for the TEC element and the temperature sensor "TE OUTPUT"
R6	Serial number of the unit
R7	Indicator / switch for line voltage (included in fuse holder)
R8	Mains connector and fuse holder

Table 12. Rear Panel Description Thorlabs TED200C [32]

PIN Out for temperature sensors

Figure A- 3 Pin Out Connector Thorlabs TED200C [32]

Pin #	Connection
5	TEC (+)
6	TEC (+)
7	TEC (+)
13	TEC (-)
14	TEC (-)
15	TEC (-)
1	Status LED (+) for TEC ON/OFF indication
4	Thermistor (+)
3	Thermistor (-), ground
10	Transducer AD 590/592 (-), LM135/335 (+)
11	Transducer AD 590/592 (+), LM135/335 (+)
2	N.C.
9	N.C.
12	N.C.
8	AGND LM135/335 (-), Status LED (-)

Table 13. Pin Out Description for connector Thorlabs TED200C [32]

Appendix B: Laser Diode Controller Thorlabs LDC200C

Frontal Panel

Figure B- 1 Front panel Thorlabs LDC200C [33]

N.	Name	Function
F1	-	5-digit LED display
F2	LED "mA"	Current display in mA
F3	LED "mW"	Power display in mW
F4	LED "OPEN"	No laser diode connected, or Interlock open
F5	LED "LIMIT"	Adjusted current limit reached
F6	LED "OTP"	Overtemperature protection is active
F7	LED "LASER ON"	Laser current is switched on
F8	Key "LASER ON"	On / Off switch for the laser current
F9	-	Knob for adjusting the current or power set value
F10	-	Line switch (ON / OFF)
F11	LIM I	Potentiometer for setting the current limit
F12	CAL	Potentiometer for calibrating the power display
F13	LED "ILD"	Display shows the laser current
F14	LED "PLD"	Display shows the optical power
F15	LED "IPD"	Display shows the photodiode current
F16	LED "ILIM"	Display shows the current limit
F17	Key "DOWN"	Select the parameter to be displayed
F18	Key "UP"	Select the parameter to be displayed
F19	LED "AG"	Selected laser polarity: anode grounded
F20	LED "CG"	Selected laser polarity: cathode grounded
F21	LED "P"	Constant power mode
F22	LED "I"	Constant current mode
F23	Key "LD POL"	Select laser polarity: anode grounded or cathode grounded
F24	Key "CONST"	Select constant current mode or constant power mode
F25	PD RANGE	Potentiometer for setting the photodiode current range

Table 14 Front panel description Thorlabs LDC200C [33]

Rear Panel

Figure B- 2 Rear panel Thorlabs LDC200C [33]

N.	Description
R1	TTL input "LD REM", 0 ... +5 V
R2	Modulation input / analog control input "MOD IN", -10V ... +10 V
R3	Analog monitoring output "CTL OUT", 0 ... ±10V
R4	Fan
R5	4 mm banana jack for chassis ground
R6	Connector "LD OUT" for laser diode, photodiode, interlock, status LED
R7	Serial number of the unit
R8	Indicator / switch for line voltage (included in fuse holder)
R9	Mains connector and fuse holder

Table 15 Rear panel description Thorlabs LDC200C [33]

Pin Out

Figure B- 3. Pin assignment LD OUT jack Thorlabs LDC200C [33]

Pin #	Connection
1	Interlock and status LASER ON / OFF
5	Ground for pin 1
7	Laser diode cathode (in case of polarity "anode grounded" - AG)
8	Laser diode anode (in case of polarity "cathode grounded" - CG)
3	Laser diode ground
2	Photodiode cathode
4	Photodiode anode

Table 16 Pin assignment LD OUT jack Thorlabs LDC200C [33]

Appendix C: Arbitrary Wave Generator TEKTRONIX (AWG 70002A)

Front Panel

Figure C- 1 Front Panel AWG Tektronix 70002A [34]

Connector	Description
CH1 and CH2 (Analog outputs) AWG70002A: two channels	These connectors supply analog signals. The channel LEDs light to indicate when the channel is enabled and the output is electrically connected. The LED color matches the user defined waveform color. The output connector utilizes the Planar Crown® Universal Connector System providing you the ability to easily replace a damaged connector. You also have the ability to use a variety of different types of connectors. The AWG70000A series products ship with SMA type adapters installed.
Marker outputs AWG70002A: CH1 and CH2 Markers	These SMA type connectors supply marker signals, two markers for each channel. The marker LEDs light when the corresponding channel is enabled and the outputs are electrically connected. Marker LEDs are always white.
USB	Two USB connectors. When OFF is lighted, the front USB connectors have been disabled from the File & Utilities > Preferences menu.
Removable hard disk drive (HDD)	The HDD contains the operating system, product software and all user data. By removing the HDD, user information such as setup files and waveform data is removed from the instrument.
Chassis ground	Banana type ground connection.

