MODELING AND EMULATION OF OPTICAL NETWORKS FOR SDN CONTROL

by

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As members of the Master's Committee, we certify that we have read the thesis prepared by **Aamir Nasir Quraishy**, titled ***Modeling and Emulation of Optical Networks for SDN Control*** and recommend that it be accepted as fulfilling the thesis requirement for the Master's Degree.

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ABSTRACT

Today's telecommunications networks are facing increasing internet traffic demands for a variety of high data-rate applications including virtual reality (VR), video-conferencing, and high-definition (HD) video streaming. Optical networks are more efficient than wired and copper networks over long distances and high speeds, and thus have been a large contributor for increasing data capacities over the past several decades. Developments in optical fiber technologies have allowed optical networks to be manufactured at steadily lower cost per bit. However networks do not just need to handle larger traffic volumes, they also need to work with existing network architectures and accommodate traffic requests with different requirements. One method for addressing this challenge is Software Defined Networking (SDN). SDN separates the control and data-plane so the data management and control decisions are made by a central controller that direct information as need be. However, developing SDN systems for optical networks at scale is difficult because optical networks need to consider signal quality and nonlinear fiber impairment.

Mininet-Optical is an optical network emulator designed to emulate a multi-layer optical network so network designers can develop SDN control algorithms. Mininet is an open-source tool for studying SDN but does not support optical networks. We developed an optical layer simulator that is integrated into Mininet Optical. We evaluated this approach using the open-source planning tool GNPy and showed strong agreement. We also developed an SDN control algorithm for provisioning optical networks with bandwidth variable transceivers

(BVTs) and examined how the SDN controller responds to diurnal traffic.

BVT technology has received attention from the SDN community because of its ability to change modulation formats to optimize network capacity and their performance depends on the quality of transmission. This adds an extra element of control that SDN controllers can use to respond to varying traffic conditions such as diurnal traffic patterns and respond to different traffic needs. In this thesis we discuss SDN control, BVTs, Diurnal traffic modeling, optical fiber transmission physics, and the mininet optical system. From this, we will examine SDN control for a network with BVTs handling requests from metro networks in residential and office areas with diurnal traffic. This work shows how BVTs operate in an SDN controlled network while responding to time varying traffic, and show non-linear impairment induced switching for heavily-loaded traffic.

CHAPTER 1

Introduction

One of the most significant innovations of the last century has been the worldwide web. It has allowed for people to access information, connected people, and during the Corona-Virus pandemic, it is instrumental for working from home and interacting with loved ones. Internet usage is growing at a rapid pace, and the demands of internet use have become more varied and complex [1]. As such, the internet needs to not only handle more data but also become more flexible to handle different traffic demands. One proposed solution to this is software-defined networking (SDN).

SDN separates the control plane from the data plane so that an operator or controller can determine where and when information is forwarded. Platforms to test these controllers and ensure their viability, especially in large networks are an important tool for research and development. One way to test SDN control systems is using deployed networks. However, this runs into problems of interfering with the network and causing potential disruption to the system. Furthermore most networks are owned and operated by private internet service providers (ISPs) who may not support this form of testing on their networks. The other is to create test-beds that can run SDN control systems such as the Cosmos Testbed [2]. However, time needs to be arranged and reserved on physical test-beds and physical test-beds can be expensive. The last solution is to create a virtual test-bed to allow a user to design networks on a computer. This is a goal of Mininet-Optical, to create a system that can allow for the testing and experimentation of software-defined optical networks (SDONs) on a desktop or personal computer (PC). The University of Arizona has been developing Mininet Optical in partnership with Trinity College Dublin to support SDN in optical networks.

Previous work looked at Mininet Optical and its simulation of cloud radio access networks (CRAN) [3] and in disaggregation of optical networks [4]. This thesis will examine emulating SDN traffic control in optical networks, and how Mininet Optical models optical network transmission. This will be accomplished by comparing Mininet Optical's Quality of Transmission estimation (QoT-E) with the open source GNPy engineering planning system. This thesis will also examine bandwidth variable transceivers (BVTs) and how they respond to the dynamic diurnal traffic demands. This will be done by comparing the required resources, traffic blocking, and network utilization of different transmission schemes and margins to show the cost/benifits of different modulation methods and provide an example of the prototyping capabilities of Mininet-Optical. This thesis will also examine BVT switching caused by non-linear impairment in response to diurnal traffic requests.

The following sections will discuss SDN, specifically for optical networks, as well as the open challenges in SDN (Section 1.1). Section 1.2 will then examine BVTs and diurnal traffic modelling to provide context for the work done here. The next chapter will focus on the transmission physics modelled in our emulated fiber network and the quality of transmission (QoT) metrics used by the system (Chapter 2). Chapter 3 will discuss the Mininet system, its motivation, and the structure of Mininet-Optical, Mininet-Optical's SDN control architecture. Chapter 4 will go into the details of the SDN control algorithm, and the network logic by which it assigns lightpath traffic and the provisioning metrics it examines. Chapter 5 will examine the signal modulation cases and how the use of different BVTs affects the lightpath count, blocking rates, and channel utilisation, as well as the non-linear interference effects on heavily loaded systems. Chapter 6 will conclude this thesis by reviewing key points and what future areas of studies are available for SDN using Mininet-Optical.

1.1 Software Defined Networking and Open Challenges

In the 2000s the internet protocol (IP) networks were reaching a new level of complexity which impeded further growth. To implement high-level network policies network operators needed to configure each component separately using low-level and vendor-specific commands [5]. One of the goals of the early internet was a decentralized system that could handle diverse and varied hardware. This allowed for the freedom of growth and widespread use. However, the fact that the network systems had become so diverse led networks to become more complex, inflexible, and convoluted. This became apparent by the difficulty of switching from IPV4 to IPV6 a task that was taking well over a decade. It was evident that the system that existed was not sustainable for future growth. At the same time, several Fortune 500 companies such as Google, Microsoft, Facebook, and Apple needed to be able to control how data flowed inside their data centers and the closed-source software in their switches and routers made it difficult to do.

To solve these problems a new system of "Software-Defined Networking" was introduced. The principle behind it was to take the switching hardware and implement an open 'control layer' which a user or another system could communicate with and direct the flow of information. This principle became known as "control and data plane separation" where one 'layer' would make decisions for the network's operation (the control layer), and another 'layer' would enact those changes and accommodate data commands (Data layer).

When SDN was first introduced, it was not initially well received, however with the growth of the internet, and the needs of large data centers, the timing was right for wide scale adaptation and this led to the founding of the Open Networking foundation [6] to promote the awareness and growth of SDN. One area of growth has been to extend SDN principles to optical networks. The open challenges and research areas of SDONs: are Simplicity and Efficiency, North-Bound Interface (NBI), Reliability, security and Privacy, Scalability, Standardization, Multi-layer Networking, Multidomain Networks, Fiber-Wireless Networking, QoS and Energy Efficiency, and Performance Evaluation. Overall, these challenges need to lead to increasing network performance while decreasing cost [7]. The rest of this section discusses the above mentioned areas of research, what they are, some of the challenges, as well as the possible impacts of Mininet-Optical's virtualization to advance SDN research.

1.1.1 Simplicity and Efficiency

Currently, optical networks are large heterogeneous systems that have multiple components from various vendors. For example, a network topology may be a transceiver from II-VI transmitting over a ROADM from Lumentum and amplified with an EDFA from Baudcom. All these have different components that need to be able to work together successfully without interfering with the larger network. Currently, because of the proprietary software systems in the equipment from multiple vendors, each network node needs to be configured manually for all of them to work together. This process can be inefficient and time-consuming. However, one area of development for SDON components is creating native functions that can be abstracted to the software layer and controlled and configured by a network controller. One possible direction is open-source middle-ware that would allow different nodes to be able to communicate with other network nodes from other vendors, as well as with a centralized controller. This was what happened with Openflow, where it was proposed as an optional middle-ware protocol that system-vendors could support without having to open up their proprietary software [8].

1.1.2 North-Bound Interface (NBI)

The northbound interface (NBI) is the set of command protocols that allows lower-level network components to communicate with higher-level control systems. This communication with higher levels of the network architecture is important because it allows networks to be able to make requests to a central controller, report issues, and overall communicate the condition, needs, and state of the network. For example, if a ROADM or switch is routing more traffic than it can handle it can communicate that with a central controller. The controller can then open a path with less traffic and allocate the necessary resources to resolve the issue. Being able to process requests and dynamically change to account for those requirements is a large part of why SDN was introduced.

Much of NBI research is not just dedicated to directing traffic but also directing traffic with different QoS requirements optimally. For example, video-conferencing does not need high data rates but needs low latency, and video streaming services like Netflix and YouTube needs high data rates, but can tolerate higher latencies. Future research areas for NBI include developing a dynamic service deployment (DSD) so networks can handle different types of traffic requests based on data-rate, bandwidth, and latency requirements. A DSD NBI will be able to make requests of the SDON to invoke an optimal infrastructure while being flexible to the ever-growing and evolving systems that will be deployed in future networks.

1.1.3 Reliability, Security and Privacy

While SDN allows for greater flexibility and usability of the system, it can also exacerbate certain network issues. The centralized nature of SDON means that control failures, faulty behaviors, and malicious security infringements can cause greater performance losses and extensive disruptions. Furthermore these issues could lead to a failure of trust in SDNs in the long term. The area of SDONs is more open, with more research being done including implementing a 'security-enhanced signaling scheme of SDON' [9].

One possible area of development for Mininet systems is to create a security-test application programming interface (API) that can simulate malicious cyber-attacks and allow for the development of network tests to check for cyber attacks as well as control algorithms to battle these situations.

1.1.4 Scalability

One important factor to know about an SDN system or controller is how much information it can manage and handle. The scalability of an SDN system is its ability to work well on larger and more complex networks. However it is not easy to test. Optical network components are quite expensive. A fiber spool costs hundreds of dollars [10], an erbium-doped fiber amplifier (EDFA) costs thousands [11], and a ROADM can cost tens of thousands of dollars [12]. To be able to test network software, on a large-scale networks need hundreds to thousands of these components and could easily lead to an experiment costing millions of dollars, and spanning hundreds of miles.

One way scalability can be examined is with optical network planning tools. In this respect, the GNPy project sponsored by the Telecom Infra Project [13] is an open source system for modelling the transmission physics of an optical network. The engineering and planning tool calculates transmission quality in an optical network with respect to input power and fiber-network component, through a network topology. While this is a good model for network designers and engineers to look at network quality of transmission it is not good for designing SDN control layers that manage data. This is the core benefit of the Mininet-optical system. Mininet Optical is designed to run and simulate data traffic (i.e. streaming, video-casting, and other forms of traffic) in a simulated test-bed, which can model the delays, loss, and other parameters of optical packet-networks.

Scalability was a motivation cause for the creation of Mininet-Optical. Mininet's ability to create a virtual test-bed and virtual topologies allows researchers to make initial tests that can be used to test algorithms before taking them to a test-bed. Furthermore, it can allow students and early researchers to become familiar with the elements and principles of SDN without the need for large testbeds.

1.1.5 Standardization

As discussed in section 1.1.1 modern telecommunication networks are large heterogeneous systems with multiple components from different manufacturers, several of which may be industry competitors, supplying components. In order for them to work there needs to be an industry standard so that they can all communicate with each other across different network structures. Likewise, for SDONs to work their components also need to have standard inter-domain protocols in order to work across various networks. To this end, many network component manufacturers need to create a common platform in order to standardize their systems.

Many standards organizations have come about, including the Open Networking Foundation (ONF). ONF is a "non-profit operator-led consortium"[6] designed as a platform for multiple network vendors to create open-source standards that can be utilized across networks. One system of standardized development made by ONF is Open-flow which is a major contributor to protocol standardization across SDN systems [8].

1.1.6 Multi-layer Networking (vertical)

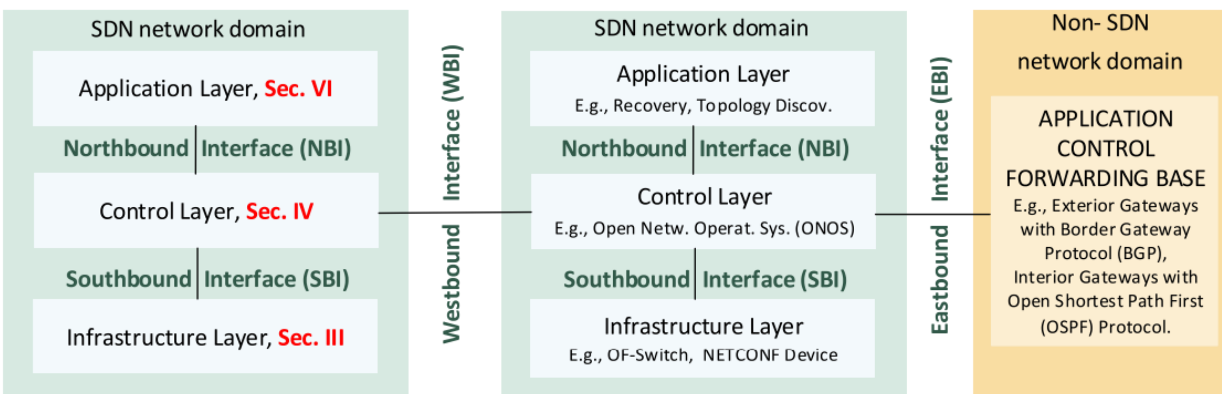


Figure 1.1 Diagram of the vertical SDN layers (application, control, infrastructure) and horizontal (SDN and non-SDN network domains) [7]. The application is an abstraction layer that specifies the shared communications protocols and interface used by hosts in network interfacing. The control layer communicates with the network infrastructure to fulfill the requests of the application layer. The infrastructure layer is the network equipment that communicate with the control layer. The interface between the application layer and control layer is the Northbound interface (NBI) and the interface between the control layer and infrastructure is the southbound interface (SBI).

Mobile network communication system models can be split into two 'layer directions,' horizontal (over multiple domains) and vertical (over the hierarchical network structure) layers (See Figure 1.1). This 'layered' perspective is used as a way for the network scientists and engineers to focus on design and engineering challenges. Vertical layer challenges deal with the hierarchical layers in an SDN domain being able to communicate with other layers in the domain's hierarchy, i.e. the control layer, application layer, and infrastructure layer being able to communicate with each other. Horizontal-layer communication deals with networks being able to work with networks from other 'domains' or other companies. i.e. AT&T being able to communicate with Verizon's network and so on.

The main feature that separates SDON from normal systems is the physical infrastructure layers, which deal with wavelength-division multiplexing (WDM) and transmitting light waves. The signal propagation through these optical systems are managed by 'optical orchestrators' which can provision signals and optical components based on instructions from the control layer. Mininet Optical works on creating a simulated optical layer modeled on transmission physics for signal propagation.

1.1.7 Multi-domain Networks

Multi-domain networks deal with the proprietary nature of networks. The US is served by network carriers such as AT&T, Version, Time Warner, and others that finance and manage their own networks. In order to enable cross-domain communication across multiple vendors, security features need to be enabled, including access control (being able to control the behaviors of other networks that access the domain), authentication (approving one's access), authorization (giving permission), and accounting (being able to see who access the information and for what purpose). Creating fast, and efficient means of fulfilling this is an important area of research.

One area of research is being able to transport optical signals across multiple domains. Currently, if an optical signal from one domain needs to cross over to another domain, the signal needs to be converted to an electrical signal, processed, then converted back to an optical signal using optical-electrical-optical (OEO) conversion. However, recent research was able to manage optical-optical signal transfer in transparent software-defined exchange (tSDX) with an OPM to enable over impairment aware service level agreements (SLA) [14]. The ability for optical signals to flow seamlessly between multiple domains without OEO conversion could lower latencies and allow for greater internet speeds for emerging low latency requirements.

1.1.8 Fiber-Wireless Networking

Previous sections discussed challenges regarding hierarchies and networks, and difficulties regarding Horizontal and Vertical layers of networking. However, network infrastructure is also composed of multiple technological infrastructures including wireless. Unlike Fiber, wireless communication has high rates of loss and lower transmission bit rates and utilizes different frequencies for transmission. Wireless networks also have their own routing mechanisms as they have to respond to mobile devices entering and leaving their field of service. However fiber plays a role in wireless networks by connecting to wireless end-nodes, and transmitting data over longer distances. With the larger data rates being offered by 5G systems, there is greater need for fiber and wireless systems to work together. For these reasons there needs to be SDN control systems that can work seamlessly between Optical fiber and Wireless networks.

Currently there is a WiFi package for Mininet [15], and this package has been used to replicate fifth generation (5G) radio LTE networks [16]. However the challenge for fiber-wireless SDN systems comes from creating a shared API that can be used for both optical networks and wireless networks.

1.1.9 QoS

Quality of Service (QoS) is the ability for an optical transmission systems to handle various types of service demands needed by end-user applications. QoS parameters include bandwidth (the rate of information sent and received), latency (the delay/speed information arrives), jitter (the variation of latency), and error correction. For example, a streaming service such as Netflix, Hulu. or YouTube needs high bandwidth but can accept higher delays in service requests. Online gaming needs relatively low bandwidth (on the order of 100 Mb/hr) but low latency [17]. Video-conferencing systems like Zoom, Microsoft Teams, and Skype can handle low-moderate bandwidth but requires low latency.

