Energy Efficient Core Optical IP Networks

Mohd Nazri Bin Mohd Warip

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Declaration

This Thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Mohd Nazri Bin Mohd Warip December 2012

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Abstract

The Internet has become an integral part of modern societies fuelling ever growing opportunities for the provision of new advanced services which better respond to quickly changing societal needs. Previously the deployment of such services have led to significant increases in energy consumption which is in strong contrast with the global drive for a greener and more energy efficient environments. Network infrastructures are required which support these growing needs but at the same time remain zero-carbon emission complaint.

Green photonic network designs centre on techniques to reduce and conserve energy within multilayer network scenarios. In this Thesis, hibernation strategies are proposed where network configurations form selective group of nodes, segmentation of links and partitioning of the light paths within connections to enable “sleep” modes. The strategy is founded on the optimisation and improved power management through a control algorithm implemented as a modification of the Generalized Multi-Protocol Label Switching (GMPLS) signalling and routing protocol. The impact of the strategy on network utilization, number of wavelengths, number of connection requests, number of nodes, network connectivity degree, and power ratio in IP routers has been evaluated on representative optical networks using a simulation framework established using OMNeT++. A trade-off is observed between energy consumption and network performance as a result of hibernation; evaluation of this methodology indicates potential reduction in energy power consumption from 30% up to 75% at the expense of reduced network performance.

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Abbreviations

ABR	Area Border Router
AC	Admission Control
ACE	Agility Control Energy
ADM	Add-Drop Multiplexer
ALU	Arithmetic Logic Unit
AS	Autonomous System
ASE	Amplifier Spontaneous Emission Noise
ASON	Automatically Switched Optical Network
ATIS	Alliance for Telecommunications Industry Solutions
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BGL	Boost Graph Library
BGP	Border Gateway Protocol
CAM	Content Addressable Memory
CD	Chromatic Dispersion
CNTC	Central Network Topology Unit
CoS	Class of Service
CPU	Central Processing Unit
CR-LDP	Constraint based Routed-Label Distribution Protocol
CSPF-TE	Constraint-based Shored Path First with Traffic-Engineering.
DCM	Dispersion-Compensating Module
DFS	Dynamic Frequency Scaling
DLE	Dynamic Light path Establishment
DiffServ	Differentiated Service
DIR	Destination-Initiated Reservation

DVS	Dynamic Voltage Scaling
DWDM	Dense wavelength-division multiplexing
DXC	Digital Cross-Connect
EAR	Energy Aware Routing
ECR	Energy Consumption Rating Initiative
EDFA	Erbium Doped Fibre Amplifier
EGP	Intra-domain or Exterior Gateway Protocol
EMS	Energy Monitoring Controller
ENERGY STAR	A joint program of the U.S. Environmental Protection Agency and the U.S. Department of Energy
EO	Electrical-Optical Conversion
EON	European Optical Network
ETSI	European Telecommunications Standard Institute
HGI	Home Gateway Initiative
EXP	Experimental field
FA	Forwarding Adjacency
FDM	Frequency Division Multiplexing
FEC	Forwarding Equivalence Class
FIFO	First In First Out
FSC	Fibre Switch Capable
FSM	Finite State Machine
FTTH	Fibre To The Home
GE	Gigabit Ethernet
GHG	Greenhouse Gases Emission
GMPLS	Generalized MPLS
HM	Hibernation Mode
IEEE	Institute of Electrical and Electronics Engineer
IETF	Internet Engineering Task Force

ICT	Information Communication Technology
IGP	Inter-domain or Interior Gateway Protocol
IGRP	Interior Gateway Routing Protocol
ILM	Incoming Label Map
ILP	Integer Linear Programming
IntServ	Integrated Service
IP	Internet Protocol
IPX	Internetwork Packet Exchange
IS-IS	Intermediate-System to Intermediate-System
ISP	Internet Service Provider
ITU	International Telecommunication Union
LSC	Lambda Switch Capable
L2SC	Layer 2 Switch Capable
L2VL	Layer 2 Virtual Link
LDP	Label Distribution Protocol
LER	Label Edge Router
LFIB	Label Forwarding Information Base
LMP	Link Management Protocol
LoL	Loss of Light
LSA	Link State Advertisements
LSC	Lambda Switch Capable
LSDB	Link State Database
LSP	Label Switch Paths
LSR	Label Switch Router
MAC	Medium Access Control
M-BGP	Multiprotocol-Border Gateway Protocol
MEMS	Micro-electro-mechanical Systems
MILP	Mixed Integer Linear Programming

MLTE	Multilayer Traffic Engineering
MPLS	Multiprotocol Label Switching
MPSoC	Multi-Processor on Chip
MPλS	Multiprotocol Lambda Switching
MVMC	Matrix-Vector Multiplier Crossbar
NCU	Network Control Unit
NetBIOS	Network Basic Input/Output System
NetBEUI	NetBIOS Extended User Interface
NGN	Next Generation Network
NNI	Network-to-Network Interface
NP-hard	Non-deterministic polynomial-time hard
NSFNET	National Science Foundation Network
OA&M	Operation Administration and Maintenance
OADM	Optical Add/Drop Multiplexer
OBS	Optical Burst Switching
OC	Optical Carrier
OCh	Optical Channel
OCh-P	Optical Channel-Path
OCh-S	Optical Channel-Section
OE	Optical-Electrical Conversion
OEO	Optical-Electrical-Optical Conversion
OIF	Optical International Forum
OMNET++	Objective Modular Network Testbed in C++
OMS	Optical Multiplex Section
ONT	Optical Network Terminal
ONU	Optical Network Unit
OOT	Opaque Optical Transponder
OPS	Optical Packet Switching

OTS	Optical Transmission Section
OSI	Open Systems Interconnection
OSNR	The Optical Signal to Noise Ratio
OSPF	Open Shortest Path First
OSPF-TE	OSPF Traffic-Engineering.
OTN	Optical Transport Network
OXC	Optical Cross-connect
OWR	Optical Wavelength-Routed
PCE	Path Computation Element
PDM	Polarisation Mode Dispersion
PI_ER	Partial Information with Exact Reservation
PON	Passive Optical Network
PPP	Point-to-Point Protocol
PSC	Packet switch capable
QoS	Quality of Service
RAM	Random Access Memory
RIP	Routing Information Protocol
RFC	Request For Comment
ROADM	Reconfigurable Optical Add-drop Multiplexer
RSVP	Resource Reservation Protocol (*Resv*)
RSVP-TE	RSVP Traffic-Engineering.
RWA	Routing and Wavelength Assignment
SBPP	Share Backup Path Protection
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SLE	Static Lightpath Establishment
SOA	Semiconductor optical Amplifier
SONET	Synchronous Optical Network

SNA	System Network Architecture
SPF	Shortest Path First
SPT	Shortest Path Trees
SRLG	Shared Risk Link Groups
SRT	Short Reach Transponder
SW	Space-Wavelength
TCAM	Ternary Content Address Memory
TCP/IP	Transmission Control Protocol / Internet Protocol
TDM	Time-division Multiplexing
TDMC	Time-Division Multiplexing Capable
TE	Traffic Engineering
TED	Traffic Engineering Database
TIA	Telecommunication Industry Association
TLV	Type-Length-Value
TTL	Time To Live
UDP	User Datagram Protocol
UNI	User-to-Network Interface
UPS	Uninterrupted Power Supply
VC	Virtual Circuit
VLSM	Variable Length Subnet Mask
VT	Virtual Topology
WDM	Wavelength-Division Multiplexing
WRN	Wavelength Route Node
XPDR	Transmitter-Responder

List of Publication

Journal Publication:

1. I. Glesk, **M.N. Mohd Warip,** I. Andonovic, '*Increasing transmission efficiency with advanced processing',* Renewable Energy and Power Quality Journal, ISSN: 2172-038X, No.9, May 2011.

Conference Publications:

1. **M.N. Mohd Warip**, I. Andonovic, I. Glesk, ' *GMPLS-Enabled Routing for Green Photonic Networks*', UK-MEC Engineering Conference 2010, University College London, UK, 8th – 9th April 2010.

2. **M.N. Mohd Warip**, I. Andonovic, I.Glesk, '*A Power Reduction Technique for GMPLS-Based Photonic Networks*', The 11th Annual Postgraduate Conference on the Convergence of Telecommunications, Networking and Broadcasting (PGNet2010), Liverpool John Moores University, UK, 21st – 22nd June 2010.

3. **M.N. Mohd Warip**, I. Glesk, I. Andonovic, '*GMPLS Energy Efficiency Scheme for Green Photonic Networks*', The IEEE 12th International Conference on Transparent Optical Networks (ICTON 2010), Munich, Germany, 27th June – 1st July 2010.

4. **M.N. Mohd Warip**, I. Andonovic, I. Glesk and D.Harle, 'GMPLS-enabled Routing Applied to Energy Photonic Networks', WGN9: IX Workshop in G/MPLS networks, Girona, Spain, 5th – 6th July 2010.

5. I. Glesk, **M.N. Mohd Warip** I. Andonovic, '*Increasing transmission efficiency with intelligence control plane',* International Conference on Renewable Energy and Power Quality (ICREPQ'11), Las Palmas de Gran Canaria (Spain), 13th to 15th April 2011.

6. **M.N. Mohd Warip**, I. Andonovic, I. Glesk (Bronze Medal Winner for the best paper), 'Energy Efficiency in Full Mesh Optical IP Networks", the 1st international Malaysia-Ireland Joint Symposium on Engineering, Science and Business (IMiEJS 2011), Athlone Institute of Technology, Republic of Ireland, 9th-11th June 2011.

7. **M.N. Mohd Warip**, I. Glesk, I. Andonomic (2011) '*Power Minimizing Techniques for Full Mesh Topology Optical IP Network*", 16th European Conference on Networks and Optical Communications (NOC 2011), IEEE UK&RI, Northumbria University, Newcastle Upon Tyne, UK, 20th – 22nd July 2011.

8. I.Glesk, **M.N. Mohd Warip**, S.K. Idris, T.B. Osadola, I. Andonovic, "*Towards Green High Capacity Optical Networks*", Proceeding SPIE Conference Volume 8306, Photonics, Devices, and System V, Pavel Tomanek, Dagmar Senderakova, Prague, Czech Republic, 24th August 2011.

Chapter 1

Introduction

1.1 Introduction

1.1.1 Evolution towards Green Optical Networks

Since its emergence, the Internet has stimulated a significant part of global economic growth. Defined by its interconnections and routing policies and underpinned by a higher level optical infrastructure, it has fuelled the increased demands for the provisioning of new and more advanced services able to dynamically react to changes within the network. These newly developed services are varied and consume ever more amounts of energy, counter to the global drive for a greener environment. Consequently there is an evolving need for an optical infrastructure that complies with zero-carbon emission principles.

Hence the research first assesses the potential for green photonics to conserve energy and meet the power constraint placed on the optical layer, controlled through an intelligent Control Plane. The adoption of an intelligent control plane for next generation optical networks enables not only traffic engineering, protection, restoration, recovery and resource re-allocation but also can potentially yield solutions for energy conservation.

Green networking is defined as any process that reduces energy consumption required to perform a given task without compromising the level of performance [169] whereas energy efficiency core networks represents energy saving consumed by optical network equipment and thus further reduce the energy consumption. The latter involves the design of energy-efficient architectures directly during the network planning stage [67]. A further explanation of energy efficiency is given in Section 2.7.5.

In Optical IP networks, power consumption can be reduced via concepts known as Green Photonics [1] and Figure 1.1 shows an example of a representative green network energy architecture. Adhering to those principles, an energy saving strategy that utilizes "Hibernation modes" is adopted and evaluated through parameters like wavelength requests, blocking probability, and heat transfer rate. Trades-off between energy savings and crucial network performance parameters are investigated.

The methodology centres on extensions to the functionality of the control plane to implement power-aware-routing in Generalized Multiprotocol Label Switching (GMPLS) networks [73][83][162][164] through enhancements of Open Shortest Path First-Traffic Engineering (OSPF-TE) [38][39] routing schemes and traffic engineering, culminating with the integration of the energy conservation algorithm and a Routing and Wavelength Assignment (RWA) [26][27][28] heuristic scheme. Through RWA schemes and path computation algorithms, all routing updates are optimized and optical impairments managed. Optimization of GMPLS routing updates reduce the traffic overload and utilization of network equipment such as Routers. By taking into account the power usage of both optical and electronic elements, algorithm design focused on energy consumption to produce greener network operation.

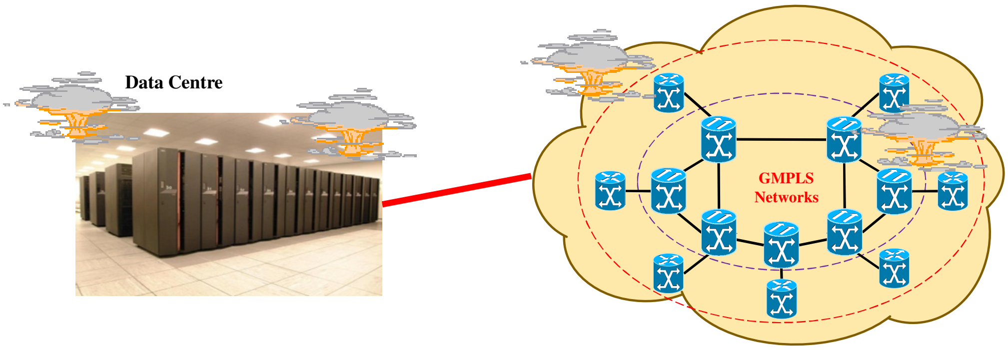


Figure 1.1: An example of Green Network Energy Architecture.

1.1.2 Greening the Optical Network Domain

Although the research focuses on Core Optical Networks, it is imperative to stress energy saving approaches in different network domains [51][94][114][116][117]. Energy efficiency techniques can be classified according to the *network domain* or the *type of energy saving mechanism,* the former relates to the core, metro and access layers, the latter can be applied either to the entire network domain, for example "sleeping mode under standby primitives' scheme" [94] or only deployed in certain network domains e.g. hibernation mode with dynamic topology optimization traffic engineering [83][104][111], most applicable to the core only. A comprehensive survey of energy saving techniques in different network domain is given in Chapter 2.

1.1.3 Potential Energy Saving in current core Optical IP networks

One of the most significant cost reduction strategies in core optical IP networks (also sometimes known as IP over Optical or IP over WDM) in terms of provisioning, operation and maintenance is savings in energy consumption. The major power consumption contributors of equipment in the network are:

i. WDM chassis; receiving/transmitting equipment such as transponders modules, short-reach optical interface transponders.
ii. Optical Switching (OXC) Chassis, opaque/transparent optical transponders, Optical-Electrical-Optical (OEO) conversion.
iii. Core Router: electronic processing, traffic grooming and aggregation in the IP layer.
iv. Optical Amplifiers: predominately the Erbium Doped Fibre Amplifier (EDFAs).
v. 3R Regenerators: signal regeneration with re-timing, re-amplification and re-shaping operations.
vi. Control Plane: signalling and routing algorithm modification.

The key to designing energy efficient optical transport network are rooted in the network architectures. Five IP over optical architecture can be identified: Basic IP over Optical [2][3], IP over SDH over Optical [2], Transparent IP over Optical [3], Translucent IP over Optical [4] and Opaque IP over Optical [4].

The characterisation of the energy consumption in any of these architectures requires metrics that capture the main elements that consume energy;

E_G : energy consumed by Core IP Router when performing routing or grooming operations in the electronic domain

E_W : set of WDMs which consume energy

E_{SDH} : energy consumption dissipated by the SDH layer

E_X : energy dissipated by OXCs

E_R : energy consumption of regenerator modules

E_{TR} : energy consumption of each WDM transponder

E_Y : energy consumed by short-reach interfaces on SDH

E_{SRT} : energy consumed by short-reach optical interface transponders interconnected between core routers and OXCs

E_{OOT} : energy dissipated by opaque optical transponders which convert long-reach to short-reach optical signals

E_A : energy consumption of optical amplifiers (viz. EDFA) within WDM spans placed at 70km intervals.

Basic Optical IP Architecture: Figure 1.2 shows the architecture of a Basic Optical IP network, segmented into the IP and the Optical layers. In the IP layer, core (IP) routers are inter-connected by point-to-point single mode optical fibre links with the optical layer providing capacity for communication between core routers via transponders. At each node, optical connections are terminated through OE (optical-electrical) and EO (electrical-optical) conversions and all traffic flows are processed electronically. Thus, there is no power consumed by optical switching; however, WDM transponders (E_{TR}), optical amplifiers (E_A) and core routers (E_G) consume energy.

SDH over Optical IP Architecture: IP flows are mapped into SDH frames (i.e., virtual containers, or VCs[3]) and these electronic signals are converted into WDM channels through transponders. Optical circuits are terminated at each node through OE conversions (Figure 1.3). The DXC switches VCs without grooming or de-grooming of traffic flows, which are aggregated, when needed, at the IP layer [2]. The short-reach interface transponders (E_Y), optical transponders (E_{TR}), DXCs (E_{SDH}), WDM de-multiplexers/multiplexers (E_W), EDFAs (E_A) and core routers (E_G) are the main contributors of energy consumption.

Transparent Optical IP Architecture: Transparent Optical IP is defined as a network whereby optical signals are transported from source to destination entirely in the optical domain (without OEO conversion) [3]. Therefore, optical channels can bypass intermediate nodes and because of this, signal regeneration is not required. Each node in a transparent IP over optical network is typically equipped with a Micro-Electro-Mechanical System (MEMS)-based [2] OXC/reconfigurable optical add-drop multiplexer (ROADM) [2][3] directly linked to a core router through WDM transponders (Figure 1.4). Transmission of traffic can be accomplished in either the electronic or optical domains; the former is implemented in the core router through traffic grooming and optical signal regeneration; the latter can be achieved by OXCs providing that no regeneration is required, bypassing light paths at intermediate core routers. The key contributors to energy consumption are WDM multiplexers/de-multiplexers (E_W), optical transponders (E_{TR}), OXCs (E_X), EDFAs (E_A) and core routers (E_G).

Translucent Optical IP Architecture: Translucent networks employ signal regenerators (to increase signal reach) at different nodes as needed. Between source and destination, a signal can be regenerated several times at intermediate nodes. The number of regenerators on a light path depends on link length [4]. Nodes have core router links to OXCs equipped with 3R-regenerators that perform re-timing, re-amplification and re-shaping at the WDM layer (Figure 1.5). The major energy consumption contributors are 3R-regenerators (E_R), WDM multiplexers/de-multiplexers (E_W), optical transponders (E_{TR}), OXCs (E_X), EDFAs (E_A) and core routers (E_G).

Opaque Optical IP Architecture: In an opaque network, both ends of a link comprise OEO interfaces, executing signal regeneration at every node. Essentially, a single hop in an opaque optical IP network is of the same length as the physical fibre link. Therefore, the architecture implements many OEO conversions, impacting its energy consumption [4]. As illustrated in Figure 1.6, the OXC communicates with other network elements via short-reach transponder (SRT) interfaces [4][16] and opaque optical transponders (OOT) [2][4][16]. The former consists of a set of the OXCs connected by fibre links to core routers, the latter is responsible for transforming long-reach to short-reach optical signals. The major contributors to energy consumption are WDM multiplexers/de-multiplexers (E_W), short-reach transponders (E_{SRT}), long-reach transponders (OOT), OXCs (E_X), EDFAs (E_A) and core routers (E_G).

The various energy consumption contributions are summarized in Table 1.1 for the five architectures.

Table 1.1: Power consumption contributors for various optical IP architectures.

Structure ***Contributor***	*Basic Optical IP Architecture*	*SDH over Optical IP Architecture*	*Transparent Optical IP Architecture*	*Translucent Optical IP Architecture*	*Opaque Optical IP Architecture*
E_G	• Electronic processing. • Electronic switching. • Traffic grooming.	• Electronic processing.	• Electronic processing. • Traffic grooming. • Routing.	• Electronic processing.	• Electronic processing.
Transponder	• E_{TR}: OEO conversion between WDM and core router.	• E_Y: Short reach OE conversion. • E_{TR}: OEO conversion between WDM and DXC.	• E_{TR}: OEO conversion between OXC and core router.	• E_{TR}: OEO conversion between OXC and core router.	• E_{SRT}: Short-reach OEO conversion between OXC and core router. • E_{OOT}: Conversion from long-reach to short reach optical signal.
E_{SDH}		• DXC electronic switching. • Traffic grooming. • OEO operation.			
E_W	WDM mux/demux mechanism (single wavelength).	WDM mux/demux mechanism (single wavelength).	• WDM mux/demux mechanism (waveband). • Routing and wavelength Assignment.	WDM mux/demux mechanism (waveband).	WDM mux/demux mechanism (waveband).
E_X			• Optical Bypass and Wavelength conversion. • All-optical switching.	• Optical hybrid switching. • Optical and electronic switching.	• Optical hybrid switching. • Optical and electronic switching.
E_R				3R regenerator	
E_A	Number of amplifiers on fibre links.	Number of amplifiers on fibre links.	Number of amplifiers on fibre links.	Number of amplifiers on fibre links.	Number of amplifiers on fibre links.

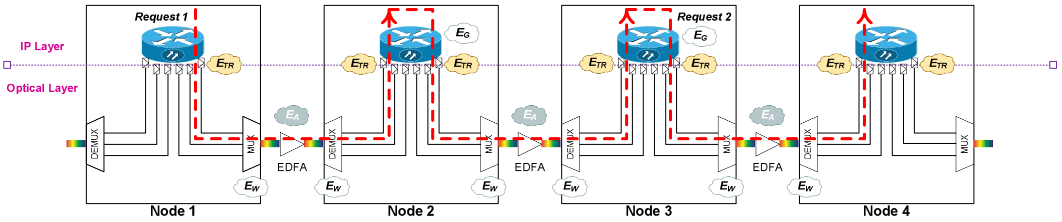


Figure 1.2: Basic Optical IP architecture.

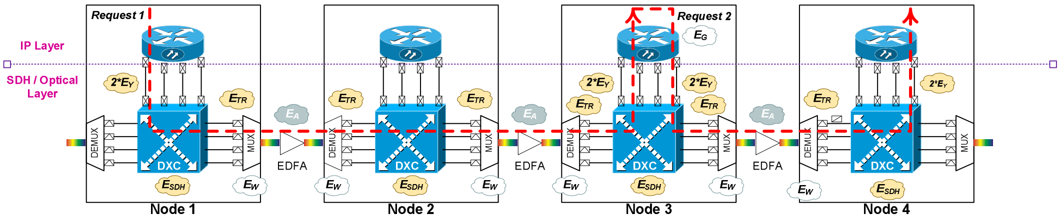


Figure 1.3: SDH over Optical IP architecture.

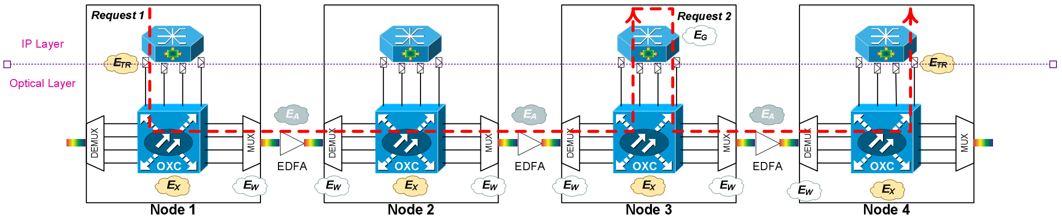


Figure 1.4: Transparent IP over Optical architecture.

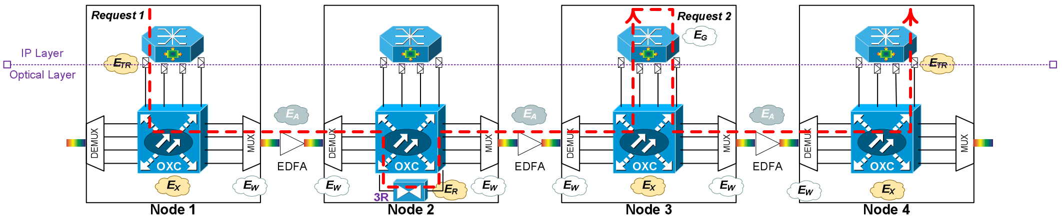


Figure 1.5: Translucent Optical IP architecture.

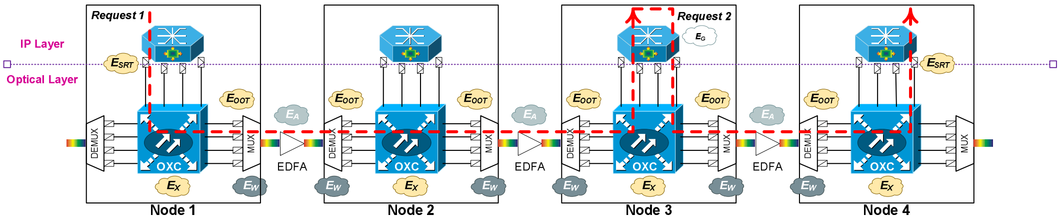


Figure 1.6: Opaque Optical IP architecture.

Given the above characteristics of the five candidate networks, the *Transparent Optical IP architecture* is adopted as the reference network for the remainder of the Thesis. Should any element of the structure be modified, the new assumption will be cited.

1.1.4 Energy Comparison Between Sleep Mode (primitive) and Hibernation Mode (Smart)

The key distinction between the sleep and hibernation modes is that the former is a primitive approach in which energy savings are performed manually, for instance by pre-setting configuration or the manual power down of nodes. The latter is a more intelligent approach where network equipments or links are put into sleep modes automatically governed by the control plane and based on the current state of the network. Table 1.2 provides a summary comparison for both schemes highlighting the salient differences.

Table 1.2: Comparison between sleep and hibernation modes.

Features	Sleep Mode	Hibernation Mode
Operation	▪Primitive or manually mechanism by switch OFF/ON network elements [51][67].	▪Smart or automatic mechanism governed by the control plane [83].
Domain	▪Separated domains control; either optical layer or IP layer [94][110].	▪Cross-layer and integrated control between optical layer and IP layer.
Approach	▪Sleep mode [51][109]. ▪Selective switch-off of optical links [109][110].	Combination of several energy saving techniques: ▪Sleep mode [51][67]. ▪Green routing [109][119]. ▪Traffic Engineering [83][104]. ▪Heuristic/ILP [116][123]. ▪Routing and Wavelength Assignment [121][125][126]. ▪Wavelength converters [123]. ▪Optical Switching bypass [116] ▪Traffic grooming [123].
Strategy	▪Cluster based architecture [118].	▪Group-Nodes. ▪Segment-Link. ▪Partitioning-Light path.
Power Saving	~50%, optical domain only [118].	Up to ~70%, optical and IP domain.
Performance	~50%, optical domain only [118].	Up to ~32%, optical and IP domain.
Protocols	▪Routing: OSPF [38][39]. ▪Signalling: RSVP [32]. ▪Management: SNMP [29].	▪Routing: OSPF-TE [38][39] ▪Signalling: RSVP-TE [141] ▪Management: LMP, SNMP[38] ▪GMPLS protocols [38][39] ▪Energy aware routing.
Administration	▪No control plane or separated optical control plane and IP control plane [16].	▪Common control plane for managing optical layer and IP layer [38][39]. ▪Cost effective [39].
Maintenance / Provisioning	▪Signalling and routing protocols for optical domain and IP domain independent [16]. ▪Static / Dynamic Light path Establishment [20][28].	▪Common signalling and routing protocols for optical and IP domains [17][18][38][39]. ▪Dynamic Light path Establishment [20].
Resources	▪High network resources; control operation both on optical domain and IP domain.	▪Optimized signalling and routing resources.

1.1.5 Green Optical Network Design

The key phases in new green optical network roll out are network planning and deployment. The former consists of an assessment of end user requirements (traffic demands and dimensioning), evaluation of feasibility energy aware network architecture designs and selection of energy conservation techniques, the later implementation considers network survivability (protection, restoration and recovery) and security challenges.

The green optical network design criteria can be summarised as follow [96][122];

i. *Network Component*: energy consumption can be reduced by using advanced network processor technologies supporting sleep modes at the core router and optical switch.

ii. *Transmission/Transport:* Long reach WDM transceiver and low attenuation low dispersion fibres increase transmission efficiency such that the metric J/b.km can be reduced.

iii. *System:* Intelligent power management strategies are needed for multi-line card equipment, which consolidate traffic from under-loaded ports, and enable synergic sleeping/wake up mechanisms amongst individual modules. For a certain amount of traffic, the configuration of multiple line cards can be optimized for reduced power consumption.

iv. *Traffic Engineering:* Network traffic can be directed to more energy efficient routes, viz. a shorter path that requires fewer in-line amplifiers. Traffic grooming can reduce the operational overhead such that power can be kept proportional to traffic as much as possible. Also, direct lightpath optical bypass at intermediate nodes without energy-intensive optical-to-electronic-to-optical (O/E/O) conversion and electronic processing can reduce a major portion of the energy consumed in the electronic domain.

v. *Network Engineering:* The network topology can be globally reconfigured and optimized by selectively shutting down under-loaded switching nodes while still maintaining network connectivity.

vi. *Network Planning:* Energy use can be considered at the network-planning stage such that all traffic demands are accommodated at a minimum total energy. Also, in optical networks, equipment can be located virtually anywhere, owing to its huge transmission capability. Therefore, relocating network services and data centres to remote renewable energy sites not only helps the environment by consuming less energy, but can also save an institution significant electricity cost.

1.2 Overview of the Thesis

The focus of the Thesis is an investigation and evaluation of energy efficient solutions in Core Optical IP networks using as a foundation, a hierarchy of hibernation modes implementing different degrees of node groupings, fibre links and light paths establishment that support a sleep state. It seeks to embed this groups-segmentation-partition strategy into an intelligent control plane implementing routing schemes targeting energy consumption and traffic engineering. Illustrated in Figure 1.7, is the Thesis outline indicating the relationships between different Chapters.

Chapter 2 provides background to the key enabler technologies of optical networking and a review of energy saving mechanisms proposed for optical IP networks. It also presents the background material on intelligent control plane standards and describes related research as well as a classification framework for power reduction techniques with particular emphasis on the core network.

Chapter 3 develops models that aid in the design and evaluation of energy efficient core optical IP networks. A simulation framework for the analysis of a distributed intelligent control plane based optical IP network is implemented using the OMNeT++ platform [132]. This framework is the foundation for the evaluation of the efficacy of the proposed energy saving schemes. The Chapter validates the framework in terms of its functionality and models.

Chapter 4 provides the principles of the energy saving algorithm and hibernation mode strategy. A Group-Nodes mechanism is proposed as a function of topology and node distribution based on a fixed (or geographical) and random (or ownership) principle. The impact of the proposed technique on power saving and network performance is assessed; results are presented and evaluated for various scenarios.

Chapter 5 details the Segment-Link approach. In this scheme, the thrust is on the selective power down of fibre links, overlayed with RWA based on a heuristic approach. Results for the proposed scheme are evaluated for both the optical fibre link only and segmentation-link scenarios.

Chapter 6 is devoted to the further enhancement of the hibernation strategy. Following the definition of the implementation of a partition-light path mechanism, RWA heuristics related light path establishment is described and compared in both "light path only" and "partition-light path" modes. Results on the trade-off between energy consumption and network performance are presented for the two modes under the same network conditions.

Chapter 7 draws conclusions, highlights the contributions of the research and provides a general discussion and evaluation of the impact of the research. Finally, possible future work is considered.

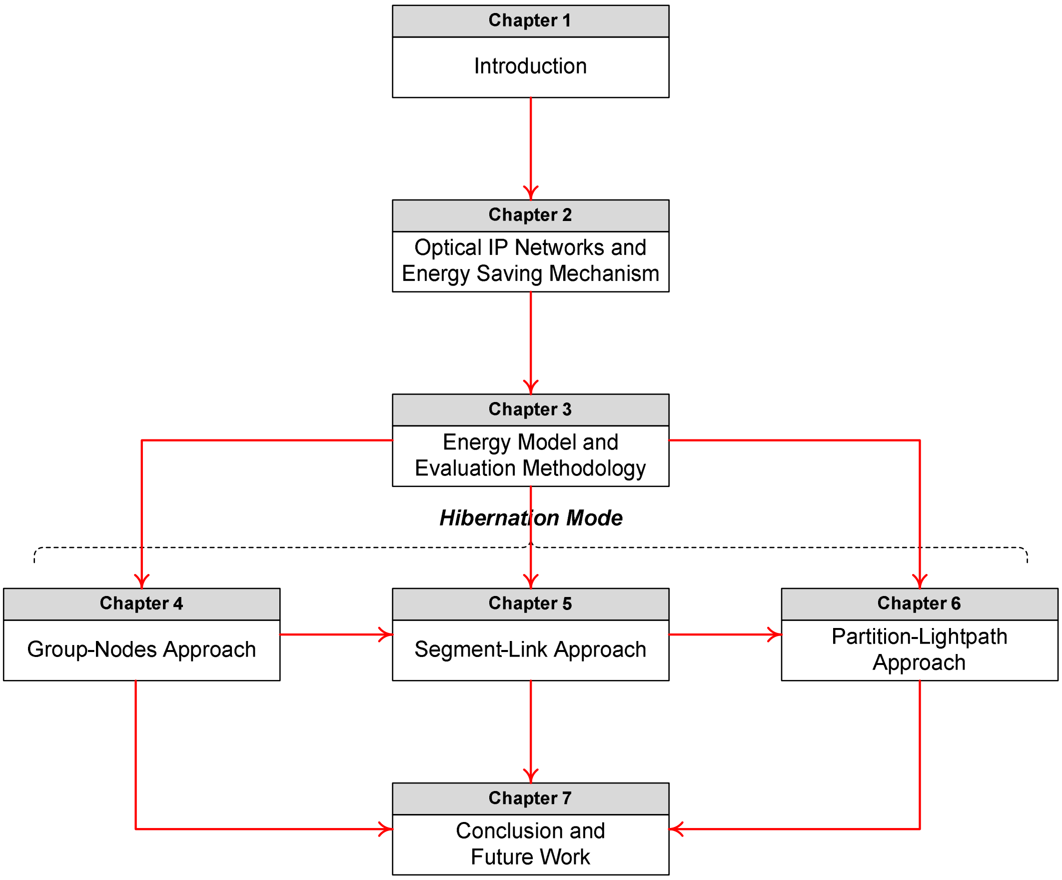


Figure 1.7: Thesis structure overview.

1.3 Main Contributions

The following contributions have been made;

- a simulation framework has been established for the evaluation of a distributed Core Optical IP networks control plane incorporating energy conservation. The framework that informs the design of energy efficient core networks is validated and utilised to assess novel strategies to energy conservation.
- an energy saving scheme for Core Optical IP networks using a Hibernation strategy has been proposed – the Group-Nodes - and evaluated. This technique has been evaluated under various grouping schemes for representative network topologies.

- an extension to the Hibernation Mode employing Segmentation-Link principles. Energy conservation through optimisation of fibre path selection has been evaluated, exploiting the benefits of RWA and Traffic Engineering.
- further energy consumption optimisation through a partition-light path scheme has been proposed and evaluated. Wavelengths are partitioned allowing more efficient use of network resources. Two main elements are:
    - an energy aware strategy for light paths establishment
    - the development of a light path re-routing scheme with support for wavelength power down.

Chapter 2

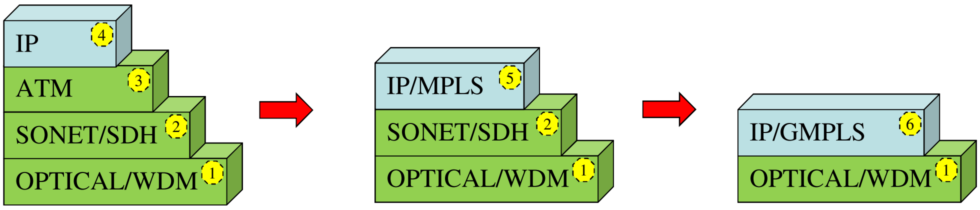
Energy Conservation in Optical IP Networks

2.1 Introduction

The Chapter provides an introduction to the key areas underpinning the main research in the Thesis. Section 2.2 summarises the evolution of Optical IP networking; Section 2.3 presents the Optical Network Structure; Section 2.4 describes the IP protocol and its implementation in Optical Networks; the ‘IP over Optical Network’ is described in Section 2.5. Section 2.6 provides an introduction of the GMPLS structure and protocols and in Section 2.7 an explanation of Network Energy Model is given; key fundamental challenges in next generation networks are also identified. Section 2.8 presents a discussion of related work on schemes that address energy consumption. Finally, a summary is provided in Section 2.9.

2.2 Evolution of Optical IP Networks

Over the past 15 years, the representation of data networks have evolved to a four layer structure [3][5][6][13][15][16][18]: IP for carrying applications and services, asynchronous transfer mode (ATM) [12][16][18] for traffic engineering, SONET (Synchronous Optical Network)/SDH (Synchronous Digital Hierarchy) for transport, and Dense Wavelength-Division Multiplexing (DWDM) for capacity (Figure 2.1). This representation however, is difficult to scale to very large volumes of traffic, and at the same time is fairly costly; multi-layer architectures typically suffer from the lowest common denominator where any one layer can limit the scalability of the entire network, as well as adding to the cost of the implementation [3][10][14][16][17][18]. Figure 2.1 simplifies the stacked layer representation to a two layer architecture [16][18].



Function	**ID**
Internet Services	4, 5, 6
Multi-Services Integration	3, 5, 6
Multiplexing/Protection	2, 6
Capacity	1

Figure 2.1: Stacked Layer and Two Layer structure representing Optical Core IP networks.

As the capabilities of both routers and OXCs grew rapidly, the high data rates at the optical transport layer suggested bypassing the SONET/SDH and ATM layers. In order to bypass these layers, their necessary functions must move directly to the routers, OXCs, and DWDMs, resulting in a simpler, more cost-efficient network transporting a wide range of data streams and very large volumes of traffic [5][6].

The two layer stack (Figure 2.1) is a viable representation of the Next Generation Internet wherein IP is embedded directly over the optical layer. Furthermore, it assumes that light paths are established on demand [5][6][16][18].

2.2.1 Network Domains

An Optical IP network can be segmented into three network domains, the Core (or backbone), Metro (or edge, regional) and Access [10][11][12][16][41][44][47]. As reflected in Figure 2.2, the core is the spine of the hierarchy, providing nationwide or global coverage. Links in the core network span long distances e.g. a link (employing optical fibres) can be a few thousands of kilometres in length, (say) providing connections between the main cities of the United States [10][16][44]. Typically, core networks rely on mesh topologies to provide increased protection and efficient utilization of network resources.