Table 17 Front Panel description AWG Tektronix 70002A [34]

Rear Panel

Figure C- 2 Rear Panel AWG Tektronix 70002A [34]

Connector	Description
Flag Outputs	SMB connectors for future capability
eSATA	eSATA port to connect external SATA devices to the instrument.
Sync Clock Out	SMA type connector to provide a synchronization signal to external devices
LAN	RJ-45 connector to connect the instrument to a network.
VGA	VGA video port to connect an external monitor to view a larger copy of the instrument display (duplicate) or to extend the desktop display. To connect a DVI monitor to the VGA connector, use a DVI-to-VGA adapter.
USB Host	Four USB Host connectors (type A) to connect devices such as a mouse, keyboard, or other USB devices. Tektronix does not provide support or device drivers for USB devices other than the supplied mouse and keyboard
USB Device	USB Device connector (type B) interfaces with the TEK-USB-488 GPIB to USB adapter and provides connectivity with GPIB based control systems.
Pattern Jump In	15-pin DSUB connector to provide a pattern jump event for Sequencing (Option 03).
Sync to Hub	Connector for future capability
Clock In	SMA type connector to provide an external clock signal.
Clock Out	SMA type connector to provide a high speed clock that is related to the sample rate.
Reference In	SMA type input connector to provide a reference timing signal (variable or fixed).
10MHz Reference Out	SMA type output connector to provide a 10 MHz reference timing signal.
Trigger Inputs A and B	SMA type input connectors for external trigger signals.
Power	Power cord input.

Table 18 Rear Panel description AWG Tektronix 70002A [34]

Interface and Screen

Figure C- 3 Screen functionalities AWG Tektronix 70002A [34]

N.	Screen element	Description
1	Play/Stop button	Starts and stops playing the waveform. The Play button icon changes to indicate the play status of the waveform. When a waveform is playing, it is only present at the output connectors if the following conditions are met. The channel is enabled. The All Outputs Off is not active (outputs are connected)
2	Workspace tabs	The workspace tabs provide access to all of the instrument functions. Home returns the workspace area to the channel plot display. Settings displays the setup controls for channel, clock, and triggers. File & Utilities displays controls for preferences, system information, help and support.
3	Channel enable	Enables the channel output. Internally connects the channel and marker output connectors to the instrument. The All Outputs Off feature overrides the channel enable control.
4	Mode selection	Switches the instrument mode. Mode selection is available from the Home tab in both the AWG mode and the Functions mode.
5	Workspace	The workspace area shows the contents of the selected tab (such as: Home, Settings).
6	All outputs off	The All Outputs Off button provides a quick disconnect of the analog outputs and marker outputs, whether those outputs are enabled or not. The outputs are electrically disconnected. When the All Outputs Off is disabled, the channel and marker outputs return to their defined state.
7	Trigger controls	The Trigger controls provide access to the trigger settings. Use Run mode to set the trigger type. Use Trigger source for external triggering. Select Coupled to couple the trigger settings for two-channel instruments
8	Status bar	The status bar displays various user messages and status indicators.
9	Waveforms and sequences	Contains all waveforms and sequences available for playout. Touch and hold (or right-mouse click) a waveform or sequence name to display menu selections to manage the lists.
10	Tools pane	Tools are used to: Display the instrument help. Restore the display to the default layout. Restore the default setup. Restore the most recently used setup. Open a saved setup. Save the current setup

Table 19 Functions AWG Tektronix 70002A [34]

Appendix D: Vertical Cavity Surface Emitting Laser VCSEL RayCan™ RC33xxxi-FFAmt 1550nm

Figure D- 1 RayCan™ VCSEL Pin Out / Dimensions [38]

Pin #	Function
1	TEC cathode (-) for cool device
2	Thermistor
3	NA
4	VCSEL cathode/mpD anode
5	TEC anode (+) for cool device
6	Thermistor
7	mPD cathode
8	VCSEL anode

