Title: A Transparent Unidirectional Wave Division Multiplexing Passive Optical Network Architecture

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Publication Date: 2012-06-21

Item record: http://hdl.handle.net/10379/3026

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A Transparent Unidirectional Wave Division Multiplexing Passive Optical Network Architecture

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The thesis is submitted to the National University of Ireland Galway for the
Degree of PhD
in the College of Engineering and Informatics

December 2011

Discipline of Information Technology
National University of Ireland Galway
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Abstract

Fiber optic networks are becoming increasingly important for new communication infrastructures. Within the optical networking domain there are many different standards and technologies. The current most advanced technology is Wave Division Multiplexing (WDM) where multiple channels are simultaneously combined onto a single strand of fiber.

WDM have been around since the early 1980s, but were only implemented into large Wide Area Networks (WANs) and Metropolitan Area Networks (MANs). One important part of the communication infrastructure is the access network or “last mile” that connects a WAN or MAN backbone to individual end-users. Until recently the access network was catered for mainly by copper communications technologies. Implementation of WDM into the access network requires cost effective designs and equipment that is capable of transmitting many transparent or colourless wavelengths. The main difficulties with implementing WDM in the access network are reducing the cost of the user's transceiver while providing an efficient network. In this thesis both aspects, i.e. a suitable WDM access network as well as a cost effective solution for the transceiver, are examined and demonstrated. The analysis of the network design and the transceiver demonstrates their feasibility to be implemented as a cost effective solution for WDM networking in the access network.

Due to the vast data transfer rates WDM can provide, an extension to the proposed design in the form of a bandwidth on demand, infrastructure and software was developed and tested.
Furthermore an alternative MAN and access network design was investigated that vastly reduces the amount of fiber needed compared with the above and other currently deployed network architectures. Analysing the results demonstrate a robust and cost efficient WDM network concept.
Acknowledgements

Dr Michael Schukat has been indispensable as my supervisor, his guidance, insightful criticisms, and patient encouragement aided in the research and writing of this thesis. I would like to thank my fellow pre and post PhD researchers that helped the years go by enjoyably. I would also like to thank all of the staff of the IT department.

Dedication

Throughout my PhD there have being some extreme highs and severe lows. It is my privilege to dedicate this PhD to my family, who throughout my life have always supported my decisions. Being self funded during most of the research, it was always good to know that they would be there financially and morally in case I ever needed it. I would especially like to dedicate this thesis to my father who died a year before he got to see me finish. I know he would have being proud of me. I would like to thank my wonderful girlfriend who put up with my college lifestyle and supported me throughout the PhD. I love you all and thanks for everything.
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>3</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>3</td>
</tr>
<tr>
<td>FIGURES</td>
<td>8</td>
</tr>
<tr>
<td>GLOSSARY</td>
<td>11</td>
</tr>
<tr>
<td>ABBREVIATIONS</td>
<td>21</td>
</tr>
<tr>
<td>CHAPTER 1</td>
<td>29</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>29</td>
</tr>
<tr>
<td>1.1 OPEN RESEARCH QUESTIONS</td>
<td>31</td>
</tr>
<tr>
<td>1.2 THESIS GOALS AND HYPOTHESIS</td>
<td>33</td>
</tr>
<tr>
<td>1.3 RESEARCH APPROACH</td>
<td>34</td>
</tr>
<tr>
<td>1.4 THESIS STRUCTURE</td>
<td>38</td>
</tr>
<tr>
<td>CHAPTER 2</td>
<td>39</td>
</tr>
<tr>
<td>MOTIVATION</td>
<td>39</td>
</tr>
<tr>
<td>2.1 A BRIEF HISTORY OF OPTICS</td>
<td>39</td>
</tr>
<tr>
<td>2.2 DEMAND FOR BANDWIDTH</td>
<td>40</td>
</tr>
<tr>
<td>2.3 HIGH BANDWIDTH SERVICES</td>
<td>41</td>
</tr>
<tr>
<td>2.3.1 Cloud Computing</td>
<td>42</td>
</tr>
<tr>
<td>2.3.2 TV Services</td>
<td>43</td>
</tr>
<tr>
<td>2.3.3 E-Health</td>
<td>44</td>
</tr>
<tr>
<td>2.3.4 E-Government</td>
<td>45</td>
</tr>
<tr>
<td>2.3.5 Tele-Education</td>
<td>45</td>
</tr>
<tr>
<td>2.4 CONCLUSION</td>
<td>46</td>
</tr>
<tr>
<td>CHAPTER 3</td>
<td>47</td>
</tr>
<tr>
<td>RELATED RESEARCH</td>
<td>47</td>
</tr>
<tr>
<td>3.1. WDM NETWORK DEPLOYMENT IN SOUTH KOREA</td>
<td>48</td>
</tr>
<tr>
<td>3.1.1 System Specification</td>
<td>49</td>
</tr>
<tr>
<td>3.1.2 Field Trial Testing</td>
<td>49</td>
</tr>
<tr>
<td>3.1.3 Network Design Research</td>
<td>50</td>
</tr>
<tr>
<td>3.1.4 ONU Research</td>
<td>51</td>
</tr>
<tr>
<td>3.2. TRANSCEIVER RESEARCH FOR WDM-PON</td>
<td>51</td>
</tr>
<tr>
<td>3.2.1 Tunable Laser Source</td>
<td>52</td>
</tr>
</tbody>
</table>
3.2.2. Sliced Broadband Source ........................................................................................................... 52
3.2.3. Reflective Sources .......................................................................................................................... 53
  3.2.3.1. Reflective Semiconductor Optical Amplifier (RSOA) .......................................................... 53
  3.2.3.2. Reflective Electro Absorption Modulator (R-EAM) ............................................................. 54
  3.2.3.3. Injection Locked Fabry-Perot Laser Diode (FPLD) .............................................................. 54
3.3. HYBRID WDM/TDM PON NETWORKS ......................................................................................... 55
  3.3.1. Stanford University Approach to WDM and TDM-PON Integration ........................................ 55
  3.3.2. WDM Access Network .............................................................................................................. 56
  3.3.3. SUCCESS-HPON Architecture ................................................................................................. 57
3.4. RAYLEIGH BACKSCATTERING (RB) ............................................................................................... 59
  3.4.1. Rayleigh Backscattering Types ................................................................................................. 60
  3.4.2. Reduction Technique of the Relative Noise caused by RB ....................................................... 62
    3.4.2.1. Optical Bandwidth Separation .......................................................................................... 62
    3.4.2.2. ONU Gain Methods ......................................................................................................... 62
3.5. DYNAMIC BANDWIDTH ALLOCATION ......................................................................................... 63
  3.5.1. Optical Burst Switching (OBS) and Dynamic Bandwidth Allocation (DBA) ................... 64
  3.5.2. Priority Queue Management in OBS ....................................................................................... 65
3.6. RELATED TECHNOLOGIES AND ARCHITECTURES ................................................................. 66
  3.6.1. Fiber Optic Cables .................................................................................................................... 67
  3.6.2. Laser Sources ............................................................................................................................ 70
    3.6.2.1. Distributed Feedback Laser (DFB) ....................................................................................... 70
  3.6.3. Receivers .................................................................................................................................. 71
  3.6.4. Modulators ............................................................................................................................... 72
    3.6.4.1. Interferometers ................................................................................................................... 72
    3.6.4.2. Electro-Absorption Modulators (EAM) ............................................................................. 72
  3.6.5. Optical Modulation Methods .................................................................................................. 72
    3.6.5.1. Amplitude Modulation ..................................................................................................... 73
  3.6.6. Optical Architectures .............................................................................................................. 74
    3.6.6.1. Access Networks ............................................................................................................. 74
    3.6.6.2. Passive Optical Networks (PONs) ....................................................................................... 74
3.7. RELATED RESEARCH CONCLUSION ......................................................................................... 76

CHAPTER 4 ............................................................................................................................................ 78
RESEARCH METHODOLOGY ............................................................................................................. 78
  4.1 STATE OF THE ART ......................................................................................................................... 78
  4.2 RESEARCH APPROACH ................................................................................................................ 79
  4.3 INITIAL SIMULATION ................................................................................................................... 79
  4.4 HARDWARE TEST BED ................................................................................................................ 80
  4.5 FULL SCALE WDM/TDM NETWORK DESIGN ........................................................................... 80

CHAPTER 5 ........................................................................................................................................... 82
DESIGN AND EVOLUTION OF PROPOSED WDM-PON ARCHITECTURE ......................................... 82
  5.1 NETWORK DESCRIPTION .............................................................................................................. 83
  5.2 TESTING METHODS ....................................................................................................................... 85
    5.2.1. BER Testing (BERT) ......................................................................................................... 86
  5.3 ANALYSIS OF NRZ AND RZ ENCODING ON A TRANSPARENT ONU .................................... 87
5.3.1. Wavelength and Spectrum Analysis ................................................................. 91
5.3.2. Eye Diagram ....................................................................................................... 92
5.3.3. Quality Factor (Q-Factor) .................................................................................. 96

5.4. CONCLUSION ........................................................................................................ 97

CHAPTER 6 .................................................................................................................. 99

OPTICAL NETWORK UNIT AND BANDWIDTH ON DEMAND .......................................... 99

6.1. COMPONENT ANALYSIS .......................................................................................... 99
6.1.1. The XFP Module .................................................................................................. 101
6.1.2. The XFP Driver .................................................................................................... 101
6.1.3. The XFP Host Board (HFRD-18.0) ...................................................................... 102
6.1.4. The XFP Network Interface Card (NIC) ............................................................. 103
6.1.5. The Host PC ........................................................................................................ 104
6.1.6. The Tunable Laser .............................................................................................. 104
6.1.7. The Modulator and Modulator Controller ........................................................ 105

6.2. COMPONENT TESTING .......................................................................................... 107
6.2.1. Modification to the XFP Module ........................................................................ 108
6.2.2. Agilent 10 GHz BER Hardware Testing ............................................................. 111

6.3. BANDWIDTH ON DEMAND (BoD) ........................................................................ 113
6.3.1. The Network Management Software ................................................................. 123
6.3.1.1. The Central Office .......................................................................................... 125
6.3.1.2. The Certificate Authority (CA) ....................................................................... 128
6.3.1.3. The NTP Server ............................................................................................. 129
6.3.1.4. The Service Provider ...................................................................................... 129
6.3.1.5. The Administrator ........................................................................................ 130
6.3.1.6. The ONU ....................................................................................................... 130
6.3.2. Software System Integration ............................................................................... 132

6.4. CONCLUSION ........................................................................................................ 133

CHAPTER 7 .................................................................................................................. 135

DUAL RING MAN-ACCESS WDM/TDM NETWORK ............................................................ 135

7.1 MAN NETWORK ARCHITECTURE .......................................................................... 136
7.2. ACCESS NETWORK ARCHITECTURE .................................................................. 138
7.3 OPTICAL NETWORK UNIT (ONU) .......................................................................... 142
7.4 SIMULATION SETUP FOR THE WDM/TDM/NETWORK ......................................... 143
7.4.1 All Optical Bridged MAN and Access Network ................................................... 144
7.4.2 MAN and Access Central Office ......................................................................... 145
7.4.3 Optical Network Unit TDM and Fault Tolerance Design ...................................... 147

7.5 SOFTWARE SIMULATION RESULTS ..................................................................... 149
7.5.1 Optical Time Domain Simulation Results ............................................................. 149
7.5.2 Eye Diagram Analysis ......................................................................................... 153
7.5.3 Optical Spectrum Analyser (OSA) ....................................................................... 155

7.6 OPTISYSTEM COMMERCIAL SYSTEM RESULTS ................................................. 159
7.6.1 OptiSystems 10 GB/s SMF Return to Zero (RZ) system ...................................... 160
7.6.2 OptiSystems Migrating to 10 GB/s Dispersion Compensation MAN Ring Network 162

7.7 CONCLUSION ........................................................................................................ 163

CHAPTER 8 .................................................................................................................. 165

6
CONCLUSIONS AND FUTURE WORK ................................................................. 165

8.1 RESEARCH HYPOTHESIS CONTRIBUTIONS ........................................... 166
8.2 FUTURE WORK ....................................................................................... 168
  8.2.1 Network Testing within an Optics Research Lab .............................. 168
  8.2.2 All Optical Packet Switching (OPS) .................................................... 168

PUBLICATIONS AND PATENTS ARISING FROM THIS THESIS ............ 169

REFERENCES ............................................................................................. 170

APPENDIX .................................................................................................... 175
  A. SECOND ACCESS NETWORK RESULTS ............................................. 175
Figures

**Figure 1:** Distance versus data rate for various communications technologies .......... 31
**Figure 2:** PON tree architecture ......................................................................................... 32
**Figure 3:** Q and BER correlation over time ........................................................................ 37
**Figure 4:** Application bandwidth requirements [20] .......................................................... 41
**Figure 5:** Cloud computing .................................................................................................. 42
**Figure 6:** Structure of the wavelength-tuneable external cavity laser (ECL) [36] .......... 51
**Figure 7:** AWG used to separate specific wavelengths ......................................................... 53
**Figure 8:** SUCCESS-HPON: a) overall architecture; b) OLT block diagram; c) ONU setup [44] .............................................................................................................................. 58
**Figure 9:** Crosstalk in an RSOA: a) CW input; b) the interferer; c) Total signal (A+B); d) PRBS output; e) RSOA output (C+D) [48] ................................................................. 60
**Figure 10:** Two types of optical back reflections [7] .............................................................. 61
**Figure 11:** Impact of the different reflections with ONU gain [7] ......................................... 61
**Figure 12:** Metro-access tree architecture [52] ..................................................................... 64
**Figure 13:** Optical bands and associated loss [53] .............................................................. 66
**Figure 14:** Different propagation modes of MMF and SMF [55] .......................................... 67
**Figure 15:** Causes of signal degradation .............................................................................. 68
**Figure 16:** The typical DFB laser output [59] ....................................................................... 71
**Figure 17:** Constructive and destructive interference ......................................................... 72
**Figure 18:** NRZ encoding [60] ............................................................................................. 73
**Figure 19:** RZ encoding [60] ............................................................................................... 73
**Figure 20:** PON tree architecture ......................................................................................... 75
**Figure 21:** WDM network design ......................................................................................... 83
**Figure 22:** Completed software simulation of network setup ............................................... 86
**Figure 23:** NRZ to RZ conversion in the electrical domain using high speed AND gate .... 88
**Figure 24:** NRZ analysis of the network .............................................................................. 89
**Figure 25:** RZ analysis of the network .................................................................................. 89
**Figure 26:** NRZ’s BER over distance .................................................................................... 90
**Figure 27:** RZ’s BER over distance ...................................................................................... 91
**Figure 28:** WDM analyser for start of network ................................................................. 91
**Figure 29:** WDM analyser for end of network ...................................................................... 92
**Figure 30:** Optical spectrum analyser .................................................................................. 92
**Figure 31:** Eye diagram analysis .......................................................................................... 93
**Figure 32:** Wide open eye diagram ..................................................................................... 95
**Figure 33:** Poor eye diagram ............................................................................................... 95
**Figure 34:** Relationship between BER versus Q factor .................................................... 96
**Figure 35:** Test network layout ......................................................................................... 100
**Figure 36:** A XFP module .................................................................................................... 101
**Figure 37:** MAX3941 typical application circuit [79] .......................................................... 102
FIGURE 84: RECEIVED SIGNAL AT THE FIRST ONU ................................................................. 153
FIGURE 85: EYE DIAGRAM OF THE FIRST ONU ................................................................. 154
FIGURE 86: FOURTH ONU .................................................................................................. 154
FIGURE 87: TDM EYE DIAGRAM ..................................................................................... 155
FIGURE 88: NO GAUSSIAN FILTERING ON 193.1 THZ .................................................... 156
FIGURE 89: GAUSSIAN FILTERING APPLIED TO 193.1 THZ .......................................... 157
FIGURE 90: MAN RING SPECTRUM 193.1 AND 193.6 THZ ........................................... 157
FIGURE 91: 193.1 THz IS DROPPED INTO THE ACCESS NETWORK .............................. 158
FIGURE 92: POWER ENTERING THE FIRST ONU ............................................................ 158
FIGURE 93: POWER LEAVING ONU ................................................................................. 159
FIGURE 94: OSA AFTER FIRST ACCESS NETWORK IS BACK ON THE MAN RING ........ 159
FIGURE 95: BER AND Q FACTOR FOR 10 GB/s RZ SYSTEM .......................................... 160
FIGURE 96: WITHOUT BESSEL FILTER .......................................................................... 161
FIGURE 97: OSA SPECTRUM WITH BESSEL FILTER ...................................................... 161
FIGURE 98: Q AND BER AT NODE 4 IN COMMERCIAL SYSTEM .................................. 162
FIGURE 99: TWO WAVELENGTHS WITH NOISE ........................................................... 163
FIGURE 100: POWER LEVELS ........................................................................................ 163
**Glossary**

**AC coupled**: Alternate Current, AC coupling only accepts AC signals.

**Access network**: An access network is that part of a telecommunications network which connects subscribers to their immediate service provider.

**Amplified spontaneous emission**: Amplified spontaneous emission (ASE) or super luminescence is light, produced by spontaneous emission that has been optically amplified by the process of stimulated emission in a gain medium.

**Amplitude modulators**: Amplitude modulation (AM) is a technique used in electronic communication, most commonly for transmitting information via a radio carrier wave.

**AND gate**: The AND gate is a basic digital logic gate that implements logical conjunction - it behaves according to the truth table.

**Array waveguide grating**: Arrayed waveguide gratings (AWG) are commonly used as optical (de)multiplexers in wavelength division multiplexed (WDM) systems.

**Asynchronous**: An asynchronous data transmission involves a mechanism called a queue. In general, a queue is a service which temporarily holds messages destined for a receiving task until that task is ready to process them. The sending task passes messages off to the queue and does not wait for a response from the receiver.

**Attenuation**: Attenuation is the rate at which the signal light decreases in intensity.

**Backbone**: Refers to the principal data routes between large, strategically interconnected networks and core routers in the Internet.

**Backward compatibility**: In the context of telecommunications and computing, a device or technology is said to be backward or downward compatible if it can work with input generated by an older device.

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1 Various definitions in this section have been taken from various (internet) resources and are not referenced.
**Bandwidth on demand:** Is a technique by which traffic bandwidth in a shared telecommunications medium can be allocated on demand and fairly between different users of that bandwidth.

**Bessel filter:** Is a type of linear filter with a maximally flat group delay (maximally linear phase response).

**Bias controller:** Bias Controller is to maintain an optical modulator's bias at the quadrature point. Along with amplitude control, bias control insures that the extinction ratio is maintained at its maximum level.

**Bidirectional:** Communication on a single strand of fiber in both upstream and downstream.

**Bit error rate:** Is the number of bit errors divided by the total number of transferred bits during a studied time interval.

**Bit:** Is the basic unit of information in computing and telecommunications; it is the amount of information stored by a digital device or other physical system that exists in one of two possible distinct states.

**Bragg grating:** A short segment of optical fiber that reflects particular wavelengths of light and transmits all others.

**Caching:** Is a mechanism for the temporary storage.

**Capital Expenditure:** Are expenditures creating future benefits.

**Central office:** Area where information is sent and received from.

**Chromatic dispersion:** Chromatic dispersion is a broadening of the input signal as it travels down the length of the fiber.

**Cladding:** Is one or more layers of material of lower refractive index, in intimate contact with a core material of higher refractive index.

**Class of service:** Is a way of managing traffic in a network by grouping similar types of traffic (for example, e-mail, streaming video, voice, large document file transfer) together and treating each type as a class with its own level of service priority.

**Clock-data recovery:** Some digital data streams, especially high-speed serial data streams are sent without an accompanying clock signal. The receiver generates a clock from an approximate frequency reference, and then phase-aligns to the transitions in the data stream with a phase-locked loop (PLL).
**Cloud computing:** This is delivery of computing as a service rather than a product. Where shared resources, software, and information are provided to computers and other devices as a measured service over a network.

**Coherent rayleigh noise:** See Rayleigh Backscattering type II.

**Colourless operation:** A device capable of transmitting on any wavelength.

**Continuous wave:** A Laser signal that has not been tuned.

**Course WDM:** A form of WDM that combines more than 2 wavelengths (Generally CWDM has a large spectrum gap between each wavelength).

**Cross-phase modulation:** Is a nonlinear optical effect where one wavelength of light can affect the phase of another wavelength of light through the optical Kerr effect.

**Crosstalk:** Is any phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel.

**Current mode logic:** Is a differential digital logic family intended to transmit data at speeds between 312.5 Mbit/s and 3.125 Gbit/s over a standard printed circuit board.

**Dense WDM:** Dense wavelength division multiplexing (DWDM) refers originally to optical signals multiplexed within the 1550 nm band.

**Digital subscriber line:** Is a family of technologies that provides digital data transmission over the wires of a local telephone network.

**Direct modulation:** Laser is directly modulated by the electrical voltage and current.

**Dispersion:** Is the phenomenon in which the phase velocity of a wave depends on its frequency, or alternatively when the group velocity depends on the frequency.

**Drive voltage:** The voltage required to run a device.

**Duty cycle:** The duty cycle of a machine or system is the time that it spends in an active state as a fraction of the total time under consideration.

**Dynamic bandwidth allocation:** see Bandwidth on demand.

**Electrical impedance:** Is the measure of the opposition that an electrical circuit presents to the passage of a current when a voltage is applied.

**Electro-absorption modulators:** Is a semiconductor device which can be used for modulating the intensity of a laser beam via an electric voltage.
**EPON:** Type of PON that uses the Ethernet protocol

**Erbium-doped fiber amplifier:** Its amplification window coincides with the third transmission window of silica-based optical fiber (C-L band).

**External modulation:** Modulation of output of a Light Source by an external device.

**Eye diagram:** Is an oscilloscope display in which a digital data signal from a receiver is repetitively sampled and applied to the vertical input, while the data rate is used to trigger the horizontal sweep.

**Fiber channel:** Is a gigabit-speed network technology primarily used for storage networking.

**Filters:** Are devices which selectively transmit light of different wavelengths, usually implemented as plane glass or plastic devices in the optical path which are either dyed in the mass or have interference coatings.