The Metro network usually spans distances of a few tens to a few hundreds of kilometres and is predominantly based on the deep-rooted legacy of SONET/SDH optical ring networks [41][47]. The Access network connects customers to service providers, enabling end users (business and residential) to connect to the rest of the network infrastructure, spanning a distance of a few kilometres. Optical access networks are usually based on tree-like topologies [16][12].

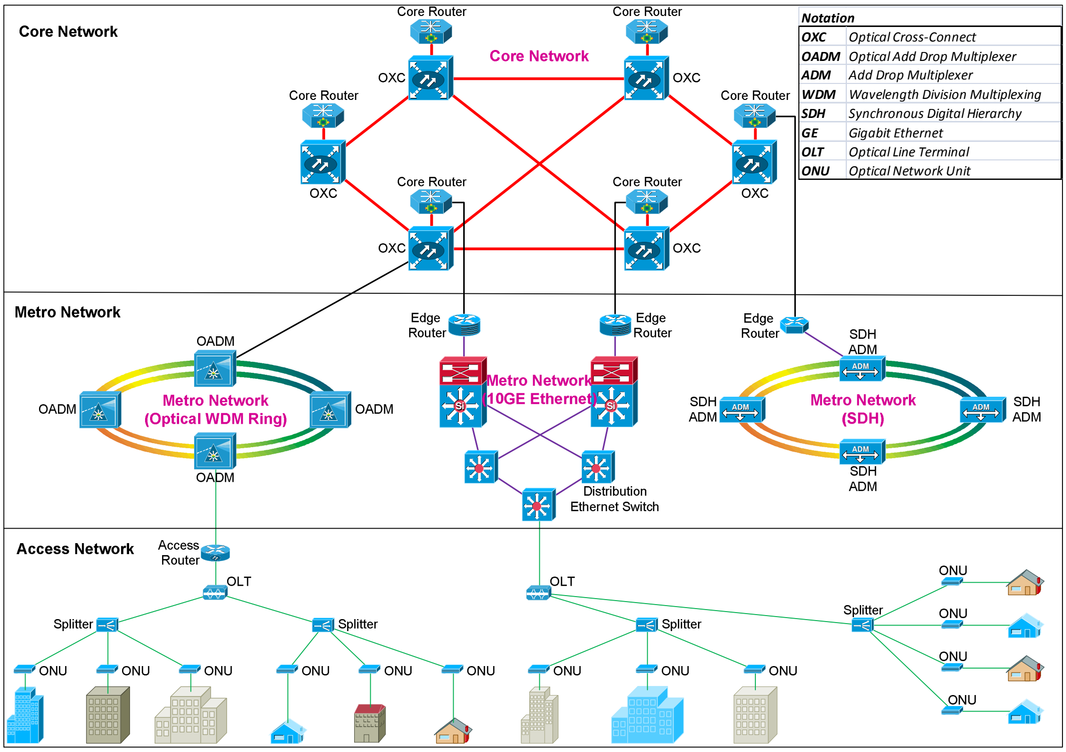


Figure 2.2: Optical IP Network Hierarchy.

2.3 Optical Network Structure

Optical Transport Network (OTN) [7][8][9] technologies are the foundation on which telecommunication operators deploy reliable, cost-effective high-capacity networks. The OTN will continue to play a significant role in the evolution of operator networks supporting future high-bandwidth services and increased network efficiencies. The OTN was developed for long-haul transport at data rates ranging from 2.5 Gb/s to 40 Gb/s per channel as recommended by ITU-T [7][8][9]. In addition, a new version of ITU-T G.709 is being defined to meet future network requirements by recommending functionality and mechanisms to support high-capacity Ethernet transport capabilities between 40 GbE and 100 GbE [7][8][9][10]. The role of the OTN is to support reliable, cost effective transmission, accommodate multiple carriers and integrate the features of SDH/SONET functionality whilst providing a scalable bandwidth resource through WDM.

The OTN was designed to meet the requirements of IP over WDM, enabling IP routers to have OTN-compatible interfaces and facilitating IP data mapping to wavelengths within a WDM overlay. OTN is true telecom-class transport designed to transport existing TDM services as well as serve as an enabler platform for emerging carrier-class Ethernet and cloud services [11]. The introduction of the IEEE 802.3ba standard supporting 100Gb/s Ethernet over OTN in the carrier network and transport areas will provision high quality broadband links with high granularity for the aggregated data flows; it will support different services classes and offers good network utilization [170].

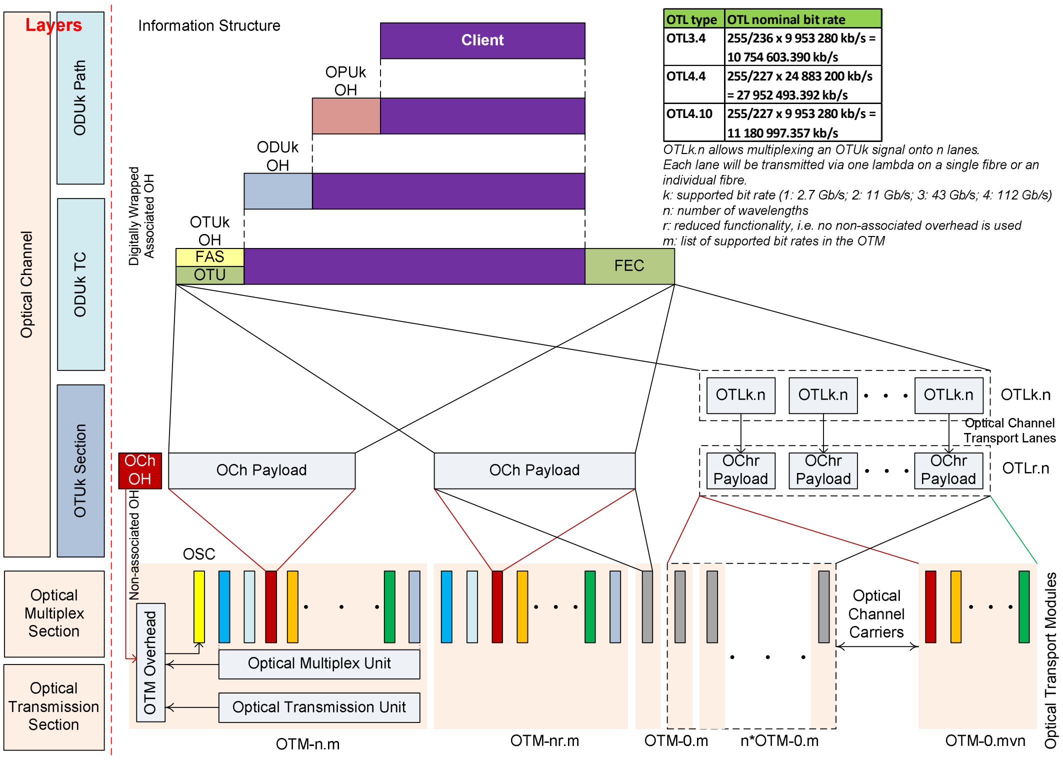
2.3.1 Optical Layer Framework

OTN technologies reside at the physical layer (Layer 1) within the Open Systems Interconnection (OSI) [7][16][29] communications model, supporting physical interfaces. OTN equipment is mainly used in the Metro and Core domains in order to construct regional and nationwide Layer 1 networks. OTN is also utilized in the Access network to provide bandwidth-intensive services for enterprise and government customers. The OTN provides significant flexibility for operators by accommodating various client signals at both wavelength and sub-wavelength rates [10].

The OTN structure comprises optical layer functionality such as multiplexing/de-multiplexing, switching and routing wavelengths and consists of three layers: the optical channel (OCh), the optical multiplex section (OMS) and the optical transmission section (OTS) (Figure 2.3) [7][8][12]:

- Optical Channel (OCh); provides a standardized method for managing end-to-end light paths based on a client-transparent infrastructure and capable of transmitting data in different formats e.g. SDH/SONET [7][12], PDH 565 Mbps [8][12] and ATM [12]. Such flexibility is achieved through optical connection re-arrangement for flexible network routing, an optical channel overhead ensuring the integrity of the optical channel adapted information, optical channel Operations, Administration and Maintenance (OA&M) [18] functions for connection provisioning, Quality of Service (QoS) [29] parameter exchange, and network survivability [16]. Furthermore, this layer is further segmented into two sub-layers, the Optical Channel-Section (OCh-S) layer and the Optical Channel-Path (OCh-P) layer.
- Optical Multiplex Section (OMS); provides the functionality that enables multiplexing of multi-wavelength (WDM) operation in the optical fibre. An optical multiplex section overhead to ensure the integrity of the multi-wavelength -multiplex adapted traffic, an optical multiplex section OA&M for section level operations and management functions and multiplex section survivability are all provided.
- Optical Transmission Section (OTS); provides the functionality for transporting signals over various optical transmission links. This is achieved through capabilities such as the optical transmission section overhead processing to ensure the integrity of the optical transmission section adapted traffic, optical transmission section OA&M for section level operations and management functions and transmission section survivability.

The OTN framing standard (independent of client layers) based on Recommendation of ITU-T G.709 [7] defines the interface between the client layers and the optical layer; referred to as the Digital Wrapper Frame or Optical Channel Wrapper (Figure 2.3).



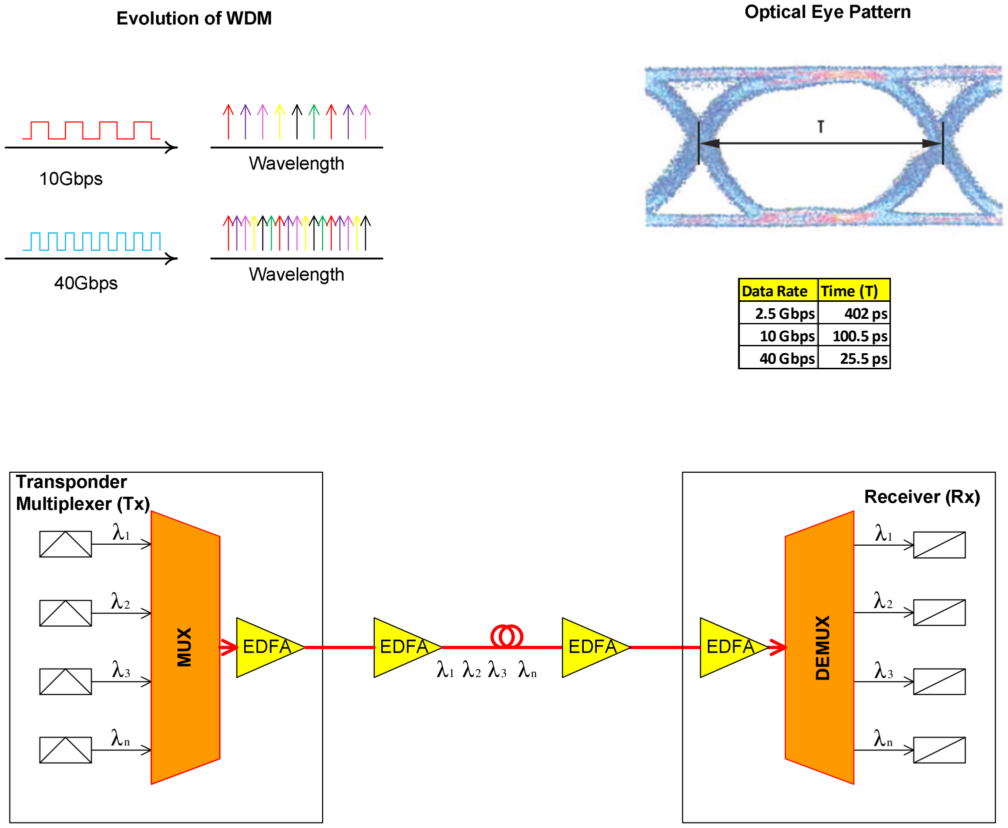
OTL type	OTL nominal bit rate
OTL3.4	255/236 x 9 953 280 kb/s = 10 754 603.390 kb/s
OTL4.4	255/227 x 24 883 200 kb/s = 27 952 493.392 kb/s
OTL4.10	255/227 x 9 953 280 kb/s = 11 180 997.357 kb/s

OTLk.n allows multiplexing an OTUk signal onto n lanes.
Each lane will be transmitted via one lambda on a single fibre or an individual fibre.
k: supported bit rate (1: 2.7 Gb/s; 2: 11 Gb/s; 3: 43 Gb/s; 4: 112 Gb/s)
n: number of wavelengths
r: reduced functionality, i.e. no non-associated overhead is used
m: list of supported bit rates in the OTM

Figure 2.3: OTN signal structure according to ITU-T Recommendation G.709 [7].

2.3.2 Wavelength Division Multiplexer (WDM)

Wavelength Division Multiplexing (WDM) is a technique to transmit data onto a common optical fibre simultaneously on various wavelength channels. In optical networks, each channel is known as a wavelength and the term lambda (λ) is used to designate the carrier [13]. Essentially, WDM is analogous to Frequency Division Multiplexing (FDM) [13] in the optical domain. With this approach, the low loss optical transmission spectrum is divided into a number of non-overlapping wavelengths (or channels) and each wavelength occupies a single communication channel. As shown in Figure 2.4, each transmitter *n* sends on a different wavelength λ_n, where $1 \leq n \leq K$.



Data Rate	Time (T)
2.5 Gbps	402 ps
10 Gbps	100.5 ps
40 Gbps	25.5 ps

Figure 2.4: WDM transport system with amplifiers. MUX stands for Multiplexer. DEMUX denotes De-multiplexer. EDFA is the Erbium Doped Optical Amplifier.

2.3.2.1 DWDM and CWDM

Two main WDM regimes exist: Dense Wavelength Division Multiplexing (DWDM) and Coarse Wavelength Division Multiplexing (CWDM) [14][15], the main difference being the channel spacing i.e. the frequency difference between adjacent channels which for the latter is nearly 100 times wider allowing network operation with relaxed specification in regard of the frequency stability of the source. Typically DWDM systems provide multiplexes above 40 channels (up to 144 channels [14]) at <2 nm wavelength spacing; CWDM systems support approximately 4 to 16 channels at a 20 nm spacing over the range of 1470 nm to 1630 nm [13].

- **DWDM**:

  DWDM systems require stable separation between wavelengths and thus precise standardization of the carrier frequency. The International Telecommunications Union (ITU-T) Recommendation G.692 accommodates 81 wavelengths at a 50 GHz (or 0.39 nm) channel spacing and 41 wavelengths with channel spacing of 100 GHz (or 0.78 nm) within the C-band (1528-1561 nm) of transmission, respectively. The grid centred at 193.1 THz, is the starting point. DWDM is expensive to build and to guarantee high-capacity requires a range of high value, reliable optical components such as fast cross-connect fabrics [14]; tuneable lasers and filters (Figure 2.6) [15]; low-noise and high-sensitivity receivers [14][15]; low-noise and wide-band optical amplifiers [14]; fast and low-noise optical sensors [15]; smart connectors because it's susceptible to Polarisation Mode Dispersion (PMD), Chromatic Dispersion (CD) and signal crosstalk [14][15]. Typically, DWDM is deployed in the core/backbone layer of the network.

- **CWDM:**

  CWDM is used for (shorter) distances up to 60 km at a data rate of 2.5 Gb/s. ITU-T G.692 [10][13] defines a set of wider wavelength spacing of up to 25 nm allocating a broader spectral occupancy and looser centre frequency stability to system designers. CWDM is much less sensitive to chromatic dispersion and other forms optical signal impairments. Therefore, it can be implemented using cheaper components and low channel counts, preferable for use in metro networks such as cable television networks, where separate wavelengths are used for downstream and upstream signals.

2.3.3 Erbium Doped Fibre Amplifier (EDFA)

An Erbium Doped Fibre Amplifier (EDFA) comprises a length of silica optical fibre, the core of which is doped with ionized atom (ions) of the rare earth element erbium Er^{3+} [16][130]. This fibre is pumped using a signal from a laser, typically at a wavelength of 980 nm or 1480 nm. In order to combine the output of the pump laser with the input signal, the doped fibre is preceded by a wavelength-selective coupler. At the output, another wavelength-selective coupler separates the amplified signal from any remaining pump signal power. Usually, an isolator is used at the input and/or output of any amplifier to prevent reflections into the gain region which can convert the amplifier into a laser, making it unusable as an amplifier [16].

The EDFA is a 1R regenerators since it only amplifies optical power; it is usually deployed at 70km intervals in point to point applications [16][130]. The major performance parameters are gain, gain flatness (amplified signals uniformly), output saturated power (P_{sat}) and Noise Figure (NF).

2.3.4 Optical Cross-Connect (OXC)

An Optical Cross-Connect (OXC) is a (space division) switch that executes routing of optical data streams from any input to any output fibre port. The OXC may be implemented as an all-optical device or using optical-electrical conversion at the input and output ports [17][18]. Such a switch is managed at the control plane for signalling and routing to establish light path connectivity [17][18].

Figure 2.5 illustrates a possible OXC structure which comprises a single stage optical fabric with a pool of wavelength converters capable of waveband or per wavelength switching [18]. Wavelength conversion can be deployed to each input fibre port of a WDM wavelength multiplex by sharing or dedicating a pool of wavelength converters. In Figure 2.5, there are two input fibre ports and two output fibre ports, each supporting a number of wavelengths. Depending on the switch configuration, the light path can be locally switched to an available output port, the wavelength set within the pool of wavelength converters. After that, the output of the wavelength converter is fabric-switched again to the appropriate output fibre on a new wavelength. Notably, if a light path route is accomplished without wavelength conversion, a signal at a particular wavelength from one input fibre port can be configured by the switch, connecting on the same wavelength but on a different outgoing fibre port [18].

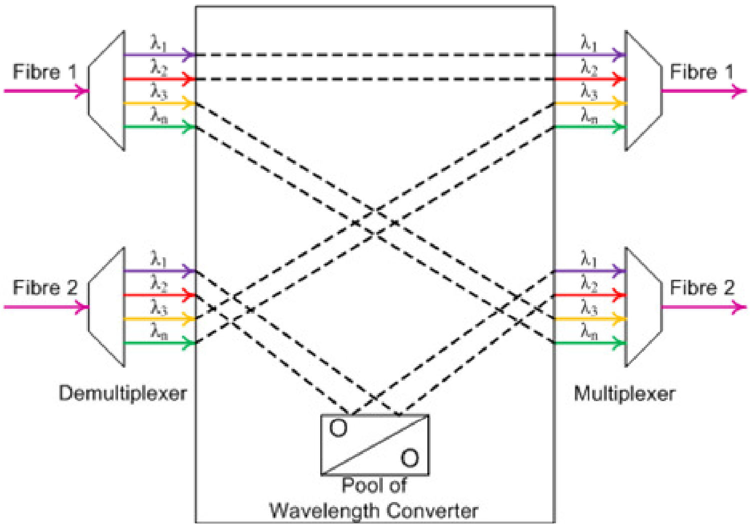
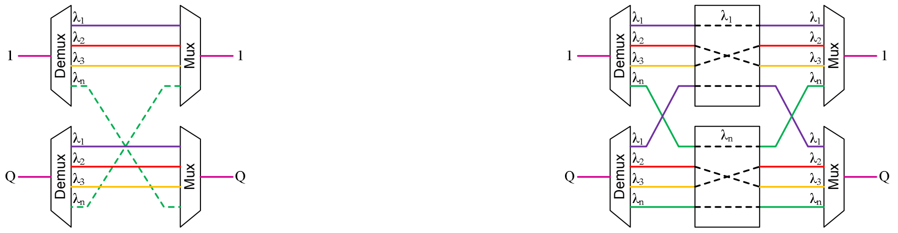


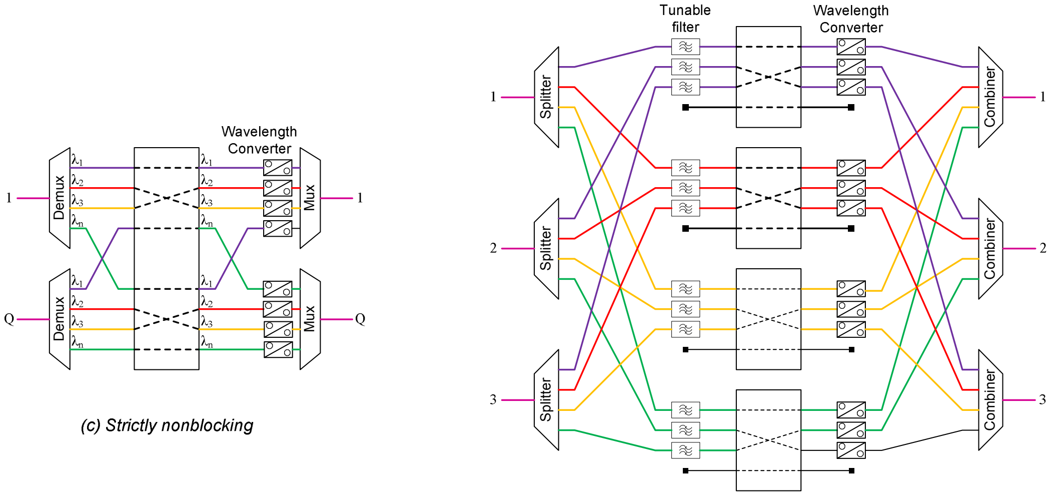
Figure 2.5: A schematic structure of an example Optical Cross-Connect.

OXC architectures can be classified as rigid, re-arrangeable, or non-blocking [19] (Figure 2.6(a)-(d)). The rigid OXC [19] (Figure 2.6 (a)) is the simplest configuration and does not provide re-arrangement. The re-arrangeable scheme of Figure 2.6 (b) utilizes the functionality of a switching matrix in space [19]. Moreover, its operation is based on wavelengths routed from any input fibre to any unused wavelength on the output fibre. For this type of OXC, the bandwidth capacity is $Q \times n \times B$, where Q is number of input/output fibre ports, n denotes the number of wavelengths in each fibre, and B is the bit rate per wavelength. The strictly non-blocking configuration (Figure 2.6(c)) utilises wavelength converters with a large space switch at the heart of the node. Wavelength conversion circumvents the constraint of two channels carried on different fibres (links) at the same wavelength routed simultaneously to a common fibre output port. The strictly non-blocking lower-dimension space (switch) is designed to manage large scale space switches (Figure 2.6(d)). The integration of tuneable filters and passive power splitters enhances channel selection [19].



(a) rigid

(b) rearrangeable



(c) Strictly nonblocking

(d) Strictly nonblocking with lower-dimension space switches

Figure 2.6: An example of Optical Cross-Connect architecture schemes: (a) rigid ;(b) re-arrangeable; (c) strictly non-blocking; (d) strictly non-blocking with lower-dimension space (fabric) switches.

2.3.5 Optical Transport Network (OTN) Engineering

OTN deployment is governed by harnessing light paths, physical and virtual topology design, wavelength conversion as well as Routing and Wavelength Assignment (RWA) strategies. These considerations are vital during the planning, design and network implementation stages to manage requirements on client signal types, bandwidth granularities, equipment compatibilities of various vendors and resource optimization.

2.3.5.1 Light paths

A light path is a transparent optical connection between two network nodes normally aided by an OXC to switch wavelengths within the WDM multiplex on each intermediate node along the path [16][20][21][122]. A light path is analogous to a virtual circuit-switched connection provided by the SDH layer [20][122]. The intermediate nodes within the route switch the light path from source to destination node. Also, the light path can be converted from one to another wavelength; the same wavelength can be used in different light paths but must not share any common links. Creating and managing light paths results in a network which is more scalable and cost-efficient through the spatial reuse of wavelengths.

In order to set up a light path successfully, there are additional considerations and constraints; wavelength-continuity, route-diversity and distinct-wavelengths [20][21].

2.3.5.2 Physical and Virtual Topology Design

The physical topology represents the physical architecture of the network and comprises a set of nodes and links supporting light paths interconnecting nodes [16][22][23]. Each node executes key functions and is subject to constraints; the physical topology design requirements depend on equipment limitations, traffic demand, node degree, redundancy, geographical constraints and administrative constrains [22][23].

Virtual Topologies (logical or light path) correspond to the light path structure between source to destination irrespective of whether it is a direct or a disjoint physical connection [22][23][24]. Therefore, a virtual topology may appear to be a similar structure to the physical topology but in essence has flexibility in topology formation viz. it may function as a static or a reconfigurable topology (Figure 2.7). Moreover, the major constraints in the design of a virtual topology include the physical topology and the routing and wavelength assignment (RWA) protocols [24].

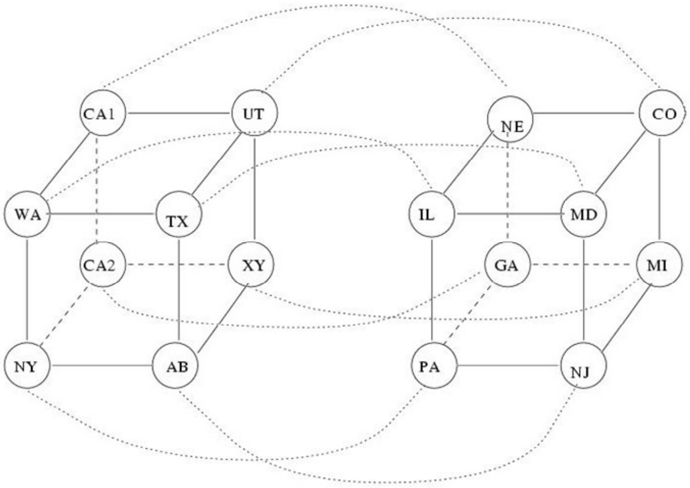


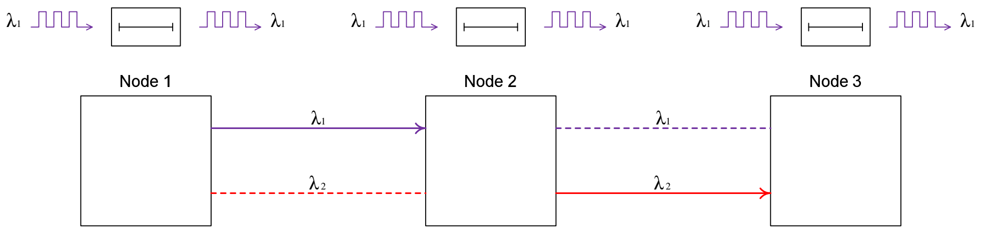
Figure 2.7: An example of a Virtual Topology connection for NSFNET [21].

2.3.5.3 Wavelength Conversion

Wavelength conversion is the technique of converting data arriving on one input wavelength onto a different output wavelength directly in the optical domain, enabling routing flexibility and improving the utilisation of WDM channels, resolving contention thereby minimizing the blocking of traffic [6][25]. Wavelength conversion obviates the 'wavelength continuity constraint' [6] in which the establishment of a light path necessitates that the same wavelength be assigned on all fibre links constituting the path.

Figure 2.8 illustrates an example of wavelength conversion in a wavelength routed network. Supposing two existing light paths have been established in the network, the first one at λ_1 between node 1 and node 2, the second at λ_2 between node 2 and node 3. If no wavelength conversion exists between node 1 and node 3, any requested light path will be blocked in spite of free wavelengths available on all links along the route. However, the request is successful if a wavelength converter at node 2 is deployed to convert data from λ_2 to λ_1 (Figure 2.8(b)). The connection between node 1 and node 3 can then be serviced by a new light path in which λ_2 links node 1 to node 2 and λ_1 from node 2 to node 3.

(a): Without Wavelength Converter



(b): With Wavelength Converter

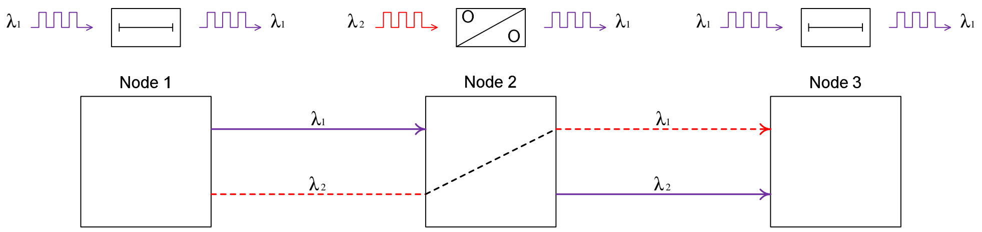
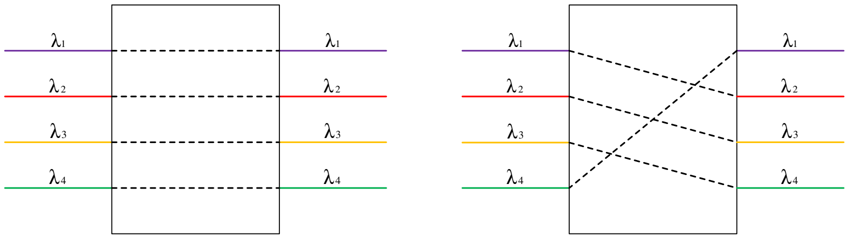


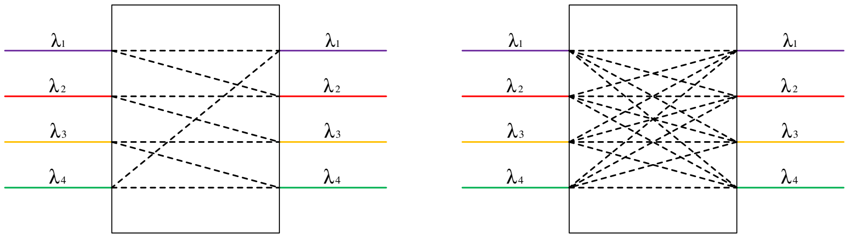
Figure 2.8: Wavelength routed network; An example of wavelength conversion. (a) without wavelength converter; (b) with wavelength converter.

Different types of wavelength conversion strategies are possible (Figure 2.9). *No conversion* indicates the connected nodes are at the same wavelength. In the case of *fixed conversion*, each wavelength at a node may be connected to pre-determined output wavelength on all output fibre ports. *Limited conversion* (or partial-conversion) utilises restricted wavelength shifting, with each input wavelength may be converted to any of a specific set of the output wavelengths. *Full conversion* denotes that any input wavelength can be converted to any output wavelength and any combination of wavelength shifting is provided. The latter technique is the most expensive but provides most routing flexibility [6][25].



No Conversion

Fixed Conversion



Limited Conversion

Full Conversion

Figure 2.9: Different categories of wavelength conversion.

2.3.5.4 Routing and Wavelength Assignment (RWA)

The determination of a route for a wavelength that is free on all links along a light path is referred to as Routing and Wavelength Assignment (RWA) [20][26]. The aim is to maximize the number of light path connections; the RWA manages requests for light paths that need to be established and assigns a suitable wavelength(s) to that light path based on the traffic demand of a network. This minimises the amount of network resources as well as verifying that no two light paths are allocated to the same wavelength on the same physical link. The routing process is used to compute the optimal route for light paths under given constraints and according to a certain criterion [20][26]. The wavelength assignment procedure determines and assigns wavelengths to light paths that can be utilised at each node by considering wavelength constraints [27]. RWA schemes depend on other factors such as traffic patterns, availability of wavelength conversion and operational objectives.

In wavelength-routed optical networks, RWA can be categorized as either static or dynamic [26][28]. The static category applies to the case in which the entire connections in the network are known in advance (fixed traffic demand) and operations are performed off-line. The objective is typically to accommodate the demand while minimizing the number of wavelengths used on all fibre links. The problem is then to establish light paths for these connections in a global fashion while minimising network resources such as the number of wavelengths or the number of fibres in the network. RWA for static traffic patterns is known as the Static Light path Establishment (SLE) [26][28]. Conversely, dynamic RWA light path setup is executed according to random connection requests and the light path terminates after some finite amount of time. The objective of the dynamic RWA is to minimize the degree of blocking (probability of contention) while at the same time maximizing the number of connections that are established over a given period of time, referred to as Dynamic Light path Establishment (DLE) [26][28]. DLE allocates light paths from source to destination node on the least congested path through an online computation algorithm.

2.3.6 The Control Plane

The Control Plane provides facilities and associated protocols that select, assign, de-allocate, and provision network resources to fulfil user service requests [37][140]. Typically this includes routing protocols that distribute topology and reachability information between interconnected networks and network elements.

The Multi-Protocol Label Switched (MPLS) Control Plane [37] is responsible for the formation and maintenance of the forwarding table (LFIB). Its functions include distribution of multi-protocol routing accommodating routing information exchange, and procedures (algorithms) to map into a LFIB. The GMPLS Control Plane executes multiple tasks and functions for the control of light paths in core networks. The GMPLS control plane architecture can be extended to support energy saving mechanisms (Figure 2.10).

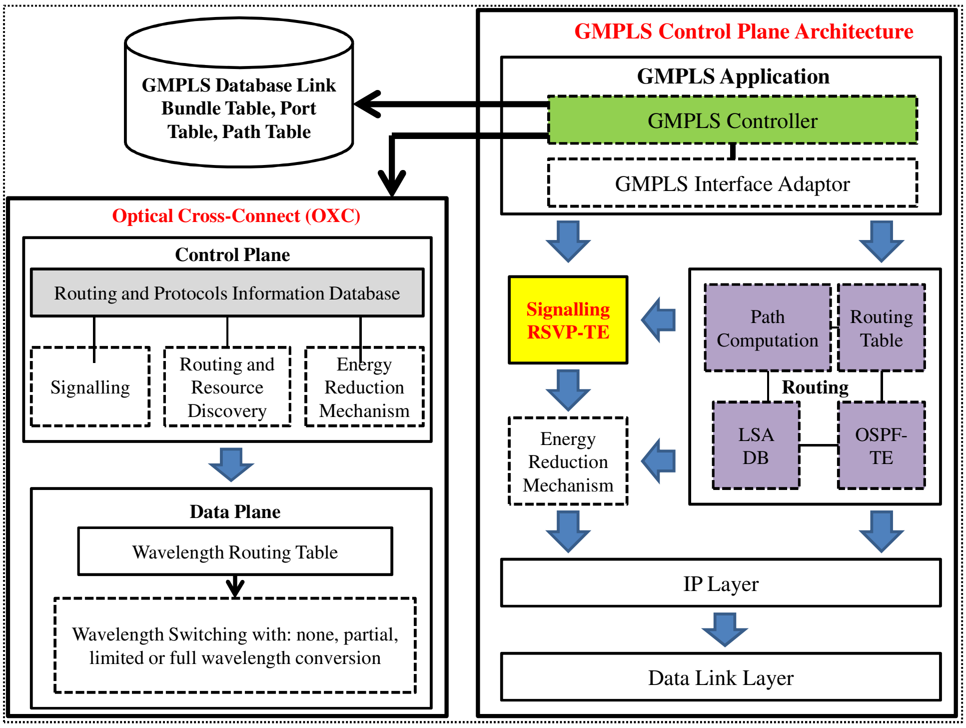


Figure 2.10: The GMPLS Control Plane Architecture.

In general, the main functions of a control plane are;

1. Signalling; establishing and maintaining connection on User-to-Network Interface (UNI) and Network-to-Network Interface (NNI).
2. Routing;
    a) Automatic topology and resource discovery, to create a local view of data plane connectivity and resource allocation.
    b) Path Computation; a connection setup determined by procedure or algorithm based on topology and resource information.
3. Neighbour Discovery; ascertains the details of its connectivity to all data plane neighbours. Local Resource Management, accounting for resource allocation.

2.4 The Internet Protocol (IP)

The network layer within the OSI Reference Model plays the key role for internetworking design. This layer has presented a lot of challenging issues in data transmission from source to destination; IT vendors have developed varieties of protocol solutions such as the System Network Architecture (SNA) [29][30], Internetwork Packet Exchange (IPX) [29], Transmission Control Protocol/Internet Protocol (TCP/IP) [29][30] and NetBIOS Extended User Interface (NetBEUI) [29][30]. In spite of that, only IP has dominated due to its robustness, flexibility, reliability and protocol compatibility; IP has become the industrial standard.

The Internet Protocol (IP) is derived from the RFC791 standard for IP version 4 (IPv4) [29], the latest being a new specification - IP version 6 (IPv6) - based on the RFC2460 standard [29]. Despite the fact that IPv6 was originally designed to replace IPv4, at present, most of the internetworking protocol implementations still regard IPv4 as standard IP.

IP is part of the TCP/IP suite, corresponding to the network layer in the OSI Reference Model and providing a connectionless best-effort delivery service within the transport layer [29]. IP is a protocol for universal data delivery across all network types. Data is packaged into datagrams that comprise control information and the payload data to be delivered [30]. Moreover, IP provides functionalities and mechanisms such as end-to-end datagram transmission, fragmentation and re-assembly of long datagrams, as well as flow control, sequencing and supporting QoS.

IP routing protocols are characterized by ‘classfull’ or ‘classless’ IP addressing/routing [29], static and dynamic routing (distance vector or link state) [30], routing metrics [30], Variable-Length Subnet Mask (VLSM) to conserve and use efficiently the total IP addresses allocation [30], route summarization across network boundaries and timers [29][30]. IP routing provides a mechanism to route packets from different network addresses classified as an inter-domain or Interior Gateway Protocol (IGP) and intra-domain or Exterior Gateway Protocol (EGP) routing protocols [30][33]. IGP is designed to distribute routing information within an Autonomous System (AS) and uses the IP address to establish the route, such as Routing Information Protocol (RIP) [29][30], Interior Gateway Routing Protocol (IGRP) [29][30], and Open Shortest Path First (OSPF) [29][30]. EGP is also used to exchange routing information among different Autonomous Systems (ASs) and depends on an AS number to construct paths, for example, Border Gateway Protocol (BGP) [29][30].

IPv4 addressing employs a fixed length of 32 bits. The address structure was originally defined to have a two-level hierarchy: network ID and host ID. The network ID identifies the network connected to the host. Consequently, all hosts connected to the same network have the same network ID. The host ID identifies the network connection to the host rather than the actual host [29]. The classfull IP addressing scheme formats are shown in Table 2.1. The IP address space is categorized into five address classes; Class A, Class B, Class C, Class D and Class E. The bit position for each class fixes the boundary between the network prefix and the host number at a separate point within the 32-bit address.

Table 2.1: IP Addressing Scheme (IPv4). Notation: n stands for network; h is host; g represents group and x denotes reserved for experiments.