In the majority of areas mentioned above QoS plays a major role in the research, and maintaining/increasing quality of service is a major end goal in the field. For example, in order to support scalability, the Open Networking Foundation introduced OpenFlow to support standardized control requirements for networks [18]. Right now OpenFlow has 34 Flow messages that can enable a controller to communicate with its southbound interface SBI. In a similar vein, one area of examination for multi-domain networks is intent-based networking (IBN), where the 'intent' of an application (i.e. streaming, live-streaming, gaming, etc.) is known by the SDN controller and the network is provisioned to enable communication systems to fulfill the demand. One possibility is to group certain service-requirements together for shared protocols. For example, video streaming like YouTube and Netflix would have one dedicated service protocol, gaming would have another, VoIP services would have other provisioning requirements, and so on. This could reduce the number of control policies needed albeit lead to a granularity of service i.e. having one-size fits most solutions that does a job decently, rather than a individualised solutions which can handle the request with greater quality of service.

Another area QoS is being studied is cloud radio access networks. As Optical systems grow, and can transmit optical signals over larger distances error-free there is a larger need to centralize the baseband unit processing at central data centers, rather than at a remote radio head. However this increases the latency to transmit signals, and so examining signal processing at data centers is an area of focus for optical networks.

1.1.10 Performance Evaluation

Naturally, many of the research areas discussed above are rooted in reducing costs, increasing quality of service and making networks more energy efficient. However to ensure successful SDN control systems metrics and methodologies need to be developed to quantify improvement in SDN systems to ensure compatibility with other systems, scalability, performance, simplicity, and efficiency. These metrics need to be testable across control and data planes interactions, as well as multiple domains and fiber-wireless systems. For SDON there also need to be methods to evaluate the signal to noise ratio and optical signal quality in the optical layer.

In Mininet-Optical we have emulated differences in monitoring schemes (placing monitors at every node, every other node, or every 7 nodes) and examining how different monitoring schemes can improve quality of transmission [19].

The Mininet Optical system was designed to support the scalability of optical networks (section 1.1.4) However it also has the ability to model different QoS requirements (section

1.1.9) and supports multi-layer networking (section 1.1.6) by enabling users to design their own NBI (section 1.1.2) and providing an in-built SBI. Currently Mininet Optical is designed to support the areas above.

1.2 Studies of Bandwidth variable transceivers and Diurnal Traffic Networks

As discussed above in the NBI section (Section 1.1.2) there is not just a growing traffic demand, but more types of traffic with different needs and requirements. The growth pf internet needs has been researched and studied that and the impact of this growth has led to increasing cost and energy usage that require new solutions to be developed to solve them [20], [21]. This section will discuss two areas of research being done to reduce cost and energy output. They are bandwidth variable transceivers and diurnal traffic studies. The examination of these two areas, will motivate the experiment done in chapter 5 which examines the impact of bandwidth variable transceivers and their ability to adopt modulation formats for different traffic distances in diurnal traffic networks.

1.2.1 Bandwidth Variable Transceivers

Bandwidth variable transceivers (BVTs) provide flexibility in networks to handle different traffic requirements [22]. However technology for elastic networks that utilize BVTs can be costly, so there is research being done on long-term benefits of elastic solutions (which implement BVTs) compared to non-elastic systems. This includes studies on energy savings [23] and cost-saving [24] in elastic networks.

A BVT is a transceiver that can transmit optical signals in more than one modulation format and can switch between modulation formats. This is useful in SDON systems because

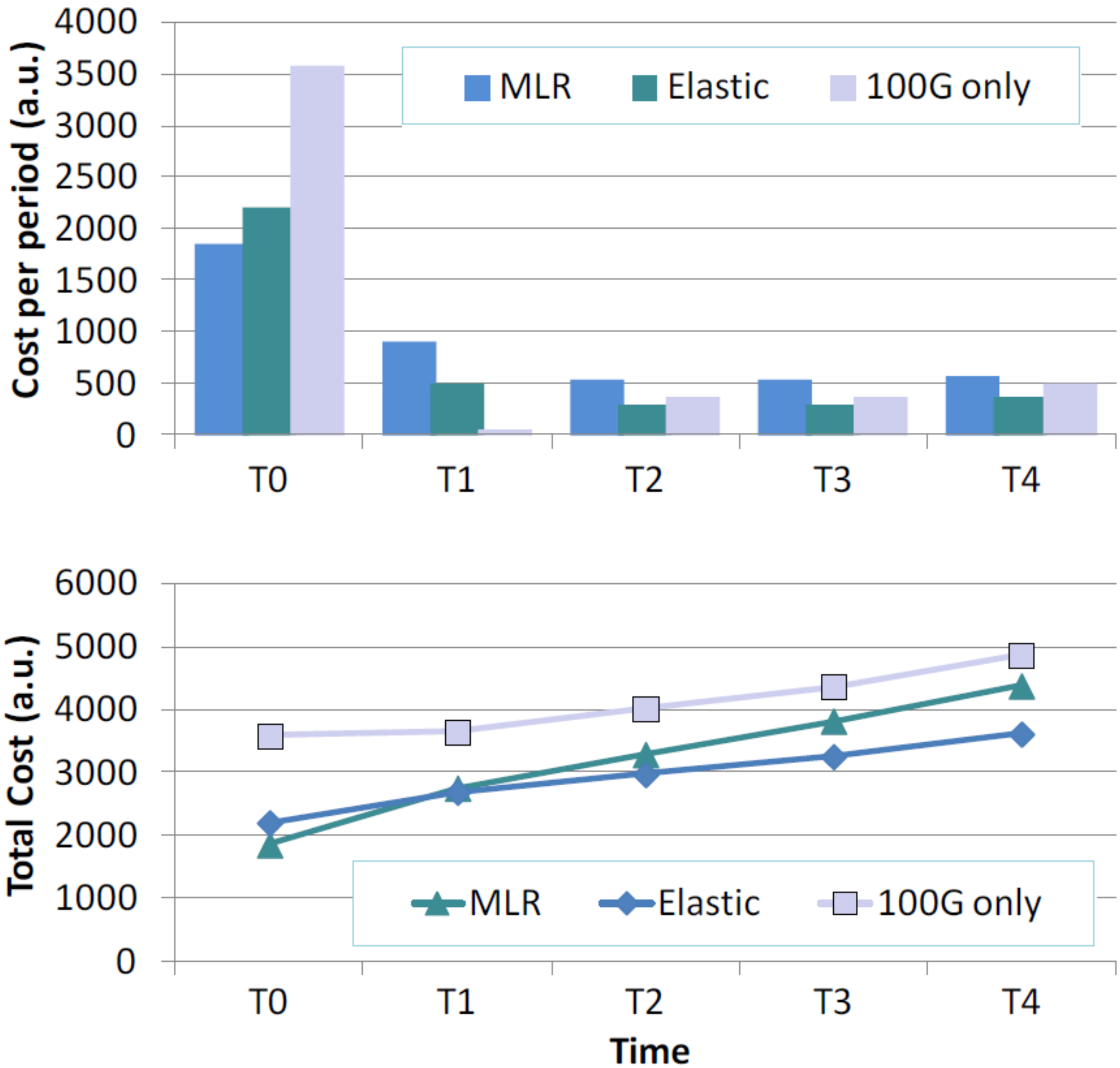


Figure 1.2 Cost difference of Mixed-line rate, Elastic and 100G solutions over time. T_n on this graph denotes a random traffic increase of 30-50% from T_{n-1}. This study was done on a simulated European core network with 32 nodes, and examined how the cost would change over time [24].

it allows the network to handle different traffic requirements that require different bit rates, spectral efficiency, and transparent reach [22]. These modulation formats have a cost-benefit trade-off of being able to increase distance or bandwidth at the cost of the other. If the data needs to travel a short distance a higher modulation format can be used, and if it is farther or there is excessive interference or attenuation, a lower modulation format can be used. Several examples of modulation formats were examined to see the reach of a modulated signal (i.e. how far an optical signal could travel with a BER of 10^{-3}) compared to the power spectral density [22].

Research has shown elastic solutions, which can adopt different transmission formats, have greater cost efficiency than fixed mixed line rate (MLR) solutions (MLR is when different modulation formats coexist on the same fiber together [25]) and static solutions, which can only carry one data rate format (i.e. 100G). Figure 1.2 examines the cost differences and overall costs of MLR and elastic 100G solutions for time intervals with randomly increasing (30-50%) traffic loads. The flexible cost solutions showed a price difference of 17% over mixed line rate solutions and a 34% increase over single rate solutions.

ROSNR of Optical Transceivers

This subsection will discuss the Required Optical-to-Signal Ratio (ROSNR) thresholds of the BVTs for 100G and 200G in simulation and practice. In order for a modulation format to be operable, the lightpath must be above the ROSNR. However, ROSNR varies due to several parameters, including the Baud rate, the forward error correction method, modulation method, and the overhead. Simulation results are shown in Figure 1.3. However this table is somewhat idealized and different numbers have been obtained in experiments. At 100G, system vendors have commercial transceivers with an ROSNR of 14.2 for proprietary forward error correction (FEC) and 15.8 for hard decision FEC (HD-FEC) [26], however PAM4 100G transceivers offer soft-decision FEC (SD-FEC) with an ROSNR of 11 dB [27]. For 200G systems, there are commercial ROSNR values of 21.2 for 16-QAM 200G systems

Modulation format	Bits per symbol	ROSNR @ 28 GBd [dB][a]	ROSNR @ 32 GBd [dB][b]	Bitrate [Gb/s]
PDM-BPSK	2	9.1	7.4	50
PS-QPSK	3	10.1	8.7	75
PDM-QPSK	4	12.1	10.4	100
6PolSK-QPSK	4.5	13.3	12.2	112
32SP-QAM	5	14.1	12.7	125
PDM-8QAM	6	15.6	13.8	150
128SP-QAM	7	17.1	15.7	175
PDM-16QAM	8	18.7	16.9	200
512SP-QAM	9	20.1	18.7	225
PDM-32QAM	10	21.7	19.8	250
2048SP-QAM	11	23.2	21.7	275
PDM-64QAM	12	24.7	22.6	300

[a] assuming HD-FEC with 7% overhead and a threshold of BER=3.8×10^{-3}.
[b] assuming SD-FEC with 23% overhead and a threshold of BER=2×10^{-2}.

Figure 1.3 Table of ROSNR values for different modulation formats with two Forward error correction methods: HD-FEC, and SD-FEC [22]. The experiments in chapter 5 will use higher thresholds of 14dB and 20 dB to examine cases of 100G-200G modulation.

and 20.6 for 12-QAMo systems (at 45.87 and 39.32 GBaud respectively) [28]. For Chapter 5, the ROSNR values used are 14 dB for 100G and 20 dB for 200G networks because that is the threshold for Lumentum Metro transceivers [29].

1.2.2 Diurnal Traffic Studies

The benefit of working with diurnal traffic patterns is that one can have some basic expectations as to how traffic will behave over time, and can make decisions based on those dynamics [30]. One can use these to make predictions and even optimize the networks for future traffic [31]. This section reviews traffic studies that examine daily traffic needs and see how developing traffic-aware systems have provided cost-saving or and energy-saving

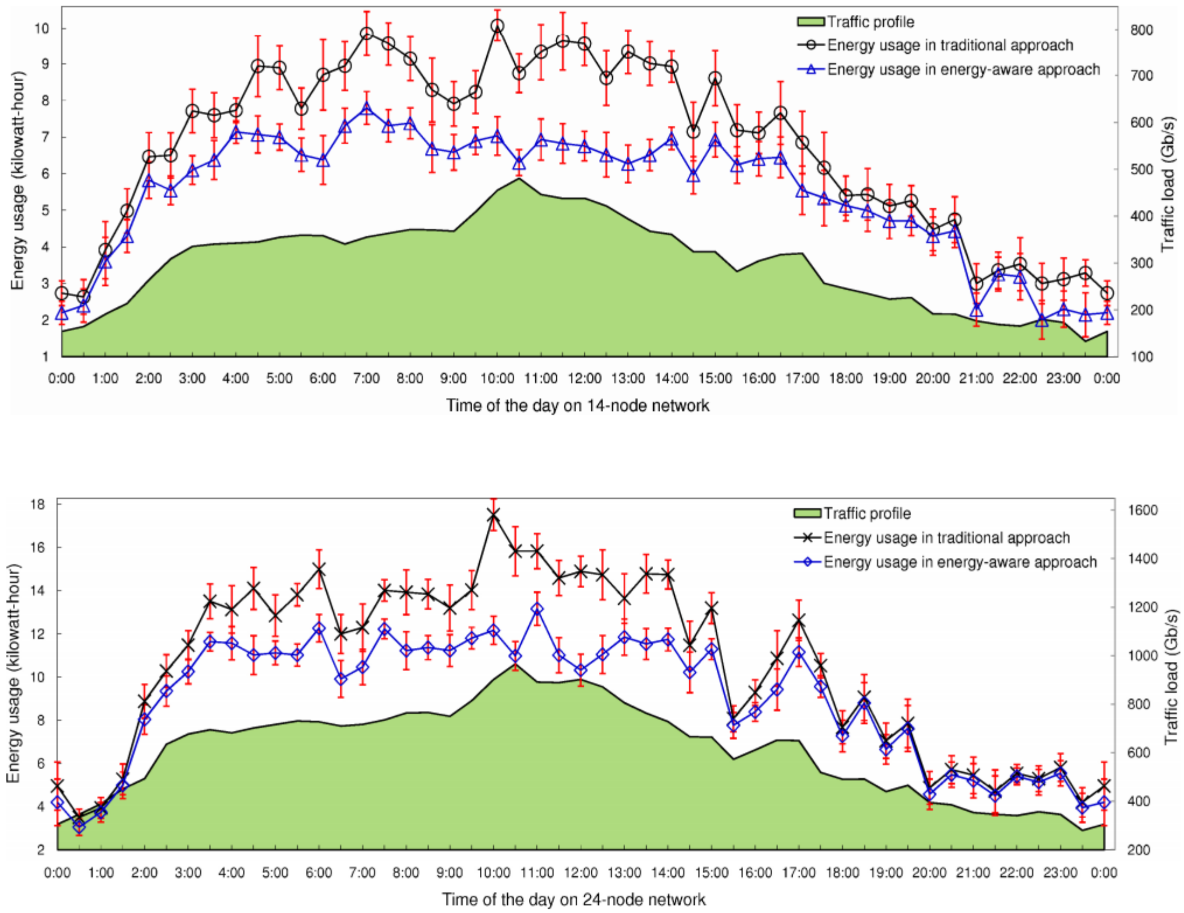


Figure 1.4 Energy saving capability from traffic-grooming in 14 and 24 node systems [32].

solutions for optical networks.

One study looked at modular optical networks with protocols for energy-efficient use [32]. The research found strong drops of energy usage in peak hours, however approximately the same energy usage in off-hours. It has also seen larger energy savings for larger networks. Figure 1.4 looks at one such traffic study that examined diurnal traffic node grooming on a 14 and 34-node network and examined traffic over a 24-hour network. On average the energy savings were around 30% for both systems, with peak power savings at the busiest times of the day.

One research study examined using traffic predictive models which examine how much a tracking heuristic can improve costs of optical network operation [31]. These systems would track how much traffic data was used at any time on the system, remember it, and then use predictive methods to provision resources based on this past data. The systems have seen a 55% increase in savings and expect to see an 82% increase with further testing [31].

1.2.3 Other strategies for Cost efficiency in Optical networks

As discussed above there is a strong body of research being done in making a greener and cost-effective network [33]. This is because currently, mobile and device networks account for 3.7% of all greenhouse gas emissions worldwide which is similar to the yearly gross output of the worldwide airline industry [34].

Some of the other studies included looking at selectively turning off network elements in IP-Network packet forwarding and green routing, and developing other packet-network protocols to save energy [35]. Other strategies include dynamic adaptation such as power scaling to manage laser outputs and idle logic which rapidly turns off optical sub-components when the system is not in use [36] and introduce sleeping and standby for other components. And lastly, there have been several studies on large scale green traffic engineering including wavelength, waveband, and multicast grooming; introducing designs and components which are power-aware, and load adaptive methods such as single-line rate (SLR), multi-line rate (MLR) and Adaptive link rate (ALR) [37].

This chapter has reviewed the role SDN studies have played in optical network research. With the work in SDN, a particular focus has been placed on BVTs, and their ability to respond to different traffic conditions and demands, including diurnal traffic networks. This chapter also examined how several SDN systems are able to save energy and cost by creating solutions that exploit knowledge of traffic dynamics, and utilize BVTs. This other research focused on BVTs through optimization and analysis. The work done in this thesis examines BVTs in time dependent dynamic traffic conditions to show how an SDN controller responds to dynamic traffic conditions as well as examining switching caused by network non-linear effects produced in these systems.

The next chapter will discuss the transmission physics used for the physical layer simulations, and chapter 3 will discuss Mininet-Optical's network emulation and how our mininet-optical transmission compares with the GNPy engineering and planning tool. These will provide context for the SDN routing algorithm (Ch. 4) that will be used in our test case to study BVTs (Ch. 5).