**Four wave mixing:** Is an inter-modulation phenomenon in optical systems, whereby interactions between 3 wavelengths produce a 4th wavelength in the signal. It is similar to the third-order intercept point in electrical systems. Four-wave mixing can be compared to the inter-modulation distortion in standard electrical systems.

**Full duplex:** A full-duplex, or sometimes double-duplex system, allows communication in both directions, and, unlike half-duplex, allows this to happen simultaneously.

**Gain:** Gain is a measure of the ability of a circuit (often an amplifier) to increase the power or amplitude of a signal from the input to the output.

**Gaussian filter:** Gaussian filters are designed to give no overshoot to a step function input while minimizing the rise and fall time.

**Gigabit:** The gigabit is a multiple of the unit bit for digital information or computer storage. 1 gigabit = 10³⁰bits = 1000000000bits.

**GPON:** The GPON (Gigabit Passive Optical Network) standard differs from other PON standards in that it achieves higher bandwidth and higher efficiency using larger, variable-length packets.

**Guard time:** A guard time is time left idle between separate TDM channels to counter any loss in signal.

**GUI:** Is a type of user interface that allows users to interact with electronic devices with images rather than text commands.
**Half duplex:** A half-duplex system provides communication in both directions, but only one direction at a time (not simultaneously).

**International telecommunication union:** Is the specialised agency of the United Nations which is responsible for information and communication technologies.

**Internet group management protocol:** Is a communications protocol used by hosts and adjacent routers on IP networks to establish multicast group memberships.

**Internet service provider:** Is a company that provides access to the Internet.

**L2/L3 switch:** Layer 2 and layer 3 are switch layers within the OSI model.

**Large Hadron collider:** Is the world's largest and highest-energy particle accelerator.

**LC receptacle:** Type of optical connector.

**Mach-Zehnder interferometer:** Is a device used to determine the relative phase shift between two collimated beams from a coherent light source.

**Maxim-IC:** Maxim Integrated Products is a publicly traded company that designs, manufactures, and sells analog and mixed-signal semiconductor products.

**Media access control:** Is a sub-layer of the data link layer specified in the seven-layer OSI model (layer 2). It provides addressing and channel access control mechanisms that make it possible for several terminals or network nodes to communicate within a multiple access network that incorporates a shared medium.

**Medical informatics:** Is a discipline at the intersection of information science, computer science, and health care.

**Megabit:** Is a multiple of the unit bit for digital information or computer storage. 1 megabit = $10^6$ bits = 1,000,000 bits = 1000 kilobits.

**Metropolitan area network:** Is a computer network that usually spans a city or a large campus.

**Modal dispersion:** Is a distortion mechanism occurring in multimode fibers and other waveguides, in which the signal is spread in time because the propagation velocity of the optical signal is not the same for all modes.

**Monochromatic source:** A monochromatic source is a source of light of a discrete wavelength.

**MPEG2:** Is a standard for the generic coding of moving pictures and associated audio information.
**MultiMode fiber:** Is a type of optical fiber mostly used for communication over short distances, such as within a building or on a campus.

**Multiplexer:** Is a device used in wavelength-division multiplexing systems for multiplexing and routing different channels of light into or out of a single mode fiber (SMF).

**Network time protocol:** Is a protocol and software implementation for synchronising the clocks of computer systems over packet-switched, variable-latency data networks.

**Non return to zero:** Is a binary code in which 1's are represented by one significant condition (usually a positive voltage) and 0's are represented by some other significant condition (usually a negative voltage), with no other neutral or rest condition.

**Non-linearities:** A nonlinear system is any problem where the variable(s) to be solved for cannot be written as a linear combination of independent components.

**Null/Peak:** Null is the lowest point of a wave and a peak is the highest.

**OECD:** Organisation for Economic Co-operation and Development is an international economic organisation of 34 countries.

**Operating expenditure:** Is an ongoing cost for running a product, business or system.

**Optical add/drop multiplexer:** Is a device used in wavelength-division multiplexing systems for multiplexing and routing different channels of light into or out of a single mode fiber (SMF).

**Optical amplifiers:** Is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal.

**Optical burst switching:** Is an optical networking technique that allows dynamic sub-wavelength switching of data.

**Optical network unit:** The ONU a device that transforms incoming optical signals into electronics at a customer's premises in order to provide telecommunications services over an optical fiber network.

**Optical packet switching:** This is a way of switching packets without the need to convert the signal into electrical data.

**Optical signal to noise ratio:** Is a measure used in science and engineering that compares the level of a desired signal to the level of background noise

**Optical spectrum analyser:** Measures the magnitude of an input signal versus frequency within the full frequency range of the instrument.
**Optical-electrical-optical:** This is when an optical signal is converted into an electrical signal and back into an optical signal.

**Optiwave OptiSystem:** Optical network simulation software.

**Oscilloscope:** Is a type of electronic test instrument that allows observation of constantly varying signal voltages.

**Packet-switched:** Is a digital networking communications method that groups all transmitted data – regardless of content, type, or structure – into suitably sized blocks, called packets.

**Passive optical networks:** Is a point-to-multipoint, fiber to the premises network architecture in which unpowered optical splitters are used to enable a single optical fiber to serve multiple premises.

**PCB board:** Is used to mechanically support and electrically connect electronic components using conductive pathways.

**Petabyte:** Is a unit of information equal to one quadrillion bytes, or 1000 terabytes.

**Phase modulation:** Is a form of modulation that represents information as variations in the instantaneous phase of a carrier wave.

**Photophone:** A device for the transmission of both articulated sounds and normal human conversations on a beam of light.

**Picture archiving communication system:** Is a medical imaging technology which provides economical storage of, and convenient access to, images from multiple modalities.

**Point to point:** Direct link between two points.

**Polarisation:** Is a property of certain types of waves that describes the orientation of their oscillations.

**Polling:** When ONUs are checked if they require bandwidth they are said to be polled.

**Power budget:** Is the allocation, within a system, of available transmitter power output to achieve the desired effective radiated power, among the various functions that need to be performed.

**Private key:** A private or secret key is an encryption/decryption key known only to the one or both parties that exchange secret messages.

**Protocol stack:** A set of network protocol layers that work together.
**Protocol transparency:** Is the ability of a protocol to transmit data over the network in a manner which is transparent (invisible) to those using the applications that are using the protocol.

**Protocol-independence:** is a family of multicast routing protocols for Internet Protocol (IP) networks that provide one-to-many and many-to-many distribution of data over a LAN, WAN or the internet.

**Protocols:** A protocol or interface is a common means for unrelated objects to communicate with each other.

**Pseudo Random Binary Sequence:** Is random in a sense that the value of an element is independent of the values of any of the other elements, similar to real random sequences.

**Public key:** a public key is a value provided by some designated authority as an encryption key that, combined with a private key derived from the public key, can be used to effectively encrypt messages and digital signatures.

**Q-factor:** is a dimensionless parameter that describes how under damped an oscillator or resonator is or equivalently, characterizes a resonator's bandwidth relative to its center frequency.

**QT framework:** is a cross-platform application framework that is widely used for developing application software with a graphical user interface.

**Quality of service:** Refers to several related aspects of telephony and computer networks that allow the transport of traffic with special requirements.

**Raw broadcast:** Refers to the un-compressed signal in a video stream.

**Rayleigh backscattering:** Is the reflection of waves, particles, or signals back to the direction they came from.

**Reconfigurable optical add drop multiplexer:** Is a device that is dynamically able to drop and add wavelengths.

**Reflection-I (type I):** Distortion caused by faults in the manufacture of optical fiber.

**Reflection-II (type II):** Distortion caused by crosstalk in bidirectional systems.

**Return to zero:** Is a Signal in which the signal drops (returns) to zero between each pulse.

**RF cable:** Is a cable that transmits within the radio frequency.
Roaming doctors: Refers to doctors that are capable of remotely give medical advice through the communications infrastructure.


Secure sockets layer: a protocol developed by Netscape for transmitting private documents via the Internet.

Seed light source: A light source that delivers its power to be reused at a distant location.

Self-phase modulation: Is a nonlinear optical effect of light-matter interaction.

Signal to crosstalk ratio: at a specified point in a circuit is the ratio of the power of the wanted signal to the power of the unwanted signal from another channel.

Signal to noise ratio: Is a measure used in science and engineering that compares the level of a desired signal to the level of background noise.

Spectral broadening: Is a widening of the wavelength.

Spectrum: Is the range of all possible frequencies of electromagnetic radiation.

Synaptic manager: Synaptic is a graphical package management program for apt. It provides the same features as the apt-get command line utility with a GUI front-end based on Gtk+.

TCP/IP: is a descriptive framework for the Internet Protocol Suite of computer network protocols.

Terabit: A terabit is a multiple of the unit bit for digital information or computer storage.

Thermostat: is the component of a control system which regulates the temperature of a system so that the system's temperature is maintained near a desired set point temperature.

Time Division Multiple Access: is a channel access method for shared medium networks. It allows several users to share the same frequency channel by dividing the signal into different time slots.

Time Division Multiplexing: is a type of digital (or rarely analog) multiplexing in which two or more bit streams or signals are transferred apparently simultaneously as sub-channels in one communication channel, but are physically taking turns on the channel.

Transceiver: Is a device comprising of both a transmitter and a receiver which are combined and share common circuitry or a single housing.

Transport layer security: are cryptographic protocols that provide communication security over the internet.
**Tree network:** This is a network which has as central root where multiple branches can subdivide out further into other branches.

**Triple play:** A combination of voice video and data.

**Type I:** see Reflection-I

**Type II:** see Reflection-II

**UDP protocol:** Is one of the core members of the Internet Protocol Suite, the set of network protocols used for the Internet.

**Water peak:** Is the part of the spectrum in fiber that is more susceptible to attenuation form moisture

**Wave division multiplexing:** Is a technology which multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelengths (i.e. colours) of laser light.

**Wide area networks:** Is a telecommunication network that covers a broad area (i.e., any network that links across metropolitan, regional, or national boundaries).

**X.509:** Is an ITU-T standard for a public key infrastructure (PKI) and Privilege Management Infrastructure (PMI).

**XFP transceiver:** Is a standard for transceivers for high-speed computer network and telecommunication links that use optical fiber.
Abbreviations

2B1Q: Two-binary, one-quaternary

3DTV: 3 dimension TV

4B3T: 4 binary 3 ternary

AC: Alternating current

AM: Amplitude modulation

AMI: Alternate mark inversion

AOM: Acousto–optic modulator

APD: Avalanche photodiode

ATM: Asynchronous transfer mode

AWG: Array wave guide

BLS: Broadband light source

BoD: Bandwidth on demand

BPON: Broadband PON

CAPEX: Capital expenditure

CCTV: Closed-circuit television

CDR: Clock-data recovery
CML: Current mode logic

CO: Central office

CRC: Clock recovery circuit

CW: Continuous wave

CWDM: Course WDM

DBA: Dynamic bandwidth allocation

DC: Direct current

DFA: Doped fiber amplifiers

DFB: Distributed feedback laser

DFB: Distributed-feedback

DPSK: Differential PSK

DQPSK: Differential quadrature PSK

DSF: Dispersion shifted fiber

DSL: Digital subscriber line

DVR: Digital video recorder

DWDM: Dense WDM

EAM: Electro absorption modulator

ECL: External cavity laser
EDFA: Erbium DFA
EOM: Electro optic modulator
EPON: Ethernet PON
EPU: End premises unit

FBG: Fiber bragg grating
FC: Fiber channel
FPLD: Fabry-Perot laser diode
FSR: Free spectral range
FTTx: Fiber to the x (x can stand for many positions)
FWC: Fixed WC
FWM: Four wave mixing

GPON: Gigabit PON

HD: High definition
HDB3: High density bipolar of order 3
HDTV: High definition TV
HD-VoD: High definition video on demand
HPS: Header-payload separator
**IGMP**: Internet group management protocol

**IP**: Internet protocol

**IPTV**: Internet protocol TV

**ITU**: International telecommunications union

**ITU-T**: ITU telecommunication standardisation sector

**KAIST**: South Korea advanced institute of science and technology

**KT**: South Korea telecom

**LAN**: Local area network

**LED**: Light emitting diode

**LiNbO3**: Lithium niobate

**MAC**: Medium access control

**MAN**: Metropolitan area network

**MBC**: Modulator bias controller

**MMF**: Multimode fiber

**MPEG**: Moving picture experts group

**MSM**: Metal-semiconductor-metal

**MZI**: Mach-Zehnder interferometer
NDVR: Network DVR

NIC: Network interface card

NRZ: Non return to zero

NZDSF: Non-zero dispersion shifted fiber

OADM: Optical add/drop multiplexer

OBS: Optical burst switching

OBS-M: OBS multiplexer

OECD: Organisation for economic co-operation and development

OEO: Optical-electrical-optical

OLT: Optical line terminal “central office”

OM#: Multimode Fiber

ONU: Optical network unit

OOK: On-off keying

OPEX: Operating expenditure

OPS: Optical packet switching

OS: Operating system

OTDM: Optical TDM

OTDV: Optical time domain visualiser

OXC: Optical cross connect
**PBS**: Polarisation beam splitter

**PMD**: Polarisation mode dispersion

**PM-DQPSK**: Polarisation multiplexed

**PMF**: Polarisation maintaining fiber

**PON**: Passive optical network

**PRBS**: Pseudo random binary sequence

**PSD**: Polarisation split and delay

**PSK**: Phase shift keying

\[ Q \]

**Q Factor**: Quality factor

**QoS**: Quality of service

\[ R \]

**RB**: Rayleigh backscattering

**RN**: Remote node

**ROADM**: Reconfigurable optical add/drop multiplexer

**RSOA**: Reflective SOA

**RZ**: Return to zero

\[ S \]

**SC/APC**: Standard connector/ angled physical contact

**SC/PC**: Standard connector/ physical contact

**SCMA**: Subcarrier multiple access
SD: Standard definition

SDH: Synchronous digital hierarchy

SDTV: Standard definition TV

SD-VoD: Standard definition video on demand

SFP: Small form-factor pluggable

SMF: Single mode fiber

SNR: Signal to noise ratio

SOA: Semiconductor optical amplifier

SONET: Synchronous optical networking

SPM: Self-phase modulation

SRS: Stimulated raman scattering

SUCCESS-HPON: Stanford University access hybrid PON

TCP/IP: Transmission control protocol/internet protocol

TDM: Time division multiplexing

TDMA: Time division multiple access

TWC: Tuneable WC

UNI: Ultrafast nonlinear interferometer

VCSEL: Vertical cavity surface emitting lasers
VDSL: Very-high-bit-rate DSL

WAN: Wide area network

WBG: Waveguide bragg-grating

WC: Wavelength converters

WDM: Wave division multiplexing

XFP: 10 Gigabit small form factor pluggable

XPM: Cross-phase modulation
Chapter 1

Introduction

International demand for network bandwidth grew sevenfold between 2006 and 2010 [1]. This growth has been met with infrastructure investments in fiber cables, long distance networks and data centers. The boom of social and content networks, including video or multimedia applications based on an internet infrastructure has being one of the main factors for growth.

The competitive communications market uses a range of technologies for data transmission. Wireless, copper, satellite and fiber all compete and complement each other within this sector, as they all have advantages and disadvantages over each other. The technology capable of delivering the required data transmissions for future communications growth over both short and large distances is fiber [2]. The fiber technology delivering the highest bandwidth is Wave Division Multiplexing (WDM). This technology combines many independent wavelengths (channels) onto a single strand of fiber. Currently the state of the art single fiber transmission speeds is 24 Terabits per second (Tb/s) and the capacity continues to increase [3]. The demand for increased Quality of Service (QoS), High Definition TV (HDTV), and cloud computing are large contributors to the increase in demand for bandwidth.

Some of the benefits that fiber communications offers over copper communications are:
Optical fiber can carry thousands of times more information than copper wire. For example, a single-strand of fiber could carry all the telephone conversations in the United States at peak hour [4].

- Fiber is more lightweight than copper. Copper weighs approximately 80 lbs/1000 feet, while fiber weighs about 9 lbs/1000 feet.
- Copper signal loss increases with higher frequencies, while fiber cables signal loss is the same across many frequencies.
- Fiber is more reliable than copper and has a longer life span.
- Fiber does not cause electromagnetic interference and is difficult to tap (eavesdrop).

Fiber optic networks make up the bulk of the global communications infrastructure. The vast majority of fiber optic technologies used globally are in Wide Area Networks (WANs) and Metropolitan Area Networks (MANs). The access network\(^2\) is currently dominated by older copper based communication technologies like Digital Subscriber Line (DSL) [5]. The inability of copper to meet the growing consumer demand for data is making optical networking a realistic successor. With relatively low fiber penetration in the access network [5] WDM deployment is a suitable solution when data in excess of a 100 MB/s per user is required.

\(^2\) The access network is any network that provides bandwidth from the local bandwidth provider to the end customer or business.
Figure 1: Distance versus data rate for various communications technologies

Figure 1 illustrates that fiber optics can reach farther distances without regeneration. The vast majority of fiber access networks deployed are variations of Passive Optical Networks (PON). The basic definition of PON is a fiber network that removes the need for electrical components between the central office transmitter and the transceiver at the end user. A PON is designed to reduce Operational Expenditure (OPEX). Examples of PON systems include Ethernet PON (EPON), Gigabit PON (GPON) and 10Gigabit EPON (10GEPON). These PONs are based on Time Division Multiplexing (TDM) and a tree architecture, where each user signal is multiplexed in the time domain.

1.1 Open Research Questions

Current Passive Optical Networks (PONs) can provide sufficient bandwidth for standard triple play services, but new communication applications like cloud computing and HDTV require greater throughput than what current PONs can support [6].

Questions that arise from analysis of current research and commercial designs are;
1. WDM communication systems require the central office and end users equipment are capable of utilising many independent wavelengths. With a large number of end users in an access network, implementing an economical solution for the end users equipment is necessary. The objective of much research in WDM systems is implementation of a colourless-transparent device at the end users ONU. The first question that this research addresses is whether an economical colourless-transparent ONU be built?

2. Tree PON architecture requires a direct fiber link from the passive splitter to the ONU. Depending on the PON technology used, the split ratio can vary (usually 1:32 or 1:64). A large amount of fiber is required when deploying current PON tree architecture. Figure 2 shows a tree network with 10 ONUs. A passive way of implementing an economical architecture needs to be examined. A complete new PON system is required once the split ratio is reached. Deployment of the network into dense urban areas requires a vast amount of fiber. The second question that this research addresses is the extent to which an alternative fiber architecture can reduce the amount of fiber required compared with a traditional tree PON?

![Figure 2: PON tree architecture](image)

3. Optical communication signals can suffer from negative distortion effects. One large distortion factor in bidirectional optical communications networks
is Rayleigh Backscattering (RB). There are two types of RB, with type II causing the most interference [7]. RB imposes limits to the transmission distance in PONs, typically 20 km [8]. When wavelengths on the same fiber are travelling in opposite directions, the effects of type II RB are increased. The third question that this research addresses is whether the negative effects of RB type II be reduced or removed from the passive network design?

4. WDM has the capability to supply large amounts of data. Optical Time Division Multiplexing (TDM) can utilise data more efficiently. By combining both WDM and TDM the advantage of high speed WDM and the efficiency of TDM can be achieved. The fourth question that this research addresses is; within the context of an all optical ring network, what is the most efficient and economical way of implementing a WDM/TDM network?

5. The bandwidth bottleneck that currently exists between the Metropolitan Area Networks (MAN) and access networks is due to Optical-Electrical-Optical (OEO) conversion. The final question that this research addresses is how an economical all-optical solution be implemented between the MAN and access bridge?

Factors driving the main volume of research within current WDM access networks are:

1. The high cost of the initial fiber deployment (network design).
2. The WDM equipment (with ONUs being the most expensive component).

By reducing these two areas, the initial Capital Expenditure (CAPEX) and the ongoing Operating Expenditure (OPEX) can be reduced to make WDM a viable access network.

1.2 Thesis Goals and Hypothesis

This thesis examines the introduction of WDM into the access network and investigates design aspects, achievable data transmission rates, robustness (e.g. tolerance to interference), and transparent ONU implementation aspects.
It will – summarising the previous section – address the following five research questions:

- Can a modulator be used as a remote transmitter at the Optical Network Unit (home router) instead of a tuneable laser transmitter?
- How does a fiber ring network reduce the amount of fiber required compared with a tree PON?
- How is distortion effects caused by Rayleigh backscattering reduced with the unidirectional network design?
- Can implementing TDM with WDM-PON deliver an economical use of bandwidth?
- How can an all optical connection between the MAN and Access network be implemented?

The overall research hypothesis can be summarised as follow:

*Does the introduction of WDM into the access network provide a technologically and economically viable alternative to providing high-speed broadband data services to end users?*

### 1.3 Research Approach

The high costs associated with optical networks prohibited the option of real world experimental testing. Simulation testing on the other hand offers a wide range of optical analysis tools at a fraction of the cost [9-10]. As such the bulk of the research for the network design and implementation was primarily through optical software simulation testing using Optiwave OptiSystem [9]. This software package is highly regarded within the academic community [9-11]. It is a mature software package that is used by a number of other Universities in education and research. In addition to that, many companies in the optical communication industry rely on this software. The use of this software is very intuitive and it comes with good online-help and other documentation. It has a database of optical networks to compare the results of the implemented designs.
OptiSystem is based on realistic modeling of fiber-optic communication systems. It possesses a powerful simulation environment of components and systems. A graphical user interface controls the optical component layout, component models, and presentation graphics. An extensive library of active and passive components is included.

The main features of OptiSystem are:

- The OptiSystem Component Library includes hundreds of validated components. Users may customise them by entering parameters that can be measured from real devices. Users can also incorporate new components based on subsystems and user-defined libraries.
- OptiSystem handles mixed signal formats for optical and electrical signals in the component library, and calculates the signals using the appropriate algorithms related to the required simulation accurately and efficiently.
- System performance is predicted by calculating Bit Error Rate (BER) and Q-Factor using numerical analysis or semi-analytical techniques for systems limited by inter-symbol interference and noise.
- Advanced visualisation tools produce Optical Spectrum Analyser (OSA) spectra, oscilloscope, and eye diagrams. Also included are WDM analysis tools listing signal power, gain, noise figure, and Optical Signal-to Noise Ratio (OSNR).