Network Class	**Dotted-Decimal Notation Ranges**	**Subnet/Multicast Bitmap**
A (/8 Prefixes)	1.0.0.0 through 126.255.255.255	0nnnnnnn.hhhhhhhh.hhhhhhhh.hhhhhhhh
B (/16 Prefixes)	128.0.0.0 through 191.255.255.255	10nnnnnn.nnnnnnnn.hhhhhhhh.hhhhhhhh
C (/24 Prefixes)	192.0.0.0 through 223.255.255.255	110nnnnn.nnnnnnnn.nnnnnnnn.hhhhhhhh
D (Multicast)	224.0.0.0 through 239.255.255.255	1110gggg.gggggggg.gggggggg.gggggggg
E (Experiment)	240.0.0.0 through 247.255.255.255	1111xxxx.xxxxxxxx.xxxxxxxx.xxxxxxxx

A set of specific ranges of IP addresses have been set aside for use in private networks, as described in RFC 1918 standard. These addresses are used within intranets that do not connect directly to the Internet, are considered *unregistered* and routers in the Internet must discard packets with these addresses [29]. A range of addresses has been defined for each IP class as shown in Table 2.2

Table 2.2: Private Address Space (Unregistered) recommended by RFC 1918.

Network Class	**Host Address Range**
A (10 / 8 Prefixes)	10.0.0.0 through 10.255.255.255
B (172.16 / 12 Prefixes)	172.168.0.0 through 172.31.255.255
C (192.168 / 16 Prefixes)	192.168.0.0 through 192.168.255.255

2.5 IP over Optical Networks

The term Core Optical IP networks (or IP over WDM) has come to be used to refer to IP over Optical networks. According to a definition provided by [18], IP over Optical transmits IP traffic in a WDM-enabled optical network to leverage both IP universal connectivity and massive WDM bandwidth capacity. It can be represented in terms of a Control and Data planes. In essence, the Data Plane Structure is an overlay model with 4 layers; Fibre Optic, Link, Light path (optical) and Label Switching Path (LSP) topology (Figure 2.11).

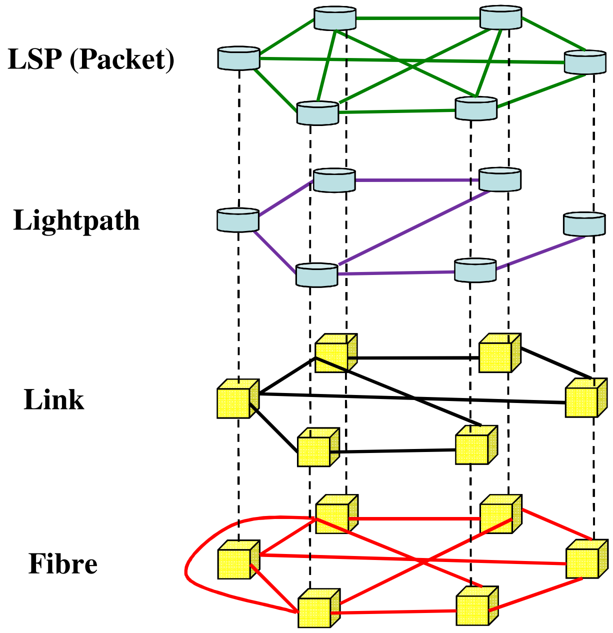


Figure 2.11: Data plane structure with overlay model.

2.5.1 IntServ

Integrated Service (IntServ) provides per-flow QoS assurances requiring resources such as bandwidth and buffering [30][31]. A flow is defined as consisting of a source IP address, destination IP address, transport protocol, source port and destination port. In this context, there is a need to provide policy control of individual flows and regulate their ability to reserve network resource [31]. IntServ describes two services that have been standardized based on RFC 1633; guaranteed services for providing real-time delivery guarantees and controlled-load service for providing low-load performance [29].

2.5.2 DiffServ

The Differentiated Services (DiffServ) standard is aimed at traffic aggregates that may not correspond to fine-grained flows [31]. In a DiffServ environment, network devices take on the responsibility for classifying packets into aggregates of desired granularity, policing traffic, and allocating static or dynamic resources to satisfy QoS requirements. DiffServ relies on administrative control of bandwidth, delay or dropping preferences, rather than per-flow signalling, to communicate service-level information to network elements. The intent is to enable a flexible definition of class-based packet handling behaviours and class-based policy control [31].

2.5.3 The Resource Reservation Protocol (RSVP)

RSVP is an IP signalling protocol for IntServ [29] as described in RFC 2205, enabling senders, receivers and routers of communication sessions (either multicast or unicast) to communicate with each other in order to set up the necessary router state. RSVP identifies a communication session through the combination of destination address, transport-layer protocol type and destination port number. Each RSVP operation only applies to packets of a particular session; therefore, every RSVP message must include details of the session to which it applies [32]. A further explanation of RSVP is provided in Appendix C.

2.5.4 Multi-Protocol Label Switching (MPLS)

MPLS is a method for forwarding packets through a network using information contained in labels attached to IP packets inserted between Layer 3 and Layer 2 headers. MPLS combines Layer 2 switching with Layer 3 routing technologies, a convergence of connection-oriented forwarding techniques and Internet Routing protocols [33][34][48]. The MPLS label consists of a short, fixed length and local significant identifier assigned to a packet and corresponds to the Forwarding Equivalence Class (FEC). Figure 2.12 depicts a MPLS labelled packet including a 20-bit Shim Header label, located in between the network and the IP headers (Table 2.3).

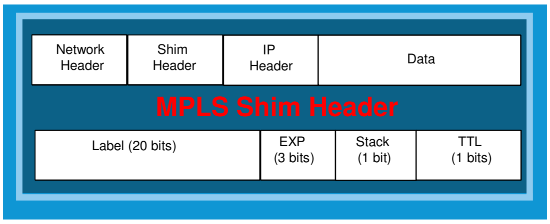


Figure 2.12: MPLS Shim Header.

Table 2.3: Contents of the MPLS Shim Header.

Field	***Bits***	***Label Description***
Label	20 bits	The MPLS label actual value.
Experiment (EXP)	3 bits	Apply to Class of Service (CoS) / Grading Services. Impact on packet queuing and discard algorithm.
Stack	1 bits	Uphold a hierarchical label stack (the last in a stack of labels).
TTL	8 bits	Time-to-live. This field is a duplicate of IP Header and accommodates similar functionality as IP TTL.

The MPLS protocol suite is illustrated in Figure 2.13.

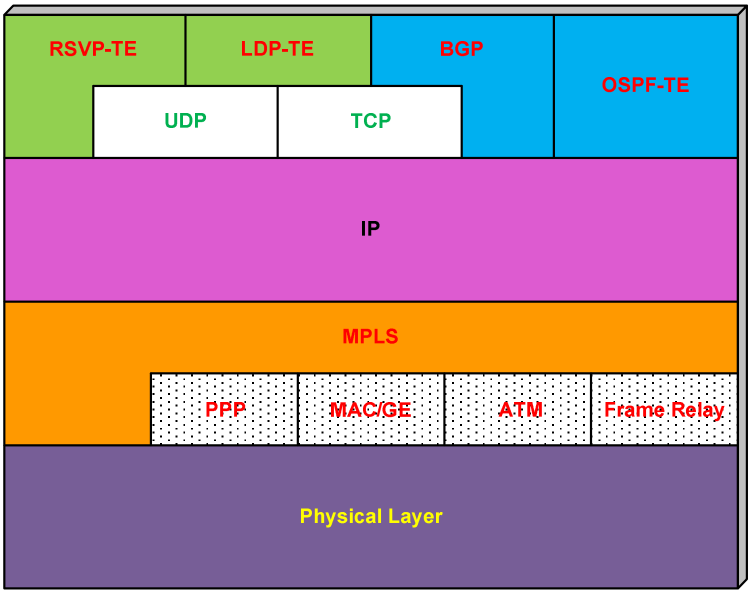


Figure 2.13: MPLS Protocol Suite.

2.5.4.1 Forwarding Equivalence Class (FEC)

The Forwarding Equivalence Class (FEC) is defined as a group of IP packets forwarded over the same path, with the same forwarding treatment [48]. The router allows packet forwarding into a finite number of disjoint subsets (FECs) and partitions the set of all possible packets. Then FEC maps all packets between the data carried in the network header, and the entries in the many-to-one Forwarding Table.

2.5.4.2 Label Switched Path (LSP)

The Label Switch Router (LSRs) uses a forwarding mechanism referred to as Label Switching [35]. Label switching relies on the setup of switched paths through the network - label switched paths (LSPs). A LSP, in the simplest case, corresponds to an IP destination prefix that appears in the forwarding tables of several routers [35]. LSPs are established using either the Resource Reservation Protocol with Traffic Engineering Extension (RSVP-TE) [35], Constraint Based Routed Label Distribution Protocol (CR-LDP) [38], Label Distribution Protocol (LDP) [38] or Multiprotocol Border Gateway Protocol (M-BGP) [48] with dedicated MPLS network traffic path. RSVP-TE dominates due to its reliability, scalability, integrated end-to-end signalling, QoS, operational significance, interoperability with IP networks and multivendor interoperability compared to others.

Consider a LSP of level *m* for a particular packet *P* as a sequence of routers, <*R1,...,Rn*> with the following properties [48]:

1. The "*LSP Ingress*" is located at a LSR R_1. It pushes a label onto *P's* label stack to yield a label stack with *m* depth.
2. Given $1 < i < n$ for all *i* such that *P's* label stack with *m* depth occurs when label is obtained from LSR *Ri*.
3. Given $t=0$, such that *P's* label stack *less than m* depth occurs when *P's* transits between LSR R_1 to LSR *R[n-1]*.
4. Given $1 < i < n$ for all *i* such that in the MPLS network, *P* label transmitted between LSR *Ri* to LSR *R[i+1]*. For instance, by using the label at the top of the label stack (the level *m* label) as an index into an Incoming Label Map (ILM) [48].
5. Given $1 < i < n$ for all *i*; Assuming that LSR *Ri* transmitted label *P* to a system *S* (data link switches), then label *P* is forwarded to LSR *R[i+1]*. Thus, *S's* forwarding decision is not based on the network header or the level *m* label, but instead depends

on the appended pushed label stack such that a level $m + k$ label where $k > 0$.Multi-Protocol Label Switching (MPLS).

2.5.4.3 Label Switch Router (LSR)

An MPLS node responsible for forwarding native Layer 3 packets and performing label distribution is known as a Label Switch Router (LSR). LSR types and operations are presented in Table 2.4, known as Edge LSR [34], ATM-LSR [33][35] and ATM edge LSR [33][35][48].

Table 2.4: LSR Types.

LSR Type	***Functions***
LSR	Labelled Packets Forwarding
Edge-LSR	1. Perform Layer 3 lookups, Next-hop IP packet forwarding, discard labels and acquire labelled packets. 2. Enforce a label stack, perform Layer 3 lookup and acquire an IP packet.
ATM-LSR	Setup ATM virtual circuits and forward ATM cells (labelled packets)
ATM edge-LSR	1. Acquire unlabelled or labelled packet (ATM cells) and forward to next-hop. 2. Accept and reassemble adjacent ATM-LSR cells to the original packet. Then, forward to next-hop as a labelled or unlabelled packet.

The edge-LSR architecture comprises an IP and label forwarding tables. Incoming IP packets are forwarded either to MPLS nodes (labelled packets) or to non-MPLS nodes (IP packets). Incoming labelled packets sent out to non-MPLS are managed through Layer 3 lookup (IP forwarding); labelled packets are forwarded to the next-hop MPLS nodes (Table 2.5).

Table 2.5: illustrates the LSR labelled packet operation.

Operation	***Function***
Pop	The stack top level extract and payload abide transmits (labelled packet or unlabelled IP packets)
Push	The stack top level substitute with labels set.
Aggregate	The stack top labels extracts and carry out Layer 3 lookup.
Swap	The stack top label substitute with other value.
Untag	The stack top label extract and forward to next hop (IP packet).

2.6 Generalized Multiprotocol Label Switching (GMPLS)

GMPLS has emerged as the Next Generation Optical Control Plane - known as Multiprotocol Lambda Switching - to support devices that perform packet switching in the time, wavelength, and space domains [37][38]. GMPLS extends the MPLS general protocol and associated protocols (OSPF Extensions, Link Bundling and Link Management Protocol – LMP [38]) to execute common control and traffic engineering through the control plane domain. GMPLS is able to manage and control multiple switching technologies and other networks such as Synchronous Optical Network (SONET) [38][39]/Synchronous Digital Hierarchy (SDH) [38][39] networks supporting Time-Division Multiplexed (TDM) links, Wavelength-Division Multiplexing (WDM) networks that provide end-to-end optical wavelength connections and optical networks for end-to-end optical fibre paths. However, the two most essential features that allow GMPLS to optimize capacity are routing and Traffic Engineering.

2.6.1 GMPLS Architecture

GMPLS switching types operate based on hierarchical LSPs. When a light path is established, a new LSP tunnels into an existing higher order LSP and sets up a new link. Hierarchical LSPs are designed and configured with flexible bandwidth levels across network devices to establish end-to-end flow. Figure 2.14 depicts the aggregation of a LSP interface hierarchy that bundles low-speed flows into higher-speed as;

1. *Fibre Switch Capable (FSC),* the highest pipe level i.e. optical fibres
2. *Lambda Switch Capable (LSC),* an intermediate pipe level i.e. All Optical Add Drop Multiplexers (ADM)/Optical Cross-connects (OXC).
3. *Time Division Multiplexing Capable (TDMC),* an intermediate pipe level i.e. SONET/SDHs/ADMs /Digital Cross-connects (DXC).
4. *Layer 2 Switch Capable (L2SC),* an intermediate pipe level i.e. Real MPLS Routers/ATM Switches/Frame Relay Switches.

5. *Packet Switch Capable (PSC),* the lowest pipe level i.e. IP Routers.

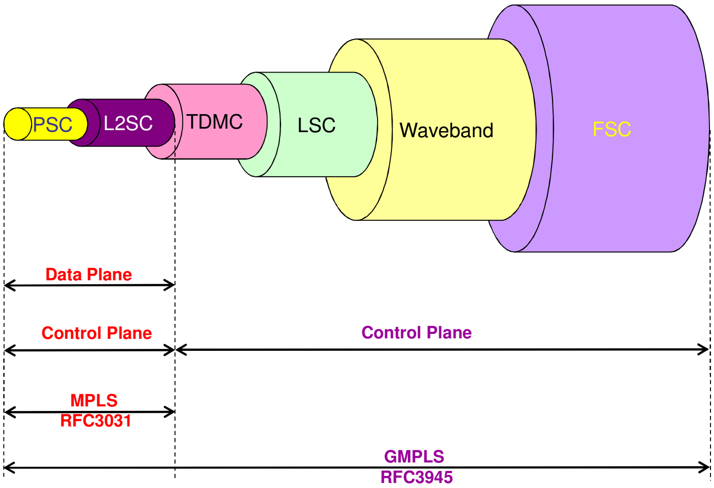


Figure 2.14: GMPLS Hierarchical LSP Pipe Levels. FSC stands for Fibre Switch Capable Interfaces i.e. PXC, OXC single or multiple fibres, Waveband – Contiguous collection of lambdas Interfaces i.e. Waveband, G.709 support optical, LSC – Lambda Switch Capable Interfaces i.e. PXC, OXC individual wavelength, TDMC – Time Division Multiplex Capable Interface i.e. SONET/SDH Cross Connect, ADM, TM, L2SC – Layer 2 Switch Capable Interfaces i.e. MPLS, ATM, Frame Relay, PSC – Packet Switch Capable Interfaces i.e. Router, MPLS.

The LSPs interface hierarchy (Figure 2.15) with different pipe levels may be nested in the following order of flow; PSC, L2SC, TDMC, and LSC into the FSC interface. GMPLS network resources are optimally utilised whilst extending system scalability.

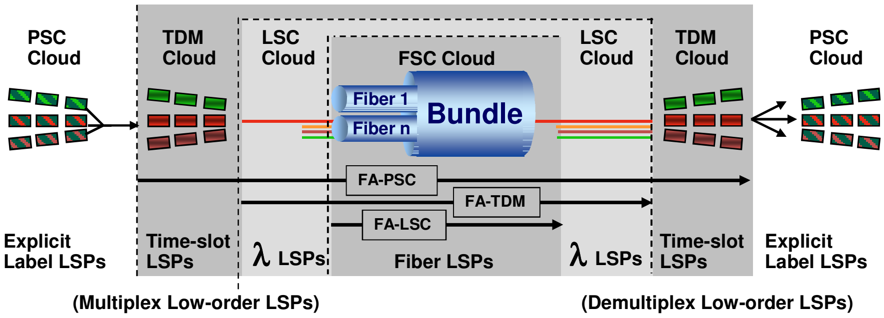


Figure 2.15: The GMPLS LSP hierarchy [36].

In respect of network control, the GMPLS suite of protocols addresses the following aspects [37];

- Topology Discovery; extended routing protocols on Open Shortest Path First (OSPF) [30] and Intermediate System to Intermediate System (IS-IS) [30] with distributed topology discovery.
- Connection Provisioning; signalling protocols are RSVP-TE [30][142] and CR-LDP [30][141] supporting an extension of SDH/SONET.
- Connection Protection and Restoration; survivability schemes based on RSVP-TE and CR-LDP signalling.
- Link Management; monitoring link property correlation, link connectivity verification, and control channel management based on the IETF Link Management Protocol (LMP) [30][37][38].

Figure 2.16 depicts the GMPLS Plane and its functions including the Management Plane (LMP – Link Management Protocol), Signalling Plane (RSVP-TE Resource Reservation Protocol Traffic Engineering), and Control Plane (Routing and Data Plane).

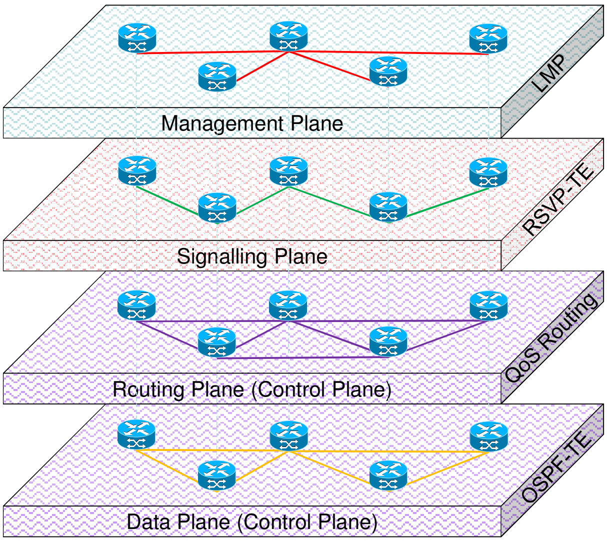


Figure 2.16: GMPLS Planes.

2.6.2 GMPLS Protocols

The three main GMPLS protocols are: signalling, routing and link management [38] (Figure 2.17). A further discussion is presented in Appendix C, explaining GMPLS standard protocols in terms of architecture and implementation. An interpretation is also provided in light of the functionality of these protocols as a platform for the simulation framework developed in this work.

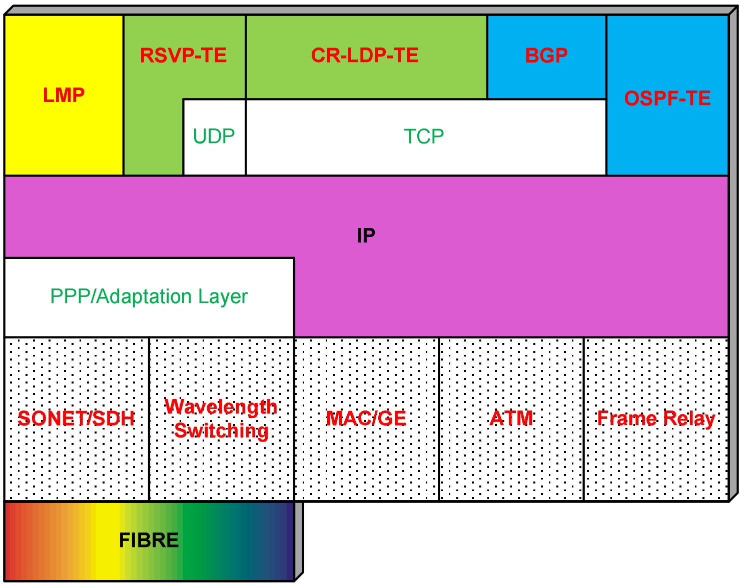


Figure 2.17: GMPLS Protocol Suite.

2.6.2.1 Signalling Protocol

GMPLS signalling is used to establish, maintain, modify and terminate LSPs or data paths between nodes. This process involves exchanges of messages within the Control Plane.

2.6.2.2 Routing Protocol

GMPLS-based WDM optical networks use routing protocols to disseminate the status and traffic carrying capacity of each wavelength (apart from reachability information). Routing in GMPLS networks are based on extensions to the link state protocols (OSPF and IS-IS).

Lifetime of paths is strongly compromised due to signal re-transmissions or link (or node) failure and routing should be able to readily find new paths to maintain connectivity and preserve QoS. Complexity becomes a critical issue and has to be minimised. Indeed, if the algorithm complexity is high, the risk is that the algorithm is not able to find usable paths, devoting all the time reacting to changes that occur dynamically in the network. Optimally, accuracy may be scarified in order to reduce computational time, using heuristic approaches [48]. Moreover, a higher computational load leads to a higher energy consumption that in turn reduces the lifetime of devices [38][48].

2.6.2.3 Link Management Protocol (LMP)

GMPLS acknowledges the fact that the Control Plane and the Data Plane are separate. Therefore, the Link Management Protocol (LMP) is introduced to manage both control and data links between neighbouring nodes. LMP is considered as a point-to-point protocol within the GMPLS domain. Four functions are implemented by LMP: control channel management, link property correlation, link connectivity verification, and link fault management. The first two functions are essential; the last two are optional [38][39].

2.6.3 MPLS and GMPLS Comparison

A comparison between MPLS and GMPLS is summarised in Table 2.6. The significant parameters for both include interfaces, connections, bandwidth allocation, propagation method, label usage, label limit, label specification, LSP payload, technology specific parameters, control channels, survivability, and LSP setup.

Table 2.6: Summary of comparison between MPLS and GMPLS[38][47][48].

Description	***MPLS***	***GMPLS***
Interfaces	Support packet/cell-based interfaces only.	Support packet/cell, TDM, lambda and fibre.
propagation method	LSP start and end on Packet/cell LSRs.	LSPs start and end on “similar type” LSRs (that is, PSC L2SC, TDM, LSC, FSC).
Bandwidth Allocation	Can be done in any number of units.	Can only be done in discrete units for some switching capabilities such as TDM, LSC and FSC.
Label Usage	Typical large number of labels.	Fewer labels are allocated when applied to bundle links.
Label Limit	No restrictions on label use by upstream nodes.	An ingress or upstream node may restrict the labels that may be used by an LSP along a single hop or the whole path. This is used, for example, to restrict the number of wavelengths that can be used in the case where optical equipment provides a small number of wavelengths.
Label Specification	Only one label format.	Use of a specific label on a specific interface. Label formats depend on the specific interface used, such as PSC, L2SC, TDM, LSC, and FSC.
LSP Payload	Labels are used for data forwarding and are carried within the traffic.	Labels are a control plane construct only in GMPLS and are not part of traffic.
Technology specific-parameters	No need for technology-specific parameters, because this is applied to packet/cell interfaces only.	Supports the inclusion of technology-specific parameters in signalling.
Control Channel	Data and control channels follow the same paths.	Separation of control and data channels.
Survivability	MPLS fast-reroute.	RSVP-specific mechanism for rapid failover (Notify message)
Establish Connection	Unidirectional LSPs	Bidirectional LSPs enable the following: • Possible resource contention when allocating reciprocal LSPs via separate signalling sessions. • Simplified failure restoration procedures. • Lower setup latency. • Lower number of messages required during setup.
LSP Setup	Labels cannot be suggested by upstream node.	Allow a label to be suggested by an upstream node and can be overwritten by a downstream node (for example, to prevent delays with setting optical mirrors)

2.7 Energy Saving in Optical IP Networks: Overview

The Optoelectronics Industry Development Association (OIDA) [1] stresses that "Green Photonics" is emerging as a vibrant technology area with a wide range of applications impacting many industries. Green photonics not only includes solid-state lighting and solar, but is growing to consider energy efficiency and heat removal in communication systems as well as environmental consequences of optoelectronics-based applications [49].

The Internet continues to support new and more advanced services. Until recently, the introduction of a new service or hardware would often be executed without consideration of its impact on the environment; such an approach is in the strongest contrast to the global drive for energy efficiency. Network infrastructures of the future must be able to support these growing needs but at the same time, the design/implementation must follow energy conservation principles.

On-going research has shown that in optical IP networks, power consumption could be reduced following concepts known as green networking [1][49]. Adhering to these principles, a novel energy saving approach is proposed with roots in "hibernation" strategies. Hibernation is designed to reduce power consumption whilst minimising the impact on network performance by taking advantage of sleep modes. A proper implementation over the network infrastructure will save energy, the operating cost to network operators, whilst delivering a reduced carbon footprint.

2.7.1 Network Energy Model Architecture

An energy profile is defined as the dependence of the energy consumption (in Watt hour, *Wh*) as a function of the traffic load or traffic throughput of a particular network component. The traffic load is expressed as a percentage of the total capacity of the network. Different energy profiles for telecommunication equipment are presented in [50] where energy consumption is a function of the load on individual network components (Figure 2.18).

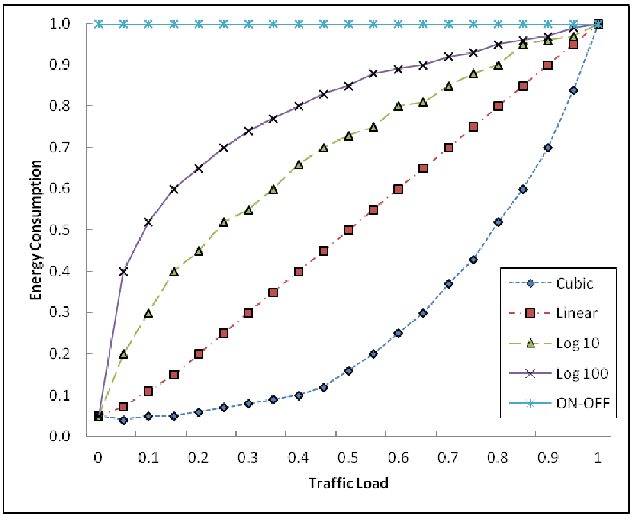


Figure 2.18: Energy profiles.

These different energy profiles can be defined [50]:

(i) *Linear*; energy consumption depends linearly on traffic load, for instance, in switch architectures like Batcher, Crossbar and Fully-Connected.

(ii) *Log10*; applied in equipment using *sleep* modes such as the low power idle technique in the Ethernet based IEEE 802.3az standard.

(iii) *Log100*; represents a ‘middle’ function between *On-Off* and *Log10* modes.

(iv) *Cubic*; corresponds to network equipment that employs energy saving techniques using Dynamic Voltage Scaling (DVS) and Dynamic Frequency Scaling (DFS).

(v) *On-Off*; represents equipment following simple two energy states, consuming full power when switched-on.

2.7.2 Network Energy Principles

Network energy saving is any process that reduces energy consumption required to perform a given task without compromising the level of performance; therefore, the aim is to minimise power consumption proportional to network utilization. Generally, the key contributors to overall network power consumption comprise equipment, capacity, demographics, service scenarios (e.g. shared services, dedicated services, real time services) and service management.

The power consumption for the network is illustrated in Figure 2.18 [51].

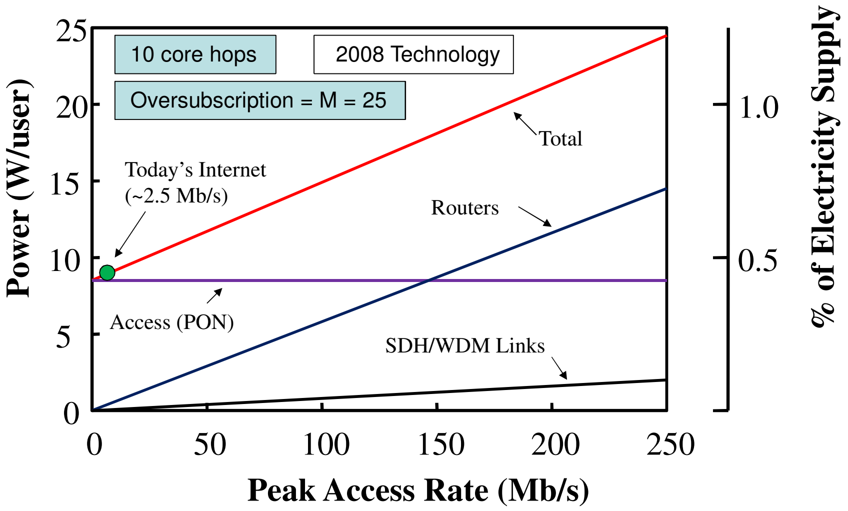


Figure 2.19: Power consumption of IP Networks [51].

The energy consumption of an access network can be estimated by;

1. Selecting an access data rate (capacity per user)
2. Calculating the power consumed by the network per user
3. Repeating for all data rates

Backhaul segments connecting access to the metropolitan layers are dimensioned by operators to provide a lower worst-case minimum transmission rate to every user, taking advantage of the bursty nature of Internet traffic. The ratio of advertised access rate to this minimum per-user rate is referred to as the over-subscription rate. Network over-subscription can be formulated as [51][52]:

$$M = \frac{Peak\ access\ rate\ sold\ to\ user}{Average\ access\ rate}$$

For instance, for Internet usage in 2008, the peak access rate sold to users was estimated to be 2.5 Mbps while the average access rate was 0.1 Mbps. Therefore, oversubscription, M was;

$$M = \frac{2.5\ Mbps}{0.1\ Mbps} = 25 \qquad (1.1)$$

2.7.3 Energy per Bit

The energy per bit consumed by the node is defined as:

$$E_b = \frac{P_T}{C} \qquad (1.2)$$

where P_T represents the node total power consumption in Watts and C is the bandwidth offered by the link in bits per second. Therefore, this energy unit is expressed in terms of joules per bits (J/b) or watts per bit per second (W/b/s).

2.7.4 Power Consumption and Traffic Load

Power Consumption of network equipment is defined as:

$$P = E_b \times C \tag{1.3}$$

where

P is power consumption of network equipment in Watts (W).

E_b is energy per bit of network equipment in Joules (J).

C is network link capacity in bits per second (b/s).

The unit measurement of power (P) per transported bit rate (data traffic) is in Watts; this metric considers peak power consumption of network equipment as a function of traffic or peak power usage per transmitted bit rate.

The elements that determine energy and power consumption for core networks include traffic load, transport volume per unit time, network architecture, topology, resilience, network survivability such as recovery techniques (protection, restoration and pre-allocated restoration), usage behaviour and temporal parallel operation of network segments.

Typical data on power consumption of main terrestrial network equipment in Core, Metro and Access layers is shown in Table 2.7 and for the main submarine/undersea network equipment in Table 2.8. A typical submarine/undersea network is illustrated in Figure 2.20.

Table 2.7: Typical Power Consumption Data of Different Terrestrial System Network Equipment from Various Networking Vendors.

Network Domain	Network Equipment	Capacity	Estimate		Power Consumption
			Heat Dissipation (Heat Flow Rate)	Energy per Bit	
Core Network	Core Router (Cisco CRS-3 Multi-Chassis System)	322 Tbps	34130 Btu/h	0.0311nJ	10 kW [53]
	Core Router (Juniper Networks TX Matrix Plus)	6.4 Tbps	43516 Btu/h	1.99 nJ	12.75 kW [54]
	Optoelectronic Switch (Alcatel-Lucent 1870 Transport Tera Switch)	4 Tbps	27304 Btu/h	2nJ	8 kW [55]
	Packet Optical Switching (Ciena 5410 Reconfigurable Switching System)	1.2 Tbps	9215 Btu/h	2.25 nJ	2.7 kW [56]
	Core WDM (Alcatel-Lucent 1830 PSS-64 Photonic Service Switch)	2 Tbps	13652 Btu/h	2 nJ	4 kW or 2 W/Gb/s [55]
	Optical Cross-Connect (MRV OXC)	N/A	778 Btu/h	N/A	228 W [57]
	SDH/SONET (Fujitsu Flaswave 9500 Packet Optical Switching)	480 Gbps	14540 Btu/h	8.875 nJ	4.26 kW [58]
	WDM Transport System (Fujitsu Flashwave 7500)	1.6 Tbps	1228 Btu/h	0.000225 nJ	360 W [58]
	WDM Transponder (ADVA Optical/Movaz FSP 3000)	80 Gbps	683 Btu/h	2.5 nJ	200 W [59]
	EDFA (Cisco ONS 15501 EDFA)	N/A	27 Btu/h	N/A	8 W [53]
	EDFA (MRV LamdaDriver EDFA EM800-OAx)	N/A	11 Btu/h	N/A	3.3 W [57]
	EDFA (Optilab EDFA-LC)	N/A	5 Btu/h	N/A	1.4 W [60]
Metro Network	Edge Router (Juniper M320 Multiservice Edge Router)	320 Gbps	11946 Btu/h	10.9375 nJ	3.5 kW [54]
	Edge Router (Cisco XR 12416 Router)	320 Gbps	14372 Btu/h	13.1625 nJ	4.212 kW [53]
	WDM (NEC TM-3000 Metro WDM 17 Slots)	800 Gbps	2389 Btu/h	0.000875 nJ	700 W [61]
	Metro WDM (Cisco ONS 15530 DWDM Multiservice Aggregation Platform)	320 Gbps	410 Btu/h	0.000375 nJ	120 W [53]
	Metro WDM (Alcatel-Lucent 1696 Metrospan)	320 Gbps	1365 Btu/h	1.25 nJ	400 W [55]
	Metro SDH/WDM (Ericsson SPO 1410)	80 Gbps	512 Btu/h	1.875 nJ	150 W[62]
	Ethernet Switch (Cisco 6513-E Chassis 13-Slot Modular)	720 Gbps	13652 Btu/h	5.56 nJ	4 kW [53]
Access Network	Optical Line Terminal (NEC ME2200 Carrier Grade Optical Access FTTx)	48 Gbps	1563 Btu/h	0.009542 nJ	458 W [61]
	Optical Line Terminal (Fujitsu FA2232U GE-PON)	1 Gbps	1365 Btu/h	0.4 nJ	400 W [58]
	Optical Network Unit (NEC ONU 2004i GE-PON)	1 Gbps	20 Btu/h	0.003 nJ	6 W [61]
	Ethernet Switch (Cisco Catalyst 4503 Switch)	48 Gbps	1568 Btu/h	27.1 nJ	1.3 kW [53]
	Optical Network Terminal (Cisco Prisma D-PON ONT FTTH)	1 Gbps	20 Btu/h	0.003 nJ	6 W[53]
	Optical Network Terminal (Zhone zNID-GPON-2424)	1 Gbps	51 Btu/h	15 nJ	15 W [63]
	Optical Network Unit (Fujitsu FA2132 GE-PON)	1 Gbps	27 Btu/h	0.008 nJ	8 W [58]

Table 2.8: Typical Power Consumption Data of Different Submarine/Undersea System Network Equipment from Various Optical Networking Vendors.

Network Domain	Network Equipment	Capacity	Estimate		Power Consumption
			Heat Dissipation (Heat Flow Rate)	Energy per Bit	
Terminal Station Equipment	WDM Submarine Line Terminal Equipment (Fujitsu Flashwave S850)	320Gbps	51195 Btu/h	46.88 nJ	15 kW [58]
	Submarine Line Terminal Equipment (Huawei Marine OptiX BWS 1600S)	1.28 Tbps	6826 Btu/h	1.56 nJ	2 kW [64]
	Power Feeding Equipment (NEC NRF Series with DC voltages 15kV and current 1.6Amp)	N/A	81912 Btu/h	N/A	24 kW [61]
Submersible Plant	Branching Unit (Alcatel-Lucent BU (400 VDC; 1Amp) for a 5000 km at up to 8000m water depth)	N/A	1365 Btu/h	N/A	400 W [55][65]
	EDFA Submarine Repeater (Alcatel-Lucent OAL Repeater (400 VDC; 300mA) for a 5000 km at up to 8000m water depth)	N/A	410 Btu/h	N/A	120 W [55][65]
	EDFA Submarine Repeater (NEC R640SW (400 VDC; 0.5A) up to 8000m water depth)	N/A	683 Btu/h	N/A	200 W [61]
Observatory Network	Science Node (Alcatel)	2.5 Gbps	34130 Btu/h	4000 nJ	10 kW [55][65][66]
	Electrical Power Converter (Alcatel)	N/A	3413 Btu/h	N/A	1 kW [55][65][66]

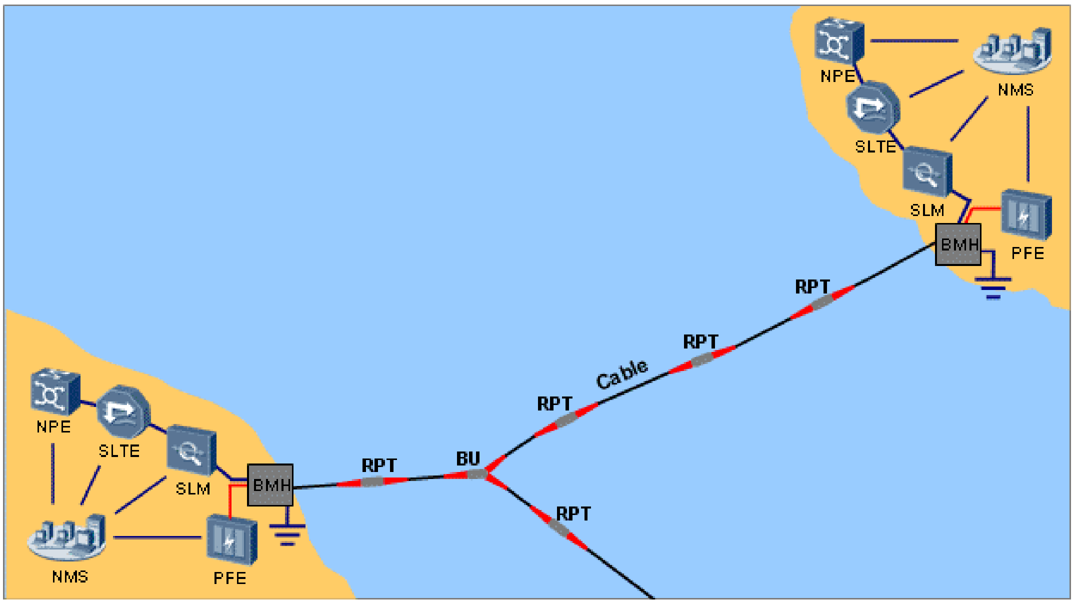


Figure 2.20: An example of the repeatered Submarine Cable Systems. NPE stands for Network Protection Equipment. SLTE is Submarine Line Terminal Equipment. SLM denotes Submarine Line Monitor. NMS represents Network Management System. PFE is Power Feeding Equipment. BMH represents 'Bach Man-Hole'. RPT is Repeater and BU denotes Branching Unit [64].