CHAPTER 2

Modeling WDM Signal Transmission in Fiber Optics Systems

Mininet-Optical is an extension of the open-source Mininet network emulator [38] (See Chapter 3) with a southbound interface that utilizes the transmission physics calculations to simulate optical transmission. These equations describe the physics of optical fiber transmission through multiple optical components and calculate the optical signal to noise ratio (OSNR), generalised OSNR (gOSNR), and other metrics. The development of the simulated southbound interface heavily referred to the GNPy project developed by the TelecomInfraProject, a system well known for optical QoT Estimation (QoT-E) calculations [13]. Section 3.2.1 shows how the Mininet optical system compares with GNPy.

For Mininet-Optical, transmission physics equations are used to create a simulated infrastructure layer and provide QoT-E for optical components (fibers, EDFA's, ROADMs, etc...) in the network. The rest of this section will be dedicated to discussing the physics used in optical system components and the equations used in Mininet-Optical for calculating OSNR and gOSNR for optical components in the Mininet-optical system. The purpose of this section is to discuss some of the derivations of amplified spontaneous emission (ASE) and non-linear interference (NLI) noise (section 2.1) and the physics related to the quality of transmission estimation (QoT-E) and transmission simulation used in Mininet-Optical.

2.1 Derivation of Transmission Physics for QoT-E

. There are two metrics Mininet-Optical provides for QoT-E. They are optical-signal to noise ratio (OSNR) and generalised OSNR (gOSNR). For an optical signal to be usable it must have a QoT which enables the signal to be easily decoded, and the information to be read by an end user. These metrics take into account the optical signal power (Power), amplified spontaneous emission (ASE) noise power, and the effective non-linear interference (NLI) noise power to calculate them (as shown below).

$$OSNR = \frac{Power}{ASE} \tag{2.1}$$

$$gOSNR = \frac{Power}{ASE + NLI} \tag{2.2}$$

The OSNR and gOSNR is a ratio of the coherency vs noise of the signal. i.e. an OSNR of 1000 means that optical noise makes up 0.1% of the data that is received. And an infinite gOSNR/OSNR would imply a perfect signal. OSNR and gOSNR are expressed in dB so a $gOSNR = 1000 \Rightarrow 10\log_{10}(1000)\text{dB} = 30\text{dB}$.

Power

Power in this context is optical-signal power out of the transceiver, line terminal, amplifier, reconfigurable add/drop multiplexer ROADM, or fiber component of the optical fiber network. *Power* here is measured in milliwatts (mW) or dBm. This is the optical signal channel power that is pure signal as compared with ASE which is additive noise and the NLI which is distortion.

Amplified Spontaneous Emission

Amplified spontaneous emission (ASE) is noise that is produced by optical amplifiers when they amplify an optical signal. Signal amplification is a physical process that uses a signal amplification medium, i.e. erbium, in erbium-doped fiber amplifiers (EDFAs), to boost the signal in the optical domain. However, in this process the amplifier excites Er^+ ions which spontaneously emit photons that also propagate down the system alongside the signal. Hence they are 'noise' in the fiber.

To calculate the ASE noise from a fiber we need to know the spontaneous emission factor n_{sp} which is a measure of the gain inversion:

$$n_{sp} = \frac{N_2\sigma_{21}}{N_2\sigma_{21} - N_1\sigma_{12}} \tag{2.3}$$

where N_1 and N_2 is the number of ions at the ground and excited energy levels (denoted by 1 and 2, respectively), and σ_{12} is the *absorption cross section* and σ_{21} is the *emission cross section*. n_{sp} is used to calculate the ASE power with the following equation:

$$P_{ASE} = 2n_{sp}(G-1)hf_0\Delta f \tag{2.4}$$

where h is Plank's constant, G is the gain, f_0 is the channel frequency and Δf is the bandwidth or the width in which the ASE noise is measured (usually 0.1nm, around 13Ghz for 1550nm signal). However $n_{sp}(G-1)$ can be used as the noise figure, and different models are used for different amplifiers. So ASE noise can also be written as

$$\boxed{P_{ASE} = n_f hf_0\Delta f} \tag{2.5}$$

Non-linear interference

The first thing to be stated about non-linear interference (NLI) noise power is that it is not physically a power like the ASE noise. As discussed above, ASE noise comes from physical photons launched into the fiber which are not related to the signal. Non-linear noise refers to how much the signal is distorted as it propagates down the fiber, and is represented as a 'noise power' in the transmission Physics.

Non-linear interference (NLI) is the power of signals interfering with one another, due to processes such as four-wave mixing, self-phase modulation and cross-phase modulation. This happens because multiple signals are being transmitted down a single medium and are interfering with one another, and interacting with the medium in a way that causes signal distortion. This effect is calculated as follows [39].

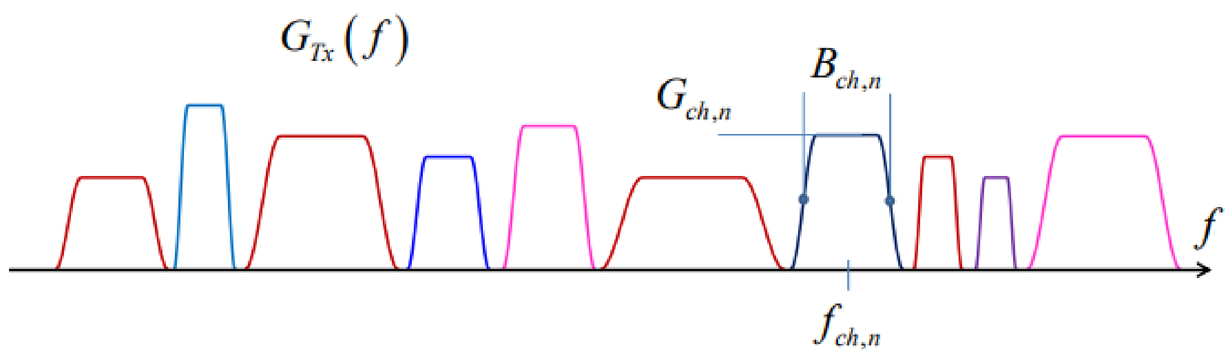


Figure 2.1 An example of a WDM gain transmission spectrum. With bandwidth $B_{ch,n}$ and flat top power spectral density $G_{ch,h}$ for a different center frequency $f_{ch,n}$. Different colors are only to represent channel diversity. Retrieved from [39].

$$\boxed{G_{\bar{E}_{NLI}}(f_{ch,i}) \approx \frac{16}{27}\gamma^2 L_{eff}^2 \sum_{n=1}^{N_{ch}} G_{ch,n}^2 G_{ch,i} \cdot (2-\delta_{ni})\psi_{n,i}} \tag{2.6}$$

where γ is the fiber non-linearity coefficient. L_{eff} is the effective length. Effective length is calculated as $L_{eff} = \frac{1-\exp(-2\alpha L)}{2\alpha}$. Where L is the span length and α is the optical fiber loss such that the optical power attenuates as $e^{-\alpha L}$. $G_{ch,i}$ is the flat top power spectral density shows in figure 2.1, δ_{ni} is Kronecker-delta (1 when $n = i$ and 0 otherwise), and $\psi_{n,i}$ is the 'psi coefficient' that calculates the channel-on-channel interference effects calculated as:

$$\psi_{n,i} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(f_1, f_2, f_{ch,i}) \cdot \chi(f_1, f_2, f_{ch,i}) \cdot g_{ch,n}(f_1) g_{ch,i}(f_2) g_{ch,n}(f_1 + f_2 - f_n) \mathrm{d}f_1 \mathrm{d}f_2 \quad (2.7)$$

where g is the normalised power spectral density, χ is the phased array term and ρ is the four-wave mixing (FWM) efficiency.

$$\chi(f_1, f_2, f) = \frac{\sin^2\left(2N_s\pi^2(f_1 - f)(f_2 - f)\beta_2 L\right)}{\sin^2\left(2\pi^2(f_1 - f)(f_2 - f)\beta_2 L\right)} \quad (2.8)$$

$$\rho(f_1, f_2, f) = \frac{\left|\int_0^{L_s} e^{\int_0^z 2\hat{g}(\zeta)\mathrm{d}\zeta} e^{-2\alpha z} e^{j4\pi^2(f_1 - f)(f_2 - f)[\beta_2 + \pi\beta_3(f_1 + f_2)]z} \mathrm{d}z\right|^2}{L_{eff}^2} \quad (2.9)$$

The next section will examine how the calculations change as the system goes through every element of the optical fiber network.

2.2 Calculations for OSNR and gOSNR by part

For the Mininet-Optical system, the OSNR and gOSNR values change as they go through several elements of the fiber system. Specifically the line terminal, fiber, EDFA, and ROADM (shown in Fig. 2.2). While our system shows 2 one-degree ROADMs, mininet optical allows us to use any degree ROADMs we want. The Optical line terminal, and transceivers (Tx/Rx) are not considered, as they only provide launch parameters, but do not contribute to QoT parameters (outside of the launch *Power*). Mininet Optical has calculations for non-linear interference and amplified spontaneous emission and signal power where the changes through

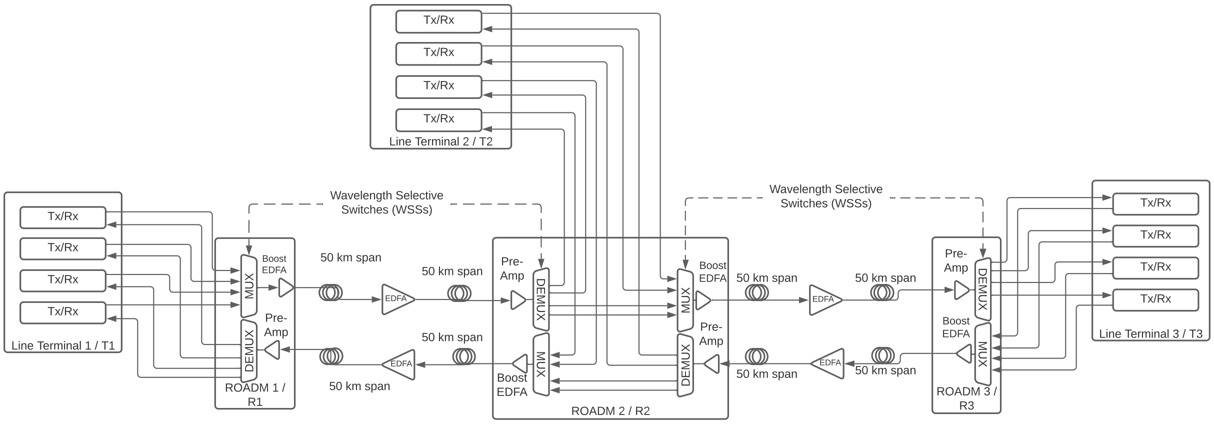


Figure 2.2 A basic linear network that shows EDFAs, Fibers, 1 and 2 degree ROADMs and line Terminals.

every node in the system are accounted for. This section will describe those changes. For each part this section will discuss the transmission power, non-linear interference power, and amplified spontaneous emission power.

2.2.1 Fiber cable

NLI noise

The core non-linear noise experienced by lightpath n by j channels comes from Equation 2.6:

$$G_{nli,n} = \begin{cases} \frac{1}{2\pi\beta_2 L_{asy}}\frac{16}{27}\gamma^2 L_{eff}^2 \sum_{ch,j}\left(\frac{p_{ch,j}}{f_{s,j}}\right)^2 \frac{p_{ch,n}}{f_{s,n}}\psi_{n,j} & \beta_2 L_{eff} \neq 0 \\ \sum_{ch,j}\left(\frac{p_{ch,j}}{f_{s,j}}\right)^2 \frac{p_{ch,n}}{f_{s,n}}\psi_{n,j} & \beta_2 L_{eff} = 0 \end{cases} \tag{2.10}$$

where γ is the nonlinear coefficient (default value is 0.78 $W^{-1}Km^{-1}$ in Mininet-Optical). f_s is the symbol rate and P_{ch} is the channel power. is the symbol rate (32 GBaud by default). $L_{asy} = 1/2\alpha$ is the asymptotic length where α is the loss coefficient (default is: $\alpha = 0.22/20\log(e)$ [1/km], this is constant for all wavelengths, but in general,α is λ dependant). L_{eff} is the effective length defined above under the discussion of equation 2.6.

Lastly the ψ coefficient (referred to in eq. 2.7) is approximated as follows:

$$\psi_{n,j} = \begin{cases} \text{arcsinh}(\frac{(\pi f_{s,n})^2}{2} L_{asy}\beta_2) & n = j \\ \text{arcsinh}(\pi^2 L_{asy}\beta_2 f_{s,n}((f_n - f_j) + \frac{f_{s,j}}{2})) & \\ -\text{arcsinh}(\pi^2 L_{asy}\beta_2 f_{s,n}((f_n - f_j) - \frac{f_{s,j}}{2})) & n \neq j \end{cases} \tag{2.11}$$

where f_n and f_s are the frequencies of the two optical signals n and j. This approximated psi coefficient removes the phased array term χ and assumes NLI accumulates linearly. It also assumes lumped amplification, that amplification is performed discretely on each channel.

Other Optical effects in Fiber

Besides non-linear effects there are other transmission physics that affect both the base signals (power) and the ASE noise. Both attenuate as they transmit down the fiber and experience Raman scattering. These effects are discussed here.

As the signals propagate, both the signal power, NLI, and ASE power dampen or attenuate. This is given by:

$$P_{out} = \frac{P_{in}}{Att} = P_{in} e^{-\alpha L} \tag{2.12}$$

where Att is the attenuation. which is calculated $e^{\alpha L}$. The second correction that is applied on the power and noise is the Raman scattering effect approximated by:

$$\delta = \frac{\beta \sum_{ch} P_{ch} L_{eff} (f_{max} - f_{min}) e^{\beta \sum_{ch} P_{ch} L_{eff} (f - f_{min})}}{e^{\beta\beta \sum_{ch} P_{ch} L_{eff} (f_{max} - f_{min})}} \tag{2.13}$$

Where $\sum_{ch} P_{ch}$ is the sum of all power channels, L_{eff} is the effective length, the f_{max} is the longest frequency in the system, and f_{min} is the shortest frequency and β is the Raman coefficient:

$$\beta = \frac{g_r}{2 A_{eff} f_R} \tag{2.14}$$

where g_r is the Raman amplification coefficiant, A_{eff} is the effective area (80 μm^2), and f_R is the Raman amplification band (15 THz for us).

2.2.2 Amplifier

The purpose of the amplifier is to compensate for signal loss and attenuation in the fiber. It does this by amplifying the signal to maintain a constant signal launch power into the fiber span.

The output power of the optical signal is:

$$P_{out} = P_{in}G \tag{2.15}$$

$$G = g_{sys}g_{\lambda} \tag{2.16}$$

where P_{in} is the input power of a single WDM optical channel, G is the total gain, g_{sys} is the system gain or wavelength-independent gain, and g_{λ} is the wavelength dependant gain or gain ripple. Since the amplification is applied to all signals, the effective nonlinear interference noise is also amplified as well:

$$P_{NLI-out} = P_{NLI-In}G \tag{2.17}$$

As the optical signal goes through an amplifier, the amplifier increases the signal power, but also introduces ASE noise. This is because, while the erbium amplifies the existing signal, it introduces unwanted photons which are added into the noise. The noise component is calculated as follows:

$$P_{ASE-out} = P_{ASE-In}G + n_f hf\Delta f(G-1) \tag{2.18}$$

This equation is derived from equation 2.4. However it is slightly rewritten to account for the existing ASE noise coming into the amplifier.

2.2.3 ROADMS

As signals propagate through the fiber, they may be amplified to an excessive power level. This can include more unnecessary noise into the network. In order to respond to this the ROADMs have a variable optical attenuator (VOA) which levels the output power to a target level for propagation through the system. The output power out of the ROADM is represented as:

$$P_{out,n} = P_{in,n}/Att \tag{2.19}$$

where the ROADM Attenuation for channel n is calculated as:

$$P_{all-in,n} = P_{in,n} + P_{ase-in,n} + P_{nli-in,n} \tag{2.20}$$

$$P_{tar,n}(dB) = P_{ref,n}(dB) - P_{ins,n}(dB) \tag{2.21}$$

$$Att_n(dB) = \begin{cases} 10 * \log(P_{all-in,n}) - P_{tar,n} & \text{if } Att > 0 \\ 0 & Att < 0 \end{cases} \tag{2.22}$$

where P_{in} is input channel power, P_{ase-in} is input ASE power, and P_{nli-in} is input nonlinear interference power. P_{ref} is reference power (0 dBm), i.e. the power the ROADM must use to maintain the optical spectrum. P_{ins} is insertion loss (17 dB), which is the signal power loss through the ROADM. P_{tar} is the optical target power coming out of the ROADM. This is used calculate the attenuation of the ROADM as the sum of all power components minus the target power. The attenuation is returned to its linear state $Att_n = 10^{Att_n(db)/10}$ and from this output ASE, signal power, and NLI for each channel is calculated as $P_{out} = P_{in}/ATT_n$.