All of the aforementioned were used in the simulation to implement the proposed system.

Synchronisation of the simulation network was implemented using a clock and pulse generator. Within a real ONU component design, the clock and bit generator would be implemented using an onboard chip, like the Maxim-IC MAX3952 16:1 serialiser. Synchronisation was required to test the TDM integration with WDM.

Apart from the simulation a substantial effort to build an ONU using off the shelf components was undertaken. The setup centred on a redesign of a commercially

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3 The following description was taken from the webpage http://www.optiwave.com
available XFP transceiver. The XFP module was adapted to use an external modulator as an alternative to the standard laser in an XFP module. The test setup was designed to demonstrate remote modulation of a signal.

As with the research approach above, the network results were also compared with other systems within OptiSystem and the industry standards in the communications industry to give the best analysis of the design.

The research results were analysed and correlated with:

- Current PON and WDM-PON network setup results as taken from OptiSystem simulations.
- Industry Bit Error Rate (BER) standards. The industries maximum acceptable BER in a telecommunications system is $10^{-9}$ [12] while some systems like Ethernet and fiber channel demand a BER as low as $10^{-12}$.
- The Q-factor, which is a parameter that directly reflects the quality of a digital optical communications signal. The higher the Q-factor, the better the quality of the optical signal. Q-factor measurement is related to the analog signal and in this respect differs from traditional BER tests. Assuming signal impairments follow a stochastic distribution, the Q-factor can theoretically be related to a BER.
- Optical power (dB) levels were monitored and related to the optical receivers sensitivity limit. These levels were measured (and corrected/boosted using amplifiers) throughout the system.
Figure 3: Q and BER correlation over time

The tools used for the simulations analyses in OptiSystem were:

- An optical spectrum analyser which can be used to examine the spectral composition of optical waveforms.

- An eye diagram analyser which can be used to visually analyse the system performance. It can indicate errors, short-long signals, poor synchronisation and noise by visually inspecting an eye pattern.

- A Bit Error Rate Tester (BERT) checks the quality of a link by sending out a known bit pattern and verifying that the received pattern matches. Bit errors occur when the patterns don’t match.

- An Optical Time Domain Visualiser (OTDV) is used to examine the signal based on time sections of the signal. It is helpful in determining the synchronisation of a system.
1.4 Thesis Structure

The structure of the thesis is as follows: chapter 2 looks at reasons and motivations for this research. It examines areas that rely on bandwidth and future examples of areas that will require greater bandwidth than is currently available to most users. Chapter 3 examines the state of the art research related to the proposed work; it inspects commercial systems, current WDM research in networks, ONU design, solutions to distortion issues on fiber and proposed bandwidth control mechanisms. It also gives a brief introduction into the related technologies. It gives the reader a better perception of the technology used in the experiment chapters. Chapter 4 lays out the methodology of how the following chapter are going to be implemented. Chapter 5 demonstrates a simulation of the remote transparent ONU. Tests examining the most common optical encoding schemes are demonstrated. Chapter 6 demonstrates hardware testing of the simulated transparent ONU and looks at how bandwidth on demand could be implemented within the network. Chapter 7 further advances the network architecture to reduce the amount of fiber required compared with tree PONs, it adds improved control of bandwidth by integrating TDM with WDM and also removes distortion factors caused by RB type 2. Chapter 8 presents the conclusions and future work. The sections following the conclusion contain a list of publications and a patent arising from this research.
Chapter 2

Motivation

There are many applications that require greater bandwidth than is currently available to the mass access market. As a result they have limited use in current network architectures. For these applications to be fully utilised, the current communications infrastructure must be advanced.

This chapter looks at the motivation behind delivering increased data to users. It also examines areas like health, education and government services and shows how they benefit from improved telecommunications [13-14].

2.1 A Brief History of Optics

The first experiment that demonstrated the refractive nature of light dates back to the 1850s. Later in 1880, Alexander Graham Bell patented an optical telephone system, called the “Photophone”. The system was designed to transmit signals through the air, but the atmosphere proved to be a less reliable medium than metal wires [15]. Almost a century later the transmission of information on optical fiber was made feasible with the introduction of the laser. Compared with copper communication, fiber optics has seen a relatively slow uptake in residential premises. Bandwidth demands per user are rising year on year and copper networks are reaching their maximum bandwidth potential. As of May 2011 the fastest transmission of information using a single laser beam over fiber optics was demonstrated by scientists at the Karlsruhe Institute of Technology in Germany at a speed of 26 Tb/s [16].
2.2 Demand for Bandwidth

WDM systems are divided into different wavelength patterns, Course WDM (CWDM) and Dense WDM (DWDM). CWDM provides a solution for combining more than 2 and up to 18 wavelengths onto a single strand of fiber, where 20 nm spacing is used between channels, this enables up to 18 channels over the entire transmission band; i.e., from 1271 nm to 1611 nm (see Table 1 for optical band transmission ranges). DWDM has the capability to transmit up to 80 concurrent wavelengths on a single strand. It accomplishes this by applying 0.4 nm spacing between each channel. Research into ultra DWDM reduces this spacing to 0.1 nm, effectively bringing the number of wavelengths per strand to 256⁴ [17].

<table>
<thead>
<tr>
<th>Band</th>
<th>Description</th>
<th>Wavelength Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>O Band</td>
<td>Original</td>
<td>1260nm to 1360nm</td>
</tr>
<tr>
<td>E Band</td>
<td>Extended</td>
<td>1360nm to 1460nm</td>
</tr>
<tr>
<td>S Band</td>
<td>Short wavelengths</td>
<td>1460nm to 1530nm</td>
</tr>
<tr>
<td>C Band</td>
<td>Convention (erbium window)</td>
<td>1530nm to 1565nm</td>
</tr>
<tr>
<td>L Band</td>
<td>Long wavelengths</td>
<td>1565nm to 1625nm</td>
</tr>
<tr>
<td>U Band</td>
<td>Ultralong wavelengths</td>
<td>1625nm to 1675nm</td>
</tr>
</tbody>
</table>

Table 1: Optical transmission windows

The optical networking sector has seen minimal growth in the access network [18]. Since copper networking is nearing its maximum potential, it is evident that fiber optical networks will become more prevalent where significant bandwidth is needed. New technologies like tablet PCs and Smartphones, and services such as High Definition TV (HDTV) and cloud computing, demand far more bandwidth than what is currently available [19]. Fiber WANs and MANs act as a backbone for many technologies including cellular wireless substations and internet service.

⁴ This number changes when more bands are used in the transmission.
providers (ISP), which provide the data for the access network. Fiber optics is currently the only reliable way of meeting high bandwidth needs, as shown in Figure 1 and Figure 4.

**Figure 4: Application bandwidth requirements [20]**

### 2.3 High Bandwidth Services

The early 2000s saw “triple play” as the next big thing in communications. Triple play is the combination of data, voice and video into one service. Recently “triple play” service has been overshadowed by services such as cloud computing,
HDTV and 3DTV services. Also medical informatics are becoming reliant on communications technologies [21] services while governments are developing their online presence to try deliver better services.

2.3.1 Cloud Computing

There are many slightly altered definitions of the cloud. The outline definition is the delivery of computing as a service rather than a product, whereby shared resources, software, and information is provided to computers and other devices as a utility over a network [22]. An example of a cloud service is online remote disk access (see Figure 4 above). Here files are kept on an external server and can be accessed by any internet-enabled device.

![Cloud Computing](image)

**Figure 5: Cloud computing**

A cloud service combines the features of many other services into one [23]:
On-demand self-service: IT services can be supplied from a web-based interface available via a self-service portal. Business units receive tailored services right when they need them.

Ubiquitous network access: available through standard internet-enabled devices.

Location independent resource pooling: processing and storage demands are balanced across a common infrastructure with no particular resource assigned to any individual user.

Rapid elasticity: consumers can increase or decrease capacity at will.

Pay per use: consumers are charged fees based on their usage of a combination of computing power, bandwidth use and/or storage.

The services can be sold on demand which means users only pay for what they use. The service is maintained by the cloud service provider and a customer only requires a communications device with a high speed internet connection [24].

2.3.2 TV Services

There are three main types of TV services, satellite, aerial, and cable. Cable-based TV services consist of Standard Definition TV (SDTV), Internet Protocol TV (IPTV), High Definition TV (HDTV) and 3DTV. Because of the high bandwidth required by many of these services, a powerful data communications infrastructure is necessary. Some fiber technologies are capable of transmitting these services, but leave little bandwidth for other services [25].

HDTV is a term that is used to describe any broadcast that transmits at (1280×720) or (1920×1080) pixels. The raw broadcast of full HDTV requires a transmission rate of 1.5 GB/s. Therefore, compression techniques are required. Using MPEG 2 encoding the transmission can be reduced to 80Mb/s which is approximately 19 times smaller than the raw transmission, but there have been newer compression techniques such as H.264 that reduce this further to 20Mb/s [26].
IPTV is a system that encodes TV for transmission using the Internet Protocol (IP) over a packet-switched network infrastructure, e.g. the internet. IPTV technology has always been limited because of the high bandwidth required to transmit video reliably. However, now that many areas of the world have access to high speed broadband, the technology has had the opportunity to progress [27].

3D TV is a new technology that has seen growth recently with 3D films and 3D TV sets. The bandwidth needed to deliver 3D channels has been estimate to be between 35-40Mb/s per channel [28]. Depending on the compression technique used, it is nearly double the bandwidth of HDTV. It is unknown yet whether 3D TV’s will succeed [29]. HDTV and 3D TV require 20MB/s and 40 MB/s per channel respectively. The increase in bandwidth puts a strain on current copper solutions but can be easily be delivered by next generation fiber networks.

2.3.3 E-Health

The current global financial turndown has a knock on effect for healthcare services [30]. ICT technologies can help remove the need to choose between quality of service and cost. Countries with modern broadband infrastructures and information systems are helping to improve health care systems [31]. Patients now have access to medical services and professionals via internet technologies such as video-conferencing, web forums and chat services. Main bandwidth requirement drivers are multiple simultaneous tele-radiology sessions (like Picture Archiving Communication System (PACS) and video-conferencing) for roaming doctor applications. The technology associated with modern PACSs can easily surpass the one GB/s per session. Within the medical society, high bandwidth services would require anything up to 10 GB/s. Roaming doctors are not only within hospitals, but can also be introduced into health educational sites [32]. These systems if progressed could encompass such services as online talk therapy, online pharmaceutical therapy and online counselling. Development in the communications infrastructure has allowed prototype medical booths to bring remote medical advice to areas that don’t have a local medical service [33]. These
remote services require large data for multimedia communication as well as the transfer of medical information.

### 2.3.4 E-Government

Governments can use the telecoms infrastructure to enhance the efficiency and effectiveness of their countries. Governments develop and improve the communication infrastructure in order to attract direct foreign investment and improve their economies. Businesses require high speed communication infrastructures and are attracted to countries with these facilities.

Technology itself would not guarantee success with e-Government but, it is necessary that any e-Government initiative must ensure that it has sufficient resources, adequate infrastructure, management support, capable IT staff, and effective IT training and support. Despite the cost of IT going down, an adequate IT infrastructure still represents the key barrier for e-Government adoption. Within this IT infrastructure the data capacity is one of the main factors impeding the proper integration of all government services [34].

### 2.3.5 Tele-Education

Tele-education can be either synchronised or asynchronised. Synchronised solutions supply bidirectional interaction between teacher and pupil, while asynchronised solutions provide pre-recorded multimedia and static documentation. Tele-education has been used to deliver continuing education programmes to health-care professionals and to run professional school education in areas that have inadequate teaching professionals [35]. Synchronised tele-education offers a much greater advantage over broadcasting non interactive information. It is the next step to having a dedicated educator in the room. Tele-education technologies have an important role to play in addressing the lack of education facilities in rural areas. A reliable tele-education service depends on an excellent communication infrastructure, one which fibre is capable of providing. It is worth noting however that satellite communications may be the only solution for extremely remote areas.
2.4 Conclusion

This chapter has examined important areas in society like health, education and government services that require large data transfer rates. The benefits of increased bandwidth per user can be seen when applications like HDTV and cloud computing are being developed. Implementing a service-based solution like cloud computing into today’s communications infrastructure would require much more bandwidth than is currently available to the majority of users. The motivation behind this research is brought about by a need to improve upon the telecommunications infrastructure and deliver a solution that will see the aforementioned services and products being implemented.
Chapter 3

Related Research

This chapter will outline the current state of research in key areas of WDM PON. It will also discuss potential roles of WDM-PON in next-generation optical broadband access networks. A commercial deployment of WDM-PON access network in South Korea and the steps taken to implement a viable system is examined.

Although WDM-PON has many advantages, it is prohibitively expensive for practical deployment. This is mainly due to the extra costs involved in the installation and maintenance of the wavelength-selected lasers (ONU) required in WDM-PON. Some solutions to this problem are discussed.

A next-generation hybrid WDM/TDM optical access network architecture called Stanford University aCCESS (SUCCESS) provides practical migration steps from current-generation Time-Division Multiplexing (TDM) - PONs to future WDM optical access networks.

Reflection and Rayleigh backscattering-induced crosstalk may cause a significant power penalty and thus limit the performance of the system. Methods examining how to mitigate Rayleigh Backscattering (RB) by spectral broadening ONU gain are examined.

Optical Burst Switching (OBS) and a Dynamic Bandwidth Allocation (DBA) protocol in a WDM/TDM hybrid network are also examined. The OBS hybrid
WDM/TDM network uses polling to check if and when an ONU requires bandwidth. In this network all the intelligence and costly equipment is located at the central office, where the DBA module is centrally implemented.

A brief overview of optical technologies and architectures used in the development of optical networking is examined. It gives a better understanding on the research being carried out in the following chapters.

3.1. WDM Network Deployment in South Korea

OECD statistics indicate that fiber penetration in the access market is substantially lower when compared with copper technologies such as DSL and cable technologies [5].

South Korea is leading the way within the area of fiber penetration [36]. The country has been, on an annual basis, one of the top innovators in optical infrastructures and optical components. It has been ranked number one in fiber bandwidth penetration by the OECD. As of June 2010, it has 17.9 per 100 inhabitants linked into a fiber infrastructure [5]. In 2002 a WDM-PON joint venture between Korea Telecom (KT) and Novera Optics Korea Inc was undertaken with the aim of developing a WDM network that would have the capacity to cater for future demands [36].

The transmission component of the ONU was based on a wavelength locked Fabry-Perot Laser Diode (FPLD). The requirement of the end-user was a symmetric bandwidth of 100 MB/s (i.e. bandwidth capable of accommodating three full HDTV channels simultaneously). While other PON technologies such as Ethernet-PON (EPON) and Gigabit-PON (GPON) were commercially available, they did not have the bandwidth capabilities to offer a symmetric bandwidth of this magnitude5.

KT and Novera produced some cost projections. They concluded that a WDM-PON architecture was the most cost effective when future bandwidth requirements

5 EPON is designed for 32 users each getting 30MB/s, but for 100MB/s symmetric bandwidth the split ratio had to be dropped to 8 users per fiber strand.
were taken into account; other advantages include protocol transparency and increased security. However, one of the key issues of WDM systems is the cost of their composite wavelength specific optical sources. KT and Novera chose wavelength locked FPLD because it was believed to be the most cost effective of the ONU sources.

3.1.1. System Specification

A point to multipoint architecture with a maximum span of 10 km and a bandwidth of 125 MB/s on 32 channels was deployed. A channel spacing of 100 GHz was used between the upstream in the C-band (1534-1559nm) and also in the downstream E–band (1426-1449nm) spectrum. The multiplexing and demultiplexing of the channels was performed using a single Array Waveguide Device (AWG). A diplexer (Two wavelength multiplexer) was used to split the two wavelengths at the OLT and the ONU.

The objective of the joint venture was to supply “triple play” services with HD quality video. The systems passed KT’s qualification test in early 2005. A subsequent field trial was then undertaken in Kwangju South Korea [36].

3.1.2. Field Trial Testing

Two real world scenarios were examined as part of the field trial, one was an apartment complex and the other a residential area. Different methods were used to install the fiber in each area. Within the apartment complex a method termed “air-blown fiber” was used. Air-blown fiber relies on the flow of compressed air to transport the fibre to its destination. Aerial fiber (where the cable is hung from poles) was utilised within the residential area. Additional fibre was only utilised when absolutely required. The span of fiber used for the field trial was 7.8 km and 8.8 km for the residential area and apartment complex respectively. Power loss associated with the apartment and residential setups were 10dB and 12dB.
respectively. Both links used 7 connectors comprised of both SC/PC and SC/APC\(^6\) types.

Services offered by the trial systems included IP-TV, HD-VoD, SD-VoD, N-PVR, EoD, and internet. Management of the WDM-PON was performed via an L2/L3 switch with Internet Group Management Protocol (IGMP) support. Layer-2 switches operate utilising Media Access Control (MAC) addresses in its caching table to quickly pass information from port-to-port. A layer-3 switch utilizes IP addresses to do the same. The IP-TV content was generated from a satellite feed encoded using MPEG2 and encapsulated into IP packets with multicast IP addresses. One HD and twenty SD channels were made available via the IP-TV service. In 2006, 2,000 homes were serviced via this fiber technology. Aerial fiber was also deployed and approximately 5,400 connections were made.

3.1.3. Network Design Research

South Korea's Advanced Institute of Science and Technology (KAIST) developed a 50 GHz channel spacing multiplexer, which is capable of further increasing the channels capacity. More recently there has been research into developing ultra dense WDM systems, which are capable of a channel spacing of up to 12.5 GHz [17]. This greatly increases the number of usable channels within the system. KAIST suggested that by applying Time Division Multiple Access (TDMA) or Subcarrier Multiple Access (SCMA), one could accommodate a greater number of users. Another technique that was investigated for ONU transmission was Reflective Semiconductor Optical Amplifier (RSOA). The performance of RSOA, however, proved sensitive to injection power.

A transition stage from TDM-PON to full WDM-PON was demonstrated by combining WDM-PON with the traditional B-PON, E-PON and G-PON systems. These systems follow the standardised ITU-T wavelength bands (up: 1260-1360nm, down: 1480-1500nm). Existing TDM-PON networks can share the same

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\(^6\) Connectors are used to terminate the end of an optical fiber. The connectors mechanically couple and align the cores of fibers so that light can pass
feeder fiber by adding a three-port wavelength combiner splitter at the transmitter and the receiver. Since the WDM signals are separated before they reach the receiver, these two separate systems can coexist on the same network.

### 3.1.4. ONU Research

One key element in a Fabry-Pérot Laser Diode (FPLD) system is the use of a polarisation independent Broadband Light Source (BLS). A BLS with lower noise than previous BLSs was proposed. A reduced noise of -135dB/Hz was reported.

A tuneable light source was also demonstrated as an independently self-lasing light source for the WDM-PON. The structure of the wavelength-tuneable External Cavity Laser (ECL) is illustrated in Figure 6. The ECL was constructed by placing a wavelength Bragg grating section in front of the LD on a planar light wave circuit. Heating of the wavelength Bragg grating tuned lasing coarsely. A phase-control heater section was inserted between the LD and the WBG for fine wavelength tuning and stable single mode lasing [36].

![Figure 6: Structure of the wavelength-tuneable external cavity laser (ECL)[36]](image)

### 3.2. Transceiver Research for WDM-PON

PONs have been around since 1988 with the introduction of Telephony PON [37]. These systems were developed as a cost effective solution for delivering
fibre to businesses. With the advent of WDM and the promise of extra capacity, low latency and service transparency WDM-PONs have become a new area of research. The main focus of WDM-PON research is the ONU transceiver. This section examines the different type of laser been researched and employed in WDM ONU setups.

3.2.1. Tunable Laser Source

A separate tunable laser is probably the best setup in terms of performance and flexibility for a WDM-PON. However, its complexity and cost prohibits it from being the most popular option in an ONU as the source. For use in WDM networks a more sophisticated laser is required at the ONU compared with EPON and GPON systems. A wavelength locker or external laser reference is required for the laser to accurately operate on the correct wavelength. Also for laser stability, external modulation is implemented rather than direct modulation. For these reasons a tunable laser is not viable option.

3.2.2. Sliced Broadband Source

A sliced broadband source uses a wideband source containing many wavelengths which is integrated with an Array Wave Guide that is designed to remove all but the necessary wavelength from the wideband of wavelengths. It separates the unwanted wavelengths from the wideband of wavelengths, see Figure 7. Each user has a specific AWG that utilises the desired wavelength for its use. This setup means that each user must have specific user equipment to reflect their wavelength. One method that is used in WDM-PONs is Fabry-Perot or Lyot-Sagnac filtering [38] which is used to slice an Amplified Spontaneous Emission (ASE) source [39].
3.2.3. Reflective Sources

Reflective sources used in ONU transceiver development are receiving much attention in the WDM networking research community, since they are cheaper than tunable lasers. A reflective device is not capable of producing a laser beam, so an external source must be used to seed the device. Generally the seed for the reflective devices comes from a high power laser source the central office.

3.2.3.1. Reflective Semiconductor Optical Amplifier (RSOA)

RSOA has been heavily researched in the access network to achieve gigabit upstream data operation. The advantage of employing RSOA, instead of a tunable laser source, is its colourless operation. Using colourless operation delivers cost effectiveness with regard to CAPEX and OPEX. When the device is operated under gain saturation\(^7\) the effective lifetime is reduced by clamping of the carrier level and in practice modulation speeds of 5 GB/s are possible [40]. The seeded RSOA approach has an advantage over the un-seeded SLED approach because the optical power of the seeded light will be much higher in the selected wavelength due to the optical gain of the RSOA [40].

The use of a pure seed source reduces the impact of chromatic dispersion for the return channel in long reach applications and avoids the excess noise produced by

\(^7\) Gain saturation – as the signal level increases, the amplifier saturates and cannot produce any more output power, and therefore the gain reduces.
the slicing process. However, when a narrow spectrum seed source is used to enable a high performance WDM-PON, the impact of coherent type II RB must also be considered. This problem can be reduced by using a separate fibre for the seed and return.