2.7.5 Energy Efficiency

In the core network, energy efficiency can be defined as [51][68]:

$$\frac{P_R}{C_R} = \frac{P_0}{C_0}(1-\alpha)^t \tag{1.4}$$

where time-dependent parameters are given by;

P_R is power consumption of router efficiency in *t* years [51]

C_R is capacity of router efficiency in *t* years [51]

P_0 is power consumption of router.

C_0 is capacity of router.

α is the annual rate of improvement (20%) of state-of-the-art technology [51][68].

Energy efficiency can be evaluated based on system capacity [61] as is shown in Table 2.9. The *throughput* is defined as the rate of successful data or message delivery flowing through the network (physical or logical link) and is measured in bits per second (bit/s). *'Goodput'* represents the number of actual useful bits per unit of time (omitting the overhead and re-transmitted data packets), determined as the ratio of the delivered data payload to the transmission time [51][61][68].

Table 2.9: Energy efficiency in optical IP networks. η is energy efficiency (Joule per bit). P_T represents Total system power (in Watt). C represents system capacity (in bits/second). γ is system throughput (in bits/second). G is system goodput (in bits/second).

Energy Efficiency (η)	**Formulae**
Measurement based on **Capacity**	$\eta_C = \frac{P_T}{C}$
Measurement based on **Throughput** (aggregate)	$\eta_\gamma = \frac{P_T}{\gamma}$
Measurement based on **Goodput** (actual useful bits)	$\eta_G = \frac{P_T}{G}$

2.7.6 Power Consumption in Electronic and Optical Network Elements

Energy efficiency can be determined through a four level segmentation under components, transmission, network and application.

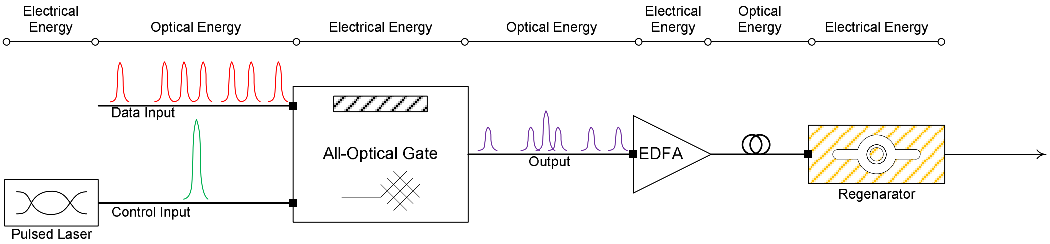


Figure 2.21: An example of total electrical power consumption in an all-optical switching gate.

Figure 2.21 shows the electrical power consumption in an all-optical switching device [70].

- **Power-aware Optical:**
    1. The optical fibre is a nonlinear medium and as a transparent all-optical pipe, no signal transformation or reshaping at intermediate nodes occurs; thus noise and signal distortions owing to non-ideal transmission devices are accumulated along the physical path. The Optical Signal to Noise Ratio (OSNR) is as a consequence considerably decreased, resulting in a compromised Bit Error Rates (BERs) [71]. Likewise, signal distortion and optical impairments managed by GMPLS Routing using a particular cost metric to determine paths must consider transmission quality (noise and propagation delay). Resources consist of wavelengths and transmitters.
    2. The power penalty for all-optical communications must be considered when high speed multimedia services are transmitted, an integrated architecture where no interfaces are needed between the IP and optical layer and where cross-layers schemes are simplified [16][71].
    3. Power degradation may lead to compromised network performance and utilisation. In optical networking, the major contribution to power consumption stems from the electronic elements, optical elements and path computation elements. Table 2.10 lists these elements and their influence on power consumption.

- **Electronic Elements:**
    - i. All-optical networks consist of an interconnection of wavelength-routed nodes comprising components such as taps, input/output amplifiers, multiplexers, and cross-connects. Previous work [64], recommends that the Network Processor should adopt a configuration that includes;
        - a) Functional Power: the Network Processor must be able to perform the required functional tasks associated with the targeted environment e.g. process packet or cells by implementing IPv4, IPv6, MPLS, GMPLS etc.

b) Electrical Power Dissipation: the Network Processor must not consume an excessive amount of power. Limitations are associated with the individual router line card on which the Network Processor resides and extends to power constraints on racks and cabinet containing such line cards.

Table 2.10: Power consumption in optical networking and electronic elements.

Medium	**Element**	**Power Degradation Parameters**
Electronics	Network Processor (CPU)	Power Consumption, ALU Power, Clock Power, Register File Power, Cache Power
	Ternary Content Address Memory (TCAM)	Dynamic Power Consumption
	Power Supply	Power Level
	Optical Line Card/Module	Memory and I/O Bus Power
	Multi-processor on chip (MPSoC)	Interconnect Network Power Consumption
Optical	Transmitter	Power level, bit ratio
	Receiver	Bandwidth multiplication noise, Thermal noise
	Wavelength multiplexer-de-multiplexer	Power attenuation, crosstalk
	Wavelength cross-connect	Power attenuation, cross-talk
	Amplifier (EDFA)	Power gain, noise (ASE)
	Dispersion-compensating module (DCM)	Power attenuation, dispersion compensation
	Fibre	Power attenuation, dispersion, non-linearities

- **Energy-Aware Optical IP Networks:**
  i. The Service Provider uses equipment that consumes significant energy. In order to reduce costs, the provider needs to find a solution that promotes low energy operation through lightweight routing algorithms that manage dynamic traffic patterns. Energy consumption associated with route request processing advocates the minimization of route requests by allocating

dynamic route expiry times. An energy-efficient routing mechanism would mean longer optical device lifetimes and higher network efficiencies [65].

ii. The maximum acceptable Bit Error Rate (BER) determines the minimum power of an optical signal at the receiver. Other physical impairments, like optical fibre non-linearity, are more complex to treat and are not included in this work. However, when the maximum power used in every component of the network is controlled, fibre non-linearities are indirectly managed due to their dependence on the signal power [64][65].

iii. The minimum power constraint (sensitivity) assures that optical data can be recovered by receivers. The maximum power constraint governs the onset of non-linear physical impairments, because it limits the aggregate power on a link to a maximum value (Figure 2.22) (Table 2.11).

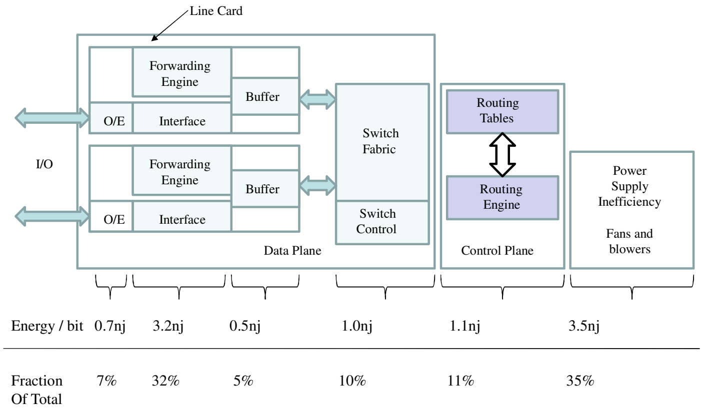


Figure 2.22: Energy per bit in Cisco Systems® High-End Router block diagram (2007).

Table 2.11: Total segment of energy consumption in Cisco Systems high-end Router.

Mechanism	***Router Components***	***Energy per Bit***	***Total Segment***
Data Plane	Optical/Electrical Converter	0.7nJ	7%
	Forwarding Engine, Interface	3.2nJ	32%
	Buffer	0.5nJ	5%
	Switch Fabric, Switch Control	1.0nJ	10%

Control Plane	Routing Tables, Routing Engine	1.1nJ	11%
Source	Power supply inefficiency fans and blowers	3.5nJ	35%

- **Power Consumption in Network Processor and Electronic-Optical Components:**
  1. The network processor executes control plane functions including connection setup/tear-down, forwarding table updates, register/buffer management, exception handing, IP-address lookup, packet classification and packet modification. It performs at the line rate using external memory such as static RAMs, DRAM or content addressable memory (CAM) [74][102]. Network processors are considered the fundamental part of routers and other network equipment.
  2. Whether it is a classic problem such as IP-lookup, or an emerging domain, many network algorithms require the ability to index and search large amounts of states with incredibly high throughput. While there is a great deal of work on advanced algorithms to speed the search through this state with traditional memories, the complexities of implementation motivate a memory design that directly supports the search primitives. CAM provides the required search capabilities with a minimum of additional cost and complexity [98][102].
  3. The fully parallel search provided by Ternary Content Address Memory (TCAM) [74][98] eases the implementation of many complex operations such as routing table lookup. Because TCAM searches every location in memory at once, the ordering of the elements in the TCAM is less important and large indexing structures can often be entirely avoided. This parallel search directly implements the requirements of some applications (such as IP-lookup), and can serve as the building block of more complex search schemes. TCAM is also used in other high-speed networking applications such as packet classification, access-list control, and pattern matching for

intrusion detection. TCAM is also being used as a co-processor to complement the main processor in several applications such as packet classification and routing lookup. In the power constrained situations that most high performance routers operate in, these searches can, if un-optimized, consume tens or hundreds of Watts. Some previous work has addressed the issue of power consumption of network processors; however they do not account for the TCAM power consumption in their framework [74][98].

2.7.7 Green Networking and Carbon Footprint Standards

Energy efficiency standards are a set of procedures, guidelines, recommendations, policies, and best practices that capture the energy performance compliance of manufactured products [67][94]. Various standardization bodies, pre-standardization forums and governments integrated their activities on energy efficiency issues; these include the European Telecommunication Standard Institute (ETSI), International Telecommunication Union (ITU), the Institute of Electrical and Electronics Engineers (IEEE), Telecommunication Industry Association (TIA), Alliance for Telecommunications Industry Solutions (ATIS), Energy Consumption Rating Initiative (ECR), Home Gateway Initiative (HGI), Internet Engineering Task Force (IETF), ENERGY STAR (a joint program of the U.S. Environmental Protection Agency and the U.S. Department of Energy) [75][76][77][78][79][80][81][82][83][84][85][86][87][88].

The standardization on energy saving compliance of networks or equipment is based mainly on regional (area continent), government policies/initiative, type of equipment and network domain. A summary of standardization activities for energy efficiency on wired networks is shown in Table 2.12, Table 2.13 and Table 2.14.

Table 2.12: Energy-Efficiency Standardization Activities related to Telecommunications Infrastructure.

Category	**Standardization**	**Compliance / Activities**	**Domain/Scope**	**Approach**
Telecom Room	ENERGY STAR Data Centre Energy Efficiency Initiatives	Recommendation for measuring and reporting overall Data Centre Efficiency	Access Network/Data Centre	[75]
	ENERGY STAR Storage Draft 2 Version 1 Specification	ENERGY STAR Program requirements for Data Centre Storage	Access Network/Data Centre NAS	[75]
	EU Codes of Conduct	European code of conduct on Data Centre Energy Efficiency	Metro Network / Data Centre	[76]
Environmental / Thermal Management	ETSI EN 300 019	Classification/Environmental conditions and tests	Equipment Engineering	[77]
	ETSI TR 102 489	Thermal management guidance for equipment and its deployment	Equipment Practice	[77]
Cabling Management / Cabinets/Racks	ETSI EN 300 119-3	Engineering Requirements for miscellaneous racks and cabinets.	Equipment Practice	[77]
	ETSI TR 102 489	Thermal management guidance for equipment and its deployment	Equipment Practice	[77]
	EN 50173-5:2007:A1:201X (pr=21329)	CENELEC CLC/TC 215 Information Technology – Generic Cabling systems – Part 5: Data Centre	Electrotechnical aspects of telecommunication equipment	[78]
Electrical Systems	ETSI EN 132-3	Power Supply Interface at the input to telecommunications and datacom (ICT) equipments	Power Source up to 400 V	[77]
	ETSI TR 102 532	The use of alternative energy solutions in telecommunications installations	Power source	[77]
	ETSI TR 102 614	Reverse powering of access network unit by end-user equipment: A4 interface	Access Network	[77]
	EU Codes of Conduct	EU code of conduct on energy efficiency and quality of AC Uninterrupted Power Supply (UPS)	Power Source	[76]

Table 2.13: Energy-Efficiency Standardization Activities related to Telecommunications Commissioning.

Category	**Standardization**	**Compliance / Activities**	**Domain/Scope**	**Approach**
Measurement / Test Method	ETSI TS 102 533	Measurement methods and limits for energy consumption in Broadband Telecommunication networks equipment	Access Network	[77]
	ENERGY STAR Draft 4 Rev. Feb-2011 Data Collection	Energy Star: Test Method for Small Network Equipment	Access Network	Link Rate [75]
	ECR Specification v3.0.1	Network and Telecom Equipment – Energy and Performance Assessment: Metrics, Test Procedure and Measurement Methodology	Core Network	[79]
	ATIS-0600015.02.2009	Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting – Transport Requirements	Metro Network	[80]
	ATIS-0600015.03.2009	Energy Efficiency for Telecommunication Equipment: Methodology for Measurement and Reporting for Router and Ethernet Switch	Metro Network	[80]
	VZ.TPR.9207 Issue 1	Verizon NEBS Compliance: TEEER Metric Quantification	Core Network	[81]
	WT-189	An energy efficiency test plan for network equipment	Core/Metro/Access Network	[82]
	WT-190	An energy efficiency test plan for end user equipment	Access Network	[82]
Operation & Maintenance	IETF draft-okamoto-ccamp-midori-gmpls-extension-reqs-00	Requirements of GMPLS Extensions for Energy Efficient Traffic Engineering	Core Network / Control Plane	[83]
Management	IETF draft-quittek-eman-reference-model-03	Reference Model for Energy Management	Core/Metro/Access Network (Router/Switch)	[84]
	IETF draft-ietf-eman-requirements-05	Requirements for Energy Management	Core/Metro/Access Network (Router/Switch)	[85]
	IETF draft-ietf-eman-framework-03	Energy Management Framework	Core/Metro/Access Network (Router/Switch)	[86]

Table 2.14: Energy-Efficiency Standardization Activities related to Telecommunications Environmental Aspects.

Category	Standardization	Compliance / Activities	Domain/Scope	Approach
Carbon Footprint	IEA Energy Efficiency	Energy efficiency policy and carbon pricing	Information	[87]
	MR-204 Issue 1	Energy Efficiency, Dematerialization and The Role of the Broadband Forum	Core/Metro/Access Network	[82]
Greenhouse Gases (GHG) emissions	ITU-T Rec A.7 (10/2008) in conjunction with FG ICT&CC	Focus group on ICTs and Climate Change in particular to production of Greenhouse Gases (GHG) (e.g. power consumption, proliferation of ICT devices, recycling material, etc)	Information	[88]

2.7.7.1 Carbon Footprint Formulation

According to 'The UK Carbon Trust' [72], the term carbon footprint is defined as the total greenhouse gas (GHG) emissions caused by an organization, event, product or person [89]. An example calculation of GHG emissions for a specific element embodies a ratio modelling approach [89]. A small chassis router of typical active power consumption of 100 W at 24 x 7 utilization, and life expectancy of 7 years is calculated as follows;

Step 1: Calculate the router's use phase GHG emissions:

E_{use} = 100 W x 8760 hrs/yr x 7 yrs x 1 kwh/1000 Wh x 0.537 kg CO_2e/kWh*

= 3293 kg CO_2e

*GHG conversion factor for appropriate region of use.

Step 2: Estimate the router's embodied-phase GHG emissions using historical Life Cycle Assessment (LCA) data showing the LCA ratio for use / embodied emissions for router is 80% / 20% [89].

$E_{emb} : E_{use} = 20\% : 80\% = 3293$ kg CO_2e x $(20\% / 80\%) = 823$ kg CO_2e

$E_{emb} = 823$ kg CO_2e

Note that full life cycle GHG emissions can also be estimated as $E_{use} + E_{emb} = 4116$ kg CO_2e.

2.7.8 Thermal Analysis in Optical IP Networks

The ICT products heat density chart [90] provides a general overview of the power consumed and heat dissipated by data processing and telecommunication equipment (Figure 2.23). The 1992 – 2014 rate of increase for heat density ranges from a low of 7% annually for tape storage to a high of 28% annually for communications equipment. All product family trends show an abrupt downward shift to 5% in the annual rate of rise starting in 2006 and continuing through 2014, when the semiconductor Industry Association's Roadmap for Semiconductors [90] is predicting a levelling off in semiconductor power consumption. The rate of increase for communications equipment was 13% annually from 1992 through 1998, at which time it increased to 28% annually. This was projected to continue through 2005 when all product families dropped to 5% annually. This drop is also manifest in the 2005 projections. The increase in heat dissipation from 2000 to 2001 alone is 500 watts/ft^2 -product (5500 watts/m^2 -product) [90].

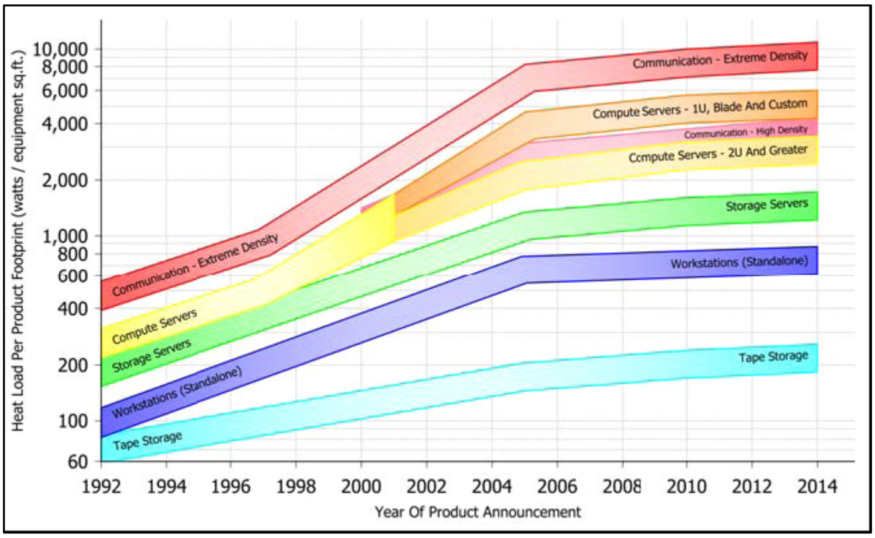


Figure 2.23: Heat Load and air cooling limit on ICT equipments [90].

2.7.8.1 Heat Dissipation

Heat dissipation (Heat transfer rate) is calculated based upon the power supply rating of the network equipment. The Heat flow rate (Q) needed to dissipate the generated heat is defined as [83]:

$$\dot{Q} = \frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x} \tag{1.5}$$

where Q is the total energy transferred in the form of heat, ΔT is surface temperature change of the equipment measured in (^{o}F), x is the distance of the heat flow, k is a heat transfer coefficient (W/(m^{2}K)) and A is a heat transferring surface area (m^2).

2.7.8.2 Heat Transfer Rate in Core Networks

For optical IP networks, the energy conversion factor in relation to heat flow rate ($\dot{Q}$) and heat transfer rate (W), can be written as [91]:

$$\dot{Q} = 1\,\text{kW} = 3413\,\text{Btu/ h} \tag{1.6}$$

where *Btu* is the British thermal unit defined as the amount of heat that raises 1 lbm (pound-mass) of water by 1°F [91]. *Btu/h* is the British thermal unit per hour and can be converted into electrical energy (1kW = 3413 Btu/h = 3.6 x 10^6 J/h [91]) as is customary in optical IP networks.

For example, a core WDM Transport System (Fujitsu Flashwave 7500) with capacity 1.6 Tb/s produces a power consumption of 360 W [58]. Thus, the heat dissipation (Heat Transfer Flow) for this core WDM is 1228 Btu/h.

Figure 2.24 shows the heat flow rate in the Core Router as function of average throughput and energy per bit. For instance, a core router with capacity 1 Tb/s consumes 10 kW of power [51][53]; the estimated heat dissipation is 34130 Btu/h and energy consumption is 10nJ per bit. A next generation core router with capacity 1 Pb/s is predicted to consume 1MW. Thus, the future heat transfer rate will be 3413000 Btu/h, 100 times higher than the 1Tb/s router and the energy consumption will rise to 1nJ per bit, 10 times less energy efficient.

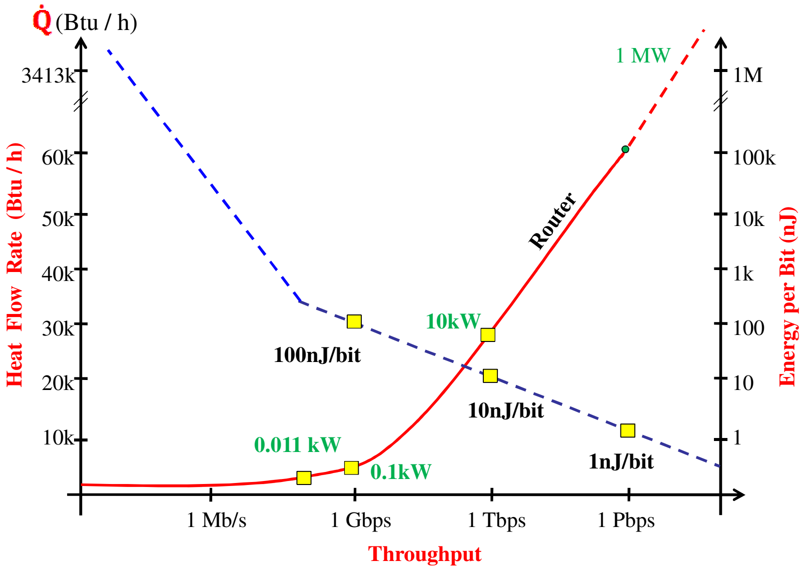


Figure 2.24: Heat flow rate in GMPLS router as a function of throughput and energy per bit.

2.7.8.3 An Absolute Energy Metric Efficiency

Another feature of thermal analysis in energy conservation is the absolute energy efficiency metric as reported in [92][93]. Noting the standard noise figure definition NF = $10\log_{10}(N)$ as in NkTB (where B is the measurement bandwidth), the absolute energy efficiency figure dB_ε is then given by;

$$\mathrm{dB}_\varepsilon = 10\log_{10}\left(\frac{\text{Power/Bit Rate}}{kT\ln 2}\right) \tag{1.7}$$

where

$kT\ln 2$ is the absolute minimum energy per bit dissipated;

k is the Boltzmann constant 1.381 x 10^{-23} J/K;

T represents the absolute temperature of the medium in Kelvin.

Note that the dB_ε metric is in terms of absolute temperature (in Kelvin), independent of the properties of any particular material and based on fundamental of classical thermodynamic efficiency (Carnot's Law). In the following analyses it is assumed that operation of network equipment is at room temperature viz. 300 K or 26.85 °C [92][93].

Example: 10 Gb/s Transmission System.

A point-to-point 10 Gb/s transmission system requires ~10 W of power. At absolute temperature of T = 300 K, its absolute energy efficiency, using Power = 10 W and Bit Rate = 10 x 10^9 b/s, is 115.4 dB_ε.

Example: Core Router

A Core Router with capacity 1Tb/s consumes 10 kW. At 300 K, the absolute energy efficiency figure of such a core router is 125.4 dB_{ε}, 10 times less energy efficient than the 10 Gb/s system of the previous example.

2.7.9 Energy Saving Techniques in Optical IP Networks

Energy conservation techniques within optical IP networks can be categorize into several classes based on the network domain (Table 2.15). In general, the criteria for classifying the energy saving approach depends on the type of equipment (electronic/optical elements), traffic patterns, routing, wavelengths assignments, control plane, data plane and energy algorithms deployed in the network domain. Approaches used are re-engineering, sleep modes, green routing, traffic engineering, energy efficient packet forwarding, time-aware energy optimization, direct light path, power sharing, traffic grooming, renewable energy, heuristic (MILP), dynamic adaptation, Routing and Wavelength Assignments [51][70][83][109][116][117][118][121][123][125][126].

Table 2.15: Summary of Energy Saving Techniques.

Energy Saving		***Network Domain***		
Technique	***Scheme***	***Core***	***Metro***	***Access***
Re-Engineering (hardware)	Energy Efficient Silicon	Ultra-low Power Design. CMOS, SOA. [51][70][94][95][96][97]	Low Power Design. CMOS. [51][94][98]	Low Power Design. Smart embedded processor. [51][52][99][100][101][102]
	Complexity Reduction	System Level Abstraction. [68][70][95][96][103][104][105][106]	System Level Abstraction. [96]	Burst Mode laser drivers; Optical Noise Reuse. [18][100][108]
Sleep Mode	Standby Primitives	Selective ON/OFF: Unused Line Cards / ports. [51][67][94][109][110].	Selective ON/OFF: Unused Line Cards / ports. [104][111][112]	Selective Nodes ON/OFF; OLT/ONU: Dozing, Power Shedding, Fast Tx-Rx ON/OFF, Deep Tx/Rx OFF. [100][113][114]
	Smart / Automated Sleep	GMPLS: sleeping the optical link only. [83][115]	WDM: sleeping the optical links only. [116][117]	N/A
		Sleeping the unused functionalities (group, wavelength). [118]	N/A	N/A
Green Routing	Energy aware routing	Chassis reconfiguration optimization. [109]	N/A	N/A
	Green OSPF Routing	Modification of OSPF protocol. [119]	Modification of OSPF protocol. [119]	N/A
Traffic Engineering (TE)	Dynamic Topology Optimization	The topologies with lower overall power consumption. [83][104]	Energy Aware Traffic Engineering. [111]	N/A
	Multilayer TE	Simple down-scaling of equipment power requirements approach and improvement on routers architecture and line cards approach. [120]	N/A	N/A
Green Provisioning	Power aware provisioning	Optical bypass (direct lightpath). [121][122]	N/A	N/A
Energy Efficient Packet Forwarding	IP Packet Forwarding	Energy consumption by transfer the smaller IP Packets. [67]	N/A	N/A
	Pipeline Forwarding	Time-Driven Switching. [70]	N/A	N/A
Time aware Energy Optimization	Scheduler	N/A	Daily / Activity Traffic Load Variation. [117]	Daily / Activity Traffic Load Variation. [117]
Power Sharing	Optical packet switching	Shared-per-wavelength. Service Disruption Blocking. [123][125]	Power sharing blocking. Nonlinear Impact Blocking. [123][125]	N/A
Traffic Grooming	(IP/WDM)	N/A	Waveband. [123]	
Renewable Energy	Solar	Heuristic. [124]	Adaptive Link. [124]	N/A
Heuristic (MILP) Approach	Optical bypass (direct light path)	Reconfiguration WDM. [116][123]	Waveband Granularity. [123]	N/A
Routing and Wavelength Assignment	(IP/WDM)	Optical bypass (Direct Light path and non-bypass); Max Disjoint Path Pair; Max Power Saving Factor; Most Amplifier; Path: least and most cost; Path Computation Element. [116][121][125][126]	N/A	N/A
Dynamic Adaptation	Adaptive Network (different line rate)	N/A	Traffic Load Adaptive Link Rate. [107][111]	Adaptive Link Rate. [107]
	Traffic Load / Volume	N/A	Idle Logic (Busy State/ idle State). [107][111]	Reduce Load: Dynamic bandwidth allocation. [107]
	Performance Scaling	N/A	N/A	Dynamic Voltage Scaling. [127]
		N/A	N/A	Frequency Scaling. [127]

2.7.9.1 Core/Backbone Networks

Based on the data presented in Table 2.7 and Table 2.8, the main contributors to energy consumption in core networks are switching and network transmission equipment such as routers, OXCs, EDFAs and transponders. In the core network, continuous operation is critical (24 hours x 7 days uptime) sensitive to downtime and follows several critical operational constraints such as network reliability, availability, Service Level Agreements (SLAs), robustness (mesh topology), routing and traffic engineering issues, network performance and bandwidth. Thus, studies of energy efficiency in the core network have been developed taking into consideration these criteria and can be classified as follows:

- Re-engineering (hardware); energy efficient silicon and complexity reduction schemes [51][68][70][94][95][96][97][103][104][105][106].
- Sleep mode; includes standby primitives and smart/automated sleep schemes [51][67][83][109][110][115][118].
- Green routing; encompassing energy aware routing and green OSPF routing schemes [109][119].
- Traffic engineering; focusing on dynamic topology optimization schemes [83][104][120][121][122].
- Energy efficient packet forwarding; optimisation of IP packet forwarding and pipeline forwarding schemes [67][70].
- Renewable energy; emphasis on alternative energy sources such as solar [124].
- Power sharing; taking advantage of power saving of shared-per-wavelength scheme by utilizing a large number of wavelength converters in the OXCs [123].
- Heuristic (ILP) approach; optical bypass schemes in IP over WDM [116][121][123][125][126].

2.7.9.2 Metro/Transport/Edge Networks

Of equal importance as the core is the metro layer, most readily segmented into three types of implementations viz. SDH/SONET network [41], Optical WDM ring [41] and Metro Ethernet [47]. These infrastructures are deployed depending on the extent of the metropolitan areas and high demand bandwidth capacity areas such as connections to regions or states, main businesses and industrial areas.

Optical Add-Drop Multiplexers (OADM) used to manage optical signals in WDM metro ring networks, is a major contributor to energy consumption. SDH/SONET ring architectures are also widely deployed in metro networks, aggregating low bit-rate traffic to high-bandwidth pipes in the core [45]. Table 2.7 summarises the power consumption within the metro networks and can be classified as follows:

- Re-engineering (hardware);
- Sleep modes including the standby primitive scheme.
- Green routing; encompassing green routing schemes.
- Time-aware energy optimization based on a scheduler scheme.
- Renewable energy; alternative sources of energy such as solar.
- Heuristic (ILP) approach; optical bypass scheme using link granularity.
- Dynamic adaptation of traffic load or volume.

2.7.9.3 Access Networks

According to [107], access networks are responsible for ~70% of the overall Internet energy consumption since most of the equipment comprise electronics components within fixed wired and wireless network implementations such as Passive Optical Network (PON) [12][100][113][114], Digital Subscriber Line (xDSL) [100][113], Worldwide Interoperability for Microwave Access (WiMAX) [99], Long Term Evolution (LTE) [99][107] and Wireless Fidelity (WiFi) [99]. Amongst the access network technologies, PON is the most energy efficient.

Energy conservation techniques investigated in the access network and can be classified as follows:

- Re-engineering (hardware);
- Sleep mode.
- Time-aware energy optimization.
- Dynamic adaptation of traffic load and performance scaling.

2.8 Related Work

This section discusses related work on energy saving in core networks and accentuates the differences with the research reported in the Thesis. A wide range of research has focused on different aspects of energy saving in telecommunications networks [51][67][107][109][110][111][112][115][116][117][119][120][122][126]; in the Thesis, the research concentrates on improving the energy efficiency of Core Optical IP networks only.

Energy saving can be broadly classified into sub-domains (Figure 2.25). Crucially, there are three key arguments being established in these studies; the first aspect is with regard to hardware design and implementation, further sub-divided to (1) complexity reduction which would eventually lead to the system level abstracted designs, and (2) Energy-efficient silicon that focuses on low power design in CMOS / SOA [51][68][70][94][95][96][97][103][104][105][106].

The second aspect relates to the criteria used to determine link rates, wherein the strategy is further classified, taking into account recent studies that have addressed *performance scaling,* a modification on dynamic voltage scaling or frequency scaling. The traffic load volume approach is based on idle logic states and *adaptive networking* that reshapes the traffic load and adaptive link rate.

The third approach centres on standby/sleep modes that directly affect the overall power consumption. Studies evaluating this strategy crucially concentrate on two main phases; standby primitives responsible for manual actions such as ON/OFF; and smart sleep/smart standby modes for automated execution using *intelligent GMPLS control plane* implementations. Here, the research concentrates on a *Hibernation strategy*, allowing the balancing of resource utilisation and performance.

Three energy saving schemes are proposed and analysed:

1. "Grouping"; in which network nodes are clustered into different groups and based on the network status are powered down.
2. Link Segmentation; where all idle links are powered down.
3. Light path Partitioning; where all idle wavelengths within link(s) are powered down.

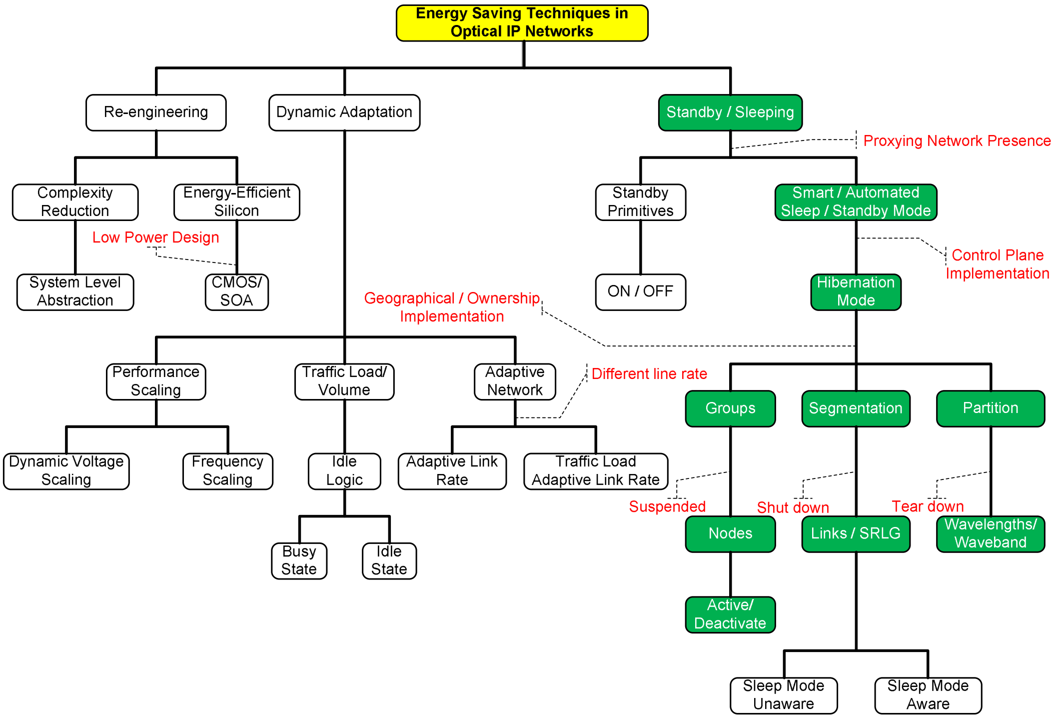


Figure 2.25: Taxonomy of Energy Saving Techniques in Optical IP Networks.

2.8.1 Sleep Mode

The Sleep Mode - also known as the Standby Mode - is implemented on network equipment and applied depending on hardware design and standardization bodies. In the core network, most of the major techniques to save energy comprise the selective turn off of idle network elements when the traffic load reduces whilst at the same time, maintaining essential network functions to support residual traffic.

A full discussion of Sleep mode can be found in [51]; the sleep mode is used in core, metro, access and video distribution networks. It is estimated that the power consumption of the Internet is about 0.4% of all electricity consumption in broadband-enabled countries and forecasts indicate that this could approach 1% as access rates increase. The energy consumption per bit of data on the Internet is around 75 µJ at low access rates and decreases to around 2-4 µJ at access rates above 100 Mb/s.

A Sleep mode can be applied to redundant network nodes as recommended by [67] by taking following steps (i) only when it is totally unused, (ii) when the traffic goes below a given threshold, leaving the responsibility to reroute the residual traffic to upper layers, and (iii) after proactively rerouting the traffic along other routes, in order to avoid traffic disruptions.

The manual implementation of an ON/OFF sleep mode of equipment in optical networks has been investigated in [109][112]; this scheme is not practical especially in large-scale networks.

2.8.2 Switch-Off of Selective Optical Links

Switch-off of selective optical links in core networks is a technique for powering down idle links or spare links and is highly dependent on traffic load. Authors in [110] proposed heuristic algorithms that consider the power consumption parameter of each link and their position within the network topology. The energy saving opportunity is owing to the power ‘unawareness’ of the RWA algorithm, as well as over-provisioning, typical of transport networks, and by the traffic load.

The authors in [51][67][104][110][111] pioneered energy saving through switch-off of selective optical links. Energy modelling has been proposed by [112] studying a number of scenarios for a specific network. The objectives are to maximize the number of idle nodes and links while still supporting existing traffic. This has been proven to be a NP-hard problem and can be formulated as a MILP (Mixed Integer Linear program). Since the problem is computationally complex, heuristics approaches have been proposed [112].

In order to reduce energy in access/metro optical fibre links, an alternative technique [94] is dynamic adaptation aimed at modulating the capacity of network devices such as link bandwidths and computational capacities of packet processing engines according to current traffic loads and services requirements. Such approaches are generally founded on two main power management functions at the hardware level, namely power scaling and idle logic. As shown in Figure 2.26, performance scaling (Figure 2.26c) causes a stretching of packet service times (i.e., header processing time in a processing engine, or packet transmission time in a link interface), while the adaptation of idle logic (Figure 2.26b) introduces an additional delay in packet service, due to the wake-up times. Finally, as outlined in Figure 2.26d, the joint adoption of both energy-aware capabilities may not lead to outstanding energy gains, since performance scaling causes longer packet service times, and consequently shorter idle periods.