This chapter described the transmission physics and QoT-E equations used to estimate the OSNR and gOSNR. The next section will discuss discuss Mininet and how Mininet-Optical works using the transmission physics described here with Mininet's packet switching logic.

CHAPTER 3

Mininet Optical and SDN Control Architecture

Mininet is a network emulator that generates software networks that can be used to to prototype SDN controllers. With Mininet Optical a user can specify a network topology that can forward packet data between virtual network components that can be used to design, test and run SDN controllers.

Mininet was developed to allow for the growth and proliferation of Software defined networking, and ease of testing. Because Mininet is an open-source system, there have been many additions and extensions that have increased its capabilities. due to an active user-base. There is mininet WiFi [15] which allows emulation of WiFi Stations and Access Points. There are also extensions for OSHI [40], SRv6 [41], and containernet [42]. Because of its open-source nature, and support from the SDN community, including the open networking community [43] it often used in academic, research, and industry circles.

The rest of this chapter will be as follows. Section 3.1 will summarize the motivations of the original Mininet project, the network emulation, and running a mininet prototype controller on a physical network [44]. Section 3.2 will discuss the Mininet-Optical SDN architecture, and how mininet optical compares with GNPy. Section 3.3 will discuss the functions used by our SDN controller to communicate with Mininet Optical and manage the lightpath information.

3.1 Mininet

The purpose of the Mininet system is to provide a network emulator, where a user can run the same code on a personal Computer (PC) or virtual machine (VM) running Linux as they would on a physical hardware testbed. Mininet works to support the SDN development process by creating a workflow that is: Flexible so new topologies and functionality can be designed in software using familiar languages and operating systems. Deployable so no changes need to be made transferring systems from the emulation to real hardware. Interactive so management of the network can be done in real-time, just like in a real system. Scalable so to prototyping tests can be examined on networks with hundreds or thousands of nodes. Realistic so the results are show strong similarities with a real network system. And share-able so experiments can easily be shared with peers who can modify and test experiments[44]. Because of these reasons Mininet has reduced the barrier of entry into SDN research by making a common platform to design and test SDN control systems, and reproducing work from previous SDN research. For example a graduate class, students worked with Mininet and reproduced results from 40 networking papers [45].

Mininet is a lightweight network prototyping environment designed for SDN control research and development. In other words, Mininet allows users to create a virtual network topology in Linux or a virtual machine, and run network commands and processes in the same way they would a physical system, and have some confidence that a physical testbed will operate the same way. A Mininet network has 4 components that are designed to reflect a network system. Links that act like a wire connecting two network elements (such as hosts, switches, etc.) Hosts are "computers" in the network. In Mininet, hosts are represented as shell processes inside their own network namespace and ethernet interface which are linked to the rest of the system and connected to a parent Mininet process that sends commands and monitors outputs. Switches receive and forward data between source and destination devices. In Mininet the virtual "switches" forward data between network elements using software OpenFlow commands. Lastly, a network controller manages the flow of data between hosts and switches in the network. In Mininet, the controller can run as a separate process in the PC/VM that controls the other processes or as its own separate host in mininet.

Figure 3.1 presents a virtual 2 node, 1 switch, network to show how the virtual network elements work together in Mininet. The two host namespaces are connected to a switch inside the root namespace (which is a separate namespace connected to host 1 and host 2 namespaces). The controller communicates with the switch and can access and control the 'mn' parent host to forward information between host 1 and host 2.

As has been discussed, the purpose of Mininet Optical is to prototype SDN control systems in an optical network. For a network to be ported over it needs to have the same network topology as the virtual Mininet network. The links must match the physical ethernet links, with the same Ethernet link connectivity. The virtual hosts must correspond to physical hosts with their own OS image. And the virtual OpenFlow switches should be replaced with physical switches configured with OpenFlow and configured with the controller. However, the controller does not need to change so long as it is able to connect to the network. With OpenFlow data-paths on switches and secure shell (SSH) servers on physical hosts the command line interface (CLI).

The work done in Mininet optical extends these emulation capabilities for optical networks. Being able to emulate optical links (fiber), optical switches (ROADMs), as well as

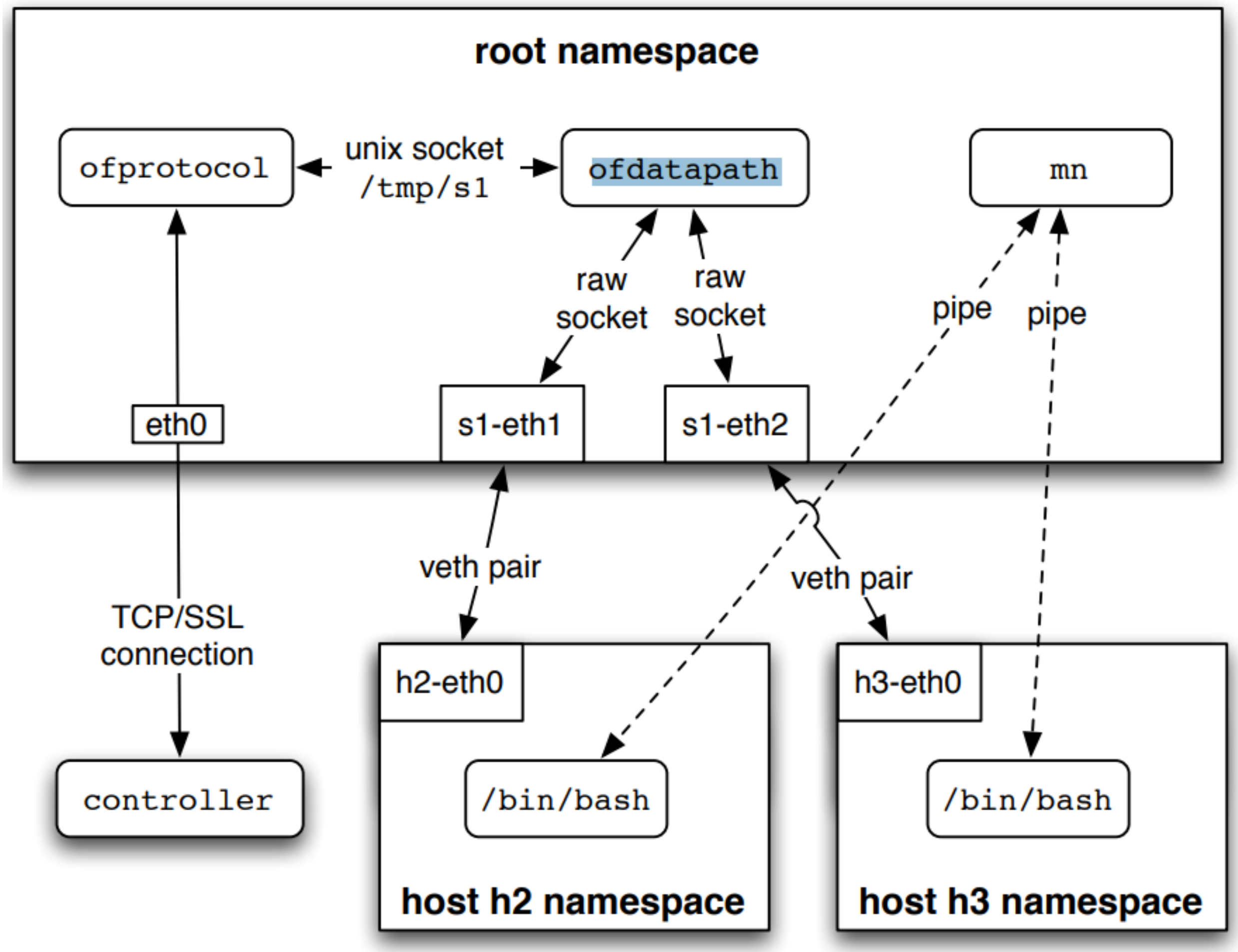


Figure 3.1 Mininet system of two hosts connected by a switch. Both network hosts exist inside their own network namespaces and are connected to a switch in a central root namespace. This root namespace has knowledge of both hosts and can transfer information between them via the switch. And the root namespace takes its commands from an outside controller that communicates commands via OpenFlow [44].

optical transceivers and line terminals.

3.2 Mininet Optical

The Mininet-Optical system being developed by the University of Arizona and Trinity College Dublin is an extension on Mininet that increases its capabilities to include optical systems. It provides an application programming interface (API) extension to support designing fiber-optic networks with fiber links, erbium-doped fiber amplifiers (EDFAs), reconfigurable optical add/drop multiplexers (ROADMs), optical line terminals (OLTs), and optical transceivers. The interface can be used to design and model optical topologies, simulate the transmission physics and run SDN control systems.

Mininet works with virtual ethernet links, whereas Mininet Optical simulates the physics of optical links. It does this by using the transmission physics outlined in chapter 2 to obtain the OSNR and gOSNR of the optical signal. With this information it is able to establish a connection if the signal is above the margin for optical transmission.

SDN control using Mininet optical has three main features that work in tandem to support one another. They are the SDN Controller, the Linux Kernel, and Mininet-Optical as seen in Figure 3.2.

The topmost layer is the SDN controller which deals with controlling the data flow in the network. The SDN controller typically has a user interface (UI), path computation element (PCE), Optical Performance monitor (OPM), northbound interface (NBI), southbound interface (SBI), routing and wavelength assignment (RWA), quality of transmission estimation (QoT-E) and a database manager (DBM). These elements which allow the SDN controller to run the network.

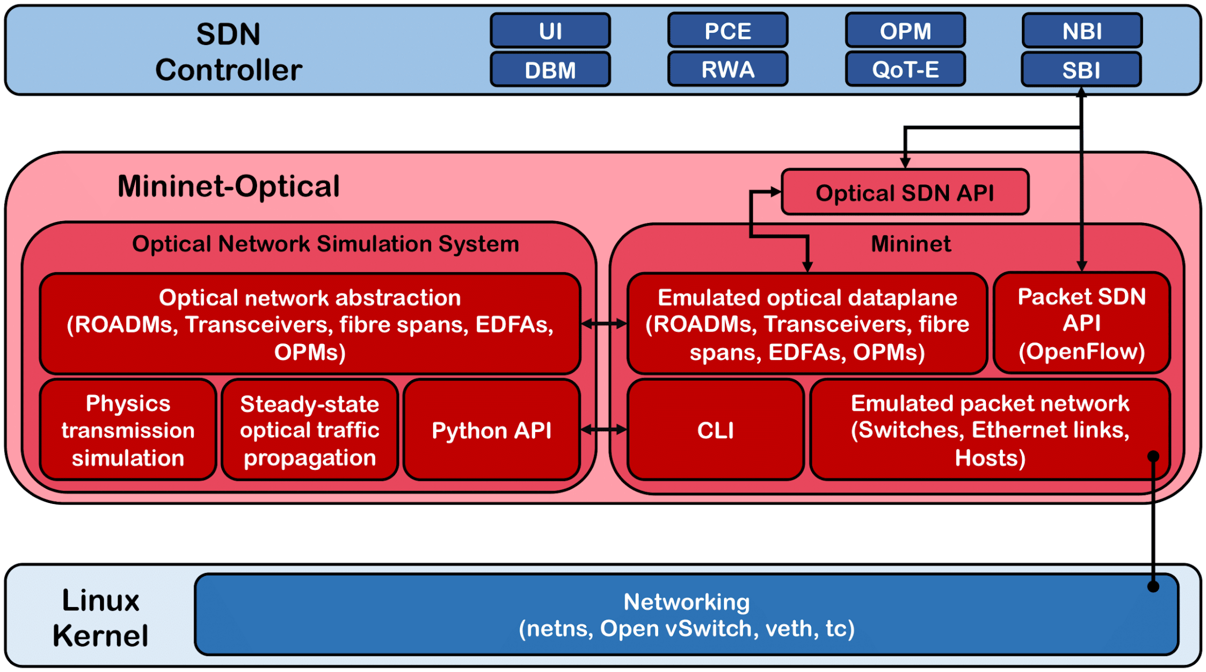


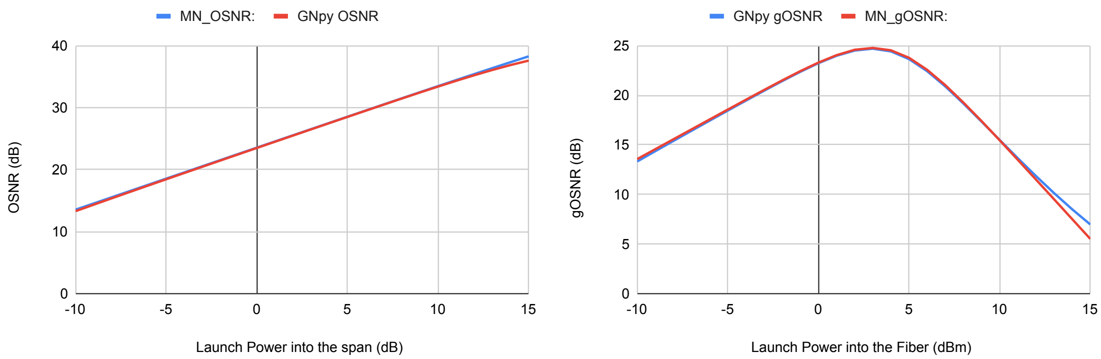
Figure 3.2 Mininet Optical Architecture with three components the SDN controller, Mininet Optical, and the Linux Kernel.

The PCE computes the most suitable path (or paths) for the signal to propagate from the source to destination considering network constraints. The RWA chooses a suitable lightpath that can transmit information between a source node and destination node in the network. The OPM monitors access the quality of the optical signal to ensure optical performance thresholds are being met and the QoT-E provides the signal OSNR and gOSNR. The reason there is both OPM and QoT-E are shown is because in real systems it would be expensive to have a monitor at every point, so having a good estimation model where the SDN controller can measure what the signal is allows us to model a system where there are a discrete number monitoring nodes. This network information of paths, channels and signal quality are communicated to the controller via the southbound interface. Finally this information can be communicated to the UI by the NBI. With this information the controller can make decisions and control the data flow of the networks.

The middle layer of Mininet optical has two main features: "simulation" and "emulation". The simulation feature simulates the transmission physics of the system and the transmission properties of a signal as it propagates from point A to point B. This includes the attenuation, loss, power gain, interference and other properties to estimate the OSNR and gOSNR of the signals. The transmission calculations are shown in section 2 of this work. The emulator uses the optical properties calculated in the simulator as the basis for how the signals will behave in emulation. From this information the emulated optical dataplane knows how packet signals will behave in the emulated optical equipment (ROADMS, EDFAs, fibers and OPMs).

The bottom-most layer that has the Networking features is the Linux Kernel or Linux operating system. All the endpoints are hosts or computers on the networks. Mininet uses the Linux Kernel to create a 'host' which sends/receives packet signals from other 'hosts' on the virtual network.

These systems work as shown in figure 3.2 with an SDN controller communicating to the optical SDN API by directing it to open optical channels to forward data. The optical and packet SDN API then communicates to the SDN controller whether the signals were successfully established, and thus providing the SDN controller with the necessary decision-making capabilities to operate the network. The emulated packet networks run on the networking logic from the Linux Kernel. The hosts are lightweight containers and the virtual switches run using open virtual switch (Open VSwitch) network name spaces (netns), virtual ethernet (veth) and Linux traffic control (tc).



(a) OSNR (b) gOSNR

Figure 3.3 Comparison of OSNR and gOSNR of mininet optical against GNPy in a 5 node linear topology.

3.2.1 Validating Mininet Optical with GNPy

As has been discussed above, Mininet Optical's virtual network was developed by modeling transmission physics in optical networks. Its important to validate this model with other transmission simulation systems. For this purpose, one goal of this thesis was to compare against the GNPy Engineering Planning Tool. However, the application programming interface (API) of the two systems is different, as Mininet-Optical requires a topology to be defined via python, GNPy defines its network topologies in spreadsheets and JSON files. In order to compare the two systems we designed similar linear test cases and examined the two systems to ensure they were similar. In figure 3.3 we show a linear 5-node test case topology with launch power into the fiber between -10 to 15 dB. As one observes, there is consistent matching between the two QoT-E systems, which shows similarity between the two systems.

3.3 Mininet-Optical SDN control functions

The SDN controller communicates with the Mininet-Optical network, sets up lightpaths, and monitors lightpaths. This section discusses the functions in the SDN controller. Our emulation has several functions used to answer traffic demands. These functions largely fall into two categories that we call 'control' functions, and 'Mininet' functions. The control functions are what the controller uses to store data internally about the state of the network. And the 'Mininet' functions communicate with the mininet-optical emulated network.