3.2.3.2. Reflective Electro Absorption Modulator (R-EAM)

Reflective Electro-Absorption Modulators (R-EAM) can be used to achieve a larger data transmission rate than RSOAs. R-EAMs can transmit at rates up to 40 GB/s. Unlike an RSOA, which amplifies the seed signal, a R-EAM needs to get all its seed power from the central office. For high bit rate systems it is most likely that lasers would be used as the seed sources, and therefore for some applications dual fibre feeding may be necessary to reduce coherent Rayleigh Backscatter (RB) noise. For lower data rates, the R-EAM scheme is attractive when it is necessary to minimise the electrical power within remote equipment. This is because the R-EAM requires a low drive voltage (< 2 V) and has intrinsically high electrical impedance [41].

3.2.3.3. Injection Locked Fabry-Perot Laser Diode (FPLD)

Fabry–Perot laser diodes (resonator) consist of two mirrors. The locking range for the wavelength is about 46nm. This can cover 58 International Telecommunication Union (ITU) wavelengths with 100 GHz spacing or 115 ITU wavelengths with 50 GHz spacing. The FPLD can be converted to a single mode laser by injection locking with an extra coherent light source. However, it is not cost-effective, as a stable coherent light source is needed. It also exhibits an optical power penalty due to back scattering induced relative intensity noise. A wideband spectrum is sliced by an AWG (see Figure 7) and used to lock a FPLD laser transmitter within the customer’s ONU. The FPLD has been used as a low cost light source in WDM-PON ONU equipment [36]. The FPLD generally operates around the 1.25 GB/s rate [42].
3.3. Hybrid WDM/TDM PON Networks

For the past two decades research into methods of how to utilise fiber within the access network have being examined. With so many competing fiber technologies and architectures, no widely commercially successful standard has been agreed upon. The lack of an international standard for WDM-PON has made it more difficult for large scale developments of WDM in the access network [43]. Technology is continuing to evolve at a rapid pace. This is particularly evident within the multimedia domain where an abundance of new technologies and standards like high bandwidth TV services continue to emerge. These advancements however come at a cost since availing of these technologies require advances in the communication networks. To help reduce the costs of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) changes in a network’s design can prove useful. The use of passive equipment like AWGs and splitters removes the need for Optical-Electrical-Optical (OEO) conversion, which in turn cuts the cost of CAPEX and OPEX in the network.

3.3.1. Stanford University Approach to WDM and TDM-PON Integration

A system that can reliably and feasibly provide a wavelength for each user is the objective of a significant amount of research. Given the current demand and technology, it is not cost effective to develop such systems at this time. TDM-PON technologies have been commercialised, providing such systems as EPON, GPON and GEPON. The next obvious step is to find a way to bring WDM-PONs into the commercial arena [36]. The SUCCESS-HPON demonstrates a way of bridging current TDM-PON and future WDM-PON infrastructures. A solution proposed by Stanford University is a hybrid WDM/TDM-PON that can utilise older TDM networks and incrementally integrate them with WDM-PON technologies. While this setup has potential, there are issues with RB within a bidirectional system, and consequently requires advanced algorithms so as to avoid collisions. The SUCCESS-HPON architecture examines employing WDM
technology and connecting into the traditional PON access networks. Fiber technology provides the backbone for most communication networks.

High bandwidth OEO equipment proves a costly solution if implemented within an optical network. The reason passive optical networking has become so prominent is because it does not require the OEO conversion from the central office to the end user. With the advent of bandwidth intensive applications (see chapter 2) older PONs (BPON EPON and GPON) prove inadequate as they are limited by their bandwidth. WDM has the potential to significantly increase the available bandwidth.

### 3.3.2. WDM Access Network

The gap between the large bandwidth available within the backbone of networks and the limited bandwidth within the access networks is an ever increasing problem. Many MAN networks are capable of transmitting vast amounts of data but are restricted by the access network infrastructure. This gap in bandwidth can cause a bottle neck to build up at the intersection between MAN and access networks. The introduction of WDM into the access network helps bridge the gap between high bandwidth MAN networks and lower bandwidth access network.

<table>
<thead>
<tr>
<th></th>
<th>Capacity</th>
<th>Cost</th>
<th>Upgradability</th>
<th>Reliability</th>
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<tbody>
<tr>
<td>Point to Point</td>
<td>High</td>
<td>High</td>
<td>Easy</td>
<td>Medium</td>
</tr>
<tr>
<td>TDM-PON</td>
<td>Medium</td>
<td>Low</td>
<td>Difficult</td>
<td>High</td>
</tr>
<tr>
<td>WDM-PON</td>
<td>High</td>
<td>High</td>
<td>Easy</td>
<td>High</td>
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Table 2: Comparison between systems [44]

Factors that must be considered when trying to integrate WDM into an access network include backward compatibility, frame format, MAC protocol development, light source, video transmission format and protection/restoration.
The SUCCESS architecture looks at some of the issues and attempts to solve them.

3.3.3. SUCCESS-HPON Architecture

The SUCCESS-HPON architecture attempts to combine WDM-PON and TDM-PON networks in order to provide a hybrid WDM/TDM optical access network. It supports both ring and tree topologies. The ring architecture acts as a backbone for the tree, see Figure 8. Major design goals are compatibility with TDM-PONs, ease of upgradability (i.e. future upgradeability from TDM-PON to WDM-PON) and protection/restoration capability [45].

The architecture of the SUCCESS-HPON is illustrated in Figure 8 below. The ring acts as the backbone for the tree by supplying wavelengths to the Remote Nodes (RN), which are then distributed to the ONUs. There is a point to point connection between the OLT and each RN and a point to multipoint connection from the RN to the ONU. The setup for the SUCCESS-HPON uses bidirectional communications in the MAN and access network (see Figure 8 a). This delivers some fault tolerance when a fiber is cut, but at the cost of greater Rayleigh Backscattering (RB) distortions, which also reduces the useable wavelength spectrum by half. This effectively halves the number of users that the network is capable of having.
Figure 8: SUCCESS-HPON: a) overall architecture; b) OLT block diagram; c) ONU setup [44]

A TDM-PON RN has two CWDM splitters per PON, while the WDM-PONs has one Course-WDM (CWDM) dropping a group of Dense-WDM (DWDM) channels. The system uses a separate wavelength for both upstream and downstream. This reduces the usable wavelengths by half, similar to the system based on OBS above. An AWG generally has a loss of 6dB regardless of the number of ports used. Thus, the more ports used the better the power budget.

In Figure 8 b) fast tuneable lasers and filters are used. The average load on the access network is low, so using tuneable components reduces the transceiver count, thus reducing CAPEX and OPEX. The system is modular, so the addition of extra tuneable devices is possible. A scheduler controls the operation of the tuneable devices. The tuneable transmitters at the central office send the downstream data and the CW to the ONU for retransmission. For feasibility reasons half duplex communication are used in the SUCCESS-HPON network as
similar tree architectures that implement full duplex require double the fiber. Sophisticated MAC protocols and scheduling algorithms are required for the bidirectional SUCCESS-HPON architecture.

A network upgrade consists of a number of stages. Firstly, the passive couplers in the TDM-PON are replaced with RNs. The sole replacement of RNs reduces the downtime of the network when upgrading. The next stage, which involves increasing the capacity of the network, has an AWG in the form of a DWDM connected to the RNs. This means a dedicated channel between the ONU and the OLT can be established. The ring network acts as a backhaul for the TDM-PON networks [46].

3.4. Rayleigh Backscattering (RB)

Bidirectional transmission over a signal fiber is used in all traditional PONs including WDM-PON. In the tree architecture doubling the amount of fiber to remove the RB effects is one option. In these PON systems RB has two ways of causing degradation of system performance. The first occurs in all optical networks were miniscule faults in the manufacture of fiber cause small reflections over the entire length of fiber. This type can be fixed by amplification methods (see Figure 9 a), b) and c)). The second type occurs when bidirectional communication is used on the same fiber; it is when mixing of similar wavelengths travelling on a single fiber interfere and increase the noise (see Figure 9 d) and e)). This noise is called Coherent Rayleigh Noise (CRN), which is the dominant noise source in a bidirectional optical fiber system [47]. Due to RB part of the downstream pulse signal is reflected back and mixed with the upstream data signal. The back reflected pulse has the same wavelength like that of the uplink data signal, which cannot be separated by using an optical filter and contributes to in-band crosstalk. The two forms of backscattering are looked at in more detail in the next section.
3.4.1. Rayleigh Backscattering Types

Rayleigh Backscattering is one of the main causes of distortion in bidirectional WDM systems. There have been many mitigation and suppression techniques like half duplex communication and spectral widening. In a full duplex WDM-PON there are three signals, two in the downstream (the data and the carrier) and one in upstream (e.g. in the opposite direction). In this circumstance the signals are exposed to crosstalk interference due to RB. The upstream signal suffers the most with twice the attenuation and component issues. There are two types of reflection that cause RB (see Figure 10); the first “type I” reflection (e.g. “Reflection-I” in the figure) on the Continuous Wave (CW) light, and the other (e.g. “Reflection-II” in the figure) is from the upstream modulated signal. Reflection-I has been extensively researched and can be minimised via signal amplification by the ONU [49]. In WDM systems the goal is to create a network as cost effective as possible. Doubling the fiber amount to have separate fibers for upstream and downstream to
remove the distortions caused by type II reflection has been overlooked due to large costs associated with fiber cable costs (see section 6.2). It has been shown that optimising the gain of the transceiver at the ONU can help minimise this reflection [7].

**Figure 10: Two types of optical back reflections [7]**

In Figure 10 reflection-II travels toward the ONU with the CW light distributed from the central office. Once the signal is modulated again it causes intensity noise at the Optical Receiver (OR) as it interferes with the upstream signal. Figure 11 shows the relative received power at the receiver versus ONU gain. Reflection-II power is increased in proportion to the square of ONU gain, since reflection-II passes through the optical amplifiers twice in the ONU. Reflection-II is the dominant noise at low ONU gain; however, the impact of reflection-II exceeds that of reflection-I when the ONU gain is high. Therefore, ONU gain optimisation is required to maximise the received SNR [7]. A brute-force solution to eliminate the influence of any reflections would be the transmission over two separate fibers.

**Figure 11: Impact of the different reflections with ONU gain [7]**

In a real WDM-PON network where multiplexers and splitters are present, gain restrictions are more relaxed due to the filtering. AWG multiplexers act as filters,
therefore improving the sensitivity slightly. All PON networks that utilise the bidirectional tree network suffer RB type I and II distortions. It has a large impact on achievable distance in bidirectional networks.

3.4.2. Reduction Technique of the Relative Noise caused by RB

This section provides an overview of different methods to reduce the influence of the RB crosstalk in a Passive Optical Network employing Wavelength Division Multiplexing. Key advantages and disadvantages of each method are given.

3.4.2.1. Optical Bandwidth Separation

At the cost of a laser-source (instead of a transparent ONU) and a wavelength duplexer in the ONU as well as a AWG at the Remote Node (RN), the improvement can be introduced through optical bandwidth separation, where the two counter-propagating signals occupy different optical RN with sub-bands [50]. Where two wavelengths are required for transmission the first wavelength is encoded with data and the second wavelength is used as a seed to be modulated and transmitted back on the same fiber. When a wavelength is terminated at the ONU, no reflection II occur. Methods based on wavelength multiplexing are bandwidth-inefficient, as two wavelengths are assigned to a single ONU. This results in the reduction of the number of ONUs by a factor of two.

3.4.2.2. ONU Gain Methods

Another way to reduce the effects of RB distortions is to vary the position of the remote node, since fiber length and split effects the gain [51]. As a result the optimal RN positioning as well as optimal ONU gain should be taken into account by network designers. However, in a real-world deployment, the position of the RN is dictated by more practical reasons i.e. urban-rural landscape, and fibre costs.
Gain optimisation of the ONU is important in reducing the effects of reflection-II RB. A deliberate setting of the gain enables the achievement of the highest Signal to Crosstalk Ratio (SCR) \[7\]. Remotely seeded ONUs has worse SCR performance than the SCR light sources at the central office.

3.5. Dynamic Bandwidth Allocation

While TDM adds some bandwidth efficiency into WDM systems, the next logical step is to dynamically assign time slots to users i.e. users are polled to see if they require bandwidth and are assigned slots only when a request is made. Bandwidth on Demand (BoD) services with a set Quality of Service (QoS) can be implemented with Optical Burst Switching (OBS).

OBS is an optical networking technique that allows for dynamic time allocation of data from the central office. OBS is viewed as a compromise between the yet unfeasible all Optical Packet Switching (OPS) and the static Optical Circuit Switching (OCS).

OBS transmits data in bursts of light from the central office to the end user. A dynamic bandwidth scheduler at the central office is responsible for signalling and QoS. In TDM-PONs the signal transmission is shared on a single wavelength. To achieve greater user penetration AWGs that combine many wavelengths are introduced and multiplexed onto a single fiber. Reconfigurable Optical Add Drop Multiplexers (ROADM) would allow dynamic add/drop functionality (see Figure 12).
3.5.1. Optical Burst Switching (OBS) and Dynamic Bandwidth Allocation (DBA)

OBS PON architectures use a central scheduler at the OLT to control the Medium Access Control (MAC) protocol in the network. The WDM/TDM network transmission requires fast tuning LDs. A burst mode receiver is used for fast level recovery and Clock-Data Recovery (CDR) is used to adapt for phase variations of the received burst.

Polling plays an important role in the DBA algorithm. A control slot with data is transmitted to each ONU. Message transmissions are cycle–based. A cycle is defined as the time interval between two consecutive polls of the same ONU. Inactive ONUs are polled less often than active ONUs so as to save bandwidth and, thus, perform more efficiently. The formula for the Cycle length ($T_c$) is:

$$T_c = T_s + T_d = N(t_{co} + t_{LD}) + T_d$$

Equation 1
Where $T_s$ is the signal period, $T_d$ is the dynamic transmission period, $N$ is the division of equal fixed control slots, $t_{co}$ is the ONU slot control time and $t_{LD}$ is the guard time that separates the slots.

The OLT is aware of all network traffic requirements and a different QoS can be provided to different categories of customers. Data loss may occur at the OLT or ONU if there is a buffer overflow. It is possible to use OBS as an optical bridge between the metro and access network.

### 3.5.2. Priority Queue Management in OBS

Bandwidth management of different Class of Service (CoS) is an important part in implementing Quality of Service (QoS). In the OBS system priority queue management is needed. The OBS system does all the scheduling at the central office for the downstream, while the upstream scheduling is implemented at the ONUs. Three queues for different CoS are implemented (P1, P2 and P3), where P1 has the highest priority, P2 has the middle, and P3 has the lowest priority. Certain services require a higher priority than others; voice would need P1, streamed video P2, and data transfer P3. When packets arrive they are assigned according to their CoS. If a queue is full and a high priority packet arrives, the lower priority packet is assigned to a different queue to allow room for the high priority packet. Also on the receiver side, an incoming low priority packet is dumped if the buffer is full of high priority packets.

Packets are aggregated into bursts until the frame is full, or a set time is reached. A transmission request is given and assigned a priority. The time on the frame burst might be different, depending on its priority. The Priority scheme is managed by the Dynamic Bandwidth Allocation (DBA) module. The DBA applies strict priority mechanism to the arrived request from the ONU. With the DBA in place a level of QoS can be guaranteed.
3.6. Related Technologies and Architectures

This chapter outlines relevant optical technologies that are necessary to examine to give a better understanding of the proceeding chapters.

Fiber cables have two main types. Single Mode Fiber (SMF) is used in long distance (>550 meters), while MultiMode Fiber (MMF) is used for short distance (up to 550 meters) communications. The proposed research focuses on SMF. When developing networks, different fiber distortions need to be accounted for. These include dispersion, attenuation, and reflection. Fiber cables can help remove or reduce some of the effects.

There are many types of lasers that are used in different situations. Generally as the wavelength spectrum increases, the costs of the lasers increase. The C and L Band (see Table 1) suffer less attenuation than the shorter wavelengths. This allows the signal to travel further. There are two ways to modulate a laser signal, firstly by direct modulation of the laser diode by varying the current supply, secondly by external modulation where changes to the light source are made after the laser has produced a beam.

![Figure 13: Optical bands and associated loss [53]](image)

Filters play an important role in selectively transmitting light with a particular frequency. They are extensively used in WDM networks to separate the different transmissions within light (i.e. add or drop specific signals). Optical amplifiers are
used in long distance communication where signal degradation occurs. Different techniques are used across the bands. Receivers obtain photonic information from the light source and convert the photonic signal into an electrical signal.

### 3.6.1. Fiber Optic Cables

The type of optical cable used in a network can make a huge difference to how an optical network functions. It can affect distance, amplification, dispersion and polarisation compensation [54].

MMF does not work well over long distances (>550 meters for 10 GB/s), as the signal suffers from degradation\(^8\). For systems requiring greater distances SMF is utilised. The main difference between MMF and SMF is the mode of transmission; SMF only travels with one mode (as seen in Figure 14). Having only one mode reduces the amount of light that leaks into the cladding (blue area in Figure 14). There are a number of special types of SMF, which have been chemically or physically altered to give special properties, such as cutoff shifted fiber, low water peak fiber, dispersion shifted fiber and non-zero dispersion shifted fiber. The proper use of these fibers can reduce distortion effects and increase the distance a signal can travel.

![Figure 14: Different propagation modes of MMF and SMF [55]](image)

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\(^8\) Only in specific circumstances and with special fiber manufacture does MMF work at these distances.
Below is a review of the different types of fiber cable as well as its strengths, special features and requirements. Causes of signal degradation are shown in Figure 15. The top part of the figure represents what is commonly called attenuation or fiber loss. The intensity of the light pulse decreases as the pulses travel along the length of the fiber. Fiber loss will decrease the amount of light that is available for the receiver, but it does not cause the signal to move out of its proper time interval.

![Figure 15: Causes of signal degradation](image)

There are two other mechanisms of signal degradation that do not involve loss of light intensity, but that do cause the pulse to broaden and move out of its time slot. The first, called modal dispersion, results from the fact that light can travel along different paths down the length of the fiber. This means that the initial short pulse will be broadened and will spread out of its time slot. The second, called chromatic dispersion, results from the variation of the index of refraction with wavelength, so that light at different wavelengths travels through the fiber at different velocities.

The two type of fiber used in the proposed system is Standard SMF fiber and Dispersion Compensating Fiber (DCF). Over large distances the effects of dispersion cause the signal to alter from its original state see Figure 15. The use of
DCF counters the dispersive broadening of modulated signals that can occur with high data rates.


Standard single-mode fiber is essentially a thin core of Germanium-doped glass surrounded by a thicker layer of pure glass. It is the most widely used type of fiber. Most WAN, MAN and access networks are implemented with standard SMF. Standard SMF may have more imperfections than other SMF types, which are caused in the manufacturing process.


Dispersion Shifted Fiber (DSF) was developed in the 1980s. It has a small percentage of the market compared with standard SMF. The development of 1550nm wavelength lasers brought about the need for DSF, which has much less attenuation than 1310 nm wavelength, see Figure 13. DSF allows optical signals to travel significantly further because it counters the effects of dispersion, effectively allowing an optical pulse to maintain its integrity over longer distances. The advent of amplifiers and WDM systems lead to DSF having destructive effects on multiple channel systems. A new type of fiber was introduced, namely Non-Zero Dispersion Shifted Fiber (NZDSF). With the introduction of NZDSF, DSF is all but disappeared [56].

3.6.1.3. Non-Zero Dispersion Shifted Fiber (NZDSF) IEC 60793 B4 / ITU G.655

NZDSF was introduced in the 1990s to solve the issue DSF had with multiple wavelength transmission. It fixed the amount of chromatic dispersion encountered in the 1530-1625 nm wavelength bands, which is commonly used by WDM. The issue of the nonlinear effect known as Four Wave Mixing (FWM) was also resolved by NZDSF. FWM is when interactions between 3 wavelengths produce a 4th wavelength in the signal. This extra signal could cause interference in a
channel that is been transmitted close to it. NZDSF reduces this effect by ensuring that some finite dispersion is applied and so the signals on adjacent wavelengths will not overlap for extended periods. Reducing the chromatic dispersion also reduces other nonlinear effects such as Self-Phase Modulation (SPM) and Cross-Phase Modulation (XPM). NZDSF is optimised for transmission in the 1530-1625 nm wavelengths but can support some 1310 nm configurations [56].

3.6.2. Laser Sources

A fiber optic network uses light as opposed to electrical signals to transmit data. Albert Einstein was the first to show how the energy in light could be focused so that it occurred at a single frequency [57]. Light Emitting Diodes (LEDs) are used in short range relatively low bandwidth applications in conjunction with MMF. There are many types of lasers used for communications, some have advantages over others, some self modulate, some can be tuned to different frequencies and some help amplify the signal. The price for lasers ranges from a tens of dollars to thousands of dollars. The different characteristics of lasers direct them to be used in different system setups, for example a Distributed Feedback Laser (DFB) is more suited to WDM, while LEDs are primarily used in MMF setups. The following sections are a review of various lasers that can be used in WDM setups.

3.6.2.1. Distributed Feedback Laser (DFB)

A DFB is a laser where the whole resonator consists of a periodic structure, i.e. an identical structural component which is joined together end to end. To change the frequency a temperature change is applied to the grating, which in turn changes the refractive index. Reflections provide feedback to the laser creating high losses at all but one wavelength, so that the laser oscillates at one frequency only, making the DFB essentially a monochromatic source. The ability to tune the DFB laser makes it useful in Dense WDM (DWDM) applications where many different wavelengths are needed [58]. The precise sharp spectrum of a DFB laser (see
Figure 16) makes it ideal for WDM systems as the wavelength will be positioned close to each other.

![DFB Laser Output](image)

**Figure 16: The typical DFB laser output [59]**

### 3.6.3. Receivers

The task of the optical receiver is to extract the information from a modulated light and return the optical signal back into its electrical form. Optical receivers are based on photodiodes. When a photon of sufficient energy strikes a photodiode, it excites an electron, thereby creating a free electron, which can be detected and converted into an electrical signal. A photodiode is a type of photodetector capable of converting light into either current or voltage, depending upon the mode of operation.