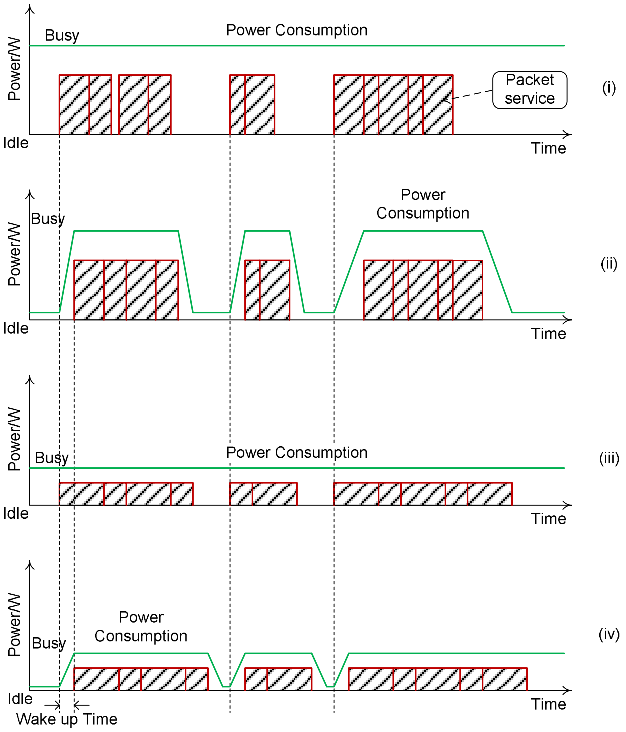


Figure 2.26: An example of packet service times and power consumption; (i) no power aware optimizations; (ii) only idle logic; (iii) only performance scaling; (iv) performance scaling and idle logic.

2.8.3 Optical Switching, Optical Amplifier and Core Node Interface Energy Efficiency

Significant contributions to the analysis of diverse energy efficient optical switching disciplines were made by authors in [105][106][128]. The authors in [128] examined the potential lowering of power consumption in optical multi-plane interconnection architectures based on space-wavelength (SW) switching. The architecture interconnects multiple cards having multiple ports, and permits flexible switching of packets from any port to any port. An intra-card scheduler was considered for scalable scheduling of packet switching; an implementation based on recent advancements in optical integration was considered. Moreover switches and couplers are realized using semiconductor optical amplifiers (SOAs) controlled by either the scheduler or the packet. The control permits space-switching operations as well as the turn OFF of SOAs when unused, in order to save power. The authors claim that multi-plane architectures offer higher throughputs by exploiting two switching dimensions compared to single-plane architectures and thereby the energy efficiency of the corresponding switch fabric is superior.

A recent contribution [106], analyses the average energy consumption per bit of matrix-vector multiplier crossbar (MVMC) and Benes optical packet switches realized through SOA technology. The authors evaluate the energy consumption by considering the amplifier spontaneous emission (ASE) noise that degrades performance; the results obtained show that the Benes switch is more efficient in power consumption than an MVMC switch under conditions of low ASE noise and when turn OFF of SOAs is taken into account.

The authors in [129] investigate the potential reduction in energy consumption of a core node interface where Optical-Electrical-Optical (OEO) conversion is used for Add/Drops functionality at the interface between the core router and the optical core node, and regeneration for signals in transit. The OEO conversion is performed by transponders; regeneration is carried out with two cable connected transponders, in a back-to-back configuration. The energy efficient node architecture proposed is based on the insertion of an optical switch at the interface between the transponders and the core router.

In [105], the authors consider the energy consumed for a continent-sized core network, showing that increasing the maximum optical path length (not requiring regeneration of the optical signal) can reduce power consumption. For a pan-European network, savings of up to 10 % are predicted.

2.8.4 Energy Minimization in Wavelength Routed Networks

Many energy saving schemes for IP over WDM are discussed in [116][117][121][123][125][126]. Some recent studies adopt a route to energy minimization by applying Routing and Wavelength Assignment (RWA) algorithms [116][117][126].

The authors in [116] study minimization by managing traffic demand using heuristics algorithms for equipment such as IP routers, EDFAs and transponders. In addition, the authors have reviewed the significant impact on traffic grooming of energy efficient designs in networks. Two proposed schemes are light path non-bypass and bypass. In case of non-bypass scheme, all light paths incident on a node must be terminated; all the data carried by these light paths is processed and forwarded. In contrast, for the case of the bypass scheme, the IP traffic at egress nodes is permitted to directly bypass intermediate routers via a cut-through light path. Results show that light path bypass can conserve more energy than non-bypass, since the number of IP routers in the link is reduced. Furthermore, the authors also evaluated the energy consumption of routers, EDFAs and transponders separately; findings indicate that the routers dissipated more energy compared to EDFAs and transponders.

Figure 2.27 presents a classification framework of energy saving techniques in IP over WDM networks.

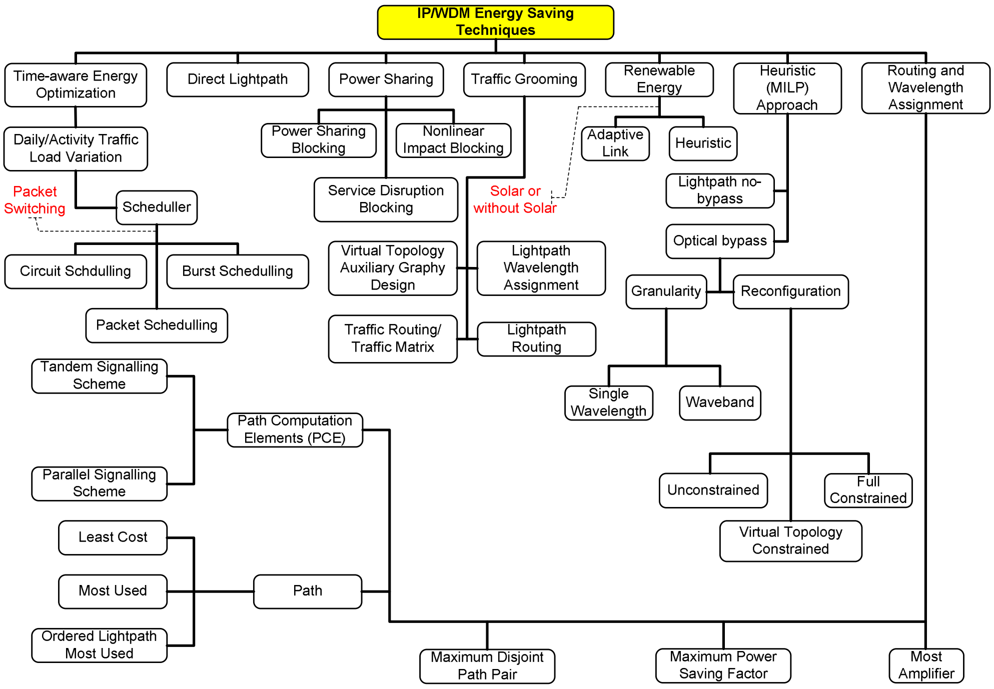


Figure 2.27: Taxonomy of IP over WDM Energy Saving Techniques.

2.8.5 Green Routing

Trends in use of Internet have placed ever increasing demands on bandwidth at the core network. One of the consequences is that the network equipment consume more power to meet the rising traffic loads. That trend stimulated the search for a core network architecture following a more systematic methodology for the efficient use of energy. Architectural selection for inter-operation between the IP and optical network layer in particular, prompted the development of *green routing* also known as *energy-aware routing* [119] to help reduce energy consumption. The authors proposed the modification of Open Shortest Path First (OSPF) routing - based on network-level strategy in IP routers - to power down some network links during low traffic e.g. at off peak hours. The main features of proposed algorithm is that only a subset of routers evaluate their Shortest Path Trees (SPT), whereas all others utilize these SPTs to determine their routing paths to deflect packet traffic and power off some network links.

The energy-aware routing proposed in [109], uses a novel routing scheme with energy consumption of network equipment as the optimization objective. The authors develop a generic model for router power consumption and apply a set of target network configurations using mixed integer optimization techniques. This includes a comparison between legacy shortest paths with energy aware routing scheme by line card or chassis re-configuration in IP routers. In such a way, energy can be minimized by optimization of the configuration and combination of hardware which leads to path traffic re-route according to traffic variation and demands.

2.8.6 Energy Aware Traffic Engineering

Traffic engineering (TE) has a significant impact upon energy conservation in the core network. Energy aware traffic engineering employs dynamic routing to distribute the traffic load with consideration of the power consumption along with determining multi paths to re-route the traffic to the best available shortest links optimizing energy saving rooted in low link utilization.

The authors in [111] proposed energy aware TE through rate adaptation by shifting the load primary link to alternatives links with lower energy states for the same source-destination pair, placing links and routers to sleep. However, the authors in [104] argue that in core networks it makes less sense to use rate adaptation (adaptive link rate) since the traffic patterns exhibit less variation.

The authors in [115] propose the use of a network control unit (NCU) in which a network node is assigned to collect traffic load information from routers, and to consequently apply a traffic engineering criterion to perform L2VLs (Layer 2 Virtual Links) reconfiguration whilst satisfying QoS constraints. The TE algorithm finds the optimal network configuration that can be achieved by remapping L2VLs on the physical topology. The optimal configuration is the one that maintains the QoS in terms of maximum link utilization and backup availability, and maximises the largest number of line cards to sleep.

Dynamic topology optimization can be achieved in the core network [104] i.e. from multiple possible topologies that satisfy the traffic demands topologies with lower overall power consumption are defined. Dynamic optimization typically exploits the daily or weekly variations in traffic load, where off-peak volumes are potentially lower than 50 % of peak volumes. In [120], the authors considered saving energy by implemented Multilayer Traffic Engineering (MLTE) techniques. MLTE uses an IP layer cost function not only managing IP flow routing as is the case in traditional single-layer TE, but also logical topology construction. Power reduction through hardware improvement on MLTE is executed using two methods; down-scaling of equipment power requirements and improvement on routers architecture and line cards focusing on reducing idle energy consumption such as scaling back clock rates, power down parts of the hardware on very short time scales, match line rates with traffic volume.

2.8.6.1 Power Aware Connection Provisioning

Service or connection provisioning is defined as multiple serial operations and power efficiency is evaluated for both optical bypass or direct-light path and traffic grooming. The authors of [122] discuss using power consumption in service provisioning (i.e. operational power); following a Traffic Engineering approach will improve energy efficiency of the core network depending on strategy i.e. optical bypass versus traffic grooming, operations -electronic domain versus optical domain - and routes. In addition, the relationship with network load, overhead network capacity on power aware service provisioning was developed.

2.9 Summary

This Chapter provides a general review of different elements related to optical networks, IP protocol, and GMPLS protocols. The main aim is however to introduce and classify the strategies to power reduction in Optical IP networks including the network energy principle, energy efficient designs and classification framework for energy saving techniques.

A discussion of related work on power reduction strategies is presented. Energy saving techniques can be classified at the highest level according to the network domain. Re-engineering, sleep modes (primitive), green routing, traffic engineering, energy efficient packet forwarding, time-aware energy optimization, direct light path, power sharing, traffic grooming, heuristic (MILP) approach, dynamic adaptation, Routing and Wavelength Assignments are reported approaches to creating a more energy efficient core layer. Based on a critical analysis of the state-of-the-art, a 'hibernation ' principle is adopted as a route to energy conservation because the intelligent control plane can be enhanced to support smart or automatic sleep modes which facilitates easy deployment and progresses existing techniques which have only applied primitive or manual sleep modes.

The next Chapter is dedicated to defining and implementing a simulation framework which provides the foundation with which to evaluate energy saving approaches in distributed GMPLS- based optical IP networks.

Chapter 3

Green Core Optical IP Networks: Model Methodology and Implementation

3.1 Introduction

There are two feasible routes to evaluating the ever increasing range of potential energy efficiency strategies in core optical IP networks: mathematical analysis and simulation. The former uses mathematical techniques to emulate communication networks constrained by certain parameters; such models are best suited to evaluate simple networks topologies. The latter methodology uses an extensive simulation environment hosted on significant computing platforms to analyse the performance of representative network topologies e.g. the National Science Foundation Network (NSFnet) [116][117] and European Optical Network (EON) [125].

The research here harnesses the Objective Modular Network Testbed in C++ (OMNet++) simulation platform because it has been proven to provide the best functionality for optical network modelling offering a range of advantageous features as described in Section 3.2 [51][132].

3.2 OMNet++ Simulator Overview

The evaluation framework used is the OMNET++ platform, a discrete event simulation software package [132]. OMNET++ is chosen for its GMPLS modelling features and as a public-source simulator offering a generic and flexible architecture, it has evolved to be a reliable and flexible component-based simulation package providing a class library, graphical network editing and animation, data collection, graphical presentation of simulation data, and random number generator [131][132]. Furthermore the platform is workable with varieties of operating systems and C++ compilers, and has become popular with both the scientific and industrial communities.

Figure 3.1 illustrates the OMNet++ core structure that supports hierarchically nested modules in which each module is implemented as an object. Simple modules are the lowest level of the hierarchical structure; any simple model is associated with C++ file describing its behaviour. No active behaviour is associated with compound modules used for grouping or aggregating simple modules. The highest level of the hierarchical structure is a network model, communicating using messages exchanged through channels. The messages can be used to model a number of entities: events, data packets, frames, cells, bits, or control messages [132][133]. In addition, the *omnet.ini* text file provides a resilient procedure for initialising and passing module parameters.

OMNeT++ has been chosen because of the following features;

- a public-source simulator with a generic, resilient architecture mainly targeted on simulation of communication networks.
- provides reliability, is customizable and flexible component based simulator;
- an open-architecture simulation environment with strong GUI support and an embeddable simulation kernel.
- offers module parameters and support hierarchically nested modules.
- supports traffic and protocol modelling of networks.
- workable with varieties of operating systems and C++ compilers.

- easy to install and learn with excellent tutorial /documentation.
- free for academic and for non-profit use.

A range of simulation tools have been developed such as OMNet++, NS2 [134][137] and OPNET [134] and a full comparison between simulators is presented in [134][135][136]. Table 3.1 presents the summary of simulation functionality comparison [132].

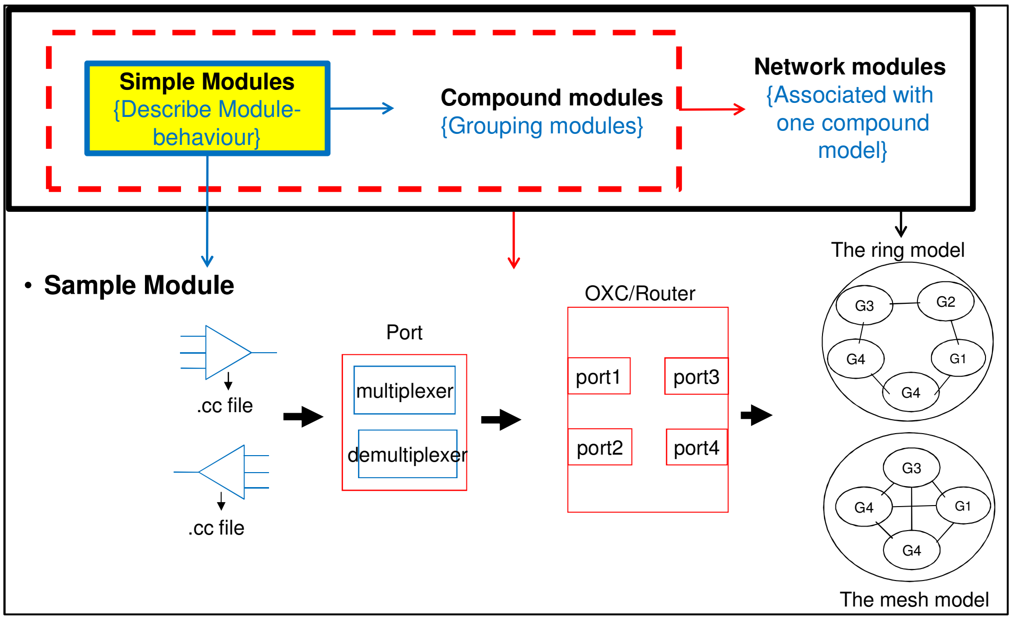


Figure 3.1: OMNeT++ simulation hierarchical model.

Table 3.1: Summary of simulation functionality tools comparison [132][137].

Tool	OMNeT++	Ns-2
Flexibility	Flexible and generic simulation network	Mainly designed for TCP/IP. Difficult to impossible for other simulation. Rigid and hardcoded programming.
Programming Model	Object-oriented, event-driven simulator written in C++ and topology descriptions written in NED language.	Mixed-mode: Object-Tcl with underlying C++ classes.
Model Management	Simulation kernel is a class library. Simple modules are reusable and flexible to combine.	Unclear boundary between simulation core and models.
Support for Hierarchical Model	Able to accommodate complex model and reusable for other simulations.	Models are "flat". Complex protocol implementation with various independent units are inconceivable.
Variety of Model Available	Excellent for simulating communication networks	Good for simulating communication protocol models.
Performance	Capable of simulating very large network topologies.	Scalable problem on simulating large network topologies.
Experiment Design	Simulation parameters are "separating model" from experiments.	Model and experiments are usually interwoven.
Embeddability	Simulation kernel could be embedded in other application; User interfaces can be modified and plug-ins.	No.

3.3 Simulation Environment Assumptions

The simulation assumptions are as follows:

I. System Model:

The network energy model components employed are based on a *terrestrial system and transparent* optical IP network structure.

II. Traffic Model:

The network topology is connected in a randomly distributed fashion with *L* links, with each link able to support the same number of wavelengths *W*. Connection requests follow independent Poisson processes with an arrival rate of α and queue lengths exponentially distributed with an expected service rate time of $1/\mu$ (in seconds) [116][118][133][162]. The selection of each wavelength assignment to a light path route is executed in an arbitrary fashion from the set of free wavelengths. As a result, all wavelengths are identical and the analysis tractable.

III. Simulation parameters:

The wavelength occupancy in fibre links on disjoint routes is considered independent of each other. The model assumptions and simulation parameters are given in Table 3.2, Section 3.10.

3.4 Core Router Model

The core router is a Label Switch Router with a GMPLS control plane supporting hibernation mode functionality deployed within an IP layer. The core router communicates with the control plane through a peer model, whilst the data plane is deployed as an overlay. This section presents the core router functionality including the core router model, control plane and core router model implementation. A more detailed explanation of the model is provided in Appendix B.

3.4.1 Core Router Model Design

The two key elements in the Router architecture comprise a control plane and data plane. In essence, the control plane comprises three main components viz. control channels, control entities (for example, signalling and routing units) and control nodes. The control plane functions includes resource discovery, signalling protocols establishments, distributed routing protocols, link management, operation and maintenance of information databases. The implementation of the control plane is either firmware or software based embedded within the router processor. Significantly, the full compatibility of the control plane with protocols is mandatory.

In contrast, the data plane (also known as forwarding plane or transport plane) is a hardware or physical implementation. It is responsible for data forwarding and switching the input LSP to the output LSP interfaces. The router has both electrical and optical switching components, of which the electrical section is used for complex computations in the electrical domain whilst the optical section is responsible for converting signals from the optical to electrical domains.

The router and OXC could be placed in separate locations or combined to form a single node with a common control plane. Moreover, each wavelength from the OXC local port is connected to a router port, the number of wavelengths that can be handled is based on the number of transceivers equipped in the router. Thus, the number of bidirectional light paths that can be simultaneously established by any router is equal (at most) to the number of transceivers. Two types of LSPs can be associated with a router, LSPs that originate/terminate on the router and LSPs that travel through the router. These paths are represented as variable-bandwidth-guaranteed paths, while a light path is represented as a discrete-guaranteed path. Thus, multiple LSPs may be aggregated in a single light path [133][152].

3.4.2 Control Plane Implementation

Figure 3.2 illustrates the control plane structure and the interaction with the data plane; the upper portion is the logical control plane and the lower portion the data plane topology. The cross-layer communications within the intelligent control plane is operated in a peer model so as to manage both the optical layer and IP layers simultaneously. In addition, the routing and wavelength assignment of light paths is derived from the IP routing discovery and knowledge.

Data plane connectivity (also known as the forwarding or transport plane) which includes transponder and router ports operates in an overlay based on a client-server approach (in this context, a server is the optical layer and a client is the router) and executes path selection during the establishment of a connection [16][18][21][22]. Consequently, the light path tunnels through the optical layer OXCs transporting IP packets.

The control plane functionality is using the GMPLS standard protocol in which signalling, routing and energy mechanism are modified at Type-Length Value structure messages header (Appendix C: Figure C.15).

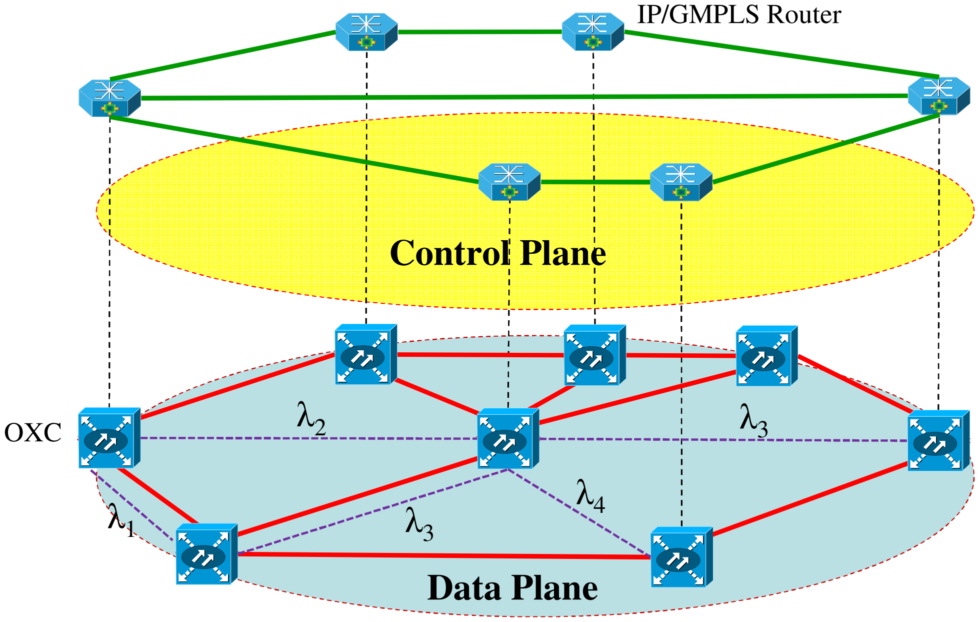


Figure 3.2: Control plane implementation.

3.4.3 Core Router Implementation

Figure 3.3 shows the OMNet++ implementation of a GMPLS Router. The router control plane follows GMPLS standards and is responsible for tracing the network topology, determining network resources, and for establishing, removing and maintaining connections. These functions are performed by a routing protocol for topology and resource discovery and a signalling protocol for connection provisioning, maintenance, and deletion [138]. A dedicated control channel is used to communicate between the router and OXC. In addition, the control channel is a physical or logical connection between signalling controllers and is responsible for Label Switching Routers (LSR) - also known as data switches - adjacent to the data plane. The router module comprises a variable number of ports enumerated as “Q” ports, and every one of these ports is assigned to an individual wavelength. Each port consists of multiplexer and de-multiplexer sub-models based on First-In-First-Out (FIFO) queuing. Both the multiplexers and de-multiplexers account for label packet swapping and message forwarding to the ‘Label Forwarding Information Base (LFIB)’ Table determining the next destination port as well as mapping the incoming and outgoing label, eventually maintaining a look-up index value.

The Label Switch Path (LSP) generator simulates the periodic generation and processing of label requests. A packet traffic generator provides a stochastic model of data packet sources governed by an exponential inter-arrival time. It creates and transmits a new packet for each LSP as well as the scheduled messages to trigger the next call, handling messages through an output gate. Each node has a 'controller' responsible for scheduling all required functions within the router. A 'Green Unit' measures energy consumption and records the overall power consumed by the router. It communicates with the Network Controller via the control channel and provides current energy status information. The Network controller, based on the available power, will decide on the hibernation mode option to be invoked.

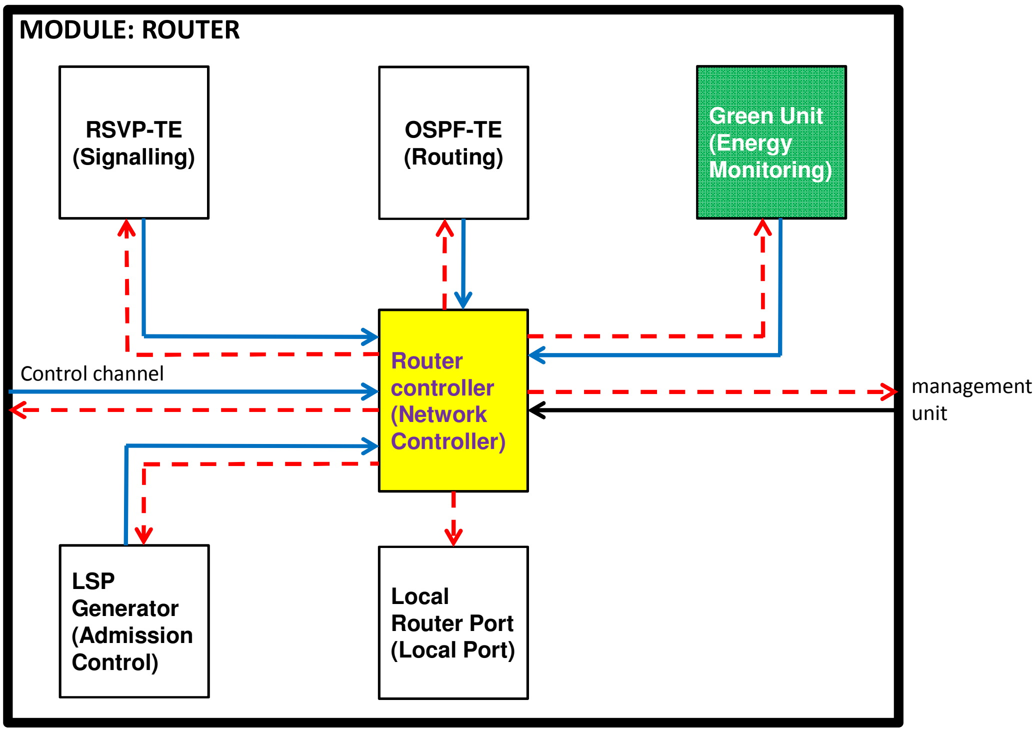


Figure 3.3: Router module implementation.

3.5 Optical Cross-Connect (OXC)

This Section explains the OXC design and implementation; a more detailed explanation of the model is provided in Appendix B.

3.5.1 OXC Model Design

The OXC Control plane has a similar structure to the core router control plane. In addition, the OXC control plane is used to discover, distribute and maintain relevant state information associated with the OTN and to establish and maintain optical channel (OCh) trails under various traffic engineering rules and policies. An OCh trail provides a point-to-point connection between two access points. At each intermediate OXC along the route of an OCh trail, the OXC switch fabric connects the trail from an input port to an output port [139]. The control plane node manages data plane node status and maintains the connection information traversing the data plane [140].

The data plane denotes the OXC switching fabric that provides the cross-connection; its function is to provision network connectivity.

3.5.2 OXC Implementation

Figure 3.4 shows the Optical Cross-Connect (OXC) Model implementation. The integrated control plane on a single common technology performs call and connection control for automatic neighbour discovery, routing, signalling and local resource management. The Wavelength Route Unit provides the functionality of the data plane and has a built-in control mechanism that allocates wavelengths upon connection requests, provides their usage information and updates the wavelength status through a wavelength-route-table.

Each node has an OXC controller responsible for controlling and scheduling all required functions and for delivering messages to remote nodes through dedicated control channels using GMPLS standard protocol messages implemented by the “cMessage” class. These messages are generated locally by the signalling unit or passed over to other nodes [133][153][154].

The ‘Green Unit’ records the overall power consumed by the OXC. It communicates with the Network Controller via a control channel and provides current energy consumption status. The Network Controller will decide on the hibernation mode option to be invoked based on available power and network state. In addition, the controller assumes the responsibility for throttling down energy consumption by means of bandwidth traffic shaping (traffic dimensioning) using scheduling and priorities. This could be done by scheduling ‘idle’ light paths through routing and wavelength assignments and prioritizing the appropriate light paths.

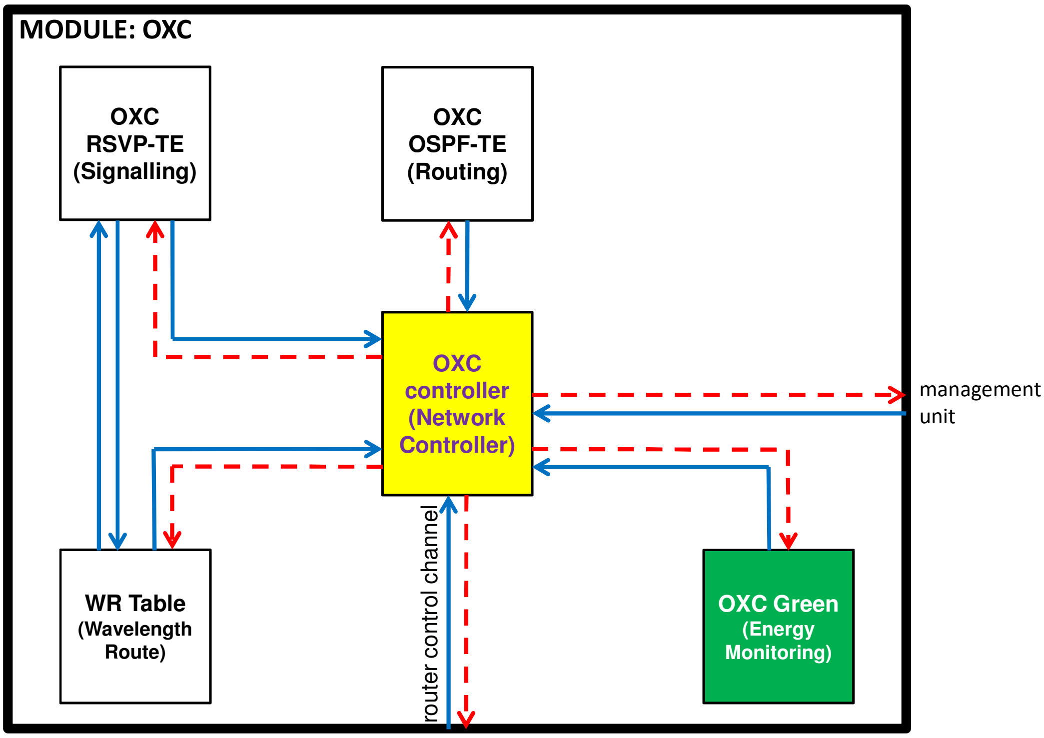


Figure 3.4: OXC model implementation.

3.6 Link Structure and Implementation

A pair of single mode fibre spans is required to form bidirectional links from source to destination node e.g. OC-192 link between adjacent OXCs. Both traffic directions are connected with unidirectional single mode fibre satisfying a specific capacity.

The link structure hierarchy supporting switching granularity can be established by nesting traffic flows at the same interface level of multiplexing for both directions. The realization of this link structure is separated into two categories: control and data links;

- *Control link*: a connection can be established as a dedicated channel with explicit capacity. In practice, such a channel can be deployed via an out-of-band channel either separated link or dedicated fibre channel (wavelength).
- *Data link*: a single fibre link is nested with multi-granular bidirectional connections in which each connection represents a bi-directional optical fibre channel.

3.7 Network Energy Model Design and Implementation

The network energy model can be represented by the mode transition diagram depicted in Figure 3.5 and Figure 3.6. By definition, the mode transition diagram denotes the events that cause a transition from one mode to another, as a consequence of activity[1].

Figure 3.5 depicts the hibernation mode transition diagram. The flow process of an event involves three states: ON, Hibernation, and OFF as illustrated in Figure 3.6. The network is fully operational (active) in ON state. The Hibernation mode could be triggered in various schemes; (1) Group – suspend unused nodes, (2) Segmentation – power down unused links and (3) Partition – power down unused wavelengths. In the OFF state, the nodes are in sleep mode (unused functionalities) with low power consumption operation.

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[1] The difference between a state transition diagram and a mode transition diagram: a state defines a system operating condition where a mode is system functionality or capability.

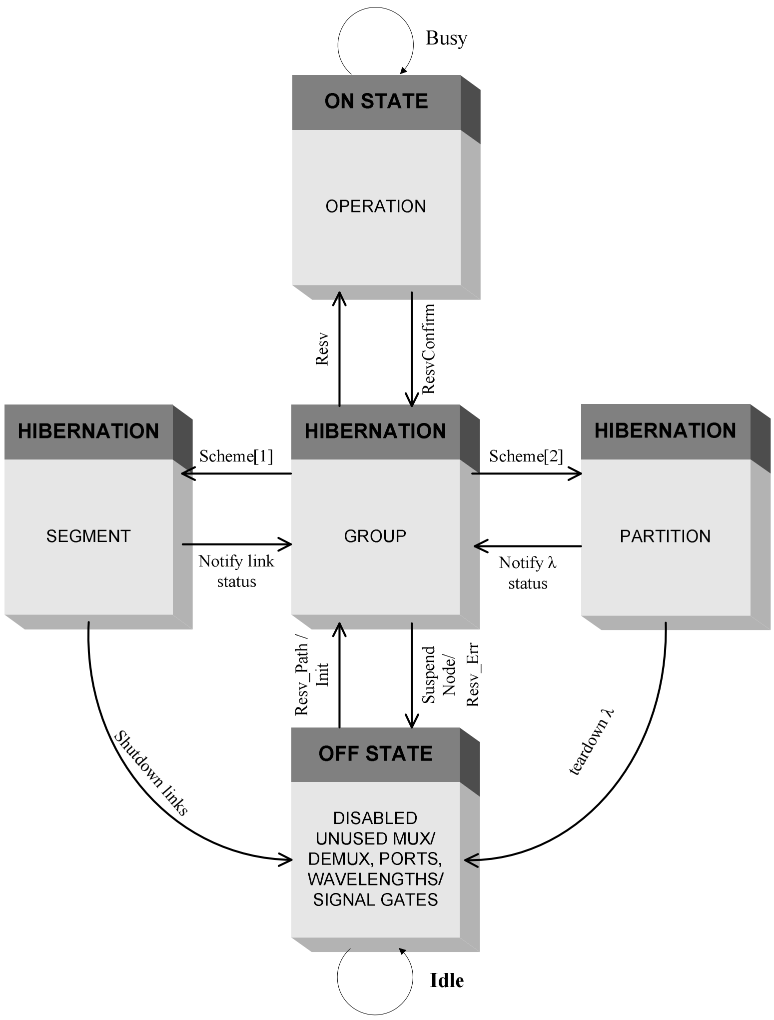


Figure 3.5: Mode Transition Diagram.

INITIALIZATION
- *Resv_Path msg* (LSP Setup).

ON → HIBERNATION → OFF
- *Resv_Confirm*: LSP Confirm message.
- Hibernation Mode could be trigger in various schemes;
  1) Group – suspend the unused nodes.
  2) Segmentation – shutdown unused links.
  3) Partition – teardown unused wavelengths.
- LSR gets a positive reply from Network Controller (NC), then it goes to the sleeping state.

OFF → HIBERNATION → ON
- *Resv* (LSP Setup): Router receives a wakeup reply.
- *Resv_Notify* (LSP Notify) and rebuild the routing table/wavelength table.

Figure 3.6: Mode Transition Operation.

3.8 Model Design and Functionality

To evaluate the effectiveness of “node hibernation”, a number of network performance characterisation exercises were performed under different scenarios. The network topology selected throughout the analyses was the National Science Foundation (NSFnet) network [116][118] supporting OC-192 and bidirectional single mode fibre links between nodes (Figure 3.7).

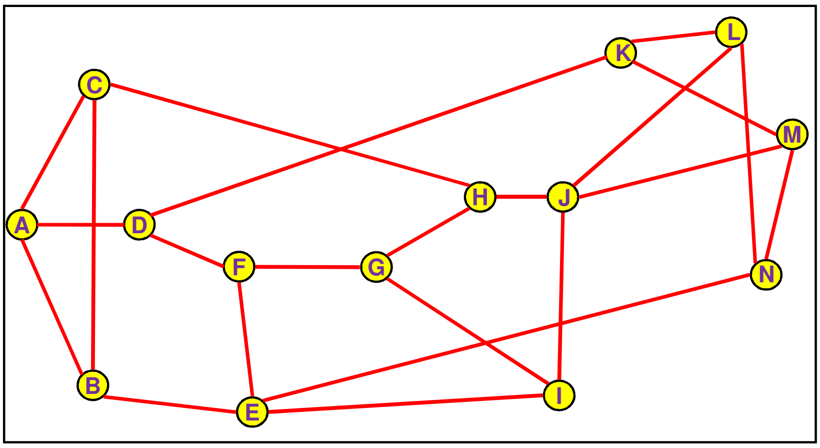


Figure 3.7: National Science Foundation (NSFnet) network.

EDFA amplifiers consume a minimum power of 1W, placed at every 70km. NSFnet is a Partial Network Topology with 14 nodes and 22 bidirectional fibre links [116][118]. Standard GMPLS signalling and routing protocols are implemented following the Internet Engineering Task Force (IETF) standard [141][142]. Uniformly distributed traffic is assumed throughout. (The ramifications of these assumptions were difficult to analyse but validate the simulations). The performance metrics taken into account include the average power consumption, blocking probability and average request blocking [53][109][111][116][133]. These metrics are important parameters and indicators of energy conservation efficiency in terms of impact on network performance, routinely used by other researches as standard benchmarks.

The iterative simulation cycle is illustrated in Figure 3.8.

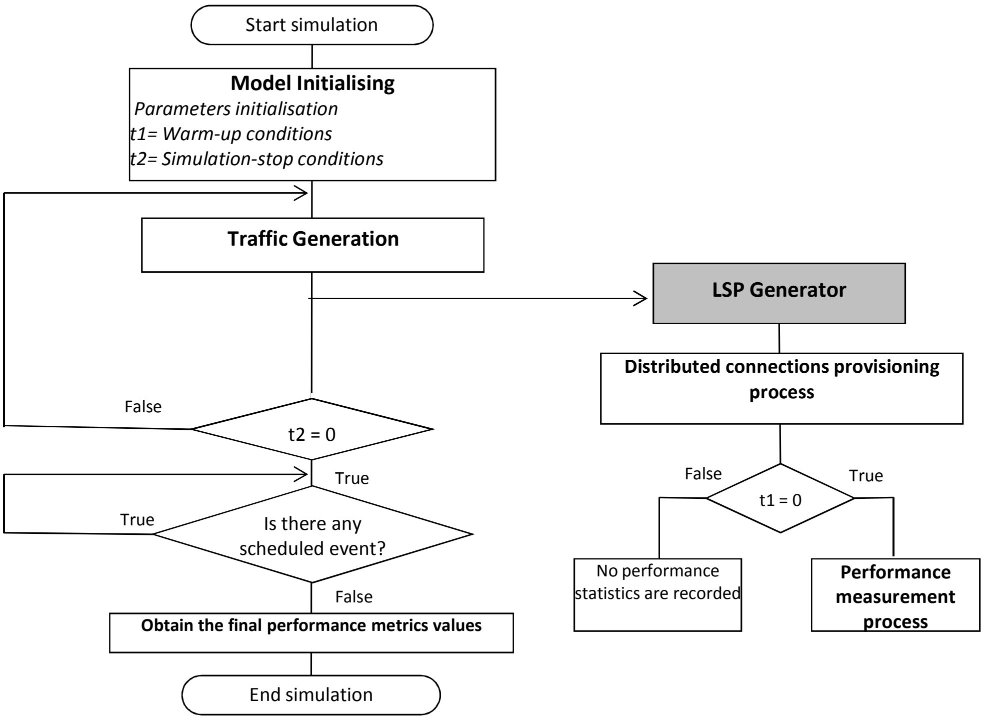


Figure 3.8: Simulation cycle flowchart.