To highlight the difference between the Mininet-Optical and control plane functions two functions that deal with provisioning the lightpath, one in the control layer class, and one in the "mininet-optical" class will be examined. The functions are **install_lightpath** and **Mininet_setupLightpath**. While they have a similar name and both setup a lightpath they do so for different layers. The **Mininet_setupLightpath** sets up the lightpath in the "physical" layer. The function installs the switch rules into the ROADM's and channels in the topology, so that a lightpath can get from the baseband unit (BBU) pool to the user remote radio head (RRH) unit. The physical layer also has information on the ASE, and NLI noise in the **Mininet_setupLightpath** function but not in the **install_lightpath** function in the control layer. On the other hand the **install_lightpath** function is called by the control layer in order to set up a lightpath (using **Mininet_setupLightpath**) as well as store information regarding the lightpath in the LIGHTPATH_INFO dictionary. It is worth noting that the LIGHTPATH_INFO dictionary does not hold information on ASE and nonlinear noise, because there is not an easy way to know how much of the noise is non-linear. On the other hand the mininet layer does not hold information on the LIGHTPATH_ID because

Function name	description
Mininet_installPath()	selects a channel that that can propagate from the source node to the destination and sets the launch power.
Mininet_monitorLightpath()	returns the measured OSNR and gOSNR from a selected OPM.
Mininet_uninstallPath()	Removes a lightpath signal from the network.

Table 3.1 'Mininet' functions that can change and access the state of the Mininet Optical network.

the physical layer doesn't change based on the lightpath ID. Below these functions will be discussed in greater detail as well as other functions used in the Mininet layer and control layer.

3.3.1 Mininet functions

The **Mininet_installPath()** function sets up a path to fulfill the traffic requests of control layer. It also sets the launch power into the fiber, assigns the channel which propagates through the system and installs the necissary switch rules for the signal to propagate from the source node to the destination. The **Mininet_monitorLightpath()** function returns the OSNR and gOSNR for the lightpath. This can be used for debugging and seeing the network information, but in most networks only OSNR, and input power are returned. Lastly, the **Minine_uninstallPath()** shuts off the transceiver and associated lightpath in the network.

Function name	description
getLinks()	returns all links in out network.
linkSpec()	returns port ID's so mininet can install switch rules in network.
netGraph()	Provides graph of network topology and connections.
FindRoute()	Finds suitable routes from the source to destination node.
pathSelection()	Selects a route from the **FindRoute()** list that transmit from the source to destination node .
waveAvailability()	Shows all unused wavelengths between a and b.
waveSelection()	Selects an unused channel at random.
installLightpath()	Installs a lightpath from the source to destination, and sets the channel to propegate in Mininet Optical network. It also updates the list of active lightpaths.
check_lightpath_for_traf()	Sees if a 25G CPRI request can be installed on the network.
uninstall_Lightpath()	Removes a lightpath signal from the network.
install_Traf()	installs traffic request onto an active lightpath, or sets up a new lighpath if empty.

Table 3.2 'Control' functions that locally store the state of the system, and control the mininet network.

3.3.2 Control functions

The control plane has several functions it can use to access the state of the networks turn on light paths and answer traffic requests. This section will discuss those functions.

In order to successfully allocate proper resources to the network there are several functions used to examine the state of the system. The **getLinks()** function returns all the links in the network as well as their ports and **linkspec()** returns the input and output port and node for one single link. **netGraph()** returns the list of all node connections. All these functions are used to gather information about the topology. The **FindRoute()** function finds the K shortest paths from the source node to the destination. **WaveAvailability()** tells you how many channels are unused and **check_lightpath_for_traf()** sees if the lightpath is being fully utilised, or can accommodate a traffic request.

After necessary information about the system is obtained, then choices can be made on how to allocate network resources. The control functions that are used to allocate network resources include **pathSelection()** which picks the shortest path from the **FindRoute()** function with available resources to accommodate the traffic request. The **waveSelection()** function selects a wavelength channel at random from the available channels and **install_Traf()** installs traffic onto that lightpath.

lighpath_info dictionary entry	Description
LIGHTPATH_ID	Identification number for a lightpath in the system. This lighpath may or may no longer be active. Every lightpath transmitted in the network gets it's own ID.
path	Path from the source terminal to destination terminal.
channel_id	Channel the lightpath is propegating on.
link_cap	Data transmition rate (100G, 200G or 50G).
traf_set	Traffic request ID's that are traversing the lightpath.
up_time	How long it takes to set-up a channel.
down_time	How long it takes to tear-down a channel.
OSNR	Optical signal to noise ratio (OSNR)
GOSNR	Generized optical signal to noise ratio (gOSNR)

Table 3.3 Lightpath information stored in the controller.

The **install_lightpath()** function installs the lightpath in the emulated network topology and stores the lightpath information in the LIGHTPATH_INFO dictionary. All the light-paths that are in use every hour have a LIGHTPATH_ID and a dictionary entry in LIGHTPATH_INFO holding the following information: path, channel_id, link_cap, traf_set, up_time, down_time, OSNR, and gOSNR. The 'path' variable stores the route which the lightpath takes from the source node to the destination. The channel_ID variable is what channel the lightpath occupies (from 1 to 91), link_cap is how many gigabits per second the channel is transmitting (50G, 100G, 200G). The traf_set is the list of traffic requests (and their respective traffic IDs) which the lightpath is accommodating. The up_time is how long it takes to set up the lightpath and turn it on and down_time is how long it takes to tear it down if it is empty. Lastly, OSNR and gOSNR are the optical figures of merit which are used to examine the signal quality of the system.

In summary, the control plane functions serve two main purposes: obtain necessary information about the network, and allocate network resources as necessary. It has several functions that allow it to see possible paths, links, available channels, and traffic load per channel. It can use this information to install light-paths and answer traffic requests. The controller also stores information of what the light-paths are in use every hour and what traffic requests are being answered. Whenever a new channel is established, it sets up the link in Mininet-Optical, and obtains the OSNR and gOSNR from the Mininet Optical topology. Using this information, it chooses how many traffic requests it can allocate on the channel. This is how the control functions and Mininet work together.

3.4 Summary

This chapter discussed Mininet, what it is and why it is a useful tool for studying SDN networks. This chapter also discussed the build of the Mininet-Optical system which implements the transmission physics for SDN. We also compared Mininet-Optical's QoT-E with GNPy to show how similar the two systems were. Lastly we discussed the control system equations which set up lightpaths in Mininet. The next chapter will discuss the Diurnal Traffic SDN lightpath provisioning algorithm which will be used in the experiments to examine bandwidth variable transceivers.

CHAPTER 4

Diurnal Traffic SDN lightpath Provisioning

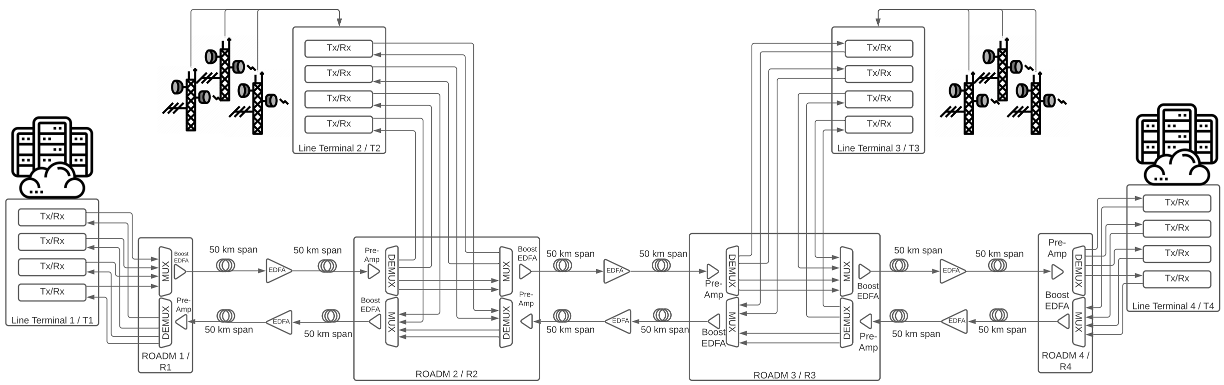


Figure 4.1 4 node network with 2 50Km spans between each ROADM node. Each Line terminal has 90 transceivers, data is sent from node 2 and 3, and received by node 1 and 4 which serve BBUs. This network architecture is used in chapter 4 and 5.

City-scale networks have traffic needs that change on a regular basis. Software-Defined networks have the potential to enable Optical fiber systems to respond to such demands. For this purpose we developed an SDN lightpath provisioning control algorithm that allocated lightpath signals in a 4 node optical fiber network topology (See figure 4.1) for a metro city network [46]. The algorithm examined traffic patterns (based on other other measured data [30]) on a two-week cycle and controlled the hourly lightpath provisioning for the network. The program allowed lightpath channels being utilized, traffic requests per channel, how the network was provisioned every hour to be observed. This generated an hourly provisioning graph which showed lightpath utilization every hour.

4.1 Basic Topology and Routing Algorithm

The network is a linear 4-node topology, and the tests worked with ROADM nodes modelling traffic management in a metro area (as shown in figure 4.2). These central ROADM nodes serve Remote Radio Heads (RRHs) in majority residential and office districts and the end nodes house Base-band Units (BBUs) in metro data-centers. The residential and office nodes serve users in that area and make a certain number of service requests every hour to the data centers are where the requests are answered by the BBUs at the ends of the network topology.

The traffic requests per hour (Figure 4.3) are obtained from a normalized traffic pattern taken from [30] for the residential and office areas. This normalised traffic pattern is converted to Common Public Radio Interface (CPRI) requests in Equation 4.1 where the total traffic load is split between the two nodes based on the weight of the node (for example, if ROADM 2 has a weight of 1 and ROADM 3 has a weight of 2 then ROADM 3 will have twice the traffic requests at its peak than ROADM 2).

$$\begin{aligned}\text{CPRI Traffic} = \text{Normalized Node Traffic} \times \text{total network traffic} \\ \times \frac{\text{ROADM Unit weight}}{\text{Total ROADM weight}}\end{aligned} \tag{4.1}$$

The traffic requests are forwarded to the BBUs using CPRI via the links between the RRH and BBU sites. When a request is made by an RRH unit and sent to the BBU unit, the SDN control algorithm checks if there are any underutilized light-paths in the system that can accommodate the traffic request for the RRH. If there is a lightpath that is open then the CPRI request is groomed into the lightpath. If the lightpath is fully loaded then a

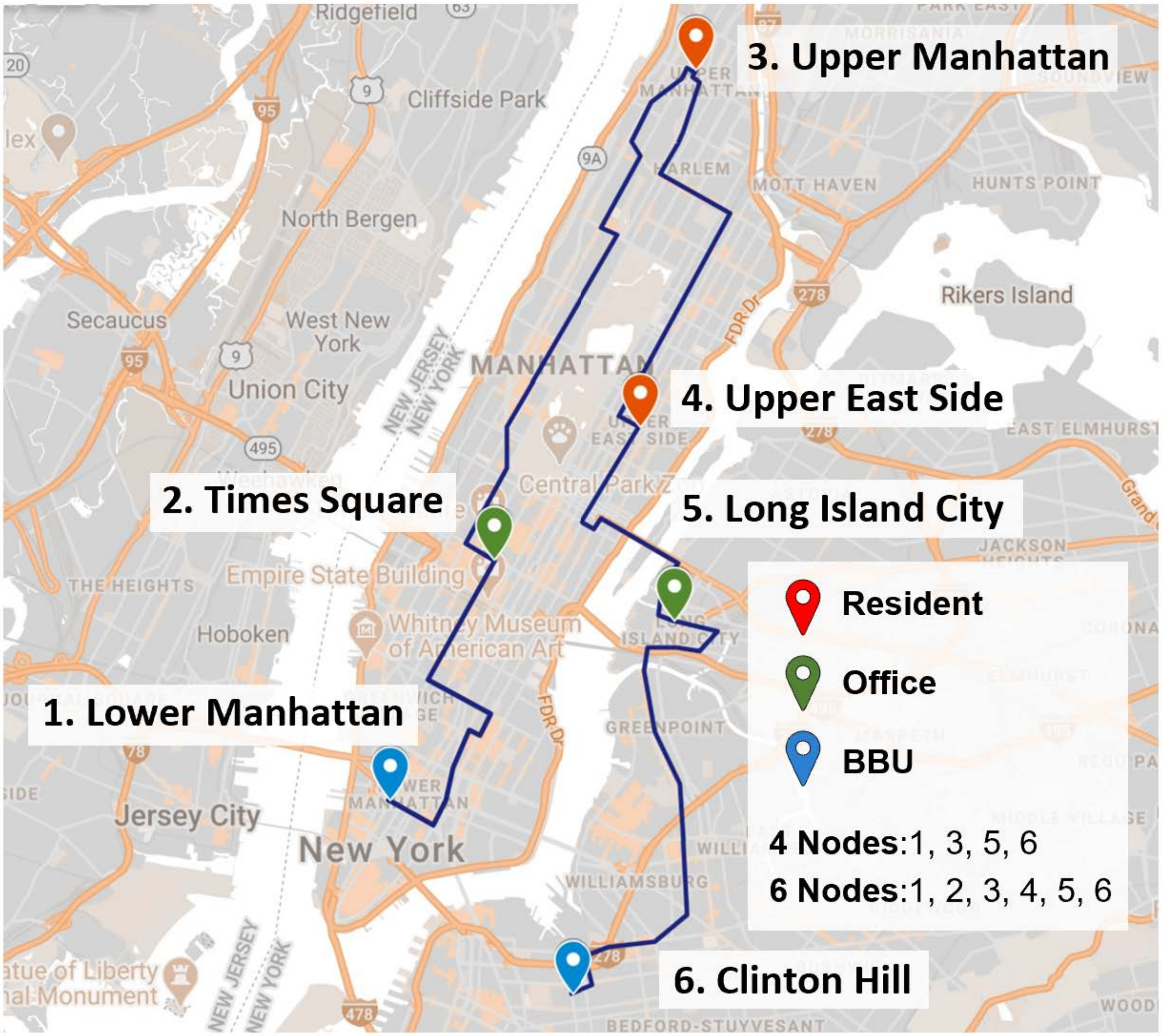


Figure 4.2 A simulated topology which serves New York City with residential and office RRH units and Data center BBUs.

new lightpath is opened to allocate traffic into the system.

The light-paths are provisioned at 200G, 100G, and 50G (where the G is Gigabits per second) and the CPRI requests are 25G. This means the lightpath can handle 2 traffic requests at 50G, 4 at 100G, and 8 at 200G. The provisioning is based on the gOSNR of the system. If the gOSNR is high enough then a 200G channel will be provisioned. For a lower gOSNR 100G light-paths will be provisioned, and at the lowest levels 50G light-paths are allocated to groom the CPRI requests.

To summarize, the SDN controller monitors the traffic demand every hour and the algorithm provisions the necessary wavelengths needed for the BBUs and optical network to answer the traffic need. The next section will describe the SDN control algorithm logic and decision making process.

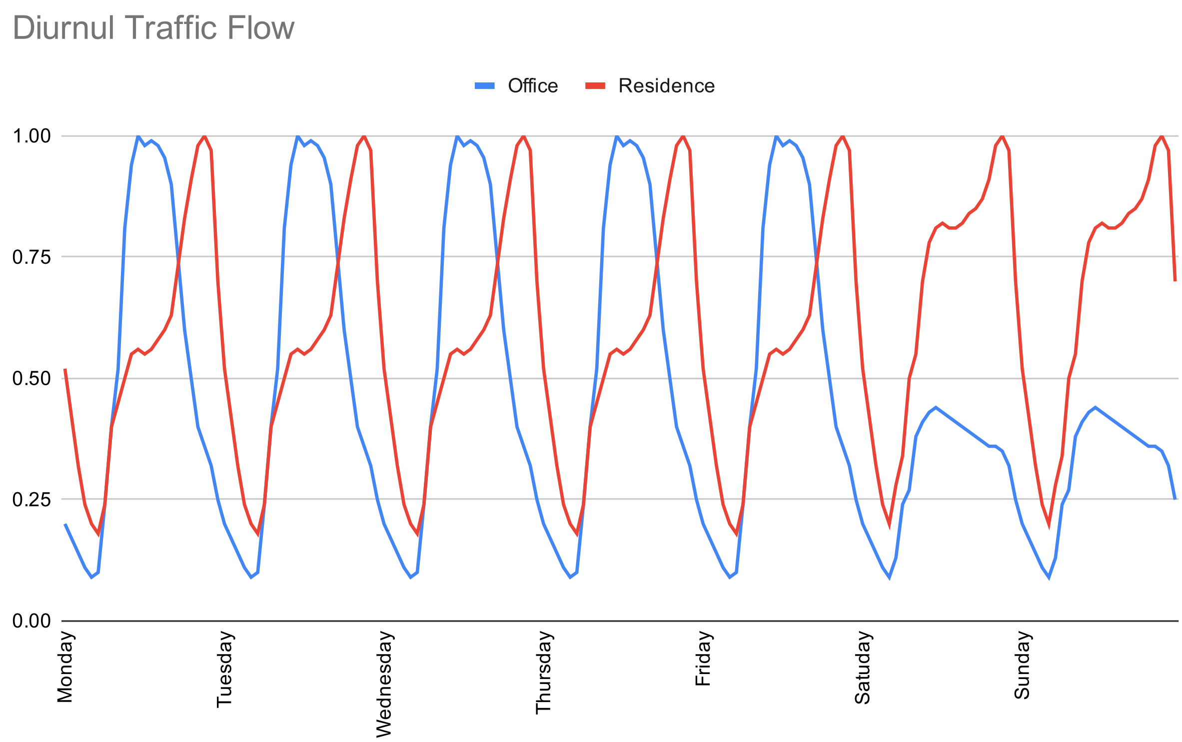


Figure 4.3 Hourly diurnal traffic flow over a 7-day week. This shows the traffic used in the OFC demo paper [46].