### 3.6.4. Modulators

An optical modulator is a device which manipulates the properties of light to embed a signal into it. There are many modulation techniques like amplitude, intensity, phase, polarisation etc. In optical systems there are two ways to implement light modulation, direct and external modulation. Direct modulation is when the light source is turned on and off by high speed switching. External modulation is when a stable light source is tuned externally. There are many modulator types and modulation methods but the main two that relate to the
proposed research are Mach-Zehnder Interferometer (MZI) and Electro-Absorption Modulators (EAM).

3.6.4.1. Interferometers

An interferometer is a device that can utilise the effects of optical interference. A Mach-Zehnder interferometer (MZI) is a type of interferometer. When a signal is split into two streams, one beam is delayed, so when they recombine the superimposed waves cause an interference effect on each other (this is called destructive interference). On the other hand if both waves are split and unhindered, this is called constructive interference. Figure 17 shows an illustration of how an interferometer works.

![Constructive and Destructive Interference](image)

Figure 17: Constructive and destructive interference

3.6.4.2. Electro-Absorption Modulators (EAM)

An EAM is a semiconductor that controls the intensity of a light beam by an electric voltage. An EAM operates when a change in the absorption spectrum is caused by an electric field, which changes the band gap energy. EAMs can operate at much lower voltages, so they are much more desirable on integrated circuits. EAMs can operate at 10s of Gigahertz. Compared with direct modulation of a laser, a higher bandwidth and reduced chirp can be obtained.

3.6.5. Optical Modulation Methods

In optical communication, modulation is the process of imprinting information onto a light beam by the use of a modulator. Modulation of light can be carried
out in different ways. New methods of modulation have increased the bandwidth by implementing better encoding techniques. The properties of light allow modulation of different polarisations. The following sections examine how encoding schemes can directly influence fiber, distance, error rate and synchronisation. The modulation method used in 10 GB/s systems is generally amplitude modulation. While other more sophisticated methods are used in faster communication networks 40 GB/s+ like Differential Quadrature Phase Shift Keying (DQPSK).

3.6.5.1. Amplitude Modulation

OOK is a method of turning the carrier on and off at high speed. Traditionally OOK was done using the NRZ scheme as illustrated in Figure 18. Self clocking of the signal is not accomplished by NRZ encoding. This can hinder TDM networks that require synchronisation. The NRZ technique is used primarily below 10 GB/s transmissions. For higher speed transmissions more complex modulation schemes are needed [60].

The Return to Zero (RZ) version of OOK makes the clock recovery a lot simpler by making the signal return to zero in the middle of a bit period (see Figure 19).

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9 A Self-clocking signal is one that can be decoded without the need for a separate clock signal or other source of synchronisation. This is usually done by including embedded synchronisation information within the signal.
Based on NRZ and RZ more complex schemes such as Differential Quadrature Phase-Shift Keying (DQPSK) have been developed.

3.6.6. Optical Architectures

How an optical network is constructed can make an enormous difference on how it functions. Greater optical losses can occur with some architecture. Improvement in network design can lead to increased distance and reduction of distortions. For example, the tree architecture of traditional PONs experience additional distortion effects compared with a ring network due to bidirectional interference (Rayleigh Backscattering type II). Optical network design requires many factors to be examined.

3.6.6.1. Access Networks

The access network in telecommunications is the network that connects the subscribers to their Internet Service Provider (ISP). One of the main competitors in the access network is Digital Subscriber Line (DSL). There are many types of DSL, but the most recent (i.e. 2006) technology is VDSL2. VDSL2 can achieve 100 MB/s over half a kilometre.

Copper based communications like DSL can never compete with optical solutions. With the vast advantages fiber has over copper technologies governments and private companies are continually deploying fiber, with the objective to reduce the CAPEX and OPEX [61-62]. There is a big shift from copper to fiber based communications. Of the current passive optical architectures EPON and GPON are the most prevalent. WDM is the next logical step once the maximum bandwidth for the different PONs is reached.

3.6.6.2. Passive Optical Networks (PONs)

A passive network delivers bidirectional communication without the need for electric power between the central office and the end user. There have been many
developments of PONs from the first ATM-PON (APON) to recent WDM-PONs. A PON has a tree point to multipoint architecture, see Figure 20. A transmitter at the central office (commonly referred to as OLT) sends a signal on an optical fiber, where it is passively split and delivered to the end users ONU\textsuperscript{10}. Developments in PON equipment technology has helped increase the split ratio and bandwidth. PONs are limited to approximately 20 km transmission distance due to the effects of Rayleigh Backscattering (RB).

![Figure 20: PON tree architecture](image)

Passive optical networks have being around for a while and have seen many iterations in the hardware that delivers the communications network. Advances in the hardware have allowed faster data to be delivered. EPON and GPON are currently the two main PONs being deployed. The advances also deliver an ability to increase the split ratio on the strands of fiber to increase the user base per PON.

- **APON/ BPON**: This PON uses different wavelengths to transmit video (1550nm), data (1490nm), and voice (1310nm).
- **EPON**: The main difference to its predecessor (APON/BPON) is that EPON uses the IP protocol to transmit voice, video and data. This utilises the economies-of-scale of Ethernet. A Time Division Multiple Access (TDMA) protocol is implemented, so that only one user can transmit at any given time interval.
- **GPON**: GPON natively supports Ethernet, ATM, and TDM, but most systems run just Ethernet. A higher split ratio of 1:128 can be achieved but

\textsuperscript{10} In passive optical networks ONU\textsubscript{s} are the same as End Premises Units (EPUs)
at a loss of achievable distance. In practice the ratio is typically 1:32 or smaller.

- **10GEPON**: 10G-EPON is back-compatible with EPON networks and equipment due to the use of separate wavelengths. In the downstream direction the 1GBit and 10GBit channels are separated in the wavelength domain with 1GBit transmission limited to 1480-1500 nm band and 10GBit transmissions using 1575-1580 nm band.

- **WDM-PON**: This setup uses a separate wavelength for each user. The splitter is substituted with an Array Wave Guide (AWG) to join and split multiple wavelengths. The virtual point-to-point setup can deliver huge bandwidth to each user while providing high security. Deploying a WDM-PON system to the access network is currently too expensive. Hybrid WDM/TDM-PON networks offer a stepping stone to a full WDM-PON network.

### 3.7. Related Research Conclusion

This chapter provided an overview of the current research been undertaken in WDM networking and consisted of:

- Examination of commercial deployments of WDM in the access network.
- A review of research on transceiver design for the ONU.
- Implementation of TDM into WDM by Stanford University aCCESS (SUCCESS) project.
- A look at Rayleigh Backscattering (RB) and how it is applicable in all current PON optical networks designs.
- How bandwidth can be assigned dynamically using polling of ONU and optical burst queues to make better use of the data recourses.
- This section has also reviewed optical equipment, encoding schemes and architectures. A broader understanding of their use will help give a better understanding with some of the choices made in the following chapters.
With these areas examined the proposed work in the following chapters can be better understood and the scope of the research acknowledged.
Chapter 4

Research Methodology

4.1 State of the Art

In the previous chapter, areas relating to the proposed research were examined. A look into commercial developments in South Korea and the steps they took in researching and developing a WDM network were examined.

Stanford University researched an approach into developing a hybrid WDM and TDM-PON. They integrated a ring MAN with current commercial tree PON architectures. This was to bridge the gap between the future full WDM-PON and current PON systems.

The effects of Rayleigh Backscattering (RB) were examined. Papers detailing the effects of RB on bidirectional communications networks were analysed and it was concluded that RB distortion plays an important role within bidirectional fiber networks. It was observed that of the two types of RB, type 2 has more destructive interference than type 1.

Optical burst switching and dynamic bandwidth allocation was studied and it was concluded that these technologies could be a solution to further increase the bandwidth efficiency within a WDM/TDM networks.

Examining current optical communications technologies and architectures was undertaken to give an overview of the technologies that will be used within the proposed research.
4.2 Research Approach

While looking at optical communication networks and their use of resources, a few areas stand out as potential areas of improvement and form the basis of this thesis. A logical 3-stage approach is adapted as follows;

Stage1: Simulation: Examining the feasibility of using a transparent modulator as a transmitter in the ONU

Stage2: Hardware testing: A test bed setup examining the use of a modulator as a transmitter

Stage3: Simulation: Examination of the MAN-Access network, while incorporating the transparent modulator from the first two stages

Throughout the simulation setup, specific industry commercial standards were adhered to. For example the maximum acceptable BER in a telecommunications system is $10^{-9}$ [12].

4.3 Initial Simulation

In Chapter 5 research regarding the feasibility of the modulator as a remote transmitter is examined. Due to considerable costs associated with setting up an optical communications network the only reasonable way to test a complete optical network is to simulate it with software. OptiSystem [9-11] is an optical communication simulation package for the design, testing, and optimization of virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from long-haul systems to LANs and MANs. It is a system level simulator based on the realistic modelling of fiber-optic communication systems. Its capabilities can be easily expanded with the addition of user components and seamless interfaces to a range of widely used tools.

The available tools supplied by Optisystem simulation software used to examine optical networks are;
• A WDM analyser which checks for any discrepancies in the various wavelengths running throughout the system.
• An optical spectrum analyser was used to examine the spectral composition of optical waveform.
• An eye diagram analyser visually analyzed the system performance. It can indicate errors, short-long signals, poor synchronization and noise by visually inspecting an eye pattern.
• BERT testing checks the quality of a link by sending out a known bit pattern and verifying that the received pattern matches. Bit errors occur when the patterns don’t match. An Optical Time Domain Visualiser is used to examine the signal based on time sections of the signal. It is helpful in determining the synchronisation of a system.

Stage one in the research demonstrates a simulation setup showing the effectiveness of using an external modulator as a remote transparent transmitter at the end users ONU. Both NRZ and RZ encoding schemes were used to benchmark the remote transmitter setup.

4.4 Hardware Test Bed

In chapter 6 a hardware test bed setup demonstrating the initial simulation setup of chapter 5 is implemented to test the effectiveness of using a transparent modulator as a remote transmitter.

The hardware setup consisted of using off the shelf components. An XFP module was used as the remote transceiver. A 10GHz LiNbO3 modulator was engineered to take the place of the laser transmitter on the XFP module. This setup allowed the XFP module to receive and transmit on many wavelengths.

4.5 Full Scale WDM/TDM Network Design

The next step is to integrate the remote transmitter design from chapter 5 and 6 and integrate it into a complete optical network architecture. The simulation
software is used again as it is the only economically feasible way is to run the network setup.

With the initial remote transceiver testing completed, a new optical architecture is designed to:

- Integrate the remote transceiver design from stage 1 and 2.
- Reduce the amount of fiber cable required compared with traditional tree PONs.
- Remove the distortion affects of type two Rayleigh backscattering.
- Introduce Time Division Multiplexing to deliver economical use of bandwidth.
- Demonstrate an all optical MAN-Access interconnection removing the need for Optical-Electrical-Optical conversion.

All the Optisystem analysis tools mentioned above in section 4.2 were used to analysis the networks feasibility.

The simulation software Optisystem [10-11] has sample network architectures in its database to compare and contrast results against. Results obtained in the thesis simulations were compared to a standard Optisystem example that consisted of a 32 channel Non Return to Zero (NRZ) and Return to Zero (RZ) WDM. By obtaining the BER and Q values from Optisystem standard WDM systems a correlation between the standard and proposed systems can be examined and analysed.
Chapter 5

Design and Evolution of Proposed WDM-PON Architecture

The motivation of the majority of WDM access network research is to enhance current systems at a reduced Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) cost [8, 20, 36, 41, 44, 63-67]. At present, bandwidth within the access network is in most cases provided via copper and cable networks and, in a small number of cases, provided using optical TDM-PONs.

The system in Figure 21 shows an illustration of the experiment used to implement the network design; it is a full WDM-PON capable of delivering 10GB/s per user. It incorporates a 10GB/s transparent remote ONU for the retransmission of a Continues Wave (CW) signal. The use of three fibers allows a full duplex communication.
The goal of this chapter is to analyse the feasibility of using an external modulator as a remote transparent transceiver. The advantage of using this design is to reduce OPEX and CAPEX cost associated with optical network. Having a colourless-transparent device like an external modulator based at the ONU allows many wavelengths to be used with the device. This is the basis behind much research in WDM access networks. The initial testing of the remote transparent transceiver is carried out using Optiwave Optisystem simulation software to test its feasibility. The follow on experiment in chapter 6 looks at hardware testing of the simulation testing carried out in chapter 5.

5.1. Network Description

As illustrated in Figure 21, a central office encompasses elements A to D with element A representing a continuous wave non-tuned laser source, which generates multiple wavelength outputs. For simplicity, three such outputs are shown labelled $\lambda_1$ to $\lambda_3$. In reality, many more such wavelengths could be outputted from the laser source. Each signal (wavelength) originating from the
laser enters a beam splitter B. While the beam splitters for each signal are illustrated as distinct from one another, a single beam splitter could split multiple signals [68]. One output signal for each wavelength is directed to a dedicated modulator C in order to encode that particular wavelength with information before transmission to a remote terminal F. The transparent modulators encode the optical signal at the wavelength output by the laser A. The modulated or encoded signal is directed from each modulator to a multiplexer D1, which combines light of different wavelengths for transmission over the network on a single strand of fiber.

The extra output of each beam splitter Bn, which is an un-encoded signal with wavelength $\lambda_1$ to $\lambda_n$, is routed directly to an additional multiplexer D2, which combines the un-encoded light signals of different wavelengths for transmission over an extra strand of optical fiber.

Each of the two strands of optical fiber, which facilitate a long-distance transmission, terminates at their corresponding demultiplexers E1 and E2. These demultiplexers form part of a local exchange, which distributes the downstream signals to individual terminals over the so-called “last mile”, and which receive the upstream signals from the terminals for transmission back to the central office.

The demultiplexer E1 receives the combined encoded signals of wavelengths $\lambda_1$ to $\lambda_n$. It then splits the combined signal into the respective component wavelengths and directs each wavelength to a separate endpoint terminal F, where an optical receiver component of the endpoint terminal receives and decodes the optical signal to recover the encoded information.

The second demultiplexer E2 receives the combined un-encoded signals of wavelengths $\lambda_1$ to $\lambda_n$, and, similar to E1, splits this combined signal into the respective component wavelengths and directs each wavelength to a separate endpoint terminal F. Terminal F receives both the encoded signal of a wavelength $\lambda_i$ as well as the un-encoded signal of the same wavelength $\lambda_i$. The un-encoded signal is passed through a transparent modulator, which uses electrical signals to encode the received signal as it passes through.
The output of the modulator is returned to the local exchange via a fiber link. A multiplexer D3, situated at the local office, combines the various received encoded upstream signals coming from each of the endpoint terminals. The wavelengths $\lambda_1$ to $\lambda_n$ are combined by the local exchange multiplexer and transmitted over an upstream fiber to a demultiplexer E3 at the central office [22].

### 5.2. Testing Methods

The experimental setup used to demonstrate the principle of the proposed technique consisted of a Distributed-Feedback (DFB) laser which was modulated by 10GB/s LiNbO$_3$ modulators with a NRZ and RZ signal (with a pseudo random pattern length of $2^{31}-1$). The modulated signal source was multiplexed using a Course Wave Division Multiplexer (CWDM). The first experiment was carried out to investigate the possibility of implementing a transparent remote ONU architecture using RZ and NRZ encoding schemes while examining the achievable distance.

Software simulation tests using OptiSystem were designed to compare the different encoding schemes of NRZ and RZ within the remote transparent network illustrated in Figure 22. The software simulations incorporated performance tests for both NRZ and RZ and compared them. These consisted of:

- A WDM analyser used to check for any discrepancies in the different wavelengths running throughout the system and to examine the power levels.
- An eye diagram analyser is used to visually analyse the system performance. This can highlight errors, short-long signals, poor synchronisation, and noise by visually inspecting an eye pattern.
- BERT testing is used to check the quality of links. It operates by sending out a known bit pattern and verifying that it and the received pattern match. A bit error has occurred when the patterns don’t match. The network is set in a loopback mode so that the transmitted packets are looped back to the same interface.
The results obtained by the optical analysis tools were collected and inputted to a graph to show what distance different encoding schemes can accomplish using a transparent ONU network layout.

Figure 22 illustrates the network layout for the system which is developed using the simulation software Optiwave. It shows 8 Continuous Wavelengths (CW) being multiplexed onto a single fiber over varying distances. Analysis of the uplink from the central office trough to the ONU and back to the central office was examined. The downlink in this experiment was not analysed since it was implemented as a standard central office to ONU link on a separate fiber.

5.2.1. BER Testing (BERT)

The BER is the most significant performance parameter of any digital communications system. It is a measure of the probability that any given bit will have been received in error. The standard maximum bit error rate specified for many systems is $10^{-9}$. This means that the receiver is permitted to generate a maximum of 1 error for every $10^9$ bits of information. Telecommunication applications specify that the maximum BER falls in the range $10^{-9}$ to $10^{-12}$ [69].
The BER depends primarily on the Signal to Noise Ratio (SNR) of the received signal which in turn is determined by the transmitted signal power, the attenuation, dispersion and the receiver noise. Measurement of the BER is not a trivial process, particularly at high bit rates. The effects of noise and other signal degradation processes can be investigated qualitatively by inspecting the “eye diagram” of the system. Signal and BER degradation trends can be observed due to the effects of signal attenuation and dispersion.

The following tests of RZ and NRZ used a maximum BER of $10^{-9}$ as a limit for determining the distance the network is capable of successfully transmitting using NRZ and RZ. Both encodings showed different tolerances to fiber non-linearities, which demonstrated that in a transparent ONU ring network, different encoding schemes can have an influence on the transmission distance.

5.3. Analysis of NRZ and RZ Encoding on a transparent ONU

NRZ modulation has been used extensively in many data communications systems, primarily because of its simplicity and low bandwidth requirements (which is about 50% lower than that required by RZ modulation). Due to its simplicity and low cost, NRZ is the standard modulation technique used within optical communication networks. RZ modulation is mainly used within submarine systems where the extra cost of the equipment can be justified. However, more recently 10GB/s systems are incorporating RZ modulation due to its higher peak power, higher signal-to-noise ratio, and lower bit error rate when compared to NRZ. In addition, RZ modulation allows for the transmission of data over greater distances when compared with NRZ (see Figures 24-27 below).

A 10-GB/s NRZ and RZ scheme is experimentally demonstrated in a remote transparent WDM-PON access network. To evaluate the performance of the proposed system, light from a tuneable laser is externally modulated by a LiNbO3 intensity modulator with a $2^{31}-1$ Pseudo Random Binary Sequence (PRBS) and encoded separately using both NRZ and RZ. RZ signals can be generated either in the optical or electrical domain. RZ signals generated within the optical domain require an additional expensive modulator. RZ signals generated within the
electrical domain can use a high speed AND gate. The electrical approach provides a cost effective solution for RZ systems. Inphi-Corp have demonstrated a high speed NRZ to RZ conversion using an AND gate, see Figure 23 [70].

NRZ and RZ have both advantages and disadvantage when used to link and interface Optical Time Division Multiplexing (OTDM) and WDM networks. NRZ is more suited to WDM networks because of its high spectral efficiency and timing-jitter tolerance. RZ is widely employed within OTDM systems due to its tolerance of polarisation mode dispersion as well as its superior performance in terms of receiver sensitivity and transmission performance [71].

![Figure 23: NRZ to RZ conversion in the electrical domain using high speed AND gate](image)

Figure 24 and 25 illustrate the decrease in the Q factor and received power as the distance increases. It can be observed from the figures that RZ has an advantage over NRZ, when distance and power budget is taken into account. The average power budget increase observed when using RZ encoding within the remote WDM-PON network is approximately 1.06dBm, when measurements between 50 km and 70 km are analysed.
The Bit Error Rate (BER) values differ significantly between 50 km and 60 km for both RZ and NRZ encoding. At a distance of 50 km the value of the BER for RZ encoding is insignificant to matter \(5.63 \times 10^{-41}\). The NRZ test showed a smaller BER of \(2.51 \times 10^{-13}\), which is still substantially higher than the RZ BER over the same distance. This implies RZ encoding has a greater error tolerance. As telecommunications systems require a BER of \(10^{-9}\) as a minimum, the maximum
distance using NRZ and RZ encoding is obtained from this value. It is shown that the RZ encoding can increase the distance the signal can travel by approximately 7-8 km, when comparing it with NRZ encoding.

Attenuation within the system was set to 0.2 dBm/km. The receiver’s maximum sensitivity was set to -18 dBm. This value is an average of the commercial receivers on the market, as different optical receivers have different sensitivities. Using NRZ encoding and adhering to a minimum BER value of $10^{-9}$, the maximum distance achievable with this remote ONU setup was approximately 61 km (see Figure 26). Using RZ encoding the distance can be increased to approximately 69 km (see Figure 27). The results indicated a power advantage of approximately 1.06dBm when RZ encoding was employed as opposed to NRZ encoding. This translates into an increase of between 7 and 8 km in terms of the additional transmission distance.

![Figure 26: NRZ’s BER over distance](image-url)
5.3.1. Wavelength and Spectrum Analysis

The WDM-PON system was designed to transmit 8 separate wavelengths. The analysis showed distances of 50 km from the central office to the ONU and 50 km for the return trip. Figures 28 and 29 show the signal power at the start (approximately 13dBm) and end (approximately -9dBm). The power is split in 8 and reduced so as to reduce effects from high launching power in a fiber. The -9dBm is well within the threshold of most commercial receivers that typically have a sensitivity of around -25 to -18dBm. The Signal power after traversing the 100 km is approximately -9.8dBm as seen in Figure 29.
An Optical Spectrum Analyser (OSA) shows the spectrum of wavelengths, the power (dBm), and the wavelength in THz. In Figure 30 (on the left) the OSA shows the output of the first wavelength after an Array Wave Guide (AWG) is used to split the designated channel (1552.52nm=193.1THz) from the 8 wavelengths. Figure 30 (on the right) shows all 8 wavelengths combined on a single fiber strand for the main hall of the network.

5.3.2. Eye Diagram

The eye diagram is an oscilloscope display of a digital signal, repeatedly sampled and overlaid to get an approximate representation of its behaviour. Eye diagrams
are a useful tool for analysis of signal performance. They offer a look into the nature of channel imperfections. Analysis of the display can give an approximation of the signal to noise ratio, clock timing and jitter. With regard to Figure 32, it is clear from a visual inspection of the eye diagram that the performance of this system is within the acceptable ranges for communications. The most important aspects of the diagram are the size of the eye opening (signal-to-noise during sampling), and the magnitude of the amplitude and timing errors.