The stages of the cycle include model initialization, traffic generation, LSP generation, and connection provisioning and performance evaluation. As illustrated in the flowchart of Figure 3.8, the process between the traffic generation and provisioning is independent. Multiple requests are initiated simultaneously despite the status of the provisioning process, since the model operates in a randomly distributed fashion. The initial condition of the evaluation is supervision by measuring the warm-up criteria; at the start of the simulation, an initial period is defined to ensure that a steady state condition is reached. Requests are generated and processed but no performance statistics are recorded. The simulation is terminated upon completion of the appropriate simulation-time.

3.8.1 Model Initialisation

The Central Network Topology Configuration (CNTC) unit is designed to execute network connectivity by providing additional flexibility in terms of changing network topology and the graphical appearance of vector modules; such modules are identical in terms of their structure but have different parameter values. Therefore, the CNTC assigns particular values for each vector module, rather than assigning the maximum value for the whole group of vector modules, directly improving simulation resource utilisation [133][152][153][154]. OMNeT++ is used to build up the CNTC by implementing the model topology structure in NED language description (.ned) files and modules structure through an in-house C++ program. The former designates the structure of modules and interconnections in relation to simple modules, compound modules and network definitions. The latter implement model functionality and are accountable for creating network run-time. OMNeT++ has an extensive C++ simulation class library containing C++ executable simulation programs such as cPar, cTopology, cGate, cModule and cChannel.

In addition, the CNTC maintains the set of text files defined from the simulation class library *cTopology* with attributes of network connectivity and structure as follows:

a) Link-Structure file: supporting information pertaining to a link structure or series of connected links consisting of link position, length, connectivity and number of wavelengths.
b) Node-Structure file: corresponds to a simple or compound module which contains information about node coordinates, the number of ports and the number of locally dropped wavelengths.

The CNTC is also responsible for establishing and maintaining control channel connectivity between adjacent nodes. Thus, the control-channel-topology file is maintained by the CNTC to define the information and attributes for control.

The network management unit caters for requests for manual network configuration and its operation can be handled by the administrator through a text file or computer keyboard. The objective of manual configuration is to fulfil certain constrains from network nodes such as terminating at specific nodes, static light path topology establishment or testing the model process functionality.

3.8.2 Traffic Generation and Process

The total number of connection requests available is the offered load (traffic load) denoted in Erlangs [116][118][162]. Note, the arrival connection requests follow an independent Poisson process with an arrival rate of α=λ and queue lengths exponentially distributed with an expected service rate time of 1/μ (in seconds). The mean holding time is assumed to be fixed. Figure 3.9 illustrates the traffic process.

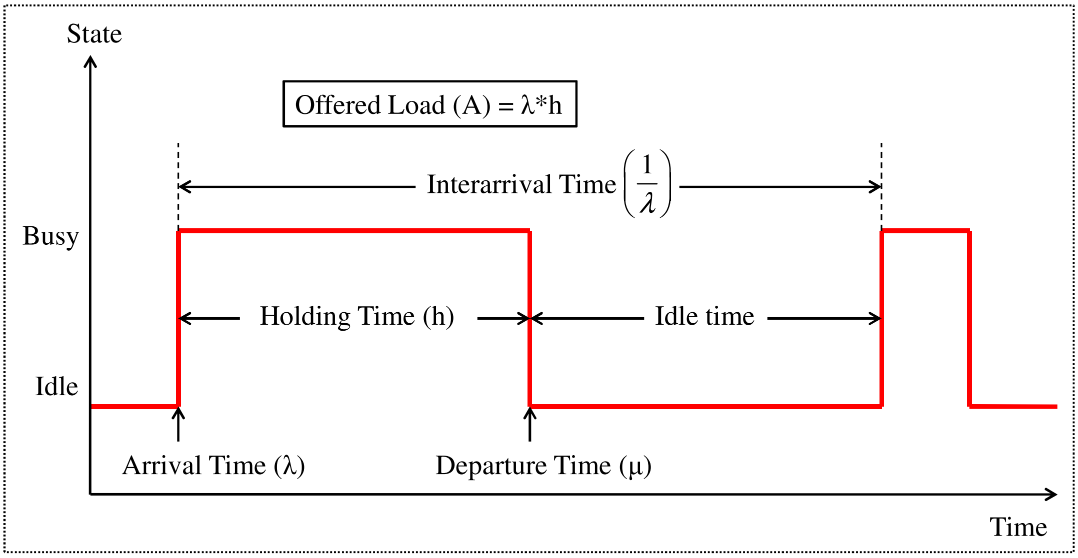


*Figure 3.9: Illustration of the Traffic process terminology. λ corresponds to the Poisson mean arrival rate per unit time. μ is the Exponential average service rate (Departure). h indicate mean connection holding time. Inter-arrival time represents the time intervals between arrivals and departures (1/λ). Offered Load (A) is product of mean arrival time and mean holding time (A=λ*h).*

As Internet traffic patterns are unpredictable and exhibit a consistent variation of traffic distribution, it is necessary for the routers to operate and manage their traffic independently. Thus, in this model, the Traffic Generator is connected to a core router and manages traffic through LSP requests. The generator produces a set of LSP connection requests and terminates requests randomly according to a Poisson distribution [38][39][133].

3.8.3 Energy Monitoring Controller

The Energy Monitoring Controller (EMS) is responsible for supervising and monitoring energy dissipation both in the IP and optical layers. On changes in energy consumption levels in the network, the EMS will advertise a notification to the network controller, a feature known as Agile Control Energy (ACE). The ACE is based on a threshold setting by the administrator e.g. a threshold limit set to 70% normalized, a measure in kW or Joules.

3.8.4 Connection Provisioning Process (Path Establishment Provisioning and Maintenance Process)

The path provisioning mechanism in GMPLS can be performed off-line and on-line and provides light paths and LSP routes at a minimum cost according to objective functions. The off-line or static method is a light path connection (or called a circuit or a trail) establishment setup in which services are manually provisioned, while the on-line method can accommodate a new request dynamically by means of signalling protocols. GMPLS provisioning involves signalling and routing processes; the former is responsible for dynamic establishment of data plane paths (LSP) through RSVP-TE messaging, while the latter governs path computation to determine appropriate routes.

The signalling functions are realized in GMPLS via protocols defined for RSVP-TE extensions and signalling messages are carried in IP datagram sent between controllers. Bi-directional GMPLS LSP establishment and termination sequence messages are depicted in Figure 3.10. The time to complete the signalling is 5ms (Path/Resv) [132][141][142]. In order for the LSR 1 Ingress Node to communicate with the next node, the message flows must be established as follows;

- LSR 1 ingress node issues the signalling request by a message for LSP establishment via a *Path* message.
- OXC nodes verify the *Path* message and determine the constraints in terms of resources and routes. Then, a provisional resource reservation is performed, and a *Path* message is sent downstream.
- When the *Path* message reaches the egress node, the constraints are also examined, and if all is well, the node reserves resources, allocates a label, and sends a *Resv* message back upstream.
- The OXC node allocates or validates the resource reservations, chooses an upstream LSP (LSP mapping to light path based on GMPLS nested hierarchy) (GMPLS-capable nodes may advertise a light path as a virtual link or TE link into the link-state protocol responsible for routing this light path and referred to as the FA-LSP provides light path reservation [141][142]), installs the received and upstream LSP in memory and send a *Resv* next upstream.
- When the *Resv* reaches the ingress node, resource reservations are complete, the LSP (light path) is added to the wavelength route table and signalling is established.
- Similarly, the LSR 1 ingress node requests the LSP set up to LSR 5 Egress; setup is acknowledged when LSP reaches LSR 5 egress.
- When the LSP packet reaches the ingress node and adds the label to its LFIB, the LSP is established.

- LSP teardown is executed via bi-directional message flows. The ingress node removes the label from its LFIB, releases the resources allocated to the LSP, and sends a *PathTear* message downstream. On receiving a *PathTear* message, each node in the network also releases the label and associated resources before sending a *PathTear* onwards. Should a *PathTear* message get lost, RSVP-TE relies on the soft state nature of RSVP to timeout the LSP remnants and continues to clean up in a downstream direction.

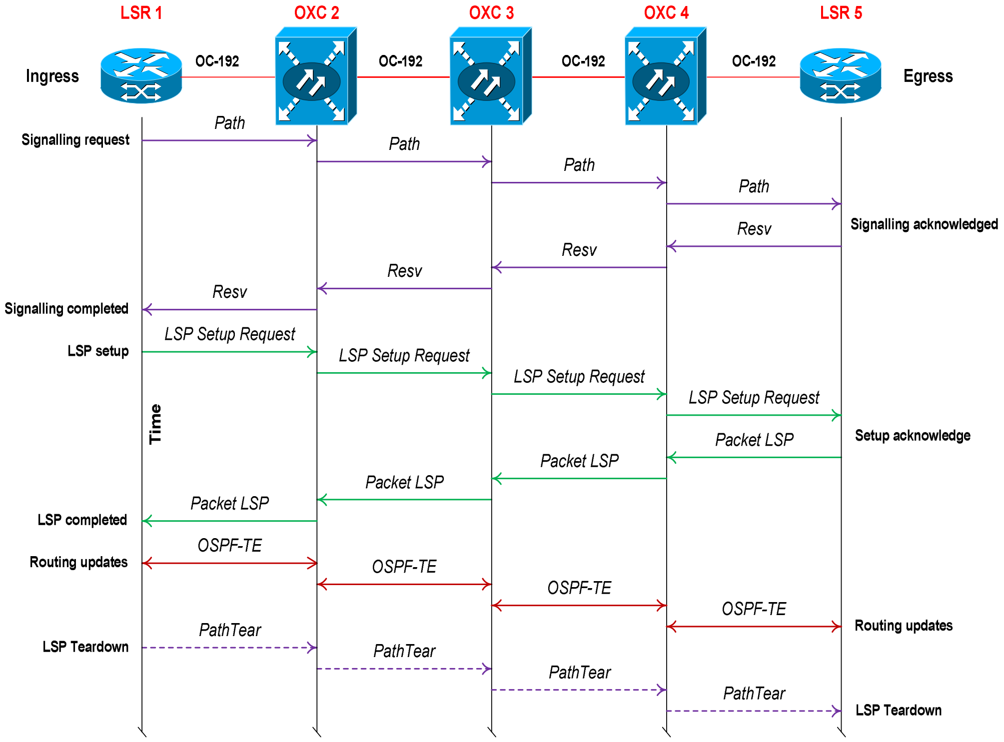
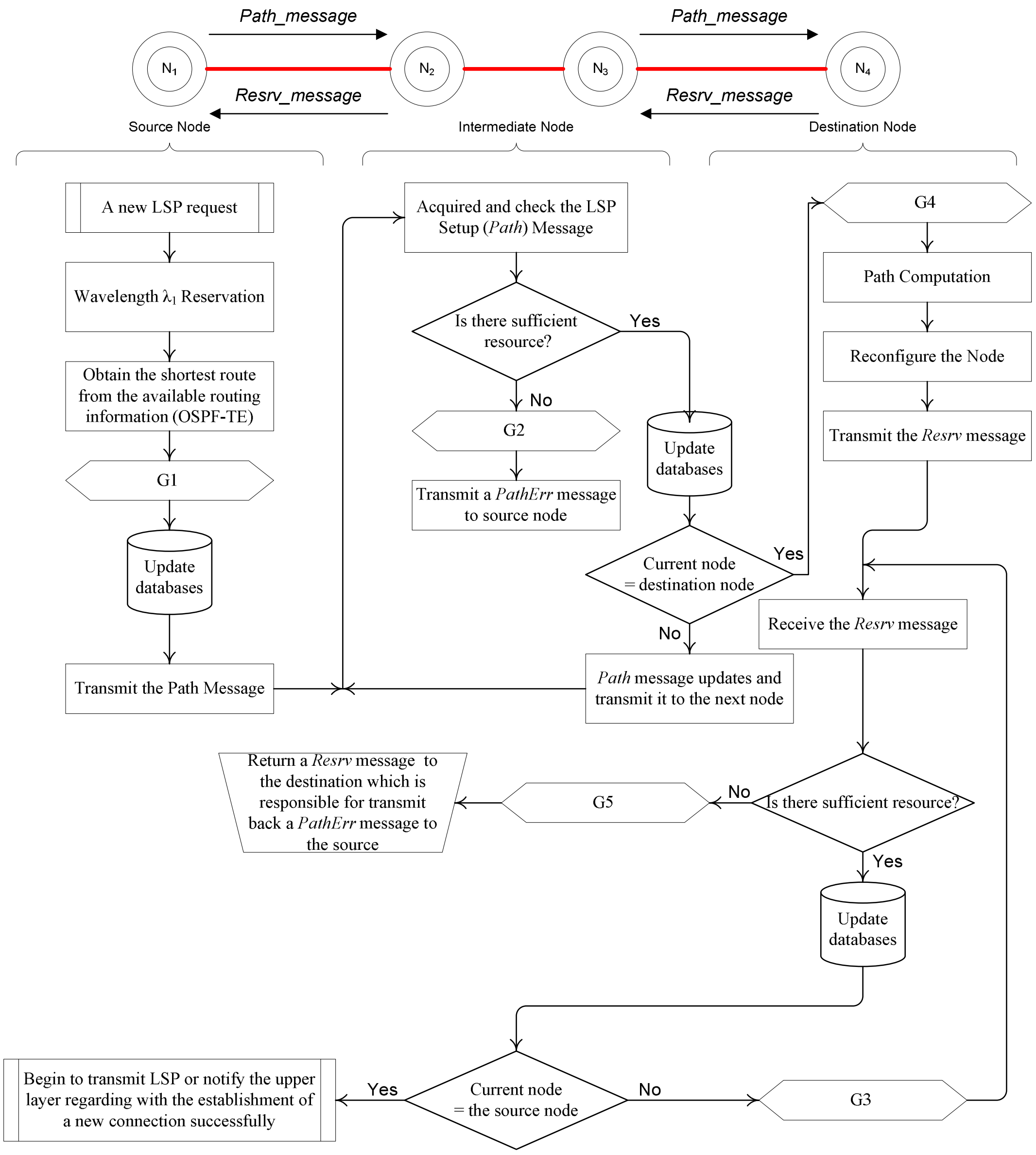


Figure 3.10: LSP establishment and termination sequence.

3.8.4.1 Signalling Protocol Implementation

In Destination-Initiated Reservations (DIR), a control message is forwarded from source to destination garnering wavelength availability information along the path. Based on this information, the destination node will select an available wavelength (if available along the path) and send a reservation request back to the source node to reserve the selected wavelength [143]. DIR is well supported within the GMPLS control plane.

The flowchart of DIR is depicted in Figure 3.11. When the explicit route for a request (light path or LSP) is successfully computed, the signalling unit at the source generates a *Path* message. This message is then forwarded from the source to the destination, collecting resource information on the way. When the destination receives the *Path* message successfully, a reservation message (*Resv* message) is forwarded back to the source. All intermediate nodes, including the source and destination, must ensure that the required resources are available when any message is received. The required resource is assigned within the *Path* message and recorded within the reservation message. In order to establish a bi-directional connection in one attempt, it is assumed that *Path* messages carry the upstream label to the downstream node while reservation messages inform the upstream node about the selected downstream label. The request is blocked if no resources are available along its route. If the request is rejected within the *Path* message route, a path error (*PathErr*) message is forwarded back to the source, while a reservation error (*ResvErr*) message is sent back to the destination when the request is rejected within the reservation message route. Once the destination receives a *ResvErr* message, it is responsible for generating and sending back a *PathErr* message along the route to the source. A more detailed explanation of RSVP-TE is provided in Appendix C.



ID	Process Description
G1	Generate *Path* message
G2	Generate a *PathErr* Message
G3	Update the message and transmit the next node. Reconfigure the node
G4	Generate a *Resrv* message
G5	Deliver a ResrvErr message

Figure 3.11: The flowchart of destination-initiated reservation (DIR) method for establishing connections in networks.

3.8.4.2 Routing Protocol Implementation

Figure 3.6 illustrates the network topology of the National Science Foundation (NSFnet) network. IP/GMPLS nodes are linked by a bi-directional pair of single mode fibres and new functions include maintaining information on total power consumption and energy per bit levels. At this stage of the simulation based analyses, the routers within nodes are placed in the "ON" state for common control plane operation and management; energy reduction techniques are applied in the optical layer. The simulation was first executed with a measurement of power consumption on selected groups (based on geographical location). The nodes in each of these groups are switched OFF when their functions are not in use with tests initially conducted with no traffic and subsequently with data transmitted.

Node Data Tables within routers are responsible for maintaining updated information on the following; (1) Network Topology; (2) Routing and Wavelength Assignment; (3) Light paths Information; (4) Forwarding Table. GMPLS signalling and routing protocols are implemented based on the Internet Engineering Task Force (IETF) standard [141][142].

The routing algorithm is governed by the power consumed by each node following a shortest path first (SPF) approach (Figure 3.6). The algorithm attempts to put as many links and nodes into a hibernation mode. During this hibernation process, the nodes advertise their routing and data tables' information to the control plane to constantly update power consumption within the network. In Hibernation the Erbium-Doped Fibre Amplifiers (EDFAs) is always ON and nodes are in low power mode by retain only minimum network operation functionalities viz. suspend their unused functionalities (e.g. unused ports / interfaces, Mux/DeMux capabilities, signalling gates, unused wavelengths, etc.).

3.8.4.3 Connection Teardown Process

In terms of GMPLS, the connection teardown mechanism provides a *deletion in progress policy* in which a *Path* message with specific objects traversing along the route is requested to release the connection at a downstream node. While this procedure is in progress, light paths are removed from the data plane and all control plane states. The destination node then initiates the teardown process. The process begins by propagating a teardown message along the connection path, initiated by either source or destination node. Such a message is responsible for network re-configuration and update of the nodes database.

In this simulation model, a LSP is released according to a random interval after its establishment, while light paths are removed if they are not being used by LSPs. The Core router performs the light path teardown procedure as follows:

1. the core router will determine and verify that an unused light path is blocked. As a result, the connection is treated by the OSPF-TE routing protocol.
2. the OXC begins the teardown process after receiving a release request message from the core router.

3.8.5 Simulation Results Analysis

Meaningful output analysis involves using a validated simulation framework to derive information with which to draw robust conclusions on the efficacy of the new concepts proposed within the research. Consequently, the performance of the simulation at a steady state is core to this goal which necessitates the removal of the initial phase of simulation to yield accurate conclusions. This initial phase is usually referred to as the transient state (part) and identifying the ending of a transient state is referred to as the transient state removal. The main heuristic technique that is usually applied for transient state elimination is the ***moving mean of autonomous replications approach***, the mean determined over a moving time interval window rather than by calculating the overall mean [144][145].

Assuming m replications each of size n, let x_{ij} denote the j^{th} observation in the i^{th} iteration, where j varies from 1 to n across the time axis and i varies from 1 to m across the replications axis. The steps below summarize the method:

i. the mean trajectory is obtained by averaging the replications.

ii. a plot of a path or trajectory for the moving average of the successive $2k+1$ values, where k represents the moving time interval window is generate.

iii. step (ii) is repeated for different values of $k = 2, 3, \ldots$, until a smooth plot is obtained.

iv. the length of transient interval is obtained by finding the knee on this plot.

Figure 3.12 shows two different moving average trajectories; the second trajectory is smooth and hence, identifying the knee is straightforward.

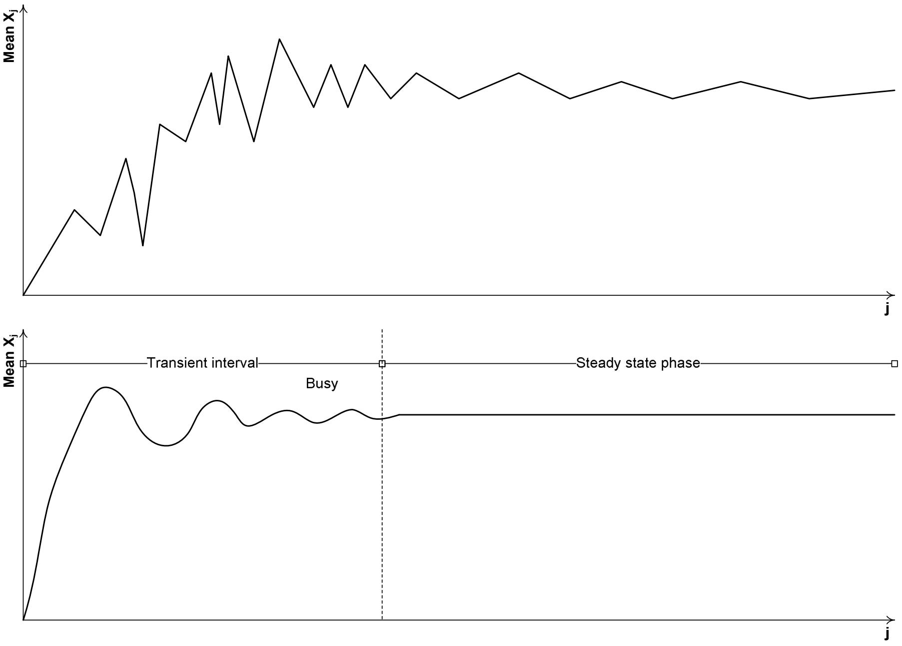


Figure 3.12: An example of autonomous replications for moving average.

3.8.5.1 Steady State Detection

The batch averages approach enables the simulation to run until an acceptable confidence interval is reached. In this approach, the long simulation run of (*n* + *n'*) is partitioned into *m* batches by removing the transient interval where *n'* signifies the transient interval length. The following steps are followed in this technique:

i. for each batch, the average is determined.
ii. after determining the average for all batches, the general average is then calculated.
iii. the variance of the batch means is then determined.

The confidence interval is then found as the summation of the entire mean and the variance. The size of the confidence interval is conversely proportional to square root of *mn*. Therefore, a stricter confidence interval can be achieved by either increasing *n* or *m* values.

3.8.5.2 Simulation Time and Number of Repetitions

The simulation time is a global variable that represents the simulated clock triggered by events. The simulation time should be appropriately chosen to guarantee a sufficiently accurate estimate of results. The simulation should be repeated with different seed (stream) values at each execution.

Assume that data is represented by V_1, V_2, ..., V_n where *n* is the number of data points; this approach creates an interval having a reasonably high and regulated probability of containing the true mean under specific assumptions given by the parameter α. In order to obtain the interval, the number of repetitions and a desirable confidence level should be given. Confidence interval estimation quantifies the confidence (probability) that the true (but unknown) statistical parameter falls within an interval whose boundaries are calculated using appropriate point estimates. The procedure to calculate the confidence interval is as follows [131][144][155][156];

Step 1: Calculate the sample mean $\left(\overline{\Theta}\right)$ using:

$$\overline{\Theta} = \frac{1}{n}\sum_{r=1}^{n} V_r \tag{3.1}$$

Step 2: Calculate the sample variance (S^2) using:

$$S^2 = \frac{1}{(n-1)}\sum_{r=1}^{n}\left(V_r - \overline{\Theta}\right)^2 \tag{3.2}$$

Step 3: Calculate the half width of the confidence interval using:

$$\text{Half width} = \frac{t_\alpha}{2}, n-1 \times \frac{S}{\left(n^{\frac{1}{2}}\right)} \tag{3.3}$$

and declare that the interval equals $\overline{\Theta} \pm \text{half width}$ where *α=(1-confidence level)* and $\frac{t_\alpha}{2}, n-1$ is calculated from the t-distribution table with *n-1* degrees of freedom.

It is desirable that the confidence interval is as small as it can possibly be. Thus, referring to Equation (3.3), the confidence interval is influenced by three key parameters:

i. The number of repetitions (n); increasing number of repetitions leads to a decreased confidence interval.
ii. The simulation time (T_E); a longer simulation time provides a better estimate of sample values V_1, V_2, ..., V_n, which reduces the sample standard deviation (S). Consequently, the confidence interval is also decreased.
iii. The confidence level (a design option); a decreased confidence level value produces a decreased confidence interval.

3.9 Model Verification and Validation

Verification is the assessment of the accuracy of the solution to a computational model. Verification relates to the process of determining that a model implementation accurately represents a conceptual description of a model and the solution to the model [146]; for instance, there are no bugs or simple mistakes in its procedures [147].

Normally validation of a computational simulation is done through comparison with experimental or practical data, determining the degree to which a model is an accurate representation of the real world from the perspective of the intended users of the model [146]. The general procedure for verification and validation of prototypes as well as the modelling process as recommended in [148] is show in Figure 3.13. The *Reality of Interest* denotes the physical systems for which data is being obtained and then their potential problem is studied. In some circumstances, the constraints can be divided and determined if they are a unit problem, component problem, subsystem or the complete system. Developing a *Conceptual Model* involves identifying the computational objective, the required level of agreement between experiments and simulation outcomes, the domain of interest, all important physical process and assumptions, the failure mode of interest, and the validation metric (quantities to be measured and the basis for comparison). Subsequently, the modeller constructs the *Mathematical Model* and the experimenter designs a *Validation Experiment*. The *Mathematical Model* is a set of mathematical equations intended to describe physical reality. The *Computer Model* is the implementation of the equations developed in the *Mathematical Model*, usually in the form of numerical discretization, solution algorithms and convergence criteria. Generally, the *Computer Model* is numerical procedure for solving the equations prescribed in the *Mathematical Model* with a computer code.

Uncertainty Quantification is performed to quantify the effect of all input and model form uncertainties on the computed simulation outcomes. Thus in addition to the model response, *Simulation Outcomes* include quantified error (or Confidence) bounds on the computed model response. *Code and Calculation Verification* assessments are performed on the Computer Model to identify and eliminate errors in programming, insufficient grid resolution, solution tolerances and finite precision arithmetic. A Code is the computer implementation of algorithms developed to facilitate the formulation and approximate solution of a class of model.

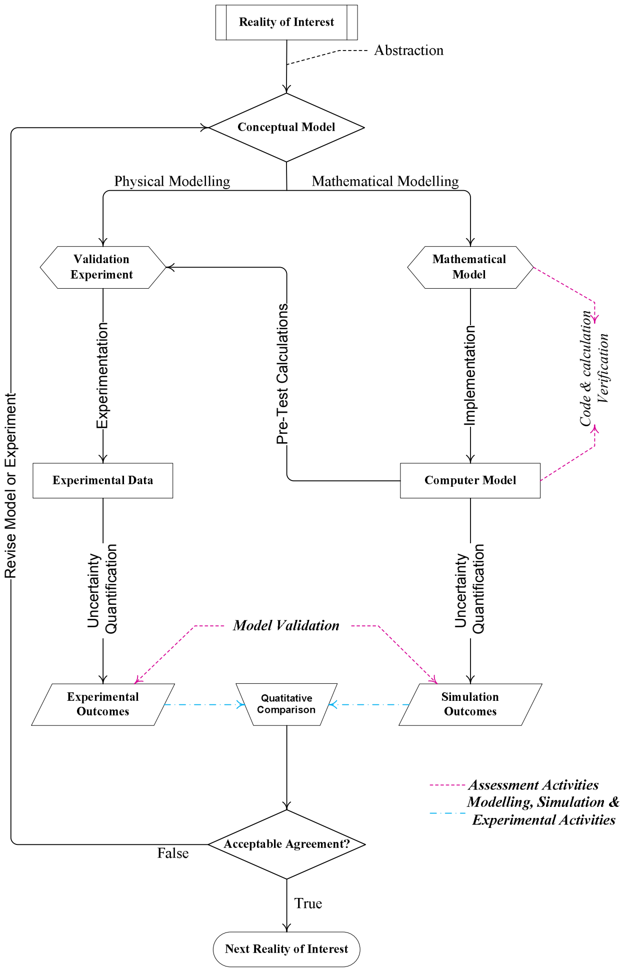


Figure 3.13: Model Development, Verification and Validation Process Flowchart [148].

The purpose of a *Validation Experiment* is to provide information needed to validate the model; therefore, all assumptions must be understood, well defined, and controlled. The *Pre-Test Calculations* link between the experimental and computational branches reflects the important interaction between the modeller and the experimenter that must occur to ensure that the measured data is needed, relevant, and accurate. Once the

Validation Experiment and Pre-Test Calculations are completed, however, the modeller and experimenter work independently until the point of comparing outcomes from the experiment and the simulation.

Table 3.2 provides input values/parameters for the simulation based analyses of the proposed network energy model. These assumptions are the foundation of the results generated throughout the Thesis. If at any time any assumption is modified, the new value will be cited.

Table 3.2: Model Assumptions and Parameters Used in the Simulation.

Parameter	**Value**
Capacity (B)	OC-192
Number of wavelength per link	8
Wavelength (λ)	1.55μm
Number of fibre/link	2 (bidirectional)
Fibre Propagation Speed	200000km/s
Control channel capacity	100Mbps
EDFA per fibre link	70 km
OXC reconfiguration time	1 ms
Wavelength conversion	Full wavelength conversion
Message Length per fibre link	2kbytes (=256 bytes x 8 λ)
Path / Reserve Message Processing Time	3ms
Other Messages Processing Time	1ms
Heat Flow Rate for 1kW	3413Btu/h
Noise Factor	5.7
IP/GMPLS Router Power Dissipate	10kW
OXC Power Consumption	100W
WDM Power Dissipate	120W
EDFA Power Output (minimum)	1 W
IP/GMPLS Router Energy Consumption	1000nJ/bit
OXC Energy Consumption	10nJ/bit
WDM Energy Consumption	12nJ/bit
EDFA Energy Consumption	0.1nJ/bit
Traffic Distribution	uniform
GMPLS Signalling Type	RSVP-TE
Connection Request	100000

3.9.1 Simulation Model Validation

The most important step in determining the value and accuracy of the simulation results is to ensure that all models have been validated. The verification and validation of the simulation models for core optical IP networks is performed using following approaches:

1. The simulation model functionality is thoroughly tested and the functions debugged offline using tools provided by OMNeT++ during model implementation. At this stage, the debug process ensures those functions operate correctly.
2. Check-up; functions are embedded into the simulation environment observed throughout the simulation e.g. verification that the programming code and OMNeT++ Tkenv Graphical User Interface (GUI) are functioning correctly.
3. Test of an example network with a simple topology consisting of two nodes and running simulations under verifiable scenarios/events. Examination of and tracing of the packet (LSP and light path) and signalling messages. Then, validation of the outcome of each simulation against expected results.
4. Optical IP networks designated to transport IP traffic in a WDM-enabled optical network has been studied extensively; published performance data and simulation results applied to some well-known networks topology exists. Therefore, results generated are compared to well-known networks and energy saving studies. Verification and validation with published results is a powerful means of validation.

3.9.2 Model Traffic Generation

The traffic model was assessed through several mechanisms to ensure traffic flows are distributed randomly, including verification of the generated traffic trace, the length distribution and the error rate. Figure 3.14 presents the mean holding time (*h*) and the mean of arrival rate (λ) showing that the simulation models are consistent with the analytical (theoretical) values, corroborating that the traffic generator is giving expected results.

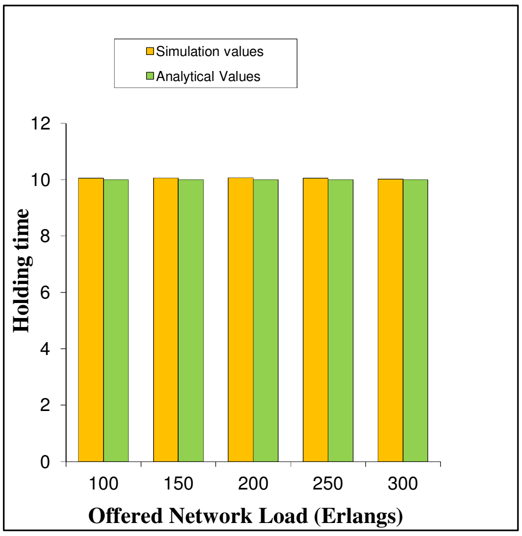


Figure 3.14: (a) Holding time versus offered load.

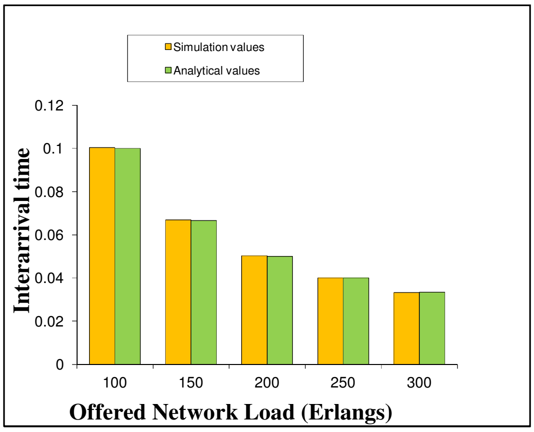


Figure 3.14: (b) Inter-arrival time versus offered load.

Figure 3.14: The model inter-arrival time and average holding time comparison with analytical values.

3.9.3 Energy Saving Duration

The Finite State Machine (FSM) is an important component within the energy saving model, playing a key role in determining state transitions from the ON to the OFF state. Figure 3.15 demonstrates the FSM ON-OFF process model assuming finite variance distributions for the ON and OFF periods where both ON/OFF are two independent processes. The model treats the ON, Hibernation Mode (HM) and OFF states.

At the beginning of the simulation, all links and wavelengths are free. LSPs are only generated during the ON state following a fixed inter-arrival time. The ON state represents active traffic activity, returning to *Busy* on the ON condition. When a request arrives during the ON state, the LSP request moves the node state to HM by triggering *Resv_Confirm.*

Consider the energy saving duration pattern shown in Figure 3.15. The Hibernation *inter-activity interval (OFF State)* is defined as:

$$T_H = \sum_{path-node}^{n} \left(\delta T_s + \tau_{off} + \delta T_w \right) \tag{3.4}$$

and

$$\left(\delta T_s + \delta T_w \right) < T_H \tag{3.5}$$

where

δT_s Non-zero Suspending interval

τ_{off} Powered OFF period

δT_w Non-zero Wake-up interval

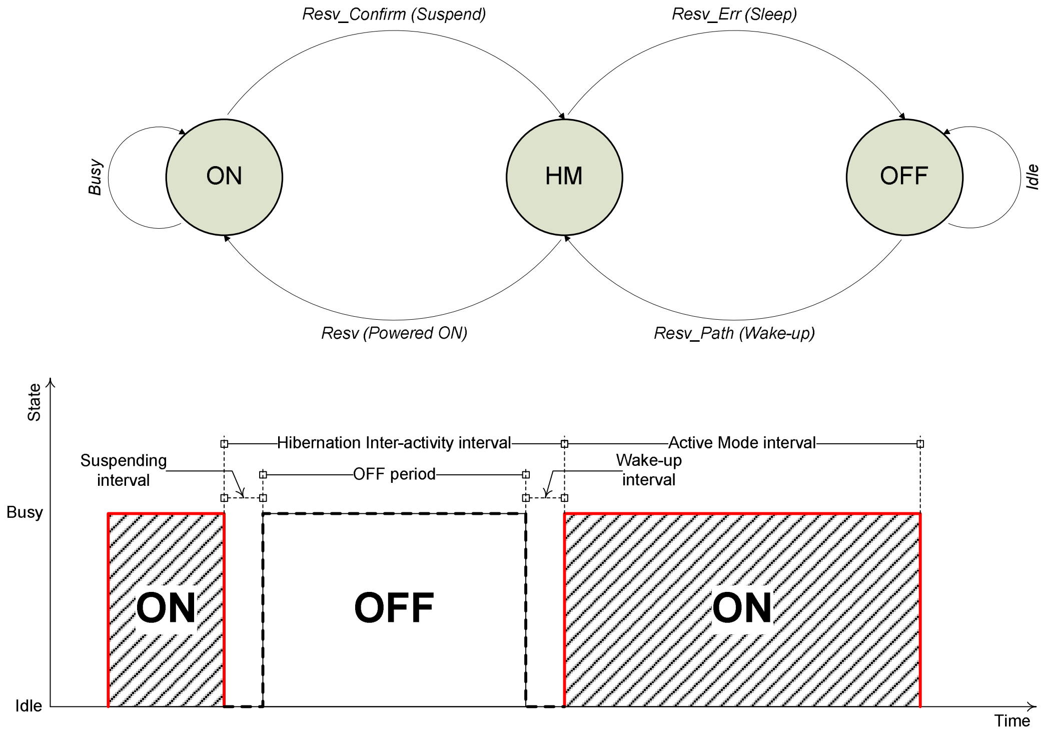


Figure 3.15: Energy Saving Duration Process.

If the variables δT_s and δT_w are independent and specified as $\left(\delta T_s + \delta T_w\right) < T_H$, then it is possible to turn off network equipment and save energy with no increase in delay (or by increasing refresh time for the *Path* and *Resv* messages).

However, since in the optical core network provisions high link capacity, and when the variables δT_s and δT_w are small i.e. $(\delta T_s + \delta T_w) \rightarrow 0$, they are assumed to be negligible.

3.9.4 Signalling Protocol

This section explains the signalling functionality including the message delay, control plane database, and data plane connectivity.

3.9.4.1 Message Delay

The message delay is the time taken to traverse each fibre link from source to destination node comprising link delay and nodal delay; the former consists of propagation and transmission delays whilst the latter consists of queuing and processing delays.

Propagation Delay corresponds to the latency in the propagation of a packet for the first bit along the link from source to destination node and is a function of the link distance and propagation speed n.b. the propagation speed in the fibre optic system is approximately 2 x 10^8 meters/second;

$$T_p = \frac{l}{V_f} \tag{3.6}$$

where

T_p = Propagation delay

l = Link length

V_f = Link propagation speed

Transmission delay represents the time required to place data onto a link, determined by link capacity and message size:

$$T_d = \frac{P_s}{C} \tag{3.7}$$

where

T_d = Transmission delay

C = Link capacity

P_s = Message size

Nodal processing delay denotes the time between the arrival of message at an input node port and the time the message is transmitted to the output port, including the time taken to process a message and to calculate a new route as well as the wavelength switching time. It is assumed that the processing time is not considered when a message is to be delivered to an adjacent node, since the signalling and routing units are not involved.