Table 20. RayCan™ VCSEL Pin Out Description [38]

Appendix E: TEKTRONIX Mixed Signal Oscilloscope (MSO 70804C)

Front Panel

Figure E- 1. Front Panel MSO Tektronix 70804C [35]

N.	Description
1	DVD/CD-RW drive
2	Front panel controls
3	USB port
4	Ground terminal
5	Recovered data output
6	Recovered clock output
7	Probe compensation output
8	Probe calibration output
9	Channel 1-4 input
10	Auxiliary Trigger input

Table 21 Front Panel Description MSO Tektronix 70804C [35]

Rear Panel

Figure E- 2 Rear Panel MSO Tektronix 70804C [35]

N.	Description
1	Removable hard disk drive
2	PS-2connector for mouse
3	USB host ports
4	Passive eSATA Port
5	RJ-45 LAN connector to connect to network
6	TekLink connector
7	GPIB port to connect to controller
8	Line Out connector for speaker
9	Mic connector for microphone
10	DVI-I Video port
11	COM1 and COM2 serial ports
12	PS-2 connector for keyboard
13	Auxiliary output
14	Reference output
15	External reference input

Table 22 Rear Panel MSO description Tektronix 70804C [35]

Appendix F: EXFO Optical Spectrum Analyzer FTB-2

Figure F- 1 EXFO Optical Spectrum Analyzer FTB-2 [35]

N.	Description
1	Power on/off
2	Switch application
3	Keyboard/screen capture
4	Battery LED
5	Stylus
6	Display port
7	Headset jack
8	Speaker
9	USB 2.0 port
10	GigE port
11	USB 3.0 port
12	Power meter and VFL
13	Two slots to house modules
14	Module screws
15	AC adapter
16	Kensington security lock slot
17	Back stand
18	Battery compartment

Table 23 EXFO Optical Spectrum Analyzer FTB-2 Description [35]

Appendix G: EXFO Variable Optical Attenuator FVA 600

Figure G- 1 EXFO Variable Optical Attenuator FVA 600 [36]

N.	Description
1	Backlit keyboard and screen
2	In/out universal optical interfaces
3	AC adapter
4	USB port for remote applications

Table 24 EXFO Variable Optical Attenuator FVA 600 Description [36]

Glossary

APD	Avalanche photo diode
AWG	Arbitrary waveform generator
BER	Bit error rate
b/s/Hz	Bits per second per Hertz
BL	Bit rate-distance product
BBU	Base band unit
BPF	Band pass filter
CAP	Carrierless amplitude phase modulation
CO	Central office
CPRI	Common public radio interface
CW	Continuous wave
dB	Decibels
DFB	Distributed-Feedback lasers
DFT	Discrete Fourier transform
DML	Direct Modulated Laser
DPSK	Differential phase-shift keying
DSO	Digital Sampling Oscilloscope
EDFA	Erbium-doped fiber amplifiers
EML	External Modulated Laser
GaAs	Gallium arsenide
GaAsP	Gallium arsenide phosphide
Gbps	Giga bit per second
GaInAs	Gallium indium arsenide
GHz	Giga Hertz
GSa/s	Giga samples per second
InAs	Indium arsenide
InGaAsP	Indium gallium arsenide phosphide
InP	Indium phosphide
IoT	Internet of things
Km	Kilometers
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light emitting diode
LIV	Light-current-voltage

mA	Milli ampere
Mbps	Mega bit per second
MCM	Multi core fiber
mW	Milliwatts
MZM	Mach-Zehnder modulator
Nm	Nanometer
NOMA	Non-Orthogonal Multi Access
OFDM	Orthogonal frequency division multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
OOK	On-off keying
OPM	Optical power meter
OSA	Optical spectrum analyzer
PRBS	pseudo random bit sequence
QAM	Quadrature amplitude modulation
SDM	Space division multiplexing
SSMF	Standard Single mode fiber
Tb/s	Tera bits per second
TEC	Thermoelectric cooler
THz	Tera Hertz
TIA	Trans impedance amplifier
TLS	Tunable laser source
uDWDM	Ultra-dense wavelength division multiplexing
μm	Micrometer
VCSEL	Vertical-cavity surface-emitting laser
VOA	variable optical attenuator
WDM	Wavelength division multiplexing