The following diagram and text describe the measurements that can be carried out from an Eye Diagram analysis:

![Figure 31: Eye Diagram analysis](image)

- \( T_{\text{cross1}} \) = time at which the first crossing occurs.
- \( T_{\text{cross2}} \) = time at which the second crossing occurs.
- \( P_{\text{top}} \) = mean of the most predominant peak in the histogram for box 1.
- \( P_{\text{base}} \) = mean of the most predominant peak in the histogram for box 2.
- \( P_{\text{cross}} \) = level at which the first crossing occurs.
- \( X \) = standard deviation of the signal at 1 or 0 (top or base)
Crossing % = 100 \left( \frac{P_{\text{cross}} - P_{\text{base}}}{P_{\text{top}} - P_{\text{base}}} \right)

**Equation 2:** Crossing % is the location of the zero crossing as a % of the eye opening

\[ EyeHeight = (P_{\text{top}} - 3(X)_{\text{top}}) - (P_{\text{base}} + 3(X)_{\text{base}}) \]

**Equation 3:** Eye Height is the vertical opening of the eye

\[ EyeWidth = (T_{\text{cross2}} - 3(X)_{\text{cross2}}) - (T_{\text{cross1}} + 3(X)_{\text{cross1}}) \]

**Equation 4:** Eye Width is the horizontal opening of the eye

Figure 32 below shows an eye diagram of the system operating over a 55 km span using NRZ. When the signal was increased past 55 km, the signal degraded significantly. Figure 33 shows a signal that is travelling over 130 km in a round trip. An example of what a good eye and a bad eye looks like is given in Figures 32 and 33 respectively.
Figure 32: Wide open eye diagram

An open eye shape signifies that the signal is stable with low jitter and noise. The signal in Figure 33 displays a signal where the transmission distance was overly extended to 130 km. By a first look it is obvious that the signal has distortions.

Figure 33: Poor eye diagram
5.3.3. Quality Factor (Q-Factor)

The Q-factor provides a qualitative measure of the receiver performance, as it is a function of the Signal to Noise Ratio (SNR). As such, the Q-factor suggests the minimum SNR required to obtain a specific BER for a given signal, see equation 6.

The Q factor of a resonator is a measure of the strength of the damping of its oscillations, or the relative linewidth. Attenuation and amplification cause a reduction in Q.

To determine a useful measure of Q the receiver’s optical power must be set to a value greater than the receiver’s sensitivity limit. Figure 34 below shows the relationship between BER and Q. As mentioned in section 4.2.1, the maximum acceptable bit error rate in a typical telecommunications system is $10^{-9}$ while some system specifications demand BERs as low as $10^{-12}$. Given the relationship between BER and Q, such specifications imply the need for Q values of 6 and 7 respectively.

\[
\text{BER} = \frac{1}{2} \text{erfc}\left(\frac{Q}{\sqrt{2}}\right)
\]

Equation 5: Relationship between BER and Q

The relationship between BER and Q can be seen where \text{erfc} is the error function and Q is:
Equation 6: Quality Factor is the vertical opening of the eye relative to the noise present

\[ Q = \frac{P_{\text{top}} - P_{\text{base}}}{(X)_{\text{top}} + (X)_{\text{base}}} \]

Where form Figure 31 above:

\( P_{\text{top}} \) = signal when a 1 is been sent

\( P_{\text{base}} \) = signal when a 0 is been sent

\( (X)_{\text{top}} \) = standard deviation of the 0 signal

\( (X)_{\text{base}} \) = standard deviation of the 1 signal

Bit-errors originate from the incorrect decoding of signals by a receiver due to the presence of noise within the signal. \( Q \) is a parameter that captures information about the SNR within the time domain and can be calculated using Equation 2. It measures the difference between a signal representing a binary 1 and signal representing a binary 0, and then provides a quotient representing the relationship between the signal differences and the product of the variation of both signals [72].

It is clear from Equation 2 that if a signal representing a binary 1 and a signal representing a binary 0 differ only slightly then \( Q \) will be small. Similarly, if the variation of both signals is high, then \( Q \) will also be small. Thus, a large value of \( Q \) means it is unlikely that a signal representing a binary 1 or a signal representing a binary 0 will be misinterpreted.

5.4. Conclusion

This chapter contains an analysis of the proposed architecture. Both NRZ and RZ encoding was tested within the transparent WDM-PON network. The analysis of the tests showed that RZ had a higher tolerance to distortions compared with NRZ and increased the transmittable distance by 7-8 km.
The feasibility of a transparent external modulator implemented as a remote transmitter in an ONU was examined using the simulation software. This led to hardware testing of an external modulator as a transmitter, by integrating it into commercial equipment (see chapter 6).

A demonstrated RB circumvention architecture using a ring-based WDM access network was shown. Significant reduction of RB can be implemented in the proposed architecture as the upstream and downstream signals were travelling separately. Experimental results showed that the proposed network can be operated at split ratio.

The feasibility tests consisted of WDM analyser showing the power of the signal, a BER analysis (to keep it within the industry standards of $10^{-9}$). The receivers sensitivity power of -18dB was adhered to but this can be changed depending on the type of receiver used. Some receivers have better sensitivity to lower powers. The analysis graphs this chapter interpreted the results from analysing different tools supplied by OptiSystem, like the WDM analyser, BER and eye diagram.
Chapter 6

Optical Network Unit and Bandwidth on Demand

This chapter examines two important areas. Firstly, further hardware testing was completed on the ONU to examine ways in which an external modulation device could be used within an optical transceiver. Secondly, a Bandwidth on Demand (BoD) implementation with the proposed setup was simulated.

6.1. Component Analysis

The network layout, as illustrated in Figure 21, highlights advantages over other PON networks such as greater bandwidth per user, increased distance over traditional WDM-PON networks and removal of reflection-II Rayleigh Backscattering (RB). The disadvantage of the network is the use of 3 fibers per user (two inputs and one output). The ONU hardware setup in Figure 35 shows the experimental setup used to test the ONU feasibility. The equipment consisted of:

- a tuneable CW laser [73]
- a XFP host board [74]
- a bias controller [75]
- a single drive Fujitsu 10Ghz LiNbO3 Mach-Zehnder modulator with low drive voltage [76]
- a high speed optical network interface card (a PCI-Express XFP card) [77]
• the physical network interface (a XFP module to slot into the interface card) [78]
• optical Single Mode Fiber (SMF)
• attenuators (to reduce the optical power entering the receiver)
• various connectors (to connect the various types of commercial equipment)
• a PC for connecting the PCI-Express card
• XFP laser and XFP receiver modules to connect to the XFP PCB module

![Figure 35: Test network layout](image)

The main part of the test equipment was the XFP evaluation board and a customised XFP module (without the XFP laser and receiver attached). The ONU in this test setup was represented by the XFP module with modifications made to attach a modulator as a replacement for of a XFP laser. Modifications to the XFP module can be seen in Figure 49. An RF cable was soldered to the RF output on the XFP board and attached to a modulator. The modulator received its
Continuous Wave (CW) signal from a distant laser source. To assist with the testing a two week loan of an Agilent 10GHz Bit Error Rate Tester (BERT) was sourced.

6.1.1. The XFP Module

It was decided that the best way to develop a test base would be to use existing hardware that could be modified. The XFP (10 Gigabit Small Form Factor Pluggable) is a hot-swappable, protocol-independent, multi-rate serial optical transceiver with a serial diagnostic interface (based on the I2C protocol). It supports Telecom (SONET OC-192 and G.709 “OTU-2”) and Datacom applications (10 GB/s Ethernet and 10 GB/s Fibre Channel). Nominal data rates range from 9.95 GB/s, 10.31 GB/s, 10.52 GB/s, 10.70 GB/s to the emerging 11.09 GB/s. The modules support all common data encodings for these technologies. The modules can be used to implement single mode or multi-mode serial optical interfaces at 850 nm, 1310 nm, or 1550 nm. Figure 40 shows a conventional off-the-shelf XFP board with the optical connectors (sender/transmitter) to the left and a forty-pin connector to the host board on the right.

![Figure 36: A XFP Module](image)

6.1.2. The XFP Driver

The XFP driver (MAX3941) is capable of driving an Electro-Absorption Modulator (EAM) at data rates of up to 10.7 GB/s. The MAX3941 driver is capable of the 1Vp-p to 3Vp-p. The MAX3941 driver on the supplied XFP test
module was restricted to the drive power requirements of the laser. Initial tests indicated that only 0.5Vp-p was outputted which is 1/6\textsuperscript{th} the desired drive voltage for the EAM. It was later discovered that some components of the XFP module needed to be altered in order to obtain the required 3Vp-p voltage [79].

The MAX3941 receives differential Current Mode Logic (CML) signals (ground referenced) with on-chip line terminations of 50 $\Omega$. The output has a 50$\Omega$ resistor for back termination and is able to deliver a modulation current of 40 mAP-P to 120 mAP-P, with an edge speed of 23 ps (from 20% to 80%), typically. This modulation current reflects an EAM drive voltage of 1Vp-p to 3Vp-p. See Figure 37 for a typical application circuit.

![Figure 37: MAX3941 Typical application circuit](image)

6.1.3. The XFP Host Board (HFRD-18.0)

The High Frequency Reference Design (HFRD) 18.0 is an XFP host board designed by Maxim-IC. The host board is used to test XFP transceiver modules in a test environment to more accurately define the modules’ performance. The host board also includes an RS-232 interface to simplify communication and control of the XFP modules from a computer.

The HFRD-18.0 XFP host board is designed to simulate an ideal environment for XFP module testing using single-ended micro-strip transmission lines. These
properties make the host board as electrically transparent as possible, allowing a more accurate assessment of the modules’ actual performance. SMA connectors, jumpers and status LEDs are provided to simplify the testing and interfacing of XFP modules [79].

**Figure 38: XFP Host board schematic**

### 6.1.4. The XFP Network Interface Card (NIC)

The PCI-Express card provided a physical interface between the XFP module and the host computer. It was decided to choose a Myricom PCI-Express (see Figure 39) since:

- The PCI-Express card allowed a fast interface with which to connect to the PC (as an alternative to using an expensive BERT).
- It had drivers for multiple versions of Windows and Unix/Linux operating systems, including Windows XP and Windows Vista.
The network card substantially reduced the CPU’s TCP/IP packet processing time by using enhanced data-handling algorithms, thereby, offering almost 10GB/s line speed performance. As a result the host PC could be used to run test software concurrently.

6.1.5. The Host PC

The host PC was used to control the software for the different components. The laser and the XFP host board needed constant monitoring to monitor their temperature and to sufficiently cool the devices. Ease of access to PCI-Express Network Interface Card (NIC) was required because subsequent tests involving the NIC and the XFP module were done.

6.1.6. The Tunable Laser

The use of a tuneable/configurable laser as the initial CW source conveys the advantage of a flexible system that can be tuned through the C and L-band spectrum. It was decided to choose Bookham’s TL5000 Integratable Tunable Laser (see Figure 40), as it provided a control and system reporting via a RS232 serial interface.
6.1.7. The Modulator and Modulator Controller

Fujitsu modulators require a low driving voltage (approx 2-3V). This low driving voltage means it is easier to incorporate the device with the XFP module's driver. A built-in Photo Diode (PD) monitor and coupler function for auto bias control offers a stable operation in long term for low DC drift. The Fujitsu FTM7928FB modulator was selected among all the other external LiNbO3 modulators due to its low driving voltage, which allowed it to be controlled with inexpensive drivers such as the MAX3941 (see Figure 41) (which is integrated into the prototype XFP module). The modulator operating wavelength is in both the C and L band. This corresponds to 1530 nm-1570 nm for the C-Band and 1570 nm-1610 nm for the L band. The band used in this experiment was the C-band, or more specifically a wavelength of 1551.72 nm was required by the receiver on the XFP module. This wavelength corresponds to channel 32 on the Dense Wave Division Multiplexing (DWDM) ITU Grid C-Band. It was discovered that the C-band was required to allow the optical receiver on the XFP module to operate.
The Bias control for the modulator was supplied by YYlabs it was needed to control the +/- 12 DC bias voltage on the modulator. A photo diode with a low profile LC receptacle is built-in for space-saving purposes. The bias controller has four settings organised into two groups for Pulse RZ (Return to Zero) and Data NRZ (Non Return to Zero) transmission. For pulse applications the bias controller is set to either null or peak control. Using the Null/Peak configuration no connection is needed with driver (MAX3941) where in Quad +/- configuration a connection to the driver is needed to help stabilise the voltage [75]. The bias setup implemented in the setup was the Null/Peak, as illustrated in Figure 42.
6.2. Component Testing

Figure 35 shows the completed setup and integration of all the hardware components. The setup shown has yielded promising results. Faults with the XFP modules hardware produced 0.5Vp-p on pin 2 of the XFP output port [11] (see Figure 44). A resistor was preventing the full 3Vp-p output of the Maxim-IC driver chip onboard the XFP module (see Figure 48). With the tools available it was not possible to remove the resistor from the PCB board. The amount of close proximity resistors made it too difficult for human manipulation of the board.

The 0.5Vp-p was demonstrated by an intermittent current detected on the XFPs receiver port. The steps that delivered results were as follows:

1. The laser transmitted 1551.72nm wavelength over Single Mode Fiber (SMF).
2. A comparative analysis was taken, first by allowing the signal to traverse the modulator when no current was applied and then with a current to examine the properties of the receiver.
3. Once the light left the modulator, it traversed over another length of fiber which leads into the XFP receiver.
4. The receiver’s electrical current was measured at zero when the modulator was not powered by the 0.5Vp-p. Once the modulator was powered, the current on the XFP module fluctuated indicating a very weak signal. However, this signal could not be interpreted into a data stream because of the low voltage supplied to the modulator.

Due to either transport damage or poor soldering a resistor was missing which is used for voltage pull up on the 10GB/s EAM driver, This was the cause for the low drive voltage (around 0.5V) on the XFP module.

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[11] Due to either transport damage or poor soldering a resistor was missing which is used for voltage pull up on the 10GB/s EAM driver, This was the cause for the low drive voltage (around 0.5V) on the XFP module.
Figure 44 shows the 0.5Vp-p measurement output from the XFP module.

![Figure 44: A 0.5Vp-p as shown using an oscilloscope](image)

### 6.2.1. Modification to the XFP Module

A new interface to a standard XFP module had to be implemented (see Figure 45) in order to connect the driver of the XFP module with the modulator via a high-speed coax cable (a 40 GHz coax cable was used because of the un-availability of 10GHz cables). A standard optical XFP receiver capable of receiving wavelengths in the 1550 nm spectrum was connected to the XFP module. The transmitter section of the module was altered to accommodate the 40 GHz coax cable by soldering it onto pin 2 of the XFP transmitter pin (Figure 46).
Pins 1, 3, 5, 7, 8 and 9 were grounded, and the removal of components connected to pin 4 and 6 eliminated the need for pins 4 and 6. Pin 4 was a thermostat for measuring temperature while pin 6 was used if a laser device was connected (Laser Anode). A new housing to fit the receiver module was salvaged from an old XFP housing module so that a secure and firm connection with the LC fiber connector could be achieved.

It was decided to choose Maxim-IC as the supplier for the XFP host board (see Figure 38) and XFP testing module (see Figure 45), as the company provided the project with some customised XFP equipment. This equipment consisted of

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12 The fragile connection between the 40 GHz GPO and the XFP board cause a few issues that required delicate care of the module.
- an XFP host board,
- a customised XFP module (without the optics attached)
- test software for the XFP module.

Figure 47: Initial test setup

The XFP testing module had the standard 10 GB/s receiver and a 10 GB/s LiNbO$_3$ modulator. The XFP host board (see Figure 38) in conjunction with the supplied software allowed testing of the XFP module after the modifications have been made.$^{13}$

To incorporate the 40 GHz RF cable onto the XFP module some hardware changes had to be made. After describing the requirements of the project to Maxim-IC support it was suggested by them that the removal of some components from the XFP module were necessary to increase the drive voltage that supplies the external modulator. It was suggested that the best approach was to mask the pins that would not be used in order to remove some of the components from the PCB. By removing the components L7, R22, R17 and L9 this would leave an AC coupled output signal on pin 2 of the transmitter side of the XFP module, which would be connected to the 40 GHz RF cable. Pins 1,3,7,8 and 9 would still be ground. Pins L7, R22, R17 and L9 are highlighted in the Figure 48.

$^{13}$ An air cooling system was built to cool the Maxim-IC XFP board while plugged into the PC
6.2.2. Agilent 10 GHz BER Hardware Testing

An opportunity to test the setup using a 10GHz BERT came about when a loan from Agilent was organised. The costs involved in doing a long test are prohibitively expensive\textsuperscript{14}.

The analyses of the BERT tests suggest that the remote transparent modulator system has the potential to work but not enough data could be obtained in the short time the BERT was available. The tested setup had a 10 GHz modulator run from the data output of the XFP module and from there to the Agilent 10 GHz receiver (see Figure 49). The test produced various eye diagrams both indicating different biasing voltages to get different error rates. Only a slight modification was made to the original setup: Instead of using the receiver contained within the XFP module, an Agilent 10 GHz receiver was used.

\textsuperscript{14} A two week loan of a 10 GHz BERT from Agilent was secured. It was sufficient for initial testing but not enough for the detailed testing that was required. The cost of such equipment is in the region of €200,000.
Figure 49: BERT test setup

The setup with the BERT produced an eye pattern, although with a high BER, see Figure 50 and 51. The results obtained using the PC and the BERT correlated with each other, showing a weak signal detected. The setup using the BERT showed a $2.043 \times 10^{-2}$ BER. This implied a received signal but not sufficient for industry standard use.

Figure 50: Bias at 3.35 BER of $2.043 \times 10^{-2}$
Figure 51: Bias at $2.09 \text{ BER of } 1.453 \times 10^{-1}$

By altering the bias for the modulator to a value of 3.35V, the error rate decreased, as shown in Figures 50-51. Development of an ONU with an industry standard output was beyond the scope of this work. The prohibitively expensive costs prevented further tests. However, a result of $2.043 \times 10^{-2}$ is somewhat promising and demonstrates the feasibility of the remote transparent ONU.

6.3. **Bandwidth on Demand (BoD)**

In conjunction with the development of the hardware ONU component as discussed above, integration of Bandwidth on Demand (BoD) was examined. One fundamental attribute of the Bandwidth on Demand feature is that it is designed to control the data transmission rate between the central office and the users host machine (ONU), therefore allowing a service provider to dynamically limit the upstream and downstream data rate. Investigations took place to determine where exactly bandwidth control should occur. The goal of this effort was to find a better way of dynamically utilising the vast amount of bandwidth that WDM networks can transmit to each user. It was proposed that dynamic control of bandwidth for each user would be the best solution to utilise the vast bandwidth WDM networking can supply to each user.

To integrate BoD into the proposed design in chapter 5 and the hardware ONU in chapter 6, it is suggested that each sending node (either the ONU or the central office) is in charge of the upstream data flow towards the other side as shown in
Figure 52. Here the central office provides a control mechanism (the primary red hooks in Figure 52) for the upstream data towards the ONU and vice-versa. On top of this both entities have the possibility to verify the rate of the incoming data stream (via the secondary green hooks) to detect inconsistencies between the actual data rate and the negotiated data rate. The central office is also a gateway between multiple ONUs and the Internet and has to control / limit the incoming and outgoing data flow towards a subnet (via the orange gateway hooks).

It was further investigated where exactly these control hooks (and particularly the primary ones) should be implemented.

Figure 53 outlines the relevant hardware / software elements within a ONU (or – with minor modifications – within a central office) where the bandwidth control can take place:

- I/O hardware
- Operating system
- User space

The most transparent and OS-independent solution can be seen in Figure 54. The entire bandwidth control is done on Network-Interface-Card (NIC) level, which results in a behaviour towards the OS similar to an ordinary Ethernet configuration over a broadcast medium that is shared between multiple hosts: While the host board artificially regulates the outgoing data flow (based on a
scheme negotiated with the central office beforehand), it indicates the operating system via Direct Memory Access (DMA) or interrupts on whether new data can be accepted or not.

Further investigations looked into the feasibility of modifying an existing host board (predominantly by modifying the internal firmware), but in the end it was decided to drop this design for the moment, as it would also have required to rebuild a host board from scratch. In the long-term on the other hand this is most desirable solution.

Figure 53: Data I/O-Specific Hardware / Software Elements

Figure 54: Solution 3: Hardware-based bandwidth-control
<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Transparency towards OS</td>
<td>- Difficult to implement as it requires</td>
</tr>
<tr>
<td></td>
<td>customised firmware</td>
</tr>
<tr>
<td>- BoD credentials move with</td>
<td>- Firmware upgrade difficult</td>
</tr>
<tr>
<td>card (and not with host)</td>
<td></td>
</tr>
<tr>
<td>- New NIC design required (to</td>
<td></td>
</tr>
<tr>
<td>store certificates persistently)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Features of a hardware-based bandwidth control

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**Figure 55: Solution 2: Protocol stack-based bandwidth-control**

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<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Pure software solution, therefore simpler to implement</td>
<td>- Requires modified or new OS core elements (difficult for non-open source code)</td>
</tr>
<tr>
<td>- Simple software upgrade mechanism</td>
<td>- OS license management required by central office</td>
</tr>
</tbody>
</table>

Table 4: Features of a protocol stack-based bandwidth control
The beauty of this approach is that bandwidth control takes exactly place, where it would be anticipated from an OS point of view – in the transport layer. This solution raises a few issues as outlined in table 4, since an OS kernel must be upgraded to facility this service and some mechanism (based on OS license management) must be introduced to make sure that unsolicited usage (based on an OS that simply bypasses the bandwidth control) takes place.

The actual implementation of the BoD system can be seen in Figure 56, whereby the control mechanism is located on user space level in form of a library that introduces a new type of “bandwidth-limited” socket. An application has to use this type of socket in order to enable BoD. While this solution demonstrates the principal concept of BoD, it does not provide any form of security or authentication.