As discussed in section 4.1 the use case is designed to examine the dynamics of diurnal traffic patterns in urban areas, where the central nodes serve residential and office traffic. This is done by provisioning light-paths to answer traffic requests and observe how the number of light-paths changes over time and how the traffic requests are answered, e.g. when one data center becomes full and needs to re-route traffic to another node.

Our Mininet Optical SDN controller provisions lightpath channel modulation based on the optical quality of transmission (QoT) of the lightpath. What this means is, if our optical system is above a certain QoT threshold for the modulation format, then it will transmit optical signals using that modulation scheme. For example if the 100G threshold is 18dB, and the 200G threshold is 28dB, then between 0-18db the channel will transmit at 50G, 18-20db will transmit at 100G, and 28dB+ will transmit at 200G.

The scenario studied is that the central nodes represent residential and offices RRHs (at nodes 2-3 in 4-node network) which make traffic requests to the data centers (nodes 1 and 4 in a 4-node network) at the ends of the network (Fig. 4.1). The total traffic request at the RRH nodes is calculated by Equation 4.1. These requests are answered with 25 gigabits per second CPRI signals. The request is made by the RRH ROADM which forwards the traffic request to the nearest available unit on one of the optical channels.

This section will provide a flowchart for the traffic provisioning algorithm (Figure 4.4), break down the SDN algorithm, and highlight the system properties and limitations the SDN controller must consider while making decisions for configuring a network.

4.1.1 SDN Decision making for lightpath provisioning and traffic grooming

Consider the case that node 3 (in the 4 node network) has an ingress traffic load of 1000 gigabits per second. In other words, the traffic demand for that hour from all users at R3 is 1000 Gb/s. The 1000 Gb/s traffic demand is divided into smaller 25G CPRI units that are groomed into the available light paths. Every lightpath in our network is modulated at 50G, 100G, or 200G. The modulation rate is decided by the quality of transmission (QoT) of the optical signal. We measure the QoT using gOSNR (see chapter 2). If signal is above

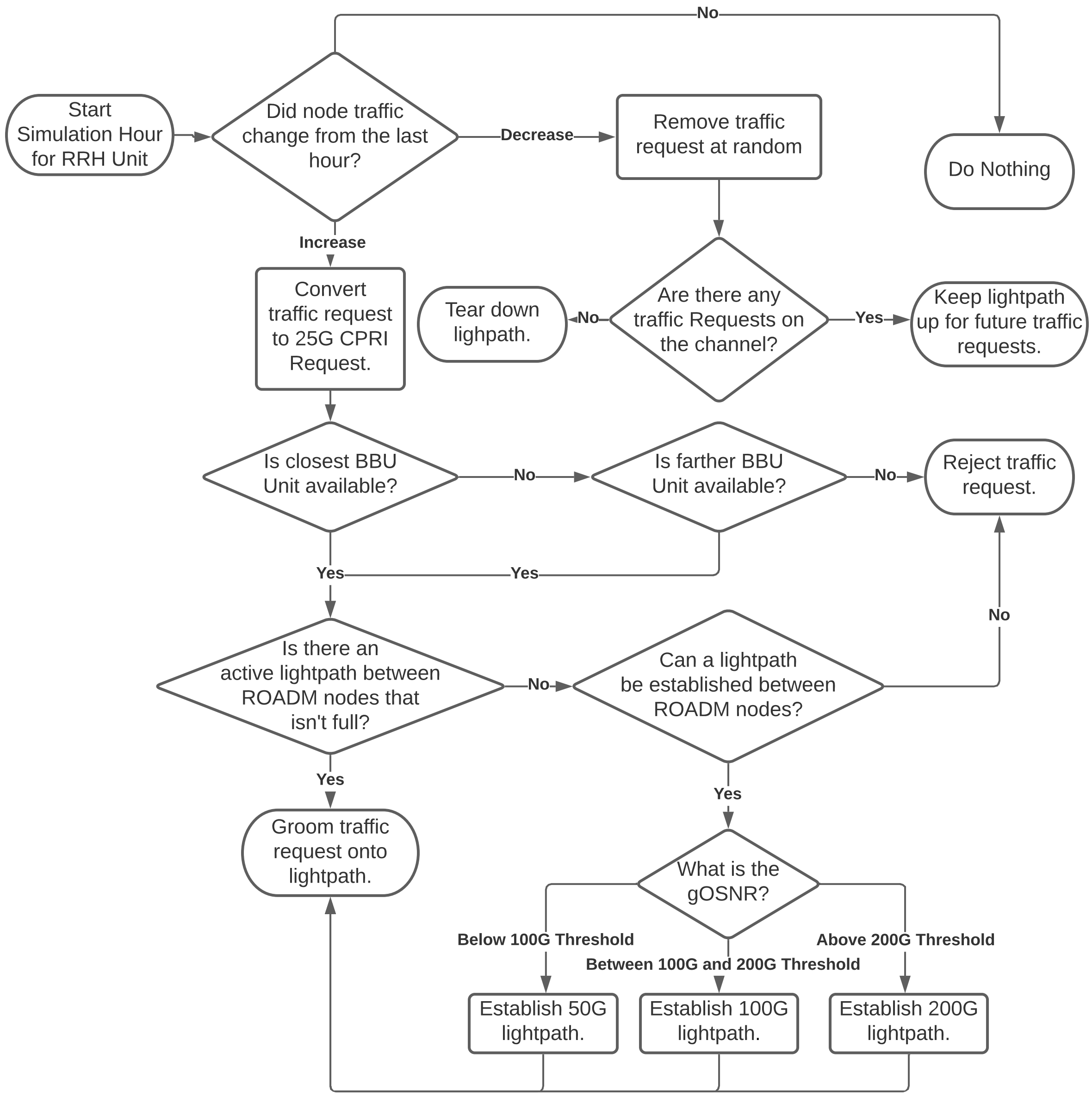


Figure 4.4 SDN lightpath provisioning algorithm flowchart.

the modulation threshold, then we can transmit at that data rate. So to answer this traffic request of 1000Gb/s we need five 200G channels, ten 100G channels, or twenty 50G channels or some combination of the three.

Now consider is the first hour of running this simulation. At this point, there are no lightpaths provisioned in the network. So the first requests are answered by the closest baseband unit (which is at ROADM 4). Because this node is so close it will have a high gOSNR, so five 200G channels can be used to accommodate this traffic request. If there is 1000 gigabit/s load the next hour, the same channels are kept open and the system stays the same.

Now say the next hour the traffic request from Node 3 drops to 800 Gigabits. This drop does not imply a loss of a 200G lightpath, rather the 25G CPRI requests are removed at random. So there may be five light-paths open but four of them may be at 3/4 capacity, or one at 3/8, and one at 5/8 capacity. If by chance all the selected wavelengths were in one channel, the channel is now empty, and the 200G lightpath is torn down.

Now consider in the third hour the traffic request is 1100 Gigabits per second. Firstly the controller sees if there are lightpaths that are not fully utilized. Suppose there is a 200G channel which is at 5/8 capacity. The network can then re-occupy that path by grooming the traffic requests into the new lightpath. After all the underutilized lightpaths are full, other lightpaths are opened and filled with the four remaining 25G traffic requests.

So far, it was assumed that the closest data center could handle all the traffic requests from Node 3, suppose that node 4 has a limit of 800 Gb/s traffic, and node 3 is requesting 1000Gb/s traffic. If this is the case (and assuming no other node has any traffic demands) then the controller accommodates the 1000G traffic request by forwarding the first 800 traffic requests to node 4 (as it is the closest) and then provisions unused channels to forward the traffic requests to node 1. Because node 1 is farther away than node 4 it has a lower gOSNR. If this gOSNR is below the 200G threshold the controller sets the rerouted channels to a lower modulation format of 100G or 50G (depending on the threshold). Since this is a lower modulation rate it needs two channels to answer a 200G traffic request.

Aside from this data center limitation, there is another limitation the system has that is based on the number of available channels. The system has at most 90 channels it can use (labeled 1-90), and each can handle up to 200G of traffic at most (assuming no traffic demands with a lower data rate). Node 3 could make a maximum traffic request of 18,000G to node 4. Or if everything was forwarded to node 1, on 100G channels then the maximum traffic load would be 9000 Gb/s. From this the maximum traffic load is calculated as follows:

$$\text{Max System Traffic} = 36,000\text{Gb/s} = 200\text{Gb/s light-paths} \times 90\text{Channels} \times 2\text{BBU nodes} \tag{4.2}$$

However because there are multiple nodes making requests utilizing the same optical channels, the SDN controller must consider wavelength continuity. Suppose node 2 sends a request to node 4 on channel 12. For this, channel 12 would use links r2-r3 and r3-r4, and this channel can only be used for requests between node 2 and 4. So node 3 could not make a request on channel 12 from node 1 or node 4 because links r3-r4 and r2-r3 are occupied. But R2 could make a request from R1 using the r2-r1 link, where channel 12 is still unused.

With all these limitations, this means not every traffic request will be answered. If all traffic channels are fully occupied then certain traffic requests cannot be answered. When this happens we have traffic rejections or wavelength blocking.

4.1.2 Performance Outputs of SDN controller

For the purpose of evaluating SDN performance we add functions with the following outputs: time, R2,R3 traffic requests, total light-paths utilized, average wavelengths per link, data center (BBU) traffic (R1,R4), rejection rate, total hourly number of 50G, 100G, 200G, and underutilized channels, and the total data being transmitted every hour(Table 4.1 shows an example output for a 4-node network).

From these hourly outputs, hourly traffic load and system dynamics in the topology can be examined. Figure 4.5a shows the total traffic load from the system users to the baseband units every hour. i.e. if R2-office is 1000, this means the total traffic request for that hour is 1000 gigabits per second. The traffic requests from these two nodes are the input parameters the SDN algorithm processes.

Figure 4.5b shows how the baseband units respond to the traffic requests. The 2 end ROADM units (t1 traffic and t4 traffic) answer the traffic requests made by the RRH units (R_2 and R_3), and the number of traffic requests answered are seen in Figure 4.5b. Using the example above, a traffic load of 1000 Gb/s from ROADM 2 is made up of 25 Gb/s CPRI requests. If all of those requests were successfully answered by ROADM 1 there would be 40 answered requests on 200G channels. The theoretical maximum a BBU can handle is 720 traffic requests (8 traffic requests times 90 200G provisioned channels).

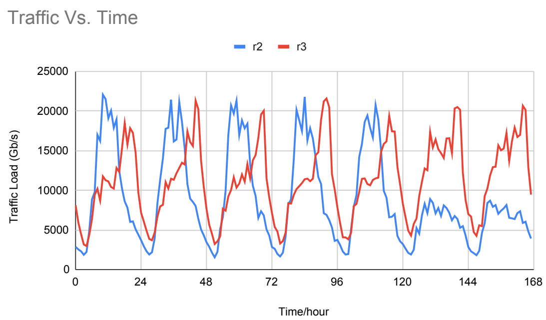
However, the system is not always transmitting signals at 200 Gb/s. Every hour the system handles traffic requests with either 200G or 100G lightpath channels as you can see in Figure 4.5c. This is decided by the gOSNR threshold or margin we set for the system. The rest of this chapter we will consider a 200G threshold of 28dB, and 100G threshold of 22dB. (This experiment will use the ROSNR of Lumentum ROADMS which are 20dB and 14dB for 200G and 100G. So the margins of this threshold case is 8 dB respectively.) If the lightpath signal has a gOSNR of 28dB or above it is provision at 200G, and if it has a gOSNR is 22dB-28dB it is set at 100G. If the traffic node can make a request to the nearest BBU node (for example R2 to R1), the gOSNR tends to be 29dB so it's always provisioned at 200G. If the traffic request needs to go to a further unit (R2 to R4) it tends to have a gOSNR of 26 so the channels are provisioned at 100G. Every hour that a traffic load drops, CPRI traffic requests removed at random. If the number of traffic requests in a lightpath falls below half capacity that channel is labeled as under-utilized.

Figure 4.5d shows the rejected traffic request ratio. Any hour the network is full and cannot handle a traffic request, that request is blocked. For example, say all traffic channels are fully occupied and ROADM 2 makes a CPRI request. If the SDN controller cannot find an unused channel or groom the requests onto an existing channel, then it will reject the request, and add it to the 'rejections' for that hour. In the end the failed traffic requests are shown in the rejection ratio which is rejected traffic requests divided by total traffic requests for the RRH node.

$$\text{Rejection ratio} = \frac{\text{Rejected requests}}{\text{Total Requests}} \tag{4.3}$$

The total active light-paths and average wavelengths per link are shown in Figure 4.5e). The average wavelength per link is all channels being used in the ROADM-to-ROADM links (i.e. r1-r2, r2-r3, r3-r4 links) divided by the number of ROADM to ROADM links (which is 3). This figure also shows the total number of channels being used to answer the traffic demand, which is all 100G and 200G channels the system is using to answer the traffic requests. From this, one can examine how many transceivers are needed to answer a request of a certain size.

Lastly, Figure 4.5f examines how the traffic demand matches up with the network provisioning. This figure compares how much traffic is being requested vs how much traffic the system is provisioned to handle. If the traffic provisioning is lower than the traffic load, that means not all the traffic is being answered. If the opposite is true (traffic provisioning is greater than the traffic request) then that means the system is being under-utilized and the traffic is being met, but unnecessary resources are being expended which the system does not need.



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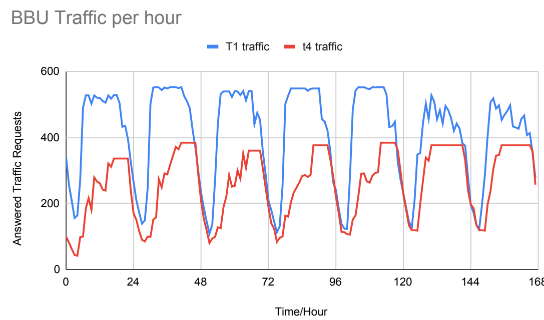

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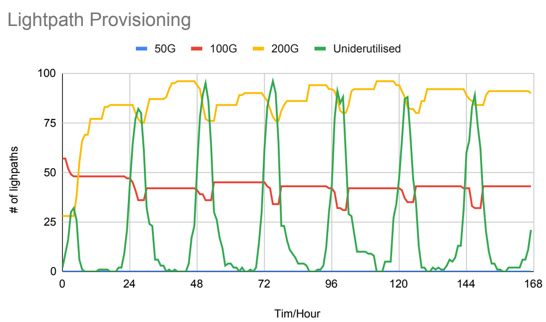

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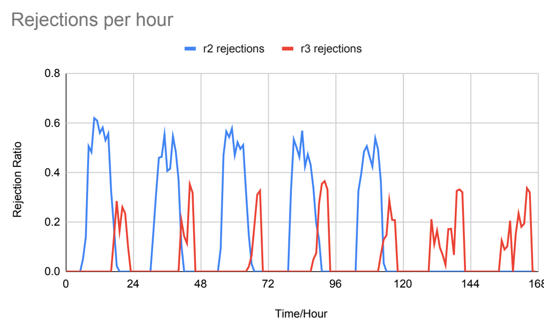

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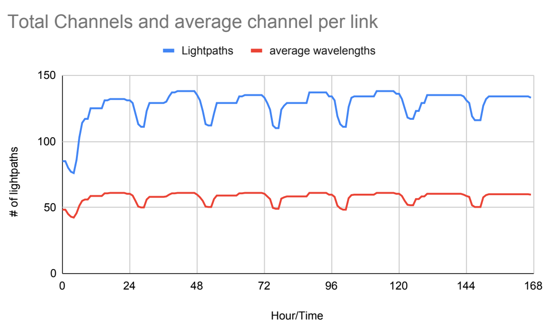

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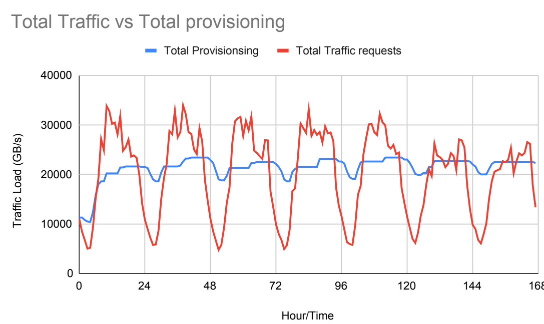


(f)

Figure 4.5 Sample results of a traffic run with (a) hourly traffic requests from residential and office are units, (b) traffic requests answered at BBU1/T1 and BBU2/T2, (c) lightpath provisioning for 100G, 200G, and underutilized channels, (d) traffic rejection rates per hour, (e) how many active lightpaths, and average lightpath per link, and (f) Hourly traffic provisioning compared to number of traffic requests.