An LSP in GMPLS requires bi-directional connectivity in order to establish the signalling. Therefore, the delay required for establishing a bi-directional connection is equal to the summation of these contributions. The total delay for setup the bidirectional connection can be expressed as:

$$T_j = \tau_{PATH} + \tau_{RESV} \tag{3.8}$$

where

T_j = Total Delay

τ_{PATH} = *Path* message delay

τ_{RESV} = *Resv* message delay

Assuming that a source is transmitting messages along link *L* to a destination through *N* nodes, the delay for the message to traverse along the link is as follows:

$$T_j = \sum_{i=1}^{2L} \left(T_p^L + T_d^L \right) + \sum_{i=1}^{2N-1} T_s^N \tag{3.9}$$

where

T_j = Total Delay

T_p^L = Link propagation delay

T_d^L = Link transmission delay

T_s^N = Node processing delay

3.9.5 Model Routing Protocol Validation

In this section, simulation results of routing protocol functionality are presented as a verification of operation. The main aim is to investigate the impact on performance parameters network connectivity, number of wavelengths per link and wavelength capacity. In addition, during the simulation process, a selected interface/port and light path are tested by monitoring the traffic or mirroring the port; tools are embedded in the kernel model for this purpose.

3.9.5.1 Effect of Network Connectivity

The model is tested in various network topologies with all fibre links of the same length (1000 km) (Figure 3.16). The key performance metric is the probability of blocking which provide the ratio of the number of rejected connections over the number of requested connections. Figure 3.17 shows the probability of blocking as a function of the numbers of links. As expected, the blocking ratio declines as connectivity is increased.

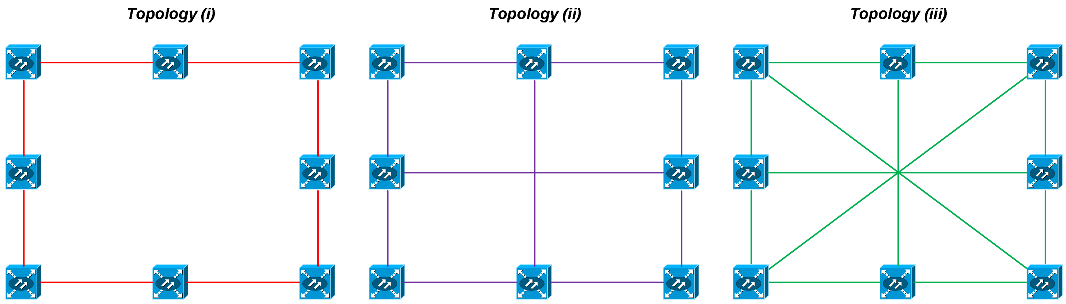


Figure 3.16: Examples of network topologies.

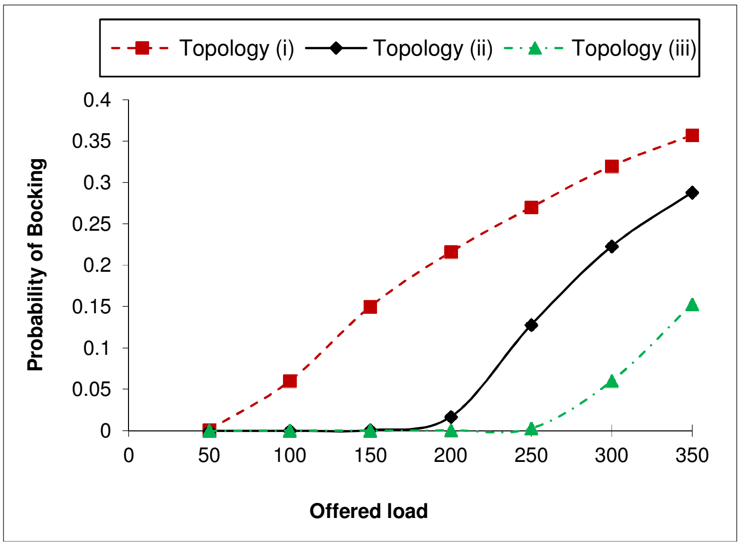
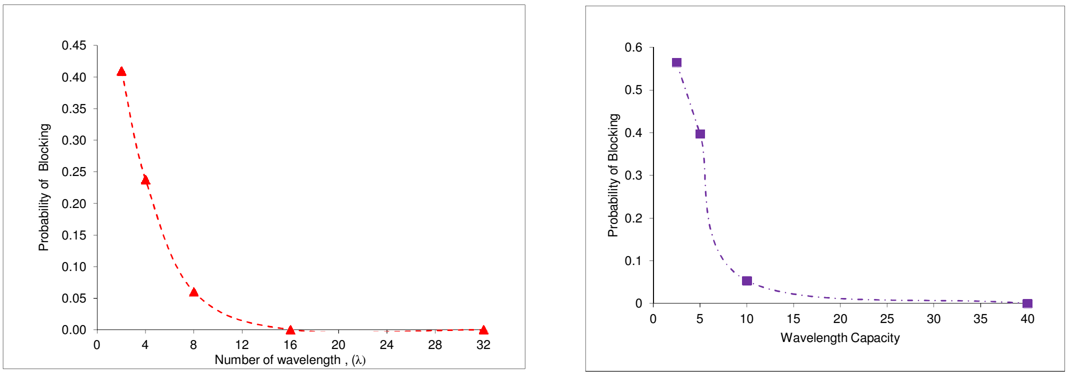


Figure 3.17: A performance comparison between various network topologies and the probability of blocking.

3.9.5.2 Effect of Number of Wavelengths and Light path Capacity

The aim of this section is to validate the impact on the network as a function of the number of wavelengths and light path capacity as a function of topologies. In the following simulations, it is assumed that topology 3 is adopted at the same network load value (300 Erlangs). The first simulation investigates the impact of the number of wavelengths per link. Figure 3.18(a) illustrates the blocking probability as a function of the number of wavelengths; as expected, the blocking ratio declines significantly as the number of wavelengths is increased.

The second test investigates the performance in terms of blocking probability as the wavelength capacity increases. Figure 3.18(b) illustrates the blocking probability as a function of wavelength capacity; as expected results show that a significant reduction in blocking probability can be achieved by increasing wavelength capacity.



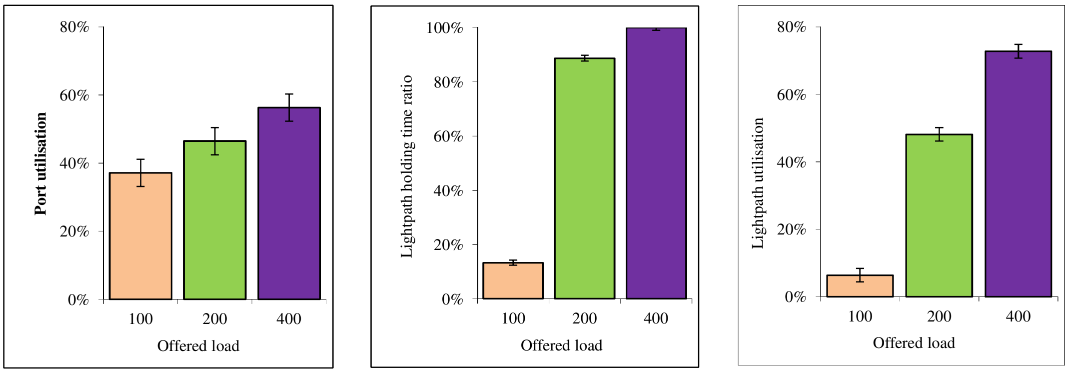
(a) (b)

Figure 3.18: Blocking probability performance as a function of: (a) wavelengths per fibre link, (b) Wavelength capacity.

3.9.5.3 Monitoring a Selected Light path and Port

This simulation investigates the effect of traffic load on an existing light path. Two performance parameters are investigated: light path utilisation and holding time ratio. The former represents the mean of used capacity within the selected light path divided by the total wavelength capacity whilst the latter defines the ratio of existing holding time of the selected light path to the total simulation time. The first simulation presents the effect of the traffic load on the operation of a selected port, determining its utilisation. This percentage is defined as the mean of the number of used wavelengths divided by the maximum number of wavelengths at that port. Figure 3.19(a) illustrates the percentage as a function of traffic load, showing that significant utilisation of ports can be achieved when the offered load is increased.

Figure 3.19(b) presents the holding time ratio of a selected light path as a function of traffic load. The simulation describes that light paths remain at a low utilisation during low offered load; Figure 3.19(c) exhibits the utilisation of a selected light path as a function of offered load, clearly demonstrating that when offered load escalates, the utilisation of a light path increases.



(a) (b) (c)

Figure 3.19: Testing for various load values in terms of lightpath utilisation: (a) a selected port utilisation, (b) a selected lightpath holding time ratio (c) a selected lightpath utilisation.

3.9.5.4 Erlang B Test

The blocking probability P_b is determined by using the Erlang-B formula [16][149][150][151]. Given that offered load equals A and the number of wavelengths is λ gives:

$$P_b(A,\lambda) = \frac{\frac{A^{\lambda}}{\lambda!}}{\sum_{i=0}^{\lambda} \frac{A^{i}}{i!}} \tag{3.10}$$

3.10 Summary

This Chapter details the simulation framework established using the OMNeT++ platform for the performance analyses of distributed Optical IP networks. The framework was explained in terms of structure, functionality and implementation. Several fundamental network functionalities were simulated to validate, verify and to build confidence in model behaviour and underpinning assumptions. The strategy behind the use of a GMPLS control plane is to broadcast information on network states and to decide, based on the collected information, the most suitable routing policy that minimizes energy consumption whilst limiting the impact on network performance.

The implemented framework is the foundation for evaluating and comparing energy efficient schemes. The following Chapters present a series of network performance characterisations for a hierarchy of hibernation mode implementations utilising the validated framework presented.

Chapter 4

Power Reduction Strategy using Hibernation Mode: Group-Node

4.1 Introduction

The Internet provisions convenient ways to entertainment, social interaction, information, and conducting business. These rapidly expanding network based activities result in power consumption increases and consequently novel *greener* concepts are gradually being implemented, innovative approaches that offer better energy conservation [1][49]. Innovations are considered *green* if they:

- generate or help to conserve energy
- help to reduce greenhouse gas emission;
- help to reduce pollution leading to improvements in public health.

Here approaches to reducing power consumption and increasing the energy efficiency via optimisation of network power management through enhanced control implemented as an extension of the GMPLS control plane, are proposed and evaluated. The impact of one strand of the methodology, the grouping of nodes following a hibernation strategy is considered firstly; an evaluation of a number of node grouping strategies in terms of power saving and network performance are executed.

This Chapter is organised as follows: Section 4.2 describes the network energy model in terms of node grouping and the corresponding implementation is presented in Section 4.3. Section 4.4 describes of the hibernation mode concept in general defining the group, segment and partition dimensions. Section 4.5 explains the hibernation mode group-nodes distribution factor. Section 4.6 describes the physical hibernation mode: group-nodes in terms of topology distribution whilst Section 4.7 presents an evaluation of the power consumption improvements owing to this methodology. Finally the Chapter is concluded.

4.2 The Energy Model For Optical IP Networks

In order to evaluate overall network power consumption and the consumed energy per bit of transmitted data, an *equivalent network energy model* (Figure 4.1) is used specifically for Internet Protocol/Generalized Multi-Protocol Label Switching (IP/GMPLS) over optical layers. In the model, a network carrier bandwidth of OC-192 and average energy consumption of 1019nJ per bit was assumed after [51][69][104]. G_n (Figure 4.1) denotes a power dissipation of 10kW within a router and energy consumption of 1000nJ/bit; X_n represents an Optical Cross-Connect (OXC) dissipating 100W and consuming10nJ/bit.

W_n denotes the Wavelength Division Multiplexing (WDM) element of the node dissipating power of 120W at an energy consumption of 12nJ/bit.

A_n represents the consumption owing to Erbium-Doped Fibre Amplifiers (EDFAs) placed at 70km intervals within links and their power consumption is estimated to be 1W with energy of 0.1nJ/bit.

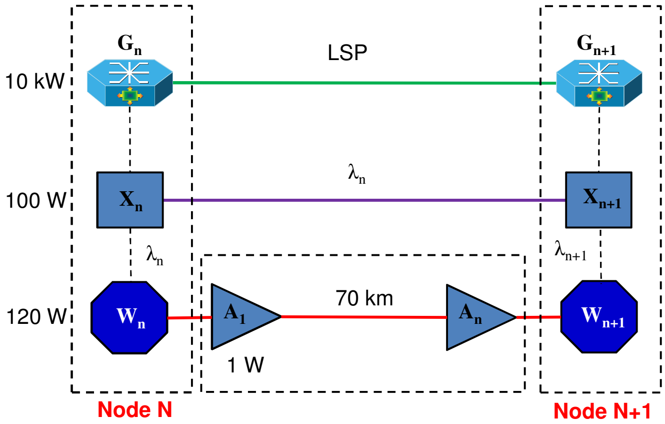


Figure 4.1: Green Optical Network Model. G_n stands for the n^{th} Generalized Multiprotocol Label Switching Router, A_n is n^{th} Erbium Doped Fiber Amplifier (EDFA), X_n represents the n^{th} Optical Cross-Connect (OXC), and λ_n is the n^{th} wavelength / lightpath.

4.2.1 Power Consumption

The energy per bit consumed by the node is defined as;

$$E_b = \frac{P_T}{C} \tag{4.1}$$

where P_T represents the node total power consumption and C is the data rate offered over the network link.

The total power consumption of the link can be defined as:

$$P_T = P_g + P_x + P_a + P_w + P_{tr} \tag{4.2}$$

where P_g, P_x, P_a, P_w, and P_{tr} represent the power consumed by the IP/GMPLS router, OXC, EDFA, WDM and transmitter respectively.

4.2.2 Energy per Bit

The total energy per data bit, E_{bit} needed to support the network offered load is defined as:

$$E_{bit} = \frac{\sum_{j=1}^{n} \left[P_g + P_w + P_{tr} \right]_j}{C} + \sum_{k=1}^{n} \left[\varepsilon_a + (\rho + 1)\varepsilon_x \right]_k + \delta \tag{4.3}$$

where

ε_a is the energy consumed by EDFA in node k;

ε_x	is the energy consumed by the node's OXC in node k;
δ	represents the noise factor associated with the Bit Error Rate (BER) and a heat transfer rate in network equipment [118];
ρ	is number of hops;
n	is the number of nodes.

4.3 Towards Better Network Energy Efficiency

The IP/GMPLS intelligent control plane can be configured to perform power aware routing through network data traffic management and control [51][69].

Figure 4.2 depicts IP/GMPLS within a Wavelength Routing Node (WRN) comprising the IP/GMPLS control plane, Optical Cross-Connect (OXC), Erbium-Doped Fiber Amplifiers (EDFAs) for in-line amplification, transmitter Tx, receiver Rx, and a 40 channel Wavelength Division Multiplexing (WDM) multiplex operating at OC-192 (~10 Gb/s) respectively.

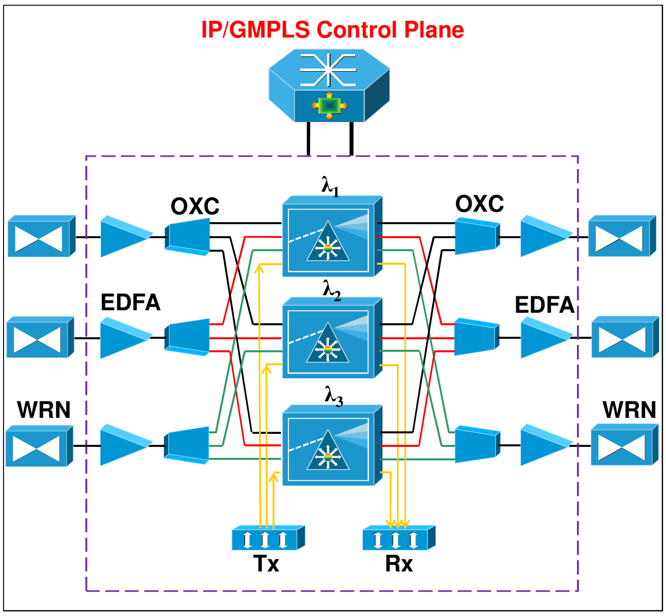


Figure 4.2: IP over optical networks with intelligent control plane. Here OXC represents an optical cross connect, WRN - wavelength routing node, Tx - transmitter, Rx i- receiver, EDFA – erbium doped fibre amplifier.

4.3.1 Network Energy Efficiency

An energy efficient system design implemented within control plane is elaborated through the Finite State Machine (FSM) sequence of Figure 4.3.

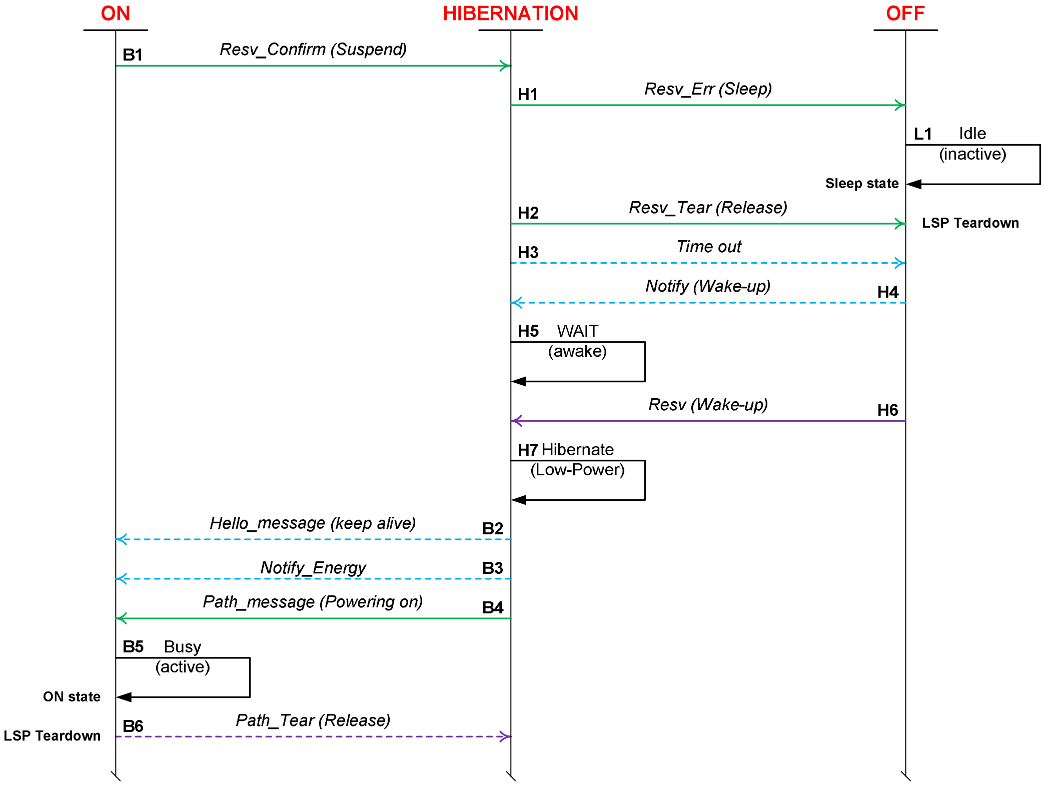


Figure 4.3: Finite State Machine (FSM) for power management.

A detailed description for each FSM state and transition are:

<u>State ON:</u> the Optical IP network is operating in Active mode.

Transition B1: LSP exchange of messages between states. LSP receives and accepts (*Resv_Confirm*) to suspend the node. The node advertises through messages of the change in condition from active to hibernation state.

Transition B2: Establish a connection by sending *Hello_Messages* to ascertain that the node is "kept active" for a particular period.

Transition B3: Trigger a *Notify_Energy* message to inform the node to move from Hibernation mode to Active state.

Transition B4: Send *Path_Message* to exit the Hibernation state; the node is preparing to enter the ON state.

Transition B5: the Node is in active mode operating at full power consumption.

Transition B6: the node exits from ON state to hibernation mode by releasing the *Path_tear* message.

State Hibernation: Network operation is suspending activities and enters low power mode.

Transition H1: Send *Resv_Err* message to enter OFF state.

Transition H2: Transmit *Resv_Tear* message to release LSP and the connection is torn down.

Transition H3: Node propagates the calculated inactivity time-out request setting up to time value of 5ms (time-out threshold to prevent link "flapping") with 3 retrial (to avoid network topology changes) response intervals (15ms response time in total).

Transition H4: Generate LSP *Notify* Message to report Node in transition to Hibernation state.

Transition H5: Transmit a *GOTO Resv_Tear* message. The node is waiting to receive either a *Notify* message or *Resv* wake-up message from an adjacent node or for the retrial timer to expire. The node is operating in hibernation mode i.e. lowest power consumption.

Transition H6: Receives an Acknowledgement through a *Notify* message. Send *Resv_message* confirming the node is waking-up from the Sleep state. Node is in the process of transitioning from the OFF to the Hibernation mode.

Transition H7: The Sleep timer starts while node is in Hibernation state. Node is placed in Low Power operation.

State OFF: Network is in the idle OFF mode.

Transition L1: Node becomes inactive since the network status is idle. The timer retry has expired and the request is OFF mode.

4.4 Description of The Hibernation Concept

The formal definition of the "Hibernation mode" H^m assumes IP/GMPLS nodes within the optical network:

$$H^m \in \sum_{\forall pqr}^{n} \left[\Psi_p \cup \Phi_q \cup \Omega_r \right] \tag{4.4}$$

$$H^m \in \bigcup_{i=1}^{n} \left[\Psi_p \Phi_q \Omega_r \right]_i \tag{4.5}$$

where the variables are defined as:

m	represents a particular configuration of the “hibernation mode” with node groupings Ψ_p, link segmentations Φ_q, and wavelength partitionings Ω_r.
Ψ_p,	represent individual groups of network nodes $\Psi_p=\{\Psi_1,\Psi_2,\Psi_3,..,\Psi_p\}$; $\Psi_p \in \alpha_u,..,\alpha_{u-1}$
Φ_q,	represent segments of network links $\Phi_q=\{\Phi_1,\Phi_2,\Phi_3,..,\Phi_q\}$; $\Phi_q \in \delta_v,..,\delta_{v-1}$
Ω_r	represent wavelength partitionings $\Omega_r=\{\Omega_1,\Omega_2,\Omega_3,..,\Omega_r\}$; $\Omega_r \in \lambda_w,..,\lambda_{w-1}$
α	represents network nodes.
δ	represents network links.
λ	represents wavelengths.
p	integer numbers representing number of groups ranging from 1 to the total number of node groups.
q	integer numbers representing segmentations ranging from 1 to the total number of segments.
r	integer numbers representing partitionings ranging from 1 to the total number of partitions.
u	integer numbers representing the number of nodes
v	integer numbers representing the number of links
w	integer numbers representing the number of wavelengths

Integer numbers p, q, r, and u, v, w represent the number of groups, segments, partitionings, nodes, links, and wavelengths, respectively and range from 1 to the total number of node groups, segmentations or partitionings, respectively. The number of nodes depends on the size of the network; the number of segmentations depends on the number of connections in the network; and the number of partitionings is determined by the number of wavelengths within the given links.

Power saving implemented using “hibernation mode” approaches define a “sleep mode” for the IP/optical network nodes. Figure 4.4 illustrates the hibernation mode as a function of grouping the nodes, link segmentation and partitioning of wavelengths.

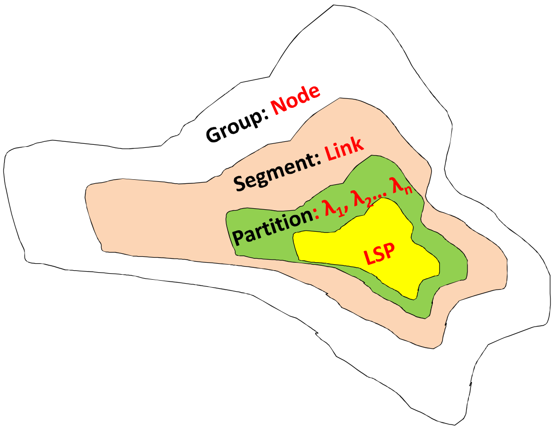


Figure 4.4: Hibernation mode configurations as a function of group (node), segmentation (link) and partition (wavelength).

Power consumption was evaluated by executing the following three steps:

First a **Grouping** (H^{Ψ}) was performed; network nodes were sorted into different groups either based on their proximity ("geographical grouping") or based on "node ownership" by various providers across the network.

Second, identified idled links were shut down to invoke additional energy conservation by a process referred to as **Links Segmentation** (H^{Φ}).

Third a **Partitioning-Lightpath** (H^{Ω}) was implemented to further optimise energy consumption by tearing down all idle light paths within the node link(s) and also by sub-grouping based on network activity status.

4.4.1 Group and Segmentation Structure

Hibernation mode operation and set-up are shown in Figure 4.5. The algorithm begins with an evaluation of power consumption, energy per bit and heat transfer rate parameters for each network element. In addition, the network controller evaluates network performance metrics such as throughput, traffic load and blocking probability which are then correlated with the power consumption data.

At this stage, if the network management wishes to enable the hibernation mode, three options based on available network resources and a Shortest Path First (SPF) computation can be executed. If the network controller located in the GMPLS control plane detects any idle nodes (no traffic activity), these nodes are grouped into a hibernation mode. The group can then be set to the OFF state and the system can immediately disable designated nodes. When the node detects any traffic or becomes active, the network controller may attempt to reduce energy consumption by identifying idle links; this option is known as the segmentation configuration. Here, the network resource identifies any idle links to be shutdown. Once the shutdown links are determined, the network will be configured to aggregate the idle links connected to the same node/destination. If all links are active, the partitioning configuration can be triggered. In this process, any idle wavelength (λ_n) will be identified for power down. The process is repeated at intervals as deemed appropriate by the network operator.

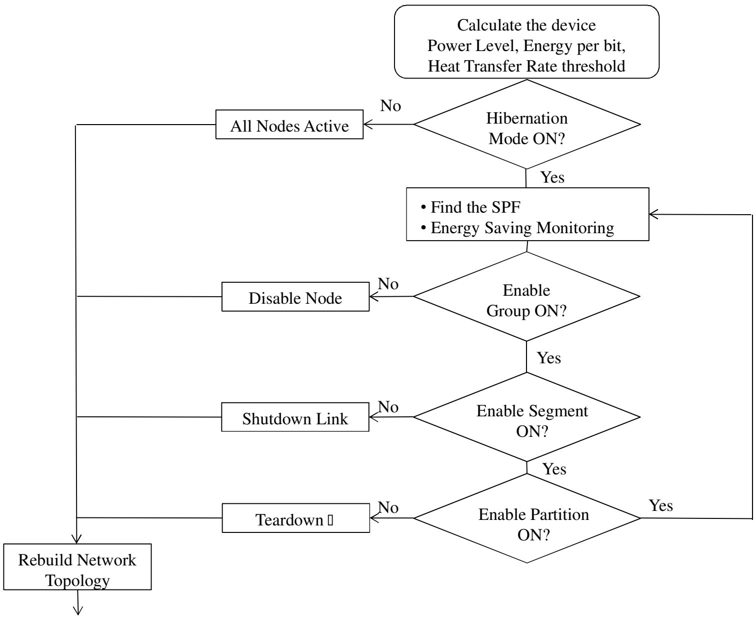
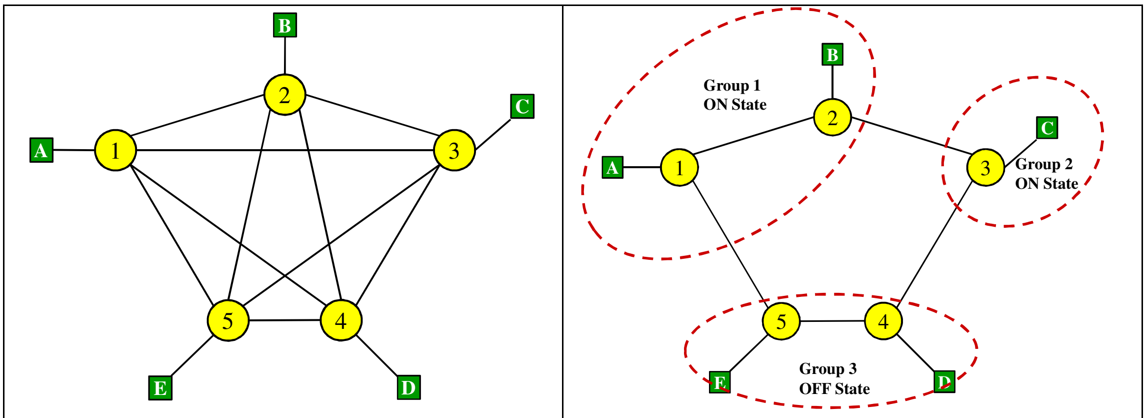


Figure 4.5: A flowchart for the hibernation mode options.

4.4.2 Hibernation Mode Structure

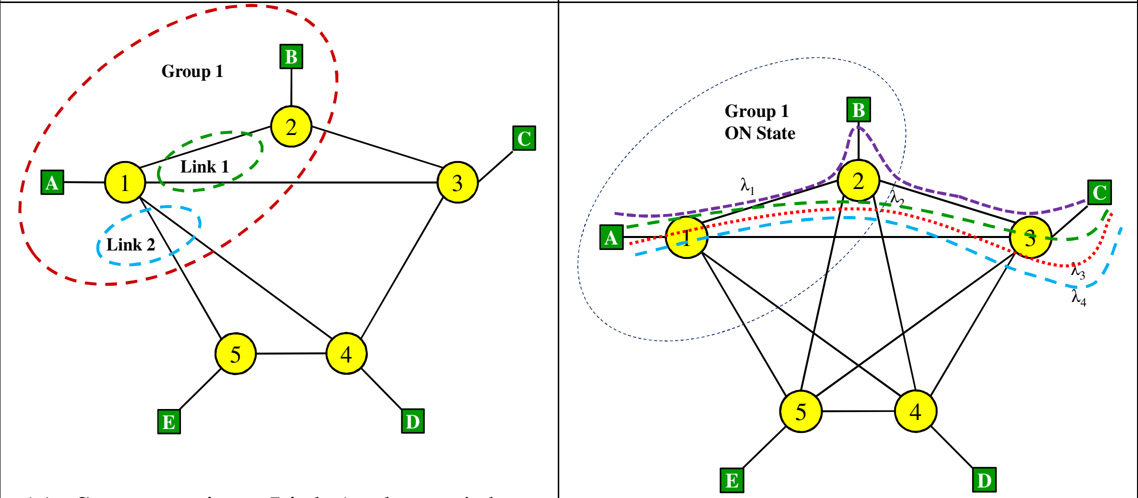
Provisioning options can be identified as shown in Figure 4.6. Figure 4.6(a) demonstrates hibernation in OFF state or Group in ON state; as illustrated the nodes are denoted as A, B, C, D, E and Optical Nodes as 1, 2, 3, 4, 5, respectively. Figure 4.6(b) shows the hibernation group option executed at the Node level (Network Equipments) only. Figure 4.6(c) shows the hibernation segmentation option in which idle links are grouped. To ease understanding, highlighting Group 1 as an example of a Group which is in active status or ON state, the Network Controller (NC) determines that within the connection between Node 1 and Node 2, Link 1 is active and Link 2 is inactive (no traffic). To reduce energy, the Control Plane (Network Controller) issues a message to shut down Link 2. Note that in Optical Networks, although Node 4 and Node 5 are disabled (shutdown), the connection on Link 2 is still dissipating energy since EDFAs within WDM are always enabled and switched on.

Figure 4.6(d) illustrates the hibernation partitioning option. Since Group 1 (Node 1, Node 2) and Node 3 are in the ON state, light paths have been established from Node 1, Node 2 and Node 3. Once the Network Controller establishes the status of the link indicating that both λ_1 and λ_2 are active wavelengths while λ_3 and λ_4 are inactive, in order to minimize the energy consumption on that link, the Controller powers down λ_3 and λ_4.



(a) "ON" State – Full Mesh Physical Topology

(b) Grouping : Node (idle)



(c) Segmentation : Link (wake up / shut down)

(d) Partitioning : Wavelength (Virtual Topology)

Figure 4.6: Hibernation Modes.

4.5 Hibernation Mode; Group Nodes Distribution Factors

The Group Node structure in relation to the hibernation mode is illustrated in Figure 4.7. In this architecture, nodes consisting of IP Router and OXC are interconnected by point-to-point optical fibre links.

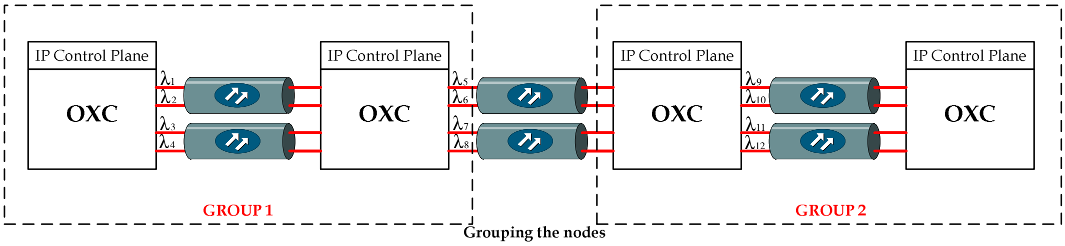


Figure 4.7: Hibernation Mode: Grouped Nodes Structure.

The exchange of messages updating energy consumption profiles can be described by a sequence diagram; Figure 4.8 illustrates the messages sequence diagram for the transition from ON to OFF state. For end-to-end provisioning - from ingress to egress node - after path computation, the wavelength is reserved by signalling. Node 1 transmits a connection request along the link to reserve the wavelength and establish an end-to-end channel through the *LSP Path/Resv Message*. The LSP setup request is then forwarded to the next node until the message request is at the egress node. If there is an idle node at an intermediate node (in this case Node 3), after the nested hold-off timer expires, the hibernation notification message is propagated back along the path to release the reserved wavelength. The loopback LSP *Resv_Confirm* message will be transmitted back along the link until at the ingress node to request the suspension of the idle node. If Node 3 receives a LSP setup request message to place the node in *Sleep* state, it sends a *Resv_Err* message to acknowledge the ingress node that Node 3 is in powering off state. As a result, the network updates the routing table and TED topology. The ingress node releases a LSP by propagating *Path_Tear* message and powers down the connection to the idle node.

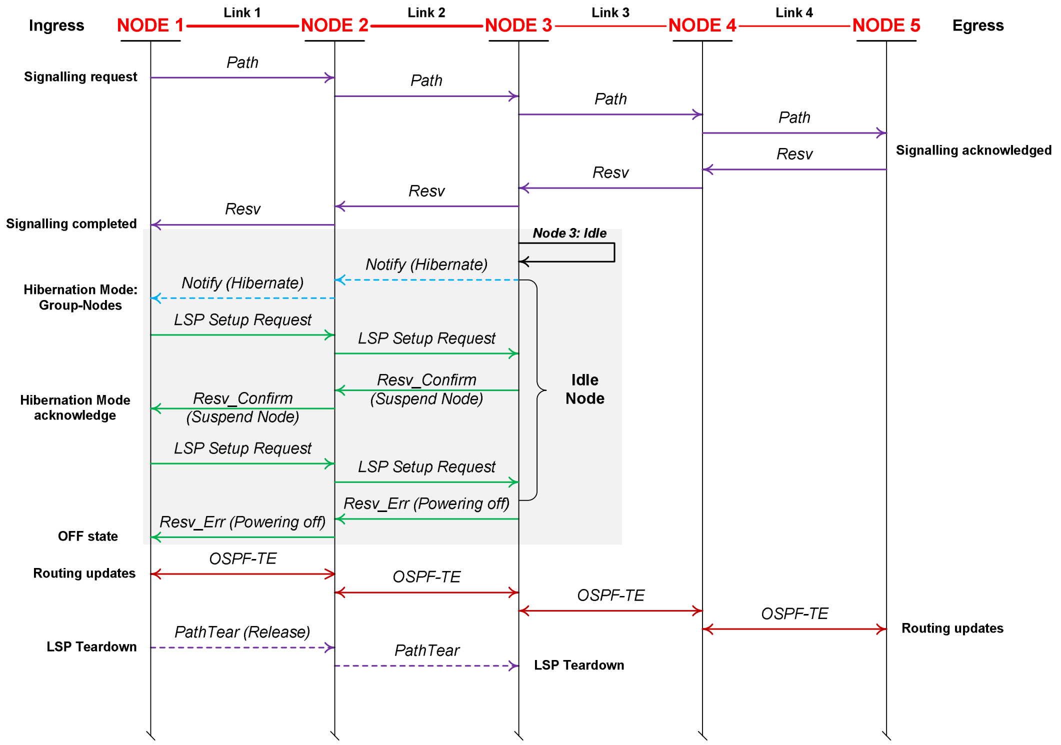


Figure 4.8: Messages Sequence Diagram for transition from ON state to OFF state of Hibernation: Group-Nodes.

Figure 4.9 presents a message sequence diagram for the transition from OFF state to ON state. Node 3 detects traffic and changes its state to BUSY (active transition state) and full power operation is resumed, confirmed by sending a notify message to inform the adjacent node that it is in the process of waking-up. A *Resv_Tear* message is sent to the ingress node to notify that node is powering to ON state.