![Figure 56: Solution 3: User space-based bandwidth-control](image)

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Pure software solution without OS overheads, therefore simple to</td>
<td>- Can be simply avoided / bypassed,</td>
</tr>
<tr>
<td></td>
<td>only suitable for demonstration</td>
</tr>
</tbody>
</table>

117
6.3.1 User manual

All console programs can be built, ready for execution, by navigating to the folder /cons and from the command line typing ./mkcons. GUI applications provided for the ONU and central office can be built by navigating to the /cli and /co folders respectively and typing make. Further information is provided in the readme file.

6.3.1.1 The Central Office

The central office can be run as a console application or as an application with a GUI. The console version allows the central office to be run on machines where QT is not supported.

The user should navigate to the folder with the appropriate central office application. The application can be run by typing ./co from the command line. All processing on the central office is stored in the log file co.txt. The more important events are also displayed in the central office interface in the ‘central office log’ tab.

Bandwidth reservations can be made via the central office interface. Each reservation requires that the ONU id be entered along with the bandwidth rate being requested. The start time is specified in seconds via a spin box. The initial time displayed in the box is the current time in seconds. For the purpose of demonstrating the system, the duration of the bandwidth reservation is measured in seconds.

For each ONU, the list of bandwidth reservations can be displayed by entering the ONU id in the 'Display reservations' tab on the central office interface. For each reservation, the start time is displayed in seconds in UNIX format. The duration is also displayed in seconds. The bandwidth rate is displayed in kB/s.
6.3.1.2 The ONU

The ONU can be run as a console application or as an application with a GUI. The application can be launched from the command line by typing `.cli <client id>`. All processing by each ONU application is recorded in a log file. The ONU GUI displays the current amount of data downloaded and the amount of data downloaded in the previous second. Data is measured in bytes. Seconds are represented in the UNIX time format, wherein time is stored as the number of seconds since 00:01 on 01/01/1970. The bandwidth rates allocated the ONU for the next x seconds are also displayed. For the purposes of the demonstration, bandwidth rates increase in steps of 10kB/s, with the minimum rate being 10kB/s. The time at which the latest bandwidth array was read from the central office is displayed.
6.3.1.3 Other Servers

The Service Provider is implemented as a console application. It can be run by typing from the command line `./sp <content file name>`. The content file name specified will be hosted by the SP, and can be downloaded by ONUs. All interactions with ONUs are recorded in a log file. The SP is shut down upon receiving the appropriate message from the administrator.
The administrator server can be run from the command line by typing 

```
./admin <command>
```

The command 0 will send messages to the central office, service provider and certificate authority to shutdown.
Figure 61: Administrator console interface

The CA is run from the command line by typing ./ca when in the appropriate folder. Requests from ONUs or COs are displayed on the screen. A request with value 9 specifies that the CAs public key certificate is requested. A request with value 7 requests that the certificate sent to the CA be signed. Request with value 2 tells the CA to shut down. All activities on the CA are recorded in a log file.

Figure 62: CA console interface
6.3.1. The Network Management Software

The proposed Bandwidth on Demand (BoD) architecture allows ONUs to reserve a higher upload/download bandwidth from their internet service provider for specific times while having a lower default rate available to their premises equipment (like a PC or HD-TV) at other times.

Applications requiring higher bandwidth (in the region of 1 GB/s) are typically used for short periods of time (1-2 hours) for applications including:

- High Definition (HD) teleconferencing
- Streaming HD content (such as movies or sport events)
- Downloading multimedia content or large amounts of data

Allocating bandwidth when it is requested by ONUs allows higher data transmission rates to be ensured when they are required, while minimising costs at other times.

Figure 63: CA log file
The system described in this document allows reservations to be made through a central office. Customers make reservations online that take effect immediately with respect to the bandwidth allocated to the ONU concerned. To communicate bandwidth allocation and secure functionality to limit the data transfer a secure channel between the ONU and the central office is required. Bandwidth requests made are also transferred to the ONU to manage upload/download limits at source.

The architecture of the system is outlined in Figure 64. A Certificate Authority server or CA is used for verification and encryption of bandwidth reservation data. A Central Office server is used for:

- making bandwidth reservations
- maintaining these reservations for each ONU
- communicating the current bandwidth rate to each ONU

A software application runs on the network interface card (NIC) or NIC driver on each ONU, controlling the amount of data transmitted, while permitting the user to view the reservations made and the current bandwidth rate. A Network Time Protocol (NTP) server is used to synchronise the time for the ONU and the central office. This ensures that the bandwidth level indicated on the central office is reflected on the ONU at the exact same time. For demonstration of the system, a Service Provider (SP) server hosts content that can be downloaded by ONUs.
6.3.1.1. The Central Office

The central office facilitates reservation of bandwidth by ONU's and communication of bandwidth rate to ONU's. Information contained within bandwidth reservations include a start and stop time, bandwidth rate and ID of corresponding ONU. In the system demonstrated, bandwidth reservation periods...
are delimited in seconds. The ID may be any parameter that can uniquely identify the ONU, such as the MAC. The central office maintains a list of active reservations for each ONU. Reservations whose active period has expired may be deleted or recorded. For each ONU, a list of these reservations is maintained.

The central office maintains a bandwidth matrix, indicating the bandwidth reserved by each ONU in the system at the current time. The matrix contains the bandwidth rate reserved by each ONU per minute over the period of an hour, with the first element representing the bandwidth and the second representing the time the matrix was updated. The matrix is updated from bandwidth reservations at set intervals. These may be, for example half-hourly, but for demonstration purposes they are updated every 10 seconds.

On a separate thread, the central office handles requests from ONUs for bandwidth data. The data is sent over a verified medium, while the central office is synchronised with the ONU via an NTP server. New threads are spawned to handle each ONU request. The request type is determined by examining a flag, and the response to the ONU generated accordingly. The request type may be to exchange public key certificates with an ONU, send bandwidth data or to shutdown.

The central office GUI facilitates booking of ONU bandwidth requests, viewing of ONU request lists and displaying central office processing. It was developed in QT framework, allowing it to be run on Windows and Linux operating systems.
Figure 66: Bandwidth reservation interface (set of reservations can be fabricated for simulation)

Figure 67: List of bandwidth reservations for first ONU 0
6.3.1.2. The Certificate Authority (CA)

In the system demonstrated bandwidth data is appended to X.509 certificates as extensions. X509 is an ITU-T standard for a public key infrastructure and privilege management infrastructure. The OpenSSL library is used for the creation of certificates and keys and for signing and verifying keys. As the bandwidth data is used to control data transfer rates, it is necessary that data received by the ONU can be verified.

On initialisation the central offices and ONUs send requests for the CAs public key certificate. They also send their own certificate to be signed by the CA\(^\text{15}\). ONUs then send requests to the central office in order to exchange public key certificates. ONUs send requests for bandwidth data to the central office as extensions within X.509 certificates. They sign these with their own private key, allowing the certificates to be verified when they are communicated to the central

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\(^{15}\) In a realistic deployment customer certificates would be transferred and signed by a CA in a more transparent and secure fashion in order to avoid identity fraud.
office using the ONUs public key certificate. Conversely, the central office signs the response certificates with its private key, allowing ONUs to verify the bandwidth data using the central office public key certificate.

6.3.1.3. The NTP Server

The Network Time Protocol (NTP) is a protocol and software implementation for synchronising the clocks of computer systems over packet-switched, variable-latency data networks. The central office and ONUs are synchronised via an NTP server. This ensures that bandwidth rates reserved by the ONUs are implemented at the correct times and that the ONU is aware of when bandwidth rates will be in effect.

Calls are made periodically to the NTP server to obtain the correct time. A timer thread is run on the central office and on each of the ONUs to maintain the exact time between calls. If the bandwidth rates were implemented based on the ONU PCs system clock, the user would be able to adjust the clock and potentially receive higher bandwidth rates that it did not pay for indefinitely. Using a separate timer thread prevents this.

6.3.1.4. The Service Provider

For the purpose of demonstrating the system, the Service Provider (SP) is implemented as a server maintaining content that can be accessed by the ONUs. This reflects potential real world applications, such as ordering HD movies online and downloading them to a media centre PC for viewing. The SP supports access from a large number of ONUs simultaneously, with each ONU serviced on a separate thread.

The SP receives requests from ONUs indicating the content they want to be sent. The content is sent to the ONUs as a stream of packets. A file pointer is maintained for each ONU, allowing the SP to send the content to the ONUs as a stream of packets and alert them when the transfer is complete.
If a service provider that is not under the control of the central office submits data to an ONU that exceeds the negotiated bandwidth, two things will happen:

1. In a connection-less data transmission scenario (based on the UDP protocol) surplus packets will be filtered by the central office and do not physically enter the network segment between the central office and the ONU. In a video conferencing scenario, entire frames would be dropped, reducing the video quality on the ONU side.

2. In a connection-oriented data transmission scenario (based on TCP), surplus packets will be filtered by the central office as well, and do not reach the ONU. Since TCP assumes that the cause of a lost segment or data packet is due to congestion in the network, the protocol will automatically reduce or adjust the data transmission rate on the service provider’s side. This means that the standard congestion avoidance mechanism (which is part of the TCP/IP protocol stack specification) complements the proposed BoD architecture.

6.3.1.5. The Administrator

In the system demonstrated an administrator server is used to control the other servers. The administrator facilitates tasks such as handling processes and files on the servers and shutting down the servers.

6.3.1.6. The ONU

The ONU represents the end user who performs HD teleconferencing, streams HD media or downloads content to his/her PC via a service provider. In the system demonstrated the control of bandwidth rates is implemented by an application running on the ONUs NIC card. Bandwidth data is downloaded by this application from the central office as required and cannot be accessed by the user. The application maintains its own clock that is independent of the system clock on the PC, preventing the user from affecting the times when bandwidth rates are in affect.
For functionality such as HD teleconferencing or streaming HD video the application would react to the current bandwidth rate by adjusting the frame rate of the video on protocol stack-level. For downloading content, the application controls the number of packets of data downloaded per second.

The ONU application runs a background thread to periodically read bandwidth data from the central office. Bandwidth rates are received as an extension to an X.509 certificate from the central office. The date indicates the bandwidth rate available for each second over the next x seconds.

The main thread of execution on the ONU application uses the bandwidth data to control the transfer of data. Calls to send and receive data over the network are made through a BoD layer. This abstracts away the controlling of data transfer in accordance with bandwidth rates. This layer keeps track of the bandwidth available per second, the amount of data already sent per second, and the amount of data that may still be transferred. For the purpose of downloading content, when the data transfer limit per second has been reached, the BoD layer instructs the ONU to wait until the rest of the second has elapsed. Downloading can begin again with the next second.

The ONU GUI displays the time maintained by the BoD application running on the NIC card, the amount of data transferred for each second, and the total amount of content downloaded with the current session. It also displays the bandwidth rates as downloaded from the central office for the next x minutes.
6.3.2. Software System Integration

The software was developed on Ubuntu Linux. Linux was chosen due the availability of libraries to implement NTP calls and to create and process X.509 certificates. Ubuntu Linux was chosen due to the ease with which it can be installed and configured. The software was written in C++ and compiled using the GNU compiler.
NTP is a protocol for synchronising the clocks of computer systems over packet switched, variable latency data networks. The ONUs and CO are synchronised with NTP by making calls to an NTP server. The calls are made over standard socket connections. A Linux machine was setup as a NTP server by synchronising to ie.ntp.pool.org, although any number of NTP servers can be used.

The OpenSSL library is used for verification of requests from ONUs to servers and of bandwidth data. OpenSSL is an open source implementation of the Secure Sockets Layer (SSL) and Transport Layer Security (TLS) protocols. This can be used to generate private-public key pairs, for generating X.509 certificates and for performing tasks such as signing and verifying certificates. It can be easily installed using the Synaptic manager on Ubuntu.

User interfaces are developed using the QT framework. This is a cross platform application development framework. The framework provides an interface designer, QT Designer, that can be use to build forms. This provides .h files that can be incorporated into a project along with code implementing the BoD system. QT provides a qmake that automatically creates a project file and a make file which can be used to build an application using the GNU compiler.

6.4. Conclusion

Much research is carried out on how to implement an economical WDM system in the access network. The main focus of the proposed research is in developing an economical colourless/transparent ONU. This chapter demonstrated how an external LiNbO3 modulator can be implemented within an ONU device. It was integrated within an XFP module, a commercial off the shelf component. The external modulator acted as the transmitter module and retransmitted the signal in a loop back to the XFP modules receiver where the signal was analysed.

A significant effort was put into hardware testing of a remote transparent ONU. The results obtained from the initial computer based setup and the testing with the BERT were encouraging. After running the simulation of the transparent ONU in chapter 5 and the hardware setup described in this chapter, it was demonstrated
that a transparent ONU has the potential to be integrated within the access network as a colourless/transparent transmitter.

Bandwidth on Demand (BoD) is an important service when available bandwidth surpasses typical user demand and a throttling of bandwidth is desirable (e.g. a >100MB/s access network would only intermittently be fully utilised by a customer). Although users’ usage of bandwidth varies, service providers currently offer static bandwidth rates ranging from 1 MB/s up to 100 MB/s, with a few SPs worldwide delivering 1 GB/s. A BoD setup will be a better option for users, where they get the bandwidth they need, when it’s needed, instead of having it available all the time. BoD utilises data more efficiently than static bandwidth amounts. The proposed two networks (in chapter 5 and 7 of this thesis) are designed to implement 10GB/s data transfer rates per user or access network, therefore the discussed BoD framework complements both setups.
Chapter 7

Dual Ring MAN-Access WDM/TDM Network

In chapter 5 simulation experiments were carried out to test a few areas in WDM-PON. Analysis on how Return to Zero (RZ) and Non Return to Zero encoding worked in a transparent ONU environment was carried out. The feasibility of a transparent external modulator implemented as a remote transmitter in an Optical Network Unit (ONU) was examined, this was followed by, in chapter 6, the hardware experimentation of an ONU. A network design was implemented that inherently removes the issues with reflective distortions due to Rayleigh Backscattering (RB) type II. This RB type is the major cause that limits the maximum transmission distance of PONs to 20 km. The tests were confirmed using the analysis tools supplied with the simulation software.

This chapter shows advancements over current PON networks in areas like economical use of bandwidth by implementing Time Division Multiplexing (TDM) with WDM and a reduction of the amount of fiber needed compared with tradition tree PON architectures, while keeping the method to circumvent RB type II distortions through architectural design. The proposed network design in this chapter also demonstrates at a way to bridge the MAN and access network all optically without the need of Optical-Electrical-Optical (OEO) conversion. This setup brings reduced latency issues with OEO conversion and helps reduce the costs associated with maintaining expensive central offices for each access network.
The ONU design implemented in this network still uses a remote transparent ONU, but has a completely different layout than the one proposed in chapter 5. The ONU design implemented in this network brings some fault tolerance to the proposed dual ring architecture.

The tools used to examine the network were similar to chapter 5, but with the addition of TDM extra analysis to check the synchronisation between the central office and ONU was needed. The tools consisted of an Optical Time Domain Visualiser (OTDV) to analyse the channel synchronisation. Eye diagram analysis was used to retrieve the BER and Q-factor of the ONUs throughout the network. The optical spectrum analyser looked at the wavelengths power and monitored the loss at locations around the network, finding which areas that may require amplification (i.e. a MAN-access bridge was the best location for optical amplification). Amplification at the access central office meant that all wavelengths were amplified in the network, not just the required wavelength for a single access point. A power budget analysis was carried out to analyse the network and find the best locations for amplification, if it’s required.

To best gauge the proposed network a comparison analysis of commercial systems that are designed in OptiSystem can be carried out. By comparing results from standard OptiSystem networks with results obtained from the proposed setup sufficient proof of design can be stated.

This chapter gives an overview of the proposed link between the Metropolitan Area Network (MAN) and the access network. A new design ONU is also implemented. Simulations of the network design as a whole are carried out using OptiSystem, where the different stages and the complete network are analysed. Comparative results of a simulated commercial WDM network are examined against the results from the proposed network to see how they compare.

7.1 MAN Network Architecture

This section demonstrates an all optical bridge that does not require Optical-Electrical-Optical (OEO) conversion between the MAN and access network. This
setup delivers cost saving on the initial Capital Expenditure (CAPEX) by removing the expensive OEO equipment, while also reducing the Operating Expenditure (OPEX) by delivering a homogeneous ONU. The key to the setup is the intersection between the MAN and access network. An Optical Add Drop Multiplexer (OADM) is implemented to drop and add the specific wavelength for the access network. The adding and dropping of wavelengths is an all optical transfer. This helps reduce latency. When greater distances are required than the distances what conventional PON (>20 km) can travel, an Erbium Doped Fiber Amplifier (EDFA) can be integrated in conjunction with the OADM at the MAN-access bridge. With the ring layout the RB issues from bidirectional communications are removed. Once the wavelength leaves the MAN, it is transferred into another ring that has its end point back at the same add/drop multiplexer that dropped it off. That wavelength then traverses the rest of the MAN ring back to the main central office. All communication is done in one direction (i.e. unidirectional communications).

Figure 71: MAN network with 4 add/drop OADM central offices

Figure 71 shows an overview of the MAN ring configuration. This setup consolidates all the expensive equipment that would have been placed at each access central office into one MAN central office.
Bandwidth on Demand services can be implemented with the use of Optical Burst Switching (OBS) with the proposed system, see section 3.5. The Optical-Electrical-Optical (OEO) junctions that used be housed at access central office would be replaced by passive OADM to add/drop wavelengths. Depending on the system amplification may be implemented at specific access points to increase the power budget if required.

7.2. Access Network Architecture

Once the wavelength has been dropped into the access stage of the network it enters another ring network. The proposed network design for the access network differs from current research in the WDM-PON domain. Current PONs like WDM-PONs and WDM/TDM-PONs use a standard tree structure for the access network. The proposed network implements a ring structure that branches off from the MAN ring. Integration of the MAN and access network as an all optical network will reduce costs by centralising all expensive equipment in the MAN central office. Upgradeability of the bandwidth in the proposed WDM/TDM is an advantage over competing systems because the transparent-colourless ONUs can utilise bandwidth up to 10 GB/s.

The ONUs can be used with any wavelength so as keep the maintenance and costs down. This is an important factor in fiber optic communication, as having a specific device for each end premises greatly increases both Capital Expenditure (CAPEX) and Operating Expenditure (OPEX). The proposed transparent device used in conjunction with the MAN-access architecture, greatly reduces the RB that is symptomatic of bidirectional systems.

The equipment in this network consists of passive optical devices (see Figure 72). This network only requires one main central office per metro-access network. Extra demand for data can be catered for by either increasing the time allocation or by the addition of more wavelengths. Additional wavelengths are added to the system through the metro and then added or dropped into the access network. It is
possible to drop more than one wavelength into each access network for highly populated urban areas. An EDFA placed at the metro access link is capable of amplifying the signal for long distance transmissions.

Each ONU receives an allocated time. The access ring setup allows the signal to traverse through each ONU; the wavelength is added back onto the MAN ring once it has traversed through all ONUs. Once the wavelength has traversed the access network it is joined back onto the MAN ring to be sent back to the main central office for decoding.

![Figure 72: Access network layout](image)

A more detailed example to demonstrate the advantages of the proposed access ring network over a tree can be seen from the following example: A MAN central office with 128 wavelengths over a single strand of fiber can deliver asymmetric 100 MB/s downstream and 10 MB/s upstream to 11520 premises (a split of 100 premises using 10 GB/s).
Comparing this with 10GEPON using a passive splitter with 100 splits the number of users is slightly greater at 12800 users because a 10 GB/s data stream is fully utilised in the downlink and a separate 1 GB/s is used for the uplink (i.e. a 10:1 ratio), where in the proposed system the 10 GB/s data stream is used for both up and downstream (i.e. a 9 GB/s downlink and 1 GB/s uplink). Using this split ratio for the 10GEPON would require a vast amount of fiber compared with the proposed ring setup. To demonstrate the extra use of fiber a simple example of a tree and ring access architecture is analysed. To do a comparative analysis the parameters for both networks is kept the same. The parameters in this example are:

- 10 ONUs with 10 meter spacing between each ONU.
- 500 meters from the access central office to the first ONU.
- 500 meters from the last ONU back to the access central office.

The setup above shows a tree layout. This example needs 500 meters of fiber for the first ONU, 510 meters for the second and so on up to 590 meters for the last with increments of 10 meters for each ONU. The amount of fiber required here equates to 5450 meters of fiber for this network.
Figure 74: Ring architecture

Using the same parameters as above a ring network in the access only uses 500 meters for the first and last stretch of fiber with 10 meters in-between each premise. So 1000 meters plus the 90 meters for the gaps between each premise gives a total of 1090 meters. It can be seen from this basic comparison that 5 times less fiber is utilised in the ring.

In a real world application where the split ratio would be far greater than 10:1 as describe in the first example above, the amount of fiber required in the tree is far greater than the ring network. Implementing the same parameters as above, this time with 100 premises, yields some interesting results. Only taking the access network fiber into account and a split of 1:100 for both networks gives the following results:

10GEPON

- 6210 meters for the incremental 10 meter gaps for 50 premises and another 6210 meters for the other 50 premises (12420 meters in best case).
- The initial 500 meters from the splitter to each 100 users gives 50 km of fiber.
- So the total approximation for one wavelength 10GEPON network is 62 km. Even in the very unlikely scenario that each user is only 500 meters away from the splitter, it still gives 50 km of fiber needed.
• Multiply this one wavelength by 128 wavelengths gives an approximate 7936 km of fiber needed to service the 12800 users at 100 MB/s downstream and 10 MB/s upstream.

10 GB/s dual ring proposal

• 1000 meters for the total gaps between the users (10*100).
• 500 meters from the initial split and 500 meters back, give an approximation of 2 km of fiber needed.
• Multiply this 2 km of fiber by 128 wavelengths gives an approximate 256 km of fiber needed to service 11520 users at 100 MB/s downstream and 10 MB/s upstream.

The results from the above example clearly show that the proposed access ring network architecture uses far less fiber than a tree network. In the example the amount of fiber used in the tree compared with the ring is 31 times greater. It must be noted in different geographical areas there can be slight changes which can slightly affect the distance per premise.

7.3 Optical Network Unit (ONU)

After the access network drops its wavelength at an ONU, the signal is split and recombined depending on what required.