Hour	r2-office	r3-resident	Lightpaths	average wavelengths
0	4320	11232	107	55.66666667
1	3672	9072	106	55
2	3024	6912	104	53.66666667
3	2376	5184	101	51.66666667
4	1944	4320	98	49.66666667
5	2160	3888	94	47.33333333
6	5184	5184	98	48.66666667
7	8640	8640	117	55.33333333
8	11232	9720	117	55.33333333
9	17496	10800	121	56.66666667

T1 traffic	t4 traffic	r2 rejections	r3 rejections
400	221	0	0
327	181	0	0
256	140	0	0
197	105	0	0
162	87	0	0
164	77	0	0
315	99	0	0
528	162	0	0
535	205	0.2165242165	0
536	248	0.4970278921	0

50G	100G	200G	Underutilized	Provisioning	Total_Traffic
0	57	50	0	15700	15552
0	56	50	1	15600	12744
0	54	50	12	15400	9936
0	51	50	34	15100	7560
0	48	50	49	14800	6264
0	45	49	50	14300	6048
0	45	53	31	15100	10368
0	46	71	7	18800	17280
0	46	71	2	18800	20952
0	46	75	0	19600	28296

Table 4.1 Sample output results from a 4-node SDN-controlled lightpath provisioning system for 10 hours of operation (Hours 0-9 of the simulation).

CHAPTER 5

SDN adaptive modulation control experiments

Research into optical network modulation schemes is ongoing (See section 1.2). Research has been done examining the cost and energy benefits of switching to bandwidth variable transceivers. Mininet Optical provides the ability to study network behaviour with different optical components, such as bandwidth variable transceivers and examine how an SDN controller will respond. It also allows us to compare the differences between modulation schemes to how they compare with one another in different traffic scenarios.

Section 5.2 examines the number of lightpaths, signal blocking, and system utilization for the optical network for different traffic loads and modulation schemes. These correlate to how many resources a network uses, how successfully it handles user demand, and how much unnecessary resources the network is utilizing. These metrics will be examined over three different traffic loads comparing three different margin levels for optical signal modulation (Margin cases 1-3 in Table 5.1). These cases will compare active channels per hour, resource utilization, traffic rejection, and differences between these network conditions. Section 5.3 will examine margin case 3 against margin case 4, and examine the traffic switching scenario when a traffic system becomes overloaded with traffic, and experiences non-linear impairment.

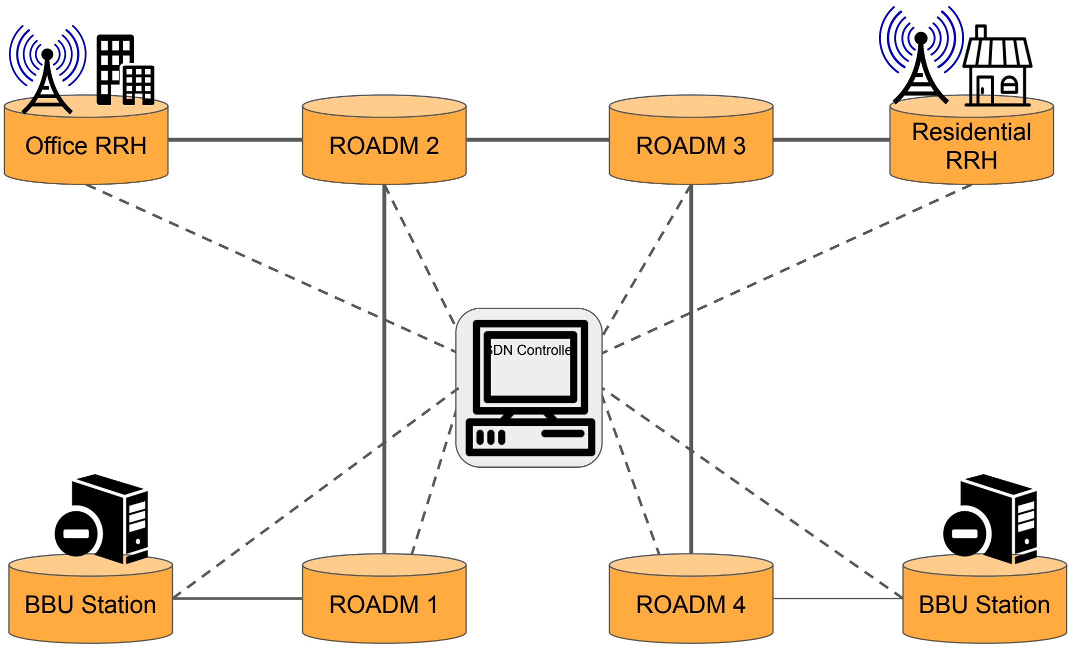


Figure 5.1 Use case scenario: 4 ROADM node network with 100km spans between each ROADM and a Line terminal attached to each ROADM. Every line terminal has up to 90 Bandwidth variable transceivers to send and receive optical signals at 50G, 100G, and 200G.

5.1 Experimental Topology and setup

Our experimental setup is a 4-node topology with up to 90 optical channels discussed in the last chapter (Figure 4.1 and 5.1). ROADMs 2 and 3 accept user traffic requests in residential and office areas respectively and ROADMs 1 and 4 are located at data centers with baseband units (BBUs)[1]. The R4 node is set to a 100 CPRI request limit for R3. This would be a similar case to a vendor with limited processing capacity. However, R1 has a capacity such that both R3 and R2 can make as many requests to R1 until it reaches its maximum number of channels. This was set up to observe traffic re-routing and examine in this situation how different modulation formats offer different kinds of resource savings and network reliability. These features are examined in section 5.2:

[1]We will Call ROADMs 1-4, R1, R2, R3, and R4.

- Total Transceivers in use per hour.
- Traffic Rejection rates per hour.
- Traffic under-Utilization every hour

All of the experiments will examine three maximum traffic demand levels, 28,800, 36,000, and 43,200 Gb/s. These traffic loads were chosen because if all BBU channels were occupied with 200G channels then the total the total BBU limit would be 36,000 Gb/s. So the three traffic loads above are 0.8x, 1,0x, and 1.2x the maximum traffic, and that is how we will refer to these traffic loads for the rest of this section.[2]

All traffic loads run on this topology will be examining 4 different margin cases shown in Table 5.1. Section 5.2 will examine the traffic static traffic cases of a 100G and 200G modulated network against a BVT case where the networks can switch between 100G/200G based on the lightpaths gOSNR. In this instance the 100G/200G, also called the 100G/200G non-switching case, has margins set so all 'short paths' (R1-R2, and R3-R4) have 200G modulation (channel transmission rate of 200Gb/s) and all the 'long paths' (R1-R3 and R2-R4) are modulated at 100G. The traffic case that will be examined in section 5.3 will look at the 100G/200G case and compare it to the 100G/200G gOSNR switching case where the switching threshold is at the expected gOSNR level for the network's 'long paths'.

5.2 Traffic Scenarios

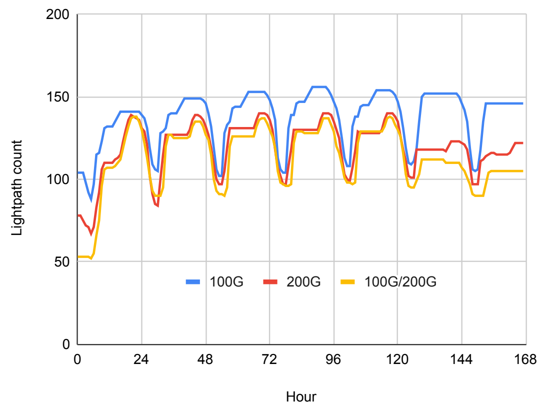
Bandwidth variable transceivers with three different transmission margins (margin cases 1-3 in Table 5.1) is examined in this section. These margins will examine the cases where all

[2]To see why this is a fully loaded system please see section 4

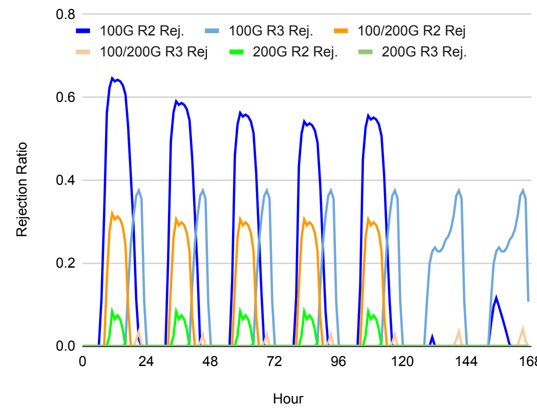
Margin Cases/Modulation Schemes	QPSK gOSNR Threshold (Margin)	16QAM gOSNR Threshold (Margin)	Description of test case
100G	18dB (4dB)	35dB (15dB)	All traffic channels are modulated at QPSK and all traffic is transmitted at 100Gb/s.
200G	18dB (4dB)	24dB (4dB)	All traffic channels are modulated at 16QAM and all traffic is transmitted at 200Gb/s.
100G/200G	18dB (4dB)	28dB (8dB)	All traffic from R2 to R1 and R3 to R4 is modulated at 16 QAM PSK and transmitted at 200Gb/s and all traffic from R3 to R1 and R2 to R4 is modulated at QPSK and transmitted at 200Gb/s.
100G/200G gOSNR switching	18dB (4dB)	25.8dB (11.8dB)	This case is similar to the 200G case, however, the 100G threshold is placed at the median expected gOSNR for the 'long' paths (R2 to R4 and R3 to R1). This is to examine the non-linear effects of the switching. NOTE: This case is only examined in is Section 5.3.

Table 5.1 4 margin cases that are examined for traffic provisioning, the thresholds that are used for 100G and 200G switching are based on Lumentum ROADMS where the ROSNR is 14dB for QPSK and 20dB for 16QAM [29]. The margin can be taken from subtracting the ROSNR from the gOSNR threshold for the respective modulation format.

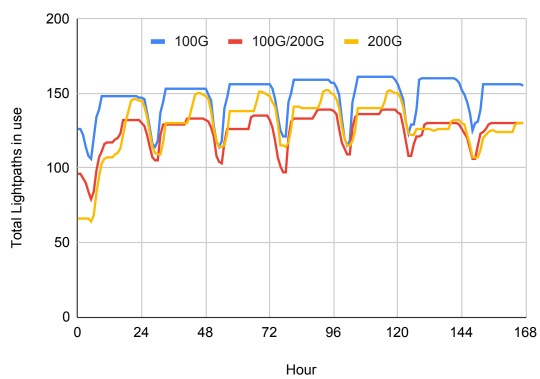
traffic channels are provisioned at 100G, at 200G, and a third case called '100G/200G' where all the 'short paths' to the nearest ROADM (R1 to R2 and R4 to R3) are 200G and all the 'long paths' (R1 to R3 and R2 to R4) transmit at 100G. Each experiment is for 167 hours (24 hours a day, 7 days a week) and examine how the total number of active lightpaths/channels change with time, and what percentage of signals are blocked every hour (figure 5.2). This section also examines how many channels are under-utilized every hour(Figure 5.3). In other words how many of the channels are at half their traffic capacity or lower in the network every hour (ex: 200G channels can hold 8 traffic requests, a 200G channel would be underutilized if it had 4 traffic requests or less).



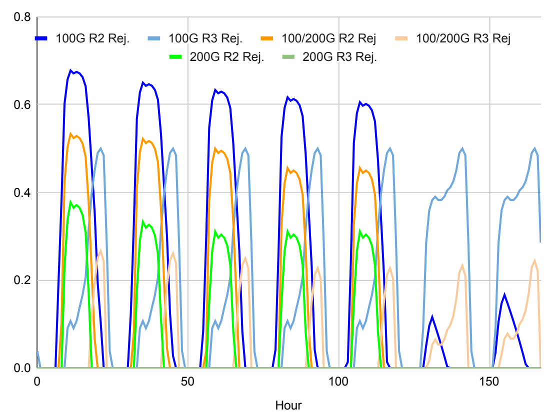
(a) Lightpath count for 0.8x Traffic load.



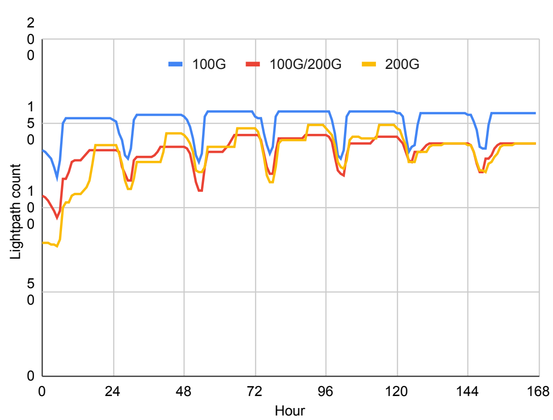
(b) Rejection ratio for 0.8x Traffic load



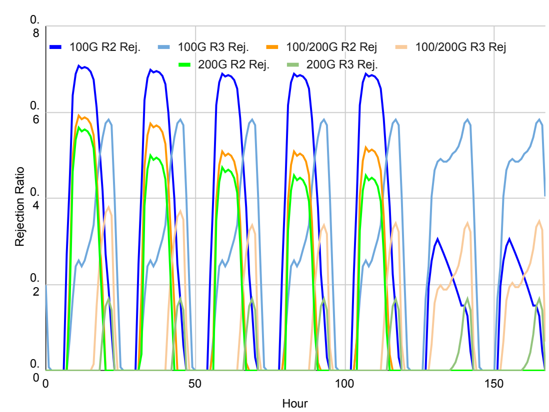
(c) Lightpath count for 1.0x Traffic load.



(d) Rejection ratio for 1.0x Traffic load



(e) Lightpath count for 1.2x Traffic load.



(f) Rejection ratio for 1.2x Traffic load

Figure 5.2 Lightpath count (Left): Three different traffic load scenarios (0.8x, 1.0x, and 1.2x) with 100G, 100G/200G, and 200G, (blue, red, yellow) for margin cases (discussed in Table 5.1). Rejection Ratio (right): R2 (dark) R3 (light) rejection ratios for 100G (blue), 100G/200G (orange), and 200G (green) modulation cases.

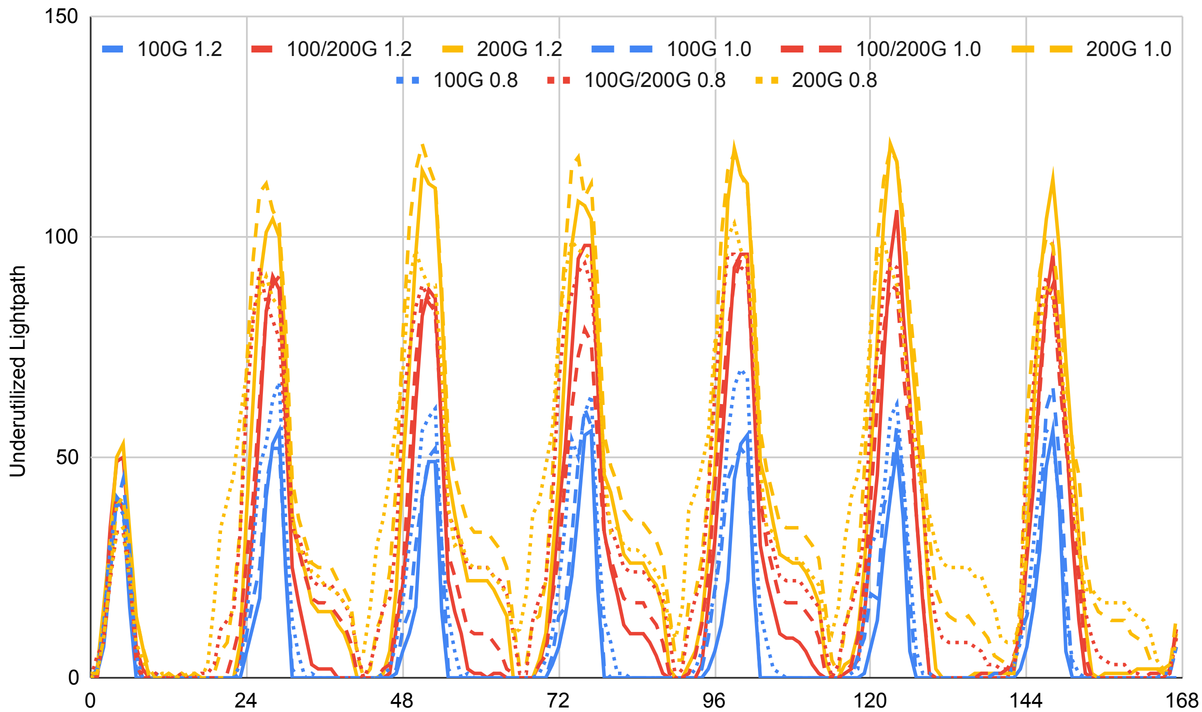


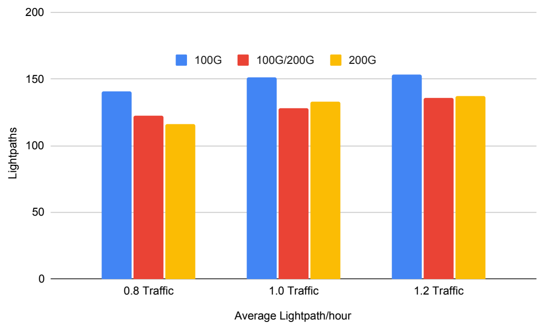
Figure 5.3 System under-utilization channels for three traffic cases. 100G, 100G/200G, and 200G cases are labeled with blue, red and yellow respectively. 1.2x, 1.0x, and 0.8x traffic loads are represented with lines, long dashes and short dashes respectively.