1. The first split gives a 50/50 ratio.
2. The first 50% power goes into a SOA amplifier to counter any loss obtained from the splitting and modulator.
3. After the amplification the modulator is used to synchronise and encode the signal designated for it.
4. After the modulator the signal is split with a specific ratio that sends enough power to the receiver.
5. The majority of the power is sent on to recombine with the second 50% power from the first split.
6. The second split is used as a type of fault tolerance if the ONU malfunctions.

The fiber from the first split and the fault line are kept the same length so when they recombine they are still synchronised. The transparent SOA and modulator only change properties of the light signal as it passes through so do not cause latency or delay between the first and second split. A control module is employed that keeps control of the Dynamic Bandwidth Allocation (DBA) and Bandwidth on Demand (BoD) as discussed in 4.5 and 6.3 respectively. An illustration of the ONU can be seen Figure 75.

![Figure 75: Optical Network Unit (ONU)](image)

7.4 Simulation Setup for the WDM/TDM/ Network

The proposed network above was tested and analysed using OptiSystem simulation software to test its feasibility [81]. The experiment involved building a MAN and access network structure like the one described above. The layout of the network follows the description of the above WDM/TDM network as close as the simulation software allowed. One area that could not be tested was the DBA proposed in section 3.5. However, TDM can be implemented using the simulation.
The following sections show the layout of the proposed design using the simulation software and the analysis of the results.

7.4.1 All Optical Bridged MAN and Access Network

The overall layout of the network consists of an all optical bridged MAN and access network. The test setup consisted of two wavelengths of 193.1THz and a second wavelength of 193.6THz delivering TDM signals to separate access central offices.

The bridged MAN access ring layout is simulated as follows (see Figure 76):

1. Two TDM signals consisting of four channels per wavelength are multiplexed onto a single strand of fiber.
2. Next the signals travel over 22 km of fiber (which includes 2 km of dispersion compensation fiber to compensate for the dispersion on the fiber link). The first wavelength of 193.1THz is dropped at the first access point. It traverses the ONUs (see section 7.4.3) and is joined back onto the ring at the same spot.
3. The second wavelength continues onto the next access point where its wavelength (193.6THz) is dropped and traverses its ONUs and also recombines onto the MAN ring.
4. Both wavelengths at this point have delivered their downstream data to the ONUs and have also been encoded by the ONUs with the upstream data.
5. The wavelengths traverse the rest of the MAN network and are sent back into the MAN central office to be decoded.

The proposed architecture differs from previous research by implementing a dual ring MAN and access network. Previous research used a ring for the MAN which acted as a drop point for conventional TDM-PON tree networks. The results from OptiSystem simulation software are demonstrated in the next sections.
7.4.2 MAN and Access Central Office

The first section of the proposed setup consists of developing TDM and implementing the separate signals onto a single wavelength. Figure 77 illustrates the simulation setup on how to implement TDM onto a wavelength. The encoding scheme used in the setup is RZ because it is relatively cheap to implement compared with other encoding schemes used in bandwidth speeds in excess of 10 GB/s, also it can be more easily synchronised than NRZ. The clock recovery of RZ can be accomplished by making the signal return to zero in the middle of the bit period so a constant stream of one’s would be represented by an alternating signal.

The duty cycle of the pulse generator was set to 0.25 bits with a rise and fall time of 0.05 bits. The position for each successive transmitter is incremented by 0.25 bits. The first pulse generator assigns the first 0 bit to 0.25 bits to the first transmitter. The second generator assigns 0.25 bit to 0.50 for the second
transmission and so on. The analysis of the bits is carried out by using an Optical Time Domain Visualiser. This tool allows the examination of the bits and their location in time through the network.

Figure 77: Central office with 4 TDM channels on a 193.1 THz signal

This WDM/TDM network was tested using two wavelengths as shown in Figure 78. Each wavelength was encoded with data as described above with four separate TDM signals. The signals are multiplexed onto a single strand of fiber for transmission along the MAN ring. The signal was transmitted over 20 km of SMF fiber with a drift of 16.75 ps/nm/km (picoseconds/nanometre/kilometre) of dispersion and an extra 2 km of -167.5 ps/nm/km Dispersion Compensation Fiber (DCF) to counter the effect of dispersion drift.
To maintain the all optical interconnect between the MAN and access network the access central office contains an Optical Add/Drop Multiplexer (OADM). This device is designed to drop or add wavelengths at specific locations (i.e. access networks). By implementing this type of setup in the access central office costly Optical-Electrical-Optical (OEO) equipment can be removed. Depending on the distance of the access central office from the MAN central office amplifier can be inserted into the network. Amplification causes noise in the form of Amplified Spontaneous Emission (ASE) within the network, so when developing the layout and power budget of network amplification locations needs to be carefully analysed. An extra benefit to using EDFA as the amplification method means that all wavelengths within the C and L band are simultaneous amplified.

7.4.3 Optical Network Unit TDM and Fault Tolerance Design

The next stage brings the signal from the access ring to the ONU where it is synchronised by a clock and pulse generator (see Figure 79). A pulse and clocking generator is used to synchronise the ONU to its designated TDM signal. An explanation of the ONU and how it was designed using OptiSystem is as follows:

1. The signal enters the ONU where it is split into two optical paths.
   a. One path is amplified with an SOA to counter any loss that may occur from splitting and loss from the external modulator. After the
amplification the signal is inputted to the modulator where it is synchronised and information is applied onto its designated time slot in the signal.

b. The other split acts as the backup, if a fault is detected in the corresponding ONU equipment.

2. The signal is split again whereby a percentage of the synchronised signal is sent to the receiver for decoding. The other split is recombined with the fault line (b above), where their combined power causes increases to the signal power

3. Once the signal is recombined it is sent to the next ONU in the access ring.

4. After the wavelength has traversed through the complete access network it is optically added back onto the MAN ring network.

This test setup was accomplished implementing two access central offices and 8 ONUs (4 per access network).

![Figure 79: Optical network unit](image-url)
7.5 Software Simulation Results

The network described above in section 7.4 went through a barrage of tests that could not have being economically efficient without the vast array of simulation software analysis tools. The tools used to analysis the proposed network consisted of an Optical Time Domain Visualiser (OTDV), an eye diagram analyser, and an optical spectrum analyser.

7.5.1 Optical Time Domain Simulation Results

An Optical Time Domain Visualiser (OTDV) is a device used to display the bit sections of optical waveforms. The OTDV was used in the proposed network to analysis the synchronisation between the MAN central office that transmits the original signal and the ONUs within the network. The default slice of bits that is analysed with the OTDV contains too many bits for the human eye to accurately visualise and compare with another bit stream, it ranges from -6.3992 bits to 134.38 bits (see Figure 80). To compare the MAN central office transmitted bits to the received bits at the ONU the bit slice needed to be magnified. The range was shortened between 10 and 20 bits.
The first set of results for the WDM/TDM setup was an examination of the time synchronisations between the MAN central office and the separate ONUs within the network. An analysis of the research is as follows:

The Optical Time Domain Visualiser (OTDV) was used to view the four different timeslots for each bit (the 4 separate channels on the wavelength). A time section of 10 bits was analysed. Figure 81 shows the time of the combined signals of all four channels as it leaves the central office. After traversing the network the signal was analysed with the OTDV to examine the quality of the TDM signal, see Figure 82. An accurate match of the transmitted optical time domain with reduced power was observed in Figure 82.
Figure 81: OTDV showing the time domain of all four channels at the start of the transmission

Figure 82: OTDV showing the time domain of all four channels after been sent through the ring network

After the ONU received the signal the next stage was to separate their designated signal. This was accomplished by a setting the duty cycle of the pulse generator to a quarter of a bit (i.e. the signal was set to only read quarter of a bit). The ONU within the ring would be set with a read pulse start value that corresponded to its
position in the network. The four channel system in this proposed network assigned the first ONU to start reading at 0 bit for 0.25 bits, the second start pulse is set to read from 0.25 bit for 0.25 bits, the third reads from 0.5 bit for 0.25 bits and the fourth starts reading at 0.75 bit for 0.25 bits. With these settings only the bits that are designated for the ONU will be converted into data.

Figure 83 shows the first signal encoded onto the signal at the MAN central office, while Figure 84 shows the time signal after it has been removed from the full signal time in Figure 81 above to match the original signal in Figure 83. This unit is used to synchronise the designated TDM signal to the ONU.

![Figure 83: OTDV first TDM signal sent from the CO](image-url)
Figure 84: Received signal at the first ONU

7.5.2 Eye Diagram Analysis

Many performance measurements can be obtained by analysing the results of the eye diagram. An examination of the eye can work out if the signal is too long, too short, poorly synced with the clock and too noisy. Signal distortion in the eye is shown by a closure of the eye pattern.

The eye diagram analysis tool allows the examination of the Bit Error Rate (BER) and Q factor within the network. This analysis was carried out to ascertain the error rate within the ONUs. A BER of $10^{-9}$ was chosen to be the maximum allowable BER in this network, as it is the industry standard BER. With four ONUs in the test setup the range from the first ONU to the last ONU was recorded.

With the first and last ONU examined it’s implied that the middle two fall between their BER. The first ONU as expected showed the lowest BER of $8.97 \times 10^{-98}$ and a Q factor of 20.95. This signal is well within the limits of industry standards of $10^{-9}$ for BER and 6 for the Q factor.
Figure 85: Eye diagram of the first ONU

The eye diagram analysis for the fourth ONU (see Figure 86) showed a lowered BER of $9.99 \times 10^{-11}$ and Q of 6.361. Again, this is well within the industry parameters.

Figure 86: Fourth ONU
Figure 86 shows the eye diagram with the BER and Q-factor of the fourth ONU, the signal BER has increased but only to $9.99 \times 10^{-11}$ BER and a Q factor of 6.361.

The appendix B has the BER, Q factor, OTDV, and Eye diagram from the second access network.

A view of the eye diagram once all the TDM signals have being integrated onto the MAN can be seen in Figure 87. This Figure illustrates the four multiplexed channels on the network. It can be clearly seen that the output signal at the access networks last ONU carries data information of four multiplexed channels. The four channels can be observed, marked from C1 to C4. They occupy 1/4 of a bit per channel, as described in section 7.5.1.

![Figure 87: TDM eye diagram](image)

7.5.3 Optical Spectrum Analyser (OSA)

This application allows you to measure WDM sub-system components such as;

- transmission sub-systems (individual components within the system)
- optical add/drop multiplexers (making certain the correct wavelength has been added/dropped at the access central office)
- examine multiplexers/de-multiplexers for parameters such as optical signal-to-noise ratio (OSNR)
- channel wavelength and power.

To examine the OSA results appropriately the many different locations along the network needed to be checked for power loss, noise interference, and wavelength spectrum. A Gaussian filter was used to remove the wide side bands that may interfere when using close proximity wavelengths, WDM needs the filtering if close proximity wavelengths are been implemented in a network. It gives a narrower view on the wavelengths used [82].

The effects of the Gaussian filter in the network can be seen in Figure 88 where no filtering is applied to the first wavelength (193.1 THz). Figure 89 shows the narrower result after the filtering is applied.

![Figure 88: No Gaussian filtering on 193.1 THz](image)

It can be seen in the above wide spectrum that if another wavelength, say 193.2 THz was used there would be some cross contamination in the signal.
It is can be observed from viewing Figure 88 and Figure 89 that filtering will permits closer WDM channelling on the fiber. The two wavelengths being analysed (193.1 THz and 193.6 THz) are multiplexed onto a single strand of fiber (see Figure 90) where they traverse the MAN ring until the first access drop point is reached.

Figure 89: Gaussian filtering applied to 193.1 THz

Figure 90: MAN ring spectrum 193.1 and 193.6 THz
The following describes the results obtained from the OSA analysis of the first fiber section consisting of 22 km of fiber. The OSA in Figure 91 shows the signal after been amplified and dropped from the main MAN into the first access network. The green represents the noise figure in the wavelength; the majority of the noise is inferred from the EDFA amplification at the access central offices.

Figure 91: 193.1 THz is dropped into the access network

After traversing the access network the approximate loss per ONU was established to be 0.5dB. Amplification is needed in the ONU to account for loss associated with loss from the modulator and passive splits.

Figure 92: Power entering the first ONU
As seen in Figure 94 the second wavelength has approximately 15dB of power for the second access point in the MAN ring. Analysis of the second access network drop delivered results that were comparable to the above results of the 193.1 THz wavelength.

### 7.6 OptiSystem Commercial System Results

OptiSystem makes available some previously established networks. A study of these networks results can be compared with the proposed design of the MAN-access ring network. The BER, Q-factor, OSA and Power analysis of these networks is shown. The objective here is to have commercial systems that have being thoroughly tested and implemented into OptiSystem as demonstration
networks. The results of these should also adhere to the industry standards of a minimum BER of $10^{-9}$ and have power levels throughout the network that fall within the acceptable limits of receiver sensitivity (approximately -18dB to -30dB) depending on the receiver used.

### 7.6.1 OptiSystems 10 GB/s SMF Return to Zero (RZ) system

This system is a one directional link to show a standard 10 GB/s RZ system using one wavelength (193.1 THz). The link traverses 25 km of fiber with a 5 dB EDFA to counter losses. The results from the setup are:

BER: $3.8595 \times 10^{-22}$

Q-factor: 9.56626

![Figure 95: BER and Q factor for 10 GB/s RZ system](image)

The OSA analysis from this system is for only one wavelength (193.1 THz). The use of a Bessel filter narrows the noise spectrum (see Figure 97). Figure 96 shows the spectrum before any filtering has been applied.
Figure 96: Without Bessel filter

Figure 97: OSA spectrum with Bessel filter
7.6.2 OptiSystems Migrating to 10 GB/s Dispersion Compensation MAN Ring Network

This system consists of a ring network with 4 add/drop nodes using two wavelengths 193.1 THz and 193.2 THz. Between each node there was 50 km of Single Mode Fiber (SMF) at 16.75ps/nm/km dispersion, 16 km of Dispersion Compensation Fiber (DCF) at -80ps/nm/km and 17.3dB EDFA gain.

![Figure 98: Q and BER at node 4 in commercial system](image)

Here the results were:

BER: $6.165 \times 10^{-33}$

Q-factor: 11.8959
The analysis from the OSA shows both 193.1THz and 193.2THz wavelengths are well within an acceptable power level of -0.36975dB for 193.1 and -0.9018dB for 193.2dB for 193.2 (see Figure 100).

### Figure 100: Power levels

#### 7.7 Conclusion

A comparison analysis on fiber usage is done between a PON tree architecture that all networks currently being researched are based on [36-37, 51-52, 63-65, 67-68, 83-87] and the proposed ring architecture in this research. The results showed a substantial deference in fiber usage. Depending on the geographical layout the amount of fiber used in both network may vary but not by much.

The proposed all optical dual ring MAN-access network demonstrated a RB circumvention architecture for the ring-based WDM access network. RB can be significantly avoided in the proposed architecture because of the unidirectional
structure of the network. Experimental results showed that the proposed network can operate a two WDM/TDM access network setup with 4 ONUs per access network. To demonstrate the reliability of the work, analysis of many sections within the network were taken and displayed.

The regulated bandwidth per user was accomplished by applying specific values on the pulse generator to cycle through a specific section of the bandwidth for a specific bit time. This allowed specific ONUs to be given a certain amount of bandwidth within the network. OptiSystem did not cater for optical burst transmission within the network. The Bandwidth on Demand was examined separately in section 6.3.

The use of all optical interconnects between the MAN and access network allowed a low latency interconnecting network where no Optical-Electrical-Optical (OEO) conversion takes place. The traditional access central offices where a MAN network would drop the bandwidth and then distributed the data by traditional PONs like EPON and GPON are removed and replaced with less expensive central offices where wavelengths are dropped/added and amplified, all optically.
Chapter 8

Conclusions and Future Work

Demand for bandwidth is growing and much research is being carried out on how that bandwidth is going to be provided. When 100 MB/s or more is required per user, fiber optics networks are the chosen medium by most network setups [36, 39, 44, 66-67, 83]. Fiber optics is the best choice because of its current and future bandwidth potential, see Figure 1. Compared with all other transmission media it can handle greater bandwidth. Much of the research that has been carried out in implementing WDM in the access network involves integration with existing PON tree architectures. The access network is primarily dominated by copper communications infrastructure. Since the global fiber access infrastructure is not standardised or implemented [5], the introduction of a more efficient ring architecture into the market is easier to implement.

The primary goal of this thesis was to assess the benefits and issues with deploying a ring access network. The implementation of a unidirectional PON as an alternative to the tree access network brings advantages with reduced type II Rayleigh Backscattering (RB) and a huge reduction for fiber cable compared with the tree architecture. A transparent ONU was demonstrated through software simulations and a hardware based test setup using commercially available equipment. The hardware test results showed that it is possible for a transparent modulator to function as a transmitter even thought a low BER was obtained. A
more detailed analysis was obtained in the WDM/TDM network using the simulation software. The WDM/TDM network established a ring based access network to be used as an alternative to what other research is proposing, like the SUCCESS network from Stanford University [44], the architecture used in the optical burst switching [67], and the commercial deployment in South Korea [36]. All the networks that have been examined in this thesis implement some tree architecture for the access network. Some networks that employ the tree architecture have proposed ways that somewhat reduce type II RB [47, 51, 68].

8.1 Research Contributions

The key contributions of this thesis are as follow:

This thesis investigates how to implement an economical WDM system in the access network. The main focus of the research is in developing an economical colourless/transparent ONU. The simulation work carried out in chapter 5 and hardware test bed setup in chapter 6 demonstrated how an external LiNbO3 modulator can be implemented within an ONU device. The simulation of the colourless/transparent ONU was analysed via benchmark tests using NRZ and RZ encoding schemes. This setup demonstrated much greater distances than current passive optical networks can achieve (with distances for NRZ and RZ of 61km and 68km respectively versus approximately 20km for existing PON). After the simulation hardware testing of the ONU, a test bed setup of an ONU using off-the-shelf components was demonstrated. The results from this chapter were observed from two forms of analysis. Firstly, a loopback configuration of an altered XFP module was tested with an external modulator acting as the transmitter. The received signal on the XFP module was analysed using an oscilloscope. Secondly, a 10Ghz BERT allowed some further analysis of the setup. The BERT gave a BER and eye diagram of the colourless/transparent ONU.

In chapter 7 the development of a new PON architecture incorporating the use of the colourless/transparent ONU from chapters 5 and 6 took place. One goal of the new architecture was to cut down on the amount of fiber cable used compared
with current tree PON networks. An example was drawn up to compare the proposed dual ring MAN-Access network with a tree PON architecture. The results from the example demonstrated that approximately 30 times less fiber was required in the proposed passive dual ring architecture compared with the passive tree PON.

While developing the dual ring architecture in chapter 7 a way to remove the distortion effects of type 2 Rayleigh Backscattering (RB) caused by bidirectional communication was examined. It became apparent to keep the network both unidirectional and passive. In order to keep the network passive the ONU had to keep the signal all-optical before it was sent onto the next ONU (see figure 79). This was achieved by the integration of the colourless / transparent ONU. Once the unidirectional signal was encoded with information it continued on to the next ONU in one direction and all optically. This unidirectional setup removed the effects of type 2 RB altogether.

Once the all-optical unidirectional ONU was tested, an efficient utilisation of the available bandwidth via TDM was tackled. In order to synchronise the incoming optical signal the external modulator of the ONU was used. It also acts as the colourless/transparent transmitter for the uplink communications signal. The test setup demonstrated the all-optical TDM setup with four ONU per access network (see section 7.5.1). This number can be increased, but for simplicity the demonstration only simulated four ONU.

An important factor in this research was the all optical nature of the dual ring MAN-access network. The access network was demonstrated to be all-optical with the introduction of the colourless / transparent ONU (see figure 79). The next area where a bandwidth bottleneck occurs is the intersection between the MAN and access network. The unidirectional setup allows for the simple use of a standard all-optical add/drop multiplexer to be used at the intersection between the MAN and access network. This setup does not require any expensive or sophisticated switching technology at these points (see section 7.4.1). At the
MAN-access bridge add/drop multiplexers all-optically drop the required wavelength to each access ring and all-optically add it back after it has traversed the all optical access ring.

In summary (and in addressing the original research hypothesis in chapter 1.2.) it can be stated that based on the collated results the introduction of WDM into the access network provides a technologically and economically viable alternative to providing high-speed broadband data services to end users.

8.2 Future Work

Areas outside the scope of this work that would contribute to furthering this research are listed below.

8.2.1 Network Testing within an Optics Research Lab

Optical testing of networks and equipment is restricted to optical research labs due to the amount of expensive test equipment that is needed. The only cost-effective solution for initial research testing of optical networks is through optical simulation software. That been said, research in an optical lab would be great to advance the proposed setup to the next stage with further hardware testing.

8.2.2 All Optical Packet Switching (OPS)

To improve on the proposed all optical MAN-access bridge, a method of optical packet switching is of great interest. It allows for optical packets to be switch without been transferred into the electrical domain. OPS delivers a transparent method for access networks to optically and dynamically communicate with each other without the need for a round trip back to a central office. An OPS network allows optical packets to be routed around faults. Work on optical logic gate is currently being carried out, that can recognise optical packet headers and route the signal accordingly [88].
Publications and Patents arising from this Thesis

Patent


Conferences

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Appendix

A. Second Access Network Results

The results from the second access network in the experiment in section 6.4 and 6.5 are shown in the following figures. The analysis demonstrates results from the network that agree with the desired outcome. The 193.6 THz channel-wavelength was used for the second access network where results from the eye diagram, BER, time division multiplexed channels and spectrum analysis was shown. In Figure 87 the eye output after the access network has traversed the network can be visualised.

![Optical Time Domain Visualizer](image)

Figure A.1 Transmitted Bit sequence on the second wavelength for the fourth ONU in the second access network
Figure A.2 Corresponding Bit sequence of the fourth ONU after traversing through the network past the First access network and through the second Access

Figure A.3. The spectrum 193.6 THz form before filtering
Figure A.4. The spectrum 193.6 THz after filtering

Figure A.5 The Eye Diagram of fourth (last) ONU within the second access network. BER of $7.42 \times 10^{-25}$