Figure 5.2 shows the data from Monday through Sunday, and the different traffic dynamics over the course of the day. Hour 0 of the simulation is when the system is turning on and lightpaths are being set up. For the next several hours there is a decrease in the traffic demand. This would be equivalent to Monday between 12am to 3 or 4am. In the beginning there are no underutilized channels as the system is turning on and meeting the traffic demand. In this hour there are no underutilized traffic channels because they were setup to meet the traffic demand, and then traffic decreases, so channels start to become underutilized (the under-utilization can be observed in figure 5.3).

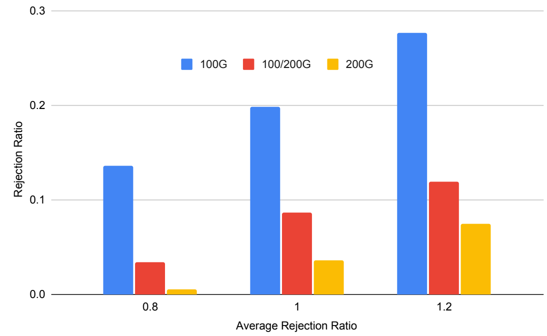
After this the system quickly rises through the morning and in 1.0x and 1.2x quickly reaches a maximum between the hours of approximately 6am until midnight. As one observes from figure 4.3 this is due to the fact that there are traffic maximums reached in the late morning for office traffic and middle evening for residential. When these graphs are combined their highs are alternating and their lows are always at night-time. This 'low' is when less rejections are observed, and lightpaths are being torn down.

A maximum channel utilization for 100G channels is observed between 6am to midnight. For 200G and 100G/200G there is a double-hump, where it reaches a lower maximum from the morning to the afternoon and then a higher maximum from the late afternoon to the evening. This shows that there is higher traffic demands between the late evening and night, likely due to high-bandwidth leisure activities such as gaming, and High-Definition streaming activities or due to the limit on R1.

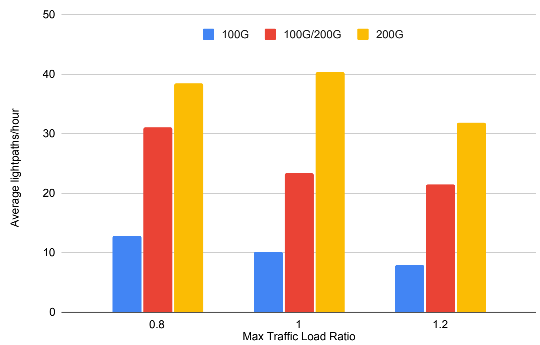
From these figures (Fig 5.2) hourly averages for lightpath channels, channel blocking, and under-utilization are calculated in figure 5.4. In all cases, 200G modulation and 100/200G modulation showed significant improvement in the number of transceivers and channel blocking/rejection ratios over the 100G cases. Both show substantially fewer wavelengths on average (figure 5.4). You can see the hourly results for 80% fully loaded Traffic, 100% fully loaded Traffic, and 120% fully loaded Traffic (Fig 5.2). Surprisingly both 200G and 100G/200G had a similar average lightpath count (Fig 5.4a). This is most likely because 200G channels are given priority over 100G channels, and the 'short path' is chosen more often than the long paths. For all cases, 100G has the most traffic blocking followed by 100G/200G and 200G has the least.



(a) Average channels per hour for 0.8x, 1.0x, and 1.2x Traffic loads



(b) Average rejection Ratios for 0.8x, 1.0x, and 1.2x Traffic loads



(c) Average system underutilization for 0.8x, 1.0x, and 1.2x Traffic loads

Figure 5.4 Hourly averages for active channels (5.4a) rejection ratios (5.4b) and underutilization (5.4c). Blue red and green orange represents 100G, 100G/200G, and 200G margin cases (From table 5.1). All margin cases are compared with respective traffic load (0.8x, 1.0x, 1.2x).

In all cases the 100G margin case has the highest number of active channels and highest rejection rates. For transceiver count (Fig 5.4a) there is a 12%, 11% and 15% improvement for 100G/200G and a 17% 11% and 10% fewer transceivers for 200G cases (for 0.8x, 1.0x, and 1.2x traffic respectively). Regarding rejections (Fig 5.4b), the 100/200G modulation case has 75%, 56%, and 57% improvement over 100G modulation and 200G modulation has 96%, 81%, and 73% fewer rejections than 100G (for 0.8x, 1.0x, and 1.2x traffic respectively).

However for traffic underutilized resources (Fig 5.3, 5.4c), there was an opposite trend from the other two graphs, and the 100G systems were the least underutilized and 200G were the most underutilized. With 100G/200G utilizing 143%, 129%, 167% the resources of 100G channels, and the 200G channels using 199%, 297%, and 298% the resources of the 100G channels (for 0.8x, 1.0x, and 1.2x traffic respectively). From this its observed that 100G channels are least likely to be underutilized, however this comes at the cost of extra transceivers and higher blocking rates.

For the cases studied here, we knew apriori which paths would be 100G and which ones would be 200G. The margins are set so the 'long' and 'short' paths only take one modulation type. However the next section will examine the case where the margin threshold is in between within the gOSNR range of the 'short paths'. This will allow for an interesting case study of non-linear effects.

5.3 100G/200G switching

Section 2.2.1 described the nonlinear impairments between channels, and how multiple active channels in a fiber decrease quality of transmission. In this section the 100G/200G switching threshold is set to the median value for the long paths to observe the non-linear effects of multiple channels on different traffic loaded channels. The 'long' paths in the system have a gOSNR range of 25.4-26.2 (Figure 5.5). So the switching threshold is set to 25.8 to examine the role the traffic load and NLI has on BVT switching.

In all six of these graphs (Figure 5.6) there are 0 underutilized channels at time 0, because this is when the channels are set up. Then there is a quick rise in underutilized channels as the traffic decreases. Then the system stops being underutilized at peak hours, and starts being underutilized again at non-peak hours (Figure 5.6). However the interesting feature is that, as the traffic loads increase there is a stronger resemblance between the switching

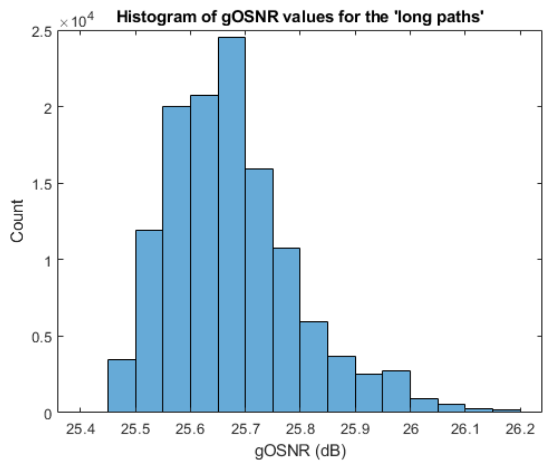


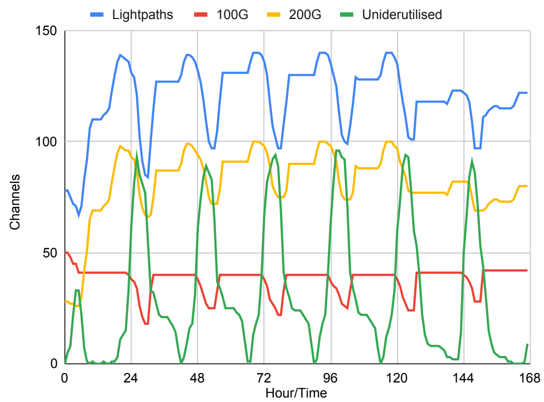
Figure 5.5 Histogram of 'long path' gOSNR values for 1.0x 100G/200G non-switching case.

and non-switching cases. As the traffic loads increase more channels become 100G until the graphs are similar (in 5.6 e and f). This is because as traffic increases, more channels are utilized and the channel nonlinear effects increase as well. So the channels are more likely to drop to the lower gOSNR of 25.5-25.8.

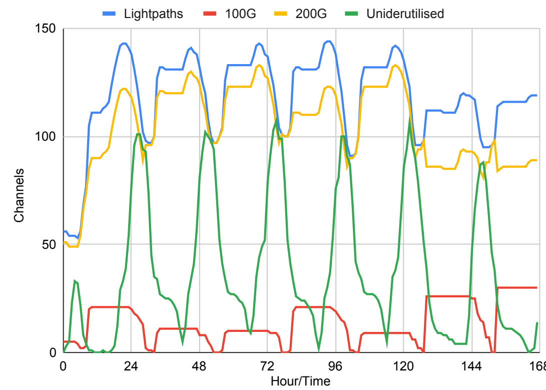
The second intriguing feature observed is that in the non-peak hours there is a sharper decrease in number of 100G channels, as well as a mild spike on the 200G channels. We can observe this most strongly at around the 4am mark where 200G signals experience a spike as 100G signals fall (In fig. 5.6d). This is because, with fewer channels, there are reduced non-linear effects, and so the span obtains a higher gOSNR. So the 100G fiber links switch to 200G data rates as connections are added and removed.

5.4 Summary

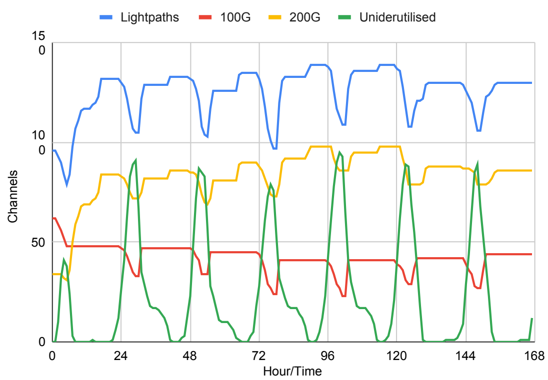
In the results above we examined 4 margin cases at three different traffic loads. The first experiment compared margin cases 1,2, and 3 (Table 5.1) at three different traffic load cases. This showed a comparison between the number of active transceivers, rejected traffic requests



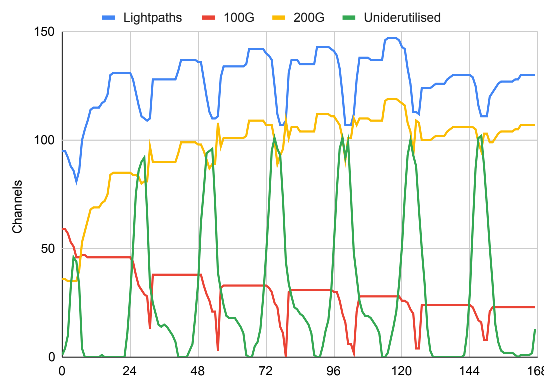
(a) 100G/200G Non-Switching for 0.8x Traffic



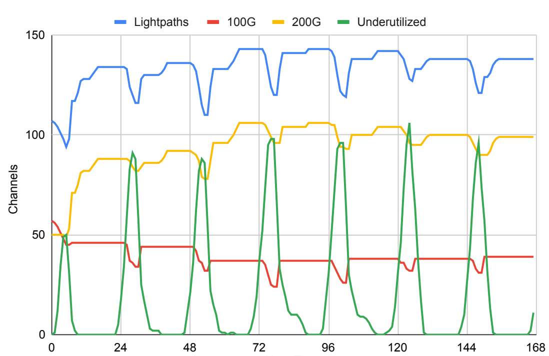
(b) 100G/200G Switching for 0.8x Traffic



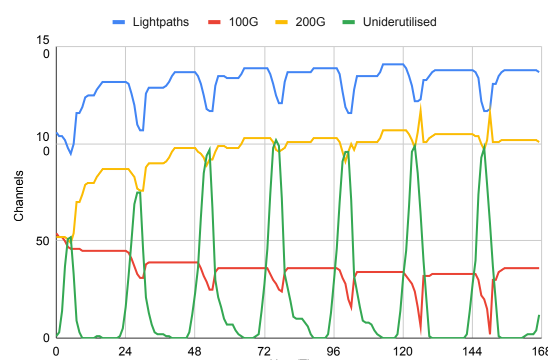
(c) 100G/200G Non-Switching for 1.0x Traffic



(d) 100G/200G Switching for 0.8x Traffic



(e) 100G/200G Non-Switching for 1.0x Traffic



(f) 100G/200G Switching for 1.2x Traffic

Figure 5.6 Dynamic lightpath provisioning for 100G and 200G channels. These graphs show the 100G (red) 200G (yellow), underutilized (green) and total (blue) lightpaths over a one week period.

and channel utilization. This use case is advantageous for a cost-benefit analysis of optical network costs, because it enables network providers to prototype different networks and observe how active a network will be, how reliable it is and how much excess energy it may consume, and make more educated decisions for optical networks.

Secondly we observed switching at the gOSNR threshold for longer optical paths (R1 to R3 and R2 to R4). Here we observed that systems with lower traffic loads tended towards a higher gOSNR as there were less channels introducing multi-channel interference. However as the traffic loads got larger both systems had more identical traffic provisioning graphs, which shows that larger traffic loads generate larger non-linear interference. We also observed that when channels were being torn down, several 100G channels began transmitting at 200G, and we saw a sharp decrease in 100G channels and a sharp increase in 200G channels as compared to the base 100G/200G case. This was due to reduced non-linear effects from less wavelengths propagating through the system.

CHAPTER 6

Conclusion

Optical Network research is continuing to advance and push the networking research community to tackle new and interesting questions. There are many questions on how to best allocate resources, how to make networks more flexible and how to successfully manage them. One field that has helped support the growth, speed, and flexibility of Optical networks is SDN. The Mininet-Optical system developed here is made with the network emulation abilities of Mininet combined with optical-transmission physics that simulate optical network capabilities.

This work showed the capabilities of an SDN controller with bandwidth variable transceiver provisioning that could operate a fiber optic network, allocate traffic on channels, and change channel provisioning based on gOSNR data. We examined the dynamic traffic provisioning effects on traffic loads of 0.8x, 1x, 1.2x the maximum traffic to examine how different data rates handle traffic and reported the differences in channel allocation, signal blocking, and system utilisation of a 200G, and 100/200G provisioned network against a 100G provisioned network. From this, improvements in channel allocation and rejection ratios, and impairment in network utilization were observed.

This study showed the ability of Mininet-Optical to prototype SDN systems by comparing it to the GNPy engineering planning system, and examined the behaviour of BVTs in varying time dynamic traffic. We were also able to observe the impact of traffic loads on non-linear impairment by setting the BVT switching threshold at our expected gOSNR. Here we were able to observe gOSNR recovery, that enabled the BVTs to modulate at a higher data rates (200G) at low traffic loads.

The team hopes to continue to develop this system as a way to serve future network researchers in aiding them in optical network experiments and enabling them to develop SDN control algorithms that can manage the networks of the future. This also has strong applications in teaching and can decrease the barrier of students learning SDN systems and enable them to develop the ability to program such systems without the need for an expensive testbed. Mininet Optical will be made available to the public and contribute to the growth of optical network research.

APPENDIX A

Acronyms

100G 100 gigabits per second

200G 200 gigabits per second

50G 50 gigabits per second

5G Fifth Generation

ALR Adaptive Link Rate

API Application Programming Interface

ASE Amplified Spontaneous Emission

AT&T American Telephone and Telegraph Company

BBU Baseband Unit

BVTs Bandwidth Variable Transceivers

CLI Command Line Interface

CPRI Common Public Radio Interface

DBM Data Base Manager

DSD Dynamic Service deployment

EDFA Erbium Doped Fiber Amplifier

FEC Forward Error Correction

FWM Four Wave Mixing

gOSNR generalized Optical Signal to Noise Ratio

HD-FEC Hard Definition Forward Error Correction

IBN Intent Based Networking

IP Internet Protocol

ISPs Internet Service Providors

MLR Mixed Line Rate

NBI Northbound Interface

NFV Network Function Virtualization

NLI Non-Linear Interference

Netns Network Namespaces

OEO Optical-Electric-Optical

OFC Optical Fiber Conference

OLTs Optical Line Terminals

ONF Open Networking Foundation

OPM Optical Performance Monitor

OSNR Optical Signal to Noise Ratio

OVS Open Virtual Switch

PCE Path Control Element

PC Personal Computer

QoS Quality of Service

QoT-E Quality of Transmission Estimation

QoT Quality of Transmission

ROADM Reconfigurable Optical Add/Drop Multiplexer

ROSNR Required Optical Signal to Noise Ratio

RRH Remote Radio Head

RWA Routing Wavelength Assignment

Rx Receivers

SBI Southbound Interface

SD-FEC Soft-Definition Forward Error Correction

SDN Software Defined Networking

SDON Software Defined Optical Networking

SLA Service Level Agreement

SLR Single Line Rate

SSH Secure Shell

TC Traffic Control

tSDX transparent Software Defined Exchange

Tx/Rx Transcievers/Receivers

Tx Transceivers

UI User Interface

VETH Virtual Ethernet

VM Virtual Machine

VOA Variable Optical Attenuation

VR Virtual Reality

WiO Women in Optics

WDM Wavelength Division Multiplexing

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