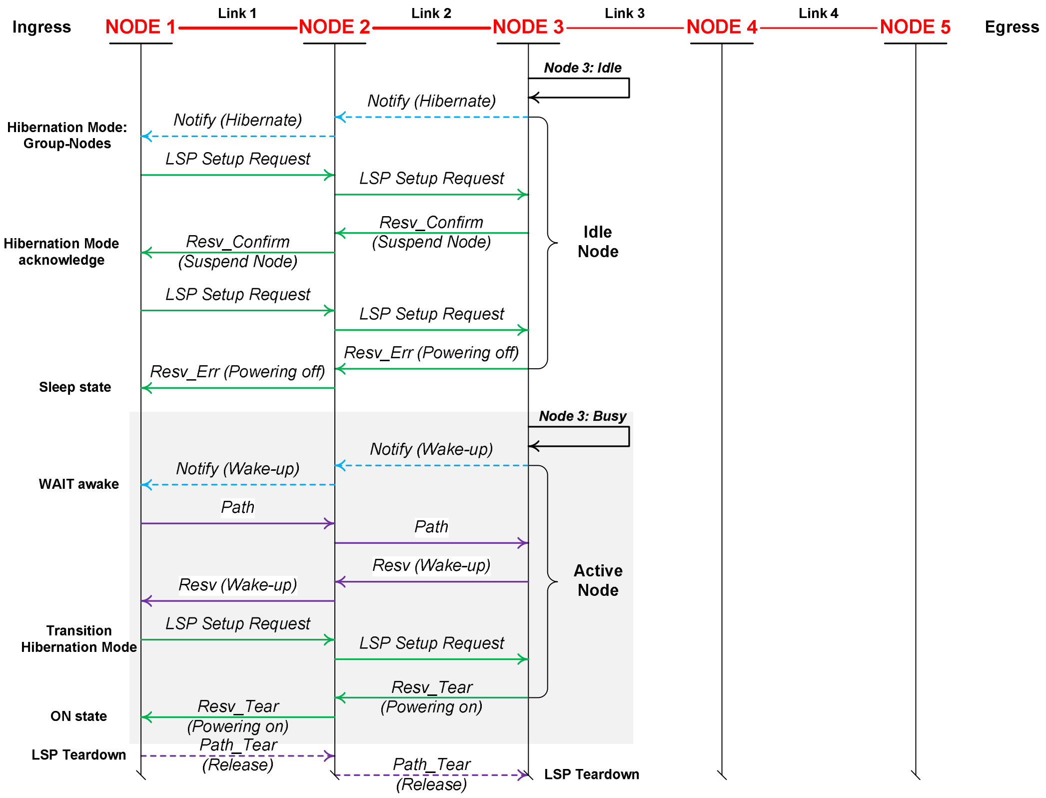


Figure 4.9: Messages Sequence Diagram for transition from OFF state to ON state of Hibernation: Group-Nodes.

4.5.1 Fixed (Geographical) Nodes Effect

Fixed node or Geographical Node groups are defined as a grouping topology that contains selected neighbouring nodes and grouped as disjoint clusters.

4.5.2 Random (Ownership) Nodes Effect

Random node or Ownership-based node groupings are defined as nodes belonging to the same owner (service provider) e.g. organization that having many entities under the same company name.

4.6 Power Saving Using Optical Bypass

Optical IP networks have the capability to optically bypass the OXC through reconfiguration at intermediate nodes, in so doing reducing the level of electronic processing at the core router with a concomitant lowering of the power consumption (Figure 4.10). For example, in this figure, Ingress Node receives the *Request Message* reservation to transmit a message to the Egress Node through an intermediate Node. The request message is transmitted on Light path λ_2 to OXC (via a WDM transponder). Light path λ_2 is then converted to Light path λ_3 (via a wavelength converter) to maintain wavelength continuity. At the Intermediate Node, power saving is achieved via optical bypass; Light path λ_3 traffic is not electronically processed at intermediate nodes, thereby minimizing the number of electronic ports (core router) necessary. At the egress node, Light path λ_3 is add-dropped at the core router for message acknowledgement.

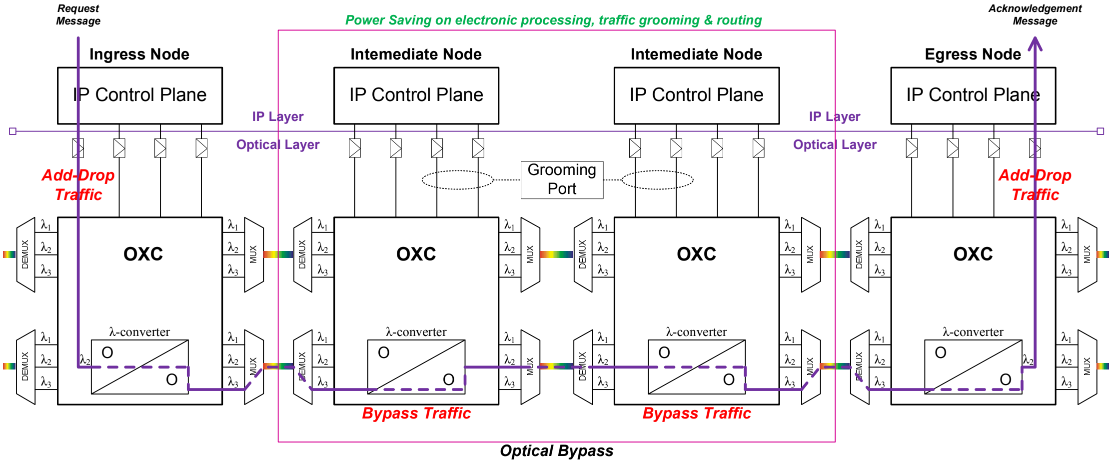


Figure 4.10: Optical bypass for power saving in optical IP networks.

4.7 Hibernation Mode; Group Nodes Variance with Topology Distribution

The two network topologies implemented to analyse energy consumption using hibernation modes are;

- Partial Mesh Network Topology: National Science Foundation (NSFnet) (Figure 4.11). The average power and energy consumption values assigned to each node are captured in the network energy model detailed in Section 4.2. In this case, the power consumption of nodes comprises the core router (10kW), OXC (100W), WDM (120W) and EDFAs (1W) at 70km intervals along links. (A further illustration of the NSFnet topology is provided in Appendix A). For example, the power consumption (reference value) between Node E and Node M (Figure 4.11) linked by single mode fibre optic across a distance of 3400km (Figure A.1: Appendix A) at a data rate of 10Gb/s is obtained by summing the power consumption of each element viz. 48W. Therefore, the total power consumption between Node E and Node M is 10.268kW and the energy per bit is 1026.8nJ (Equation 4.1).

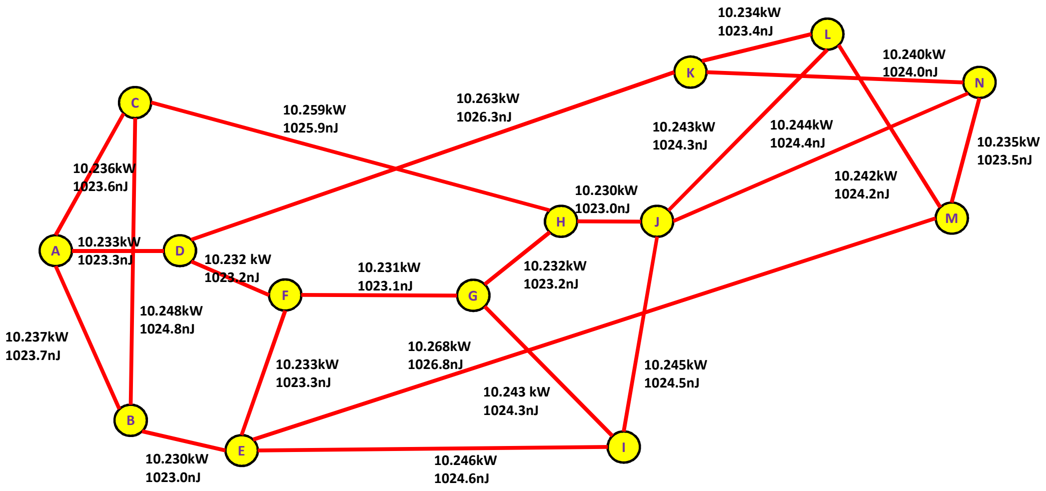


Figure 4.11: National Science Foundation (NSFnet) network.

- Full Mesh Network Topology: European Optical Network (EON) (Figure 4.12). Similarly, the average power dissipation and energy consumption values assigned to each node are captured in the network energy model detailed in Section 4.2. In this architecture, the power consumption of nodes comprises the core router (10kW), OXC (100W), WDM (120W) and EDFAs (1W) placed at 70km intervals along links. A further illustration of the EON topology is provided in Appendix A. For example, the power consumption (reference value) between Node A and Node G (Figure 4.12) linked by the single mode optical fibre across a distance of 2090km (Figure A.1: Appendix A) at a data rate of 10Gb/s is 29W. Therefore, the total power consumption between Node A and Node G is 10.249kW and the energy per bit is 1024.9nJ (Equation 4.1).

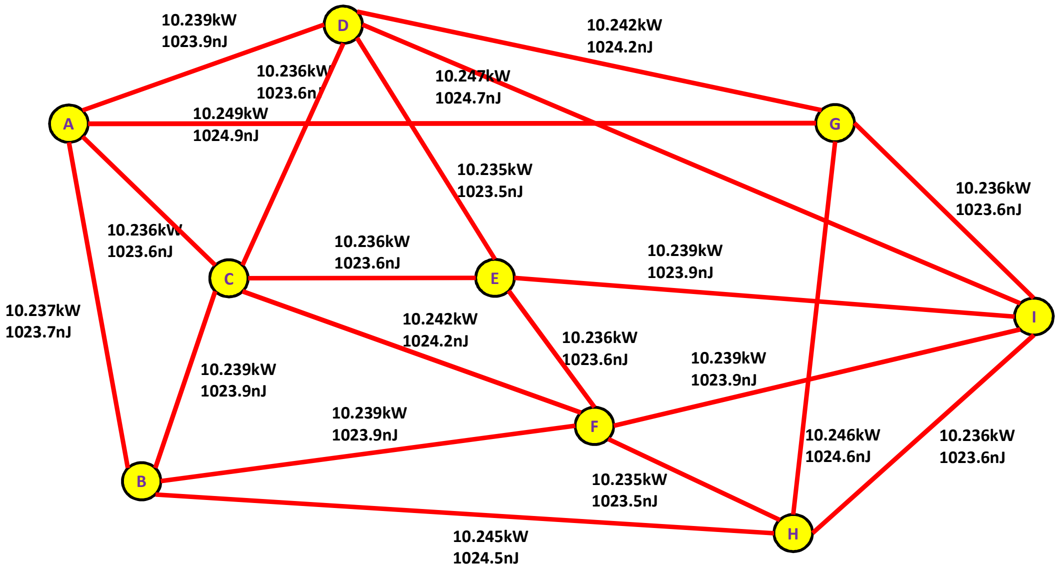


Figure 4.12: Power saving for European Optical Network (EON).

4.8 Power Consumption

The assumptions for the evaluation of power consumption are;

- that all IP/GMPLS nodes within the studied optical networks are linked by bidirectional pairs of single mode fibre,
- that each message length is fixed at 256 bytes per wavelength (or 2kbytes per link or 256 bytes x 8 wavelengths)(Table 3.2),
- that all links support an equal number of wavelengths (eight),
- and the nodal processing delay is 20ms.

All other general network parameters used in the simulations are taken from [53][57][116][118][157].

For NSFnet hibernation settings are applied to nodes based on the group membership type; these node grouping categorizations are presented in Table 4.1. The groups within transparent optical IP networks comprise transparent *islands (several sub-domains).* Two Nodes Groupings were considered: Geographical (containing selected neighbouring nodes) and Ownership-based (nodes in a given group belonging to the same owner).

Table 4.1: NSFNET Nodes Grouping Categorization.

Group	***Geographical***	***Ownership-based***
G1	Nodes{A,B,C,D}	Nodes {B,D,I,N}
G2	Nodes {E,F,G,H,I}	Nodes {A,F,H,K,M}
G3	Nodes {J,K,L,M,N}	Nodes {C,E,G,J,L}

In the analysis, the following hibernation settings were considered (ON/HM); ‘HM’ stands for Hibernation Mode on the following groups of nodes: “All Groups = ON”; “All Groups = HM”; Group “G1 & G2”; Group “G2 & G3 = HM”; Group “G1 = HM”; Group “G2 = HM” and Group “G3 = HM”. The combination of the node groupings are based on fair distribution of nodes numbers and nodes degree of freedom (number of links on each nodes).

Note that the Hibernation mode is activated (ON) when groups and segments are set to the Sleep state i.e. nodes disable their unused ports/interfaces, Mux/DeMux capabilities, signalling gates, unused wavelengths, etc., but maintain the minimum required network functions, monitoring whether nodes and links are in the idle states or whether there is active traffic in the given part of the network.

4.9 Results

Table 4.2 presents the assumptions pertaining to all the simulations in the following analyses. If any assumption is changed, the new value is presented.

Table 4.2: The basic model assumption.

Factors	***Assumptions***
Active (ON) links	Uniform [1,L] where L is number of links.
Mean of Power "ON" inter-arrival time	50 time units with the assumption that the energy consumption occurs at the steady state.
Mean of energy saving time	10 time units with the assumption that the energy saving time is generated after the energy drained occurrence time.
Number of energy saving	The simulation is repeated until the required confidence interval is achieved.

Two simulation performance metrics were determined and verified for each topology considered;

1. the suitable load
2. the steady state

Other network performance metrics such as blocking probability, network utilization, average power consumption, wavelength assignments, connection requests and number of nodes will form the basis of comparisons.

4.9.1 Power Saving Evaluation of Different Schemes

The aim is to evaluate the impact of a route to energy saving through hibernation in core optical IP network by performing the Fixed (Geographical) grouping and Random (Ownership) grouping for partial and full mesh network topologies. Note that, these results are based on *cross-layer optical/IP domain integration* and previous research produced results based in the *optical domain only*. Therefore, results are difficult to compare in terms of power savings and network performance.

Figure 4.13 illustrates the difference in average power consumption for various "Geographical Node groupings" as a function of offered network load; Figure 4.14 displays the corresponding blocking performance of the network under the same conditions. The blocking probability at the IP layer represents packets lost during data transmission.

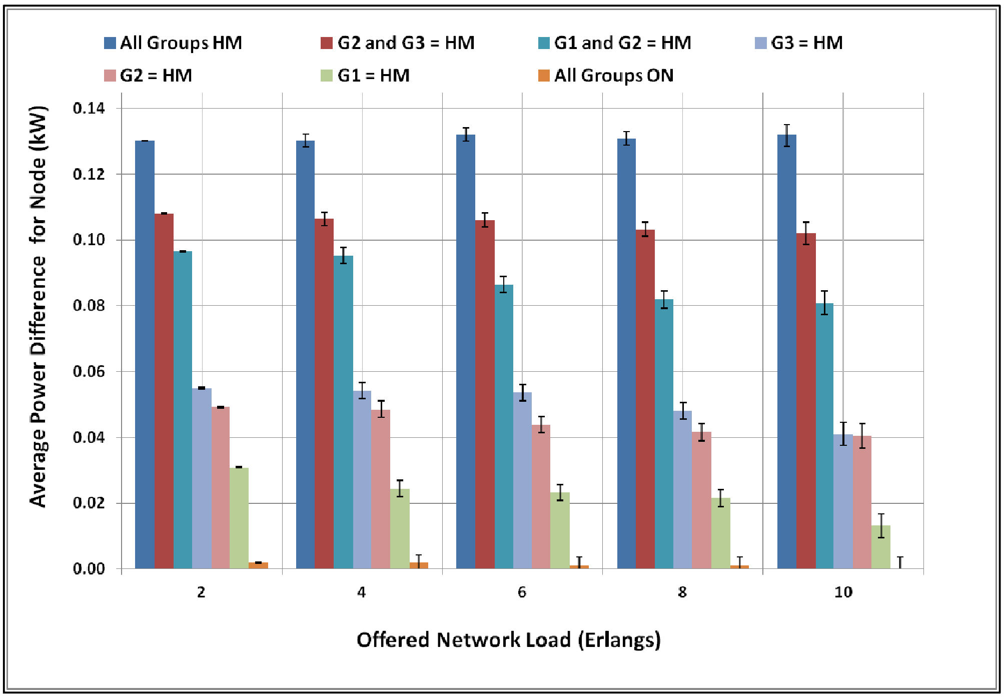


Figure 4.13: Power saving for different NSFNET Fixed (Geographical) Node groupings. 'HM' stands for Hibernation Mode.

In the case of "All Groups = HM" (case of de-activated node functionalities viz. in hibernation mode as described above) ~0.135kW or ~3% of power is saved (Figure 4.13) but the probability of blocking rises to ~70% (Figure 4.14), which is unacceptable.

In this situation, network operation is placed in the minimum low power consumption impacting traffic flows significantly.

For Groups “G2 & G3 = HM” or alternatively groups “G1 & G2 = HM” the ‘power saving per node is 0.10kW (~2%) and 0.090kW (~1.7%), respectively (Figure 4.13); the corresponding blocking probability is 50% or 10%, respectively (Figure 4.14).

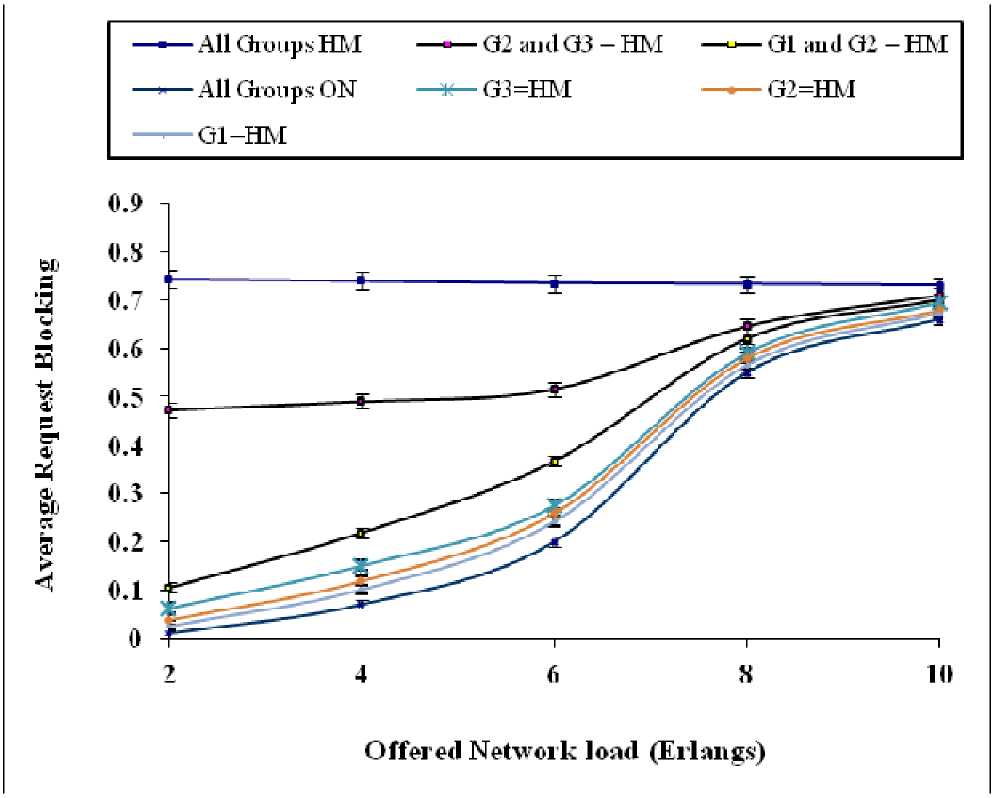


Figure 4.14: Request blocking for NSFNET Fixed (Geographical) grouping of nodes.

The total number of connection requests that are available is the network offered load (Figure 3.9) denoted in Erlangs (The unit is dimensionless). Note that, the arrival connection requests follow an independent Poisson process with an arrival rate of α and the queue lengths are exponentially distributed with an expected service rate time of 1/μ (in seconds). Therefore, network offered load (A) is product of mean arrival time and mean holding time ($A=\lambda*h$). Traffic intensity is product of network traffic load (N_L) and network capacity ($\gamma=N_L*C$) expressed in bits per seconds).

In the case of the "Ownership-based" node groupings (Figure 4.15 and Figure 4.16) for "All Groups = HM" and "All Groups = ON" deliver similar results as the Geographical node groupings. However, for the case "G2 & G3 = HM" the Ownership-based configuration yields a decreased blocking probability (~41%) whilst offering 0.11kW of energy savings (Figure 4.15).

In cases when Group "G1 = HM", or Group "G2 = HM", or Group "G3 = HM" the probability of blocking is below ~10% (Figure 4.16) thus delivering a better network performance but the power reduction/saving per node is minimal (~1%) (Figure 4.15).

For "All Groups = HM" the power consumption although reduced is not an option and is best viewed as a reference condition since the network does not deliver traffic. The case of "All Groups = ON" is also viewed as a reference as it indicates the network capability in terms of traffic delivery; for an offered load between 0 to 6 Erlangs the blocking is minimal (better than 80%); the network becomes congested when offered load is over 8 Erlangs.

In case of "G1 & G2 = HM" the blocking probability rises to ~55% as the traffic load grows from 2 to 8 Erlangs.

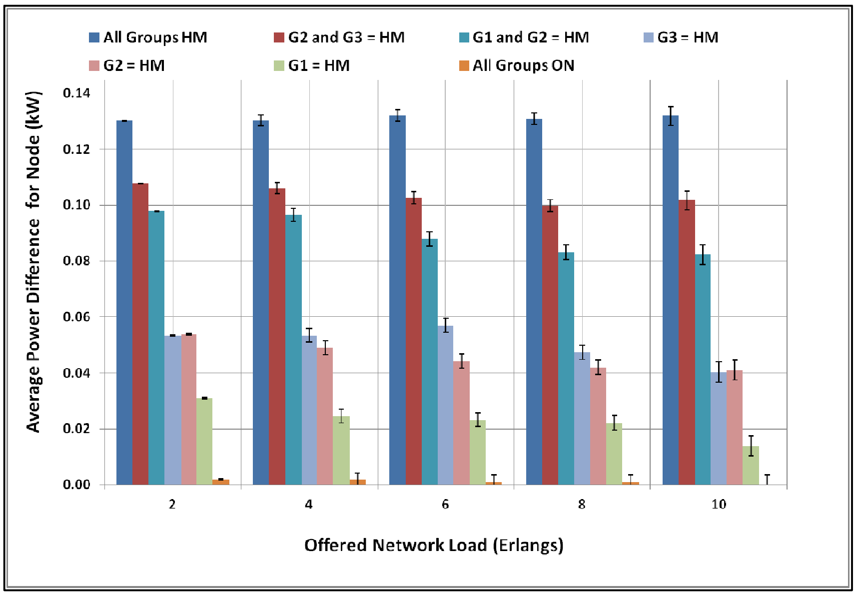


Figure 4.15: Simulation results for different NSFNET Random (Ownership) based Nodes grouping scheme. `HM' stands for Hibernation Mode.

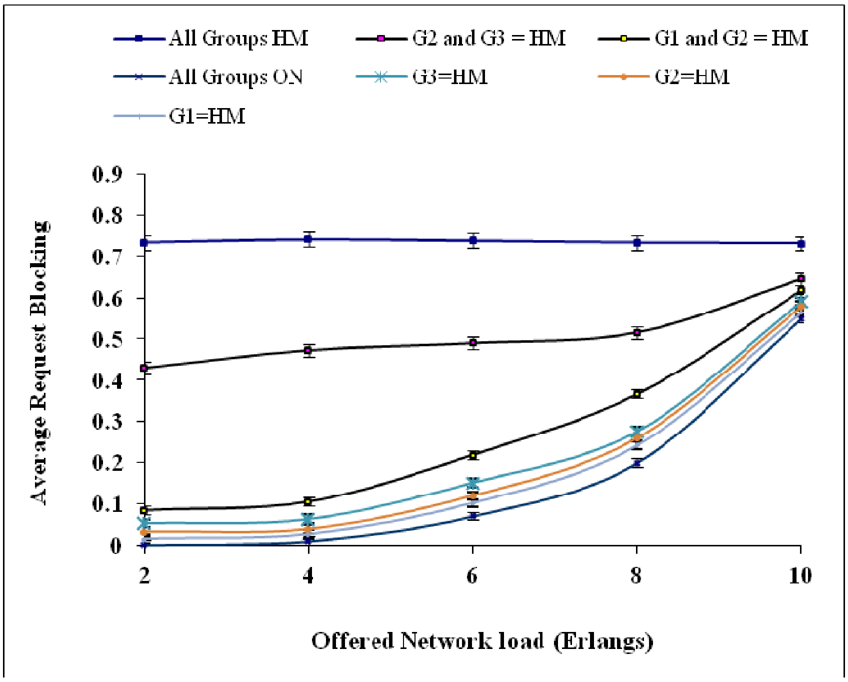


Figure 4.16: Request blocking for NSFNET Random (Ownership) grouping of nodes scheme.

In general for both groupings, the following can be concluded:

- NSFnet network becomes congested at an offered network load in excess of 8 Erlangs.
- a trade-off exists; as energy consumption decreases the blocking probability increases.
- network operators are able to select a balance between energy savings and network performance
- IP routers are assumed to be always 'ON' to maintain network operation which does not reduce significant power consumption. However, the optical domain is the layer which dominates the potential savings on power consumption.

A similar analysis was executed for a full mesh topology optical IP network represented by the European Optical Network (EON). All EON network nodes are assumed to maintain information on the total power consumption as well as energy per bit consumed.

The proposed Hibernation concept was evaluated by implementing groups defined as follows: $\Psi_1 = G_1 = [A, B]$, $\Psi_2 = G_2 = [C, D, E]$, and $\Psi_3 = G_3 = [F, G, H, I]$. These groups placed into "hibernation" or an "Sleep state", in which nodes suspend their unused functionalities (e.g. unused ports / interfaces, Mux/DeMux capabilities, signalling gates, unused wavelengths, etc.) and keep only minimum network operation functionalities.

Figures 4.17 and Figure 4.18 present the average power consumption and average request blocking for various "Geographical" (adjacent nodes) groupings as a function of offered network load for the EON network mesh topology. For "All Groups HM" (case when nodes' unused functionalities are suspended) ~0.137kW of power is saved per node' (Figure 4.17) but the probability of blocking is ~55% (Figure 4.18). For Groups

"G2 and G3 = HM" or Groups "G1 and G2 = HM", the power savings of 0.12kW or 0.10kW is obtained respectively (Figure 4.17) with a corresponding blocking probability of 33% or 10%, respectively (Figure 4.18).

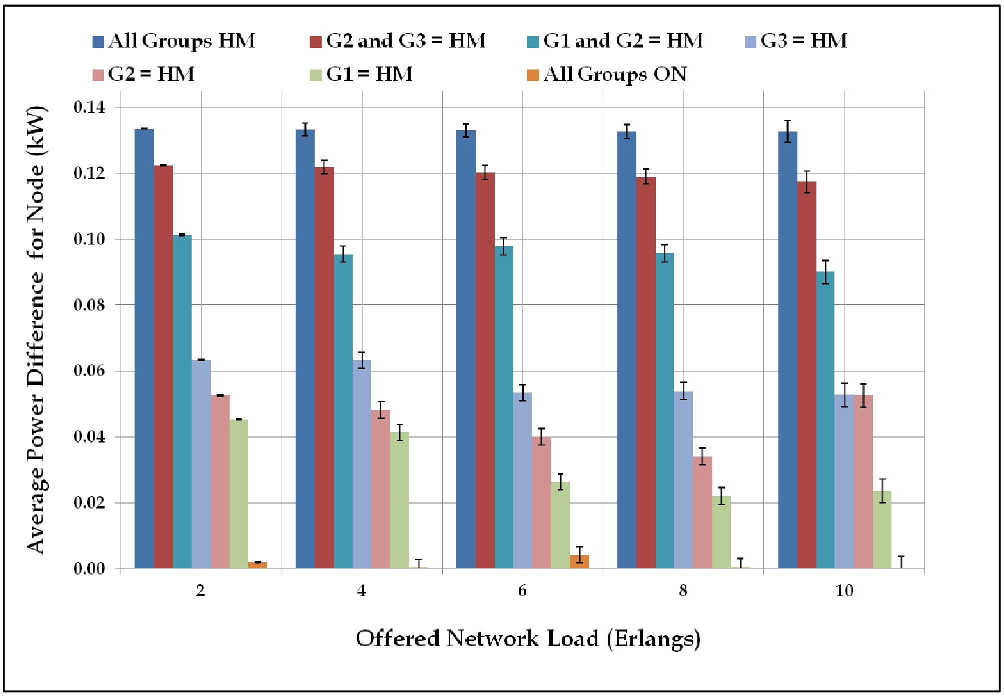


Figure 4.17: Simulation results for different EON Fixed (Geographical) Node groupings. 'HM' stands for Hibernation Mode.

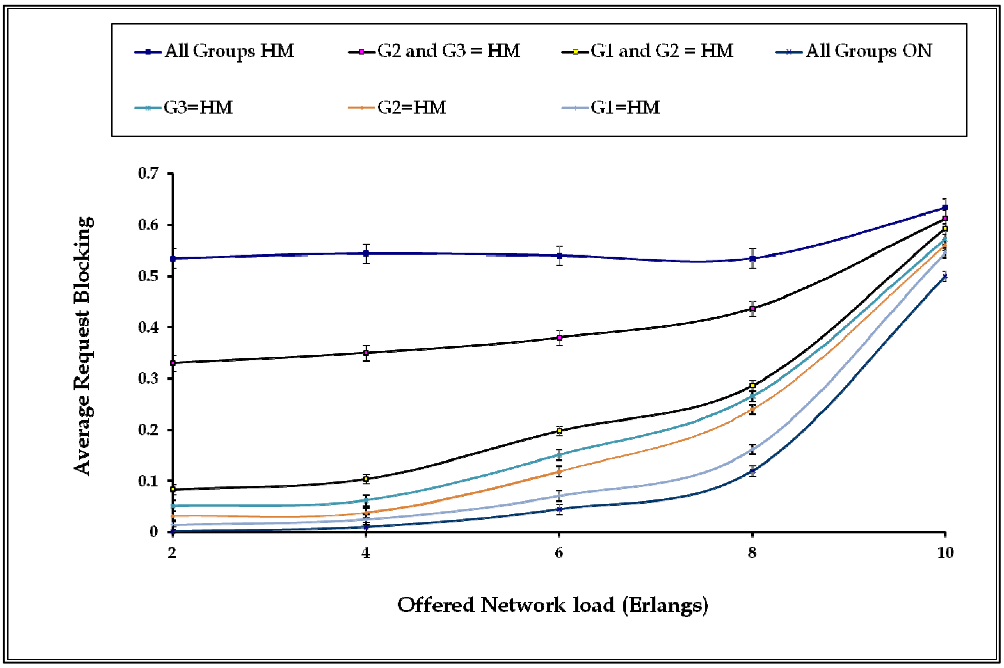


Figure 4.18: Request blocking for EON Fixed (Geographical) grouping of nodes.

"All Groups ON" yields the lowest blocking probability but the power savings per node are minimal. The EON network also becomes congested for network loads exceeding 8 Erlangs. The trade-off between a reduction in energy consumption and the probability of blocking is evident.

Figure 4.19 depicts the average power consumption for different groups with respect to offered network load and Figure 4.20 presents the blocking probability for the EON ownership (random) grouping of nodes. As expected, savings in power with ownership grouping in the full mesh (EON) topology improves when compared to the partial mesh (NSFnet) topology, particularly in the case of ownership grouping. In this case, the power savings for grouping "G2 and G3" or "G1 and G2" are most significant, the improvement being ~0.135kW and ~0.11kW respectively (Figure 4.19); the corresponding blocking probability is 29% and 8%, respectively (Figure 4.20). The reason for this is that the optical bypass at intermediate nodes reduces the number of required core router electrical ports in the IP layer and thereby, the energy owing to this electrical equipment is saved. The EON ownership-based node groupings (Figure 4.17

and Figure 4.19), “All Groups = HM” and “All Groups = ON” deliver similar results as the geographical node groupings.

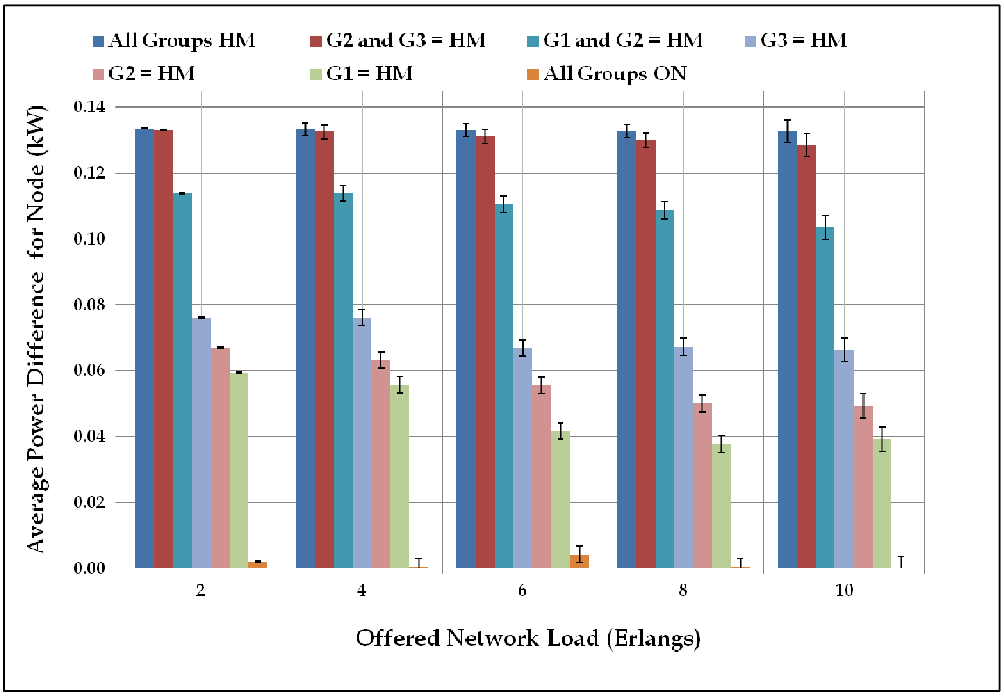


Figure 4.19: Average power consumption difference per node as a function of network load for different EON random (Ownership) node grouping.

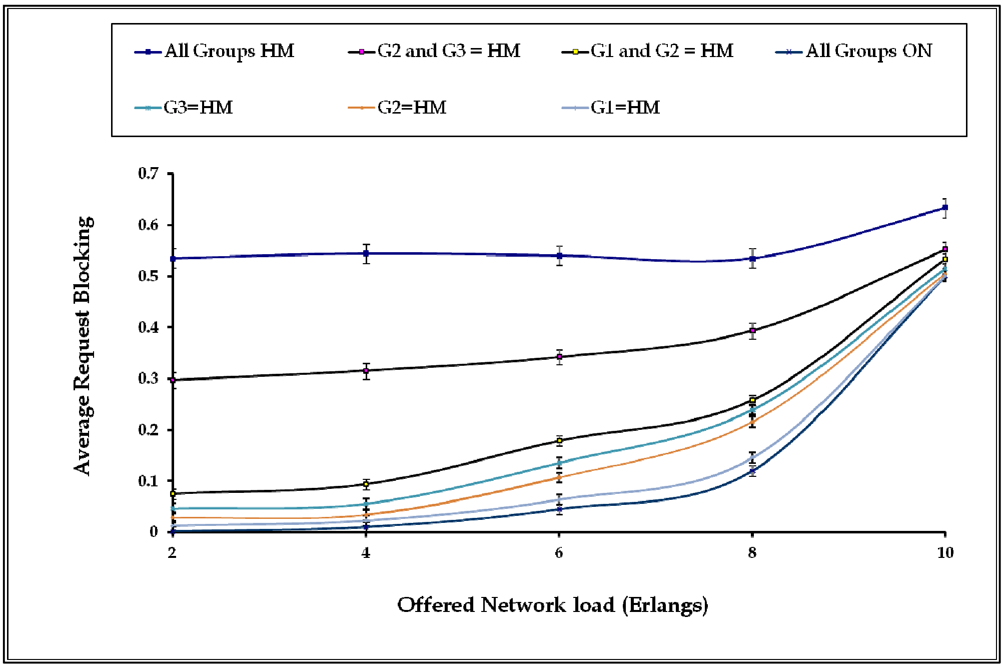


Figure 4.20: Request blocking probability as a function of network load for EON random (Ownership) grouping of nodes.

4.9.2 Power Consumption Evaluation; Network Metrics

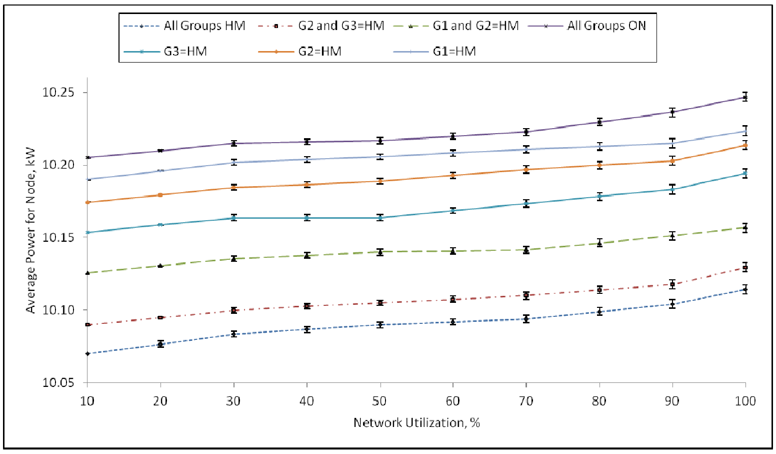
Using the full mesh EON (Figure 4.12), hibernation settings are applied to network nodes based on the group membership type (see node grouping categorization in Table 4.3).

Table 4.3: EON Node Grouping categorization.

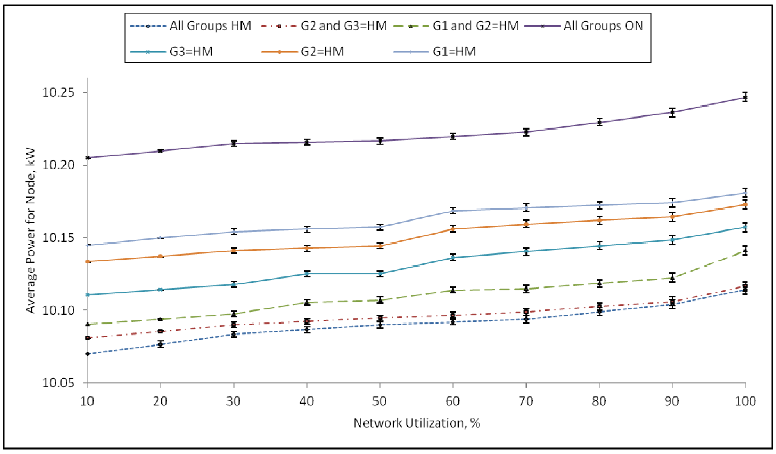
Group	Geographical	Ownership-based
G1	Nodes {A,B}	Nodes {B,H,}
G2	Nodes {C,D,E}	Nodes {D,E,G}
G3	Nodes {F,G,H,I}	Nodes {A,C,F,I}

4.9.2.1 Network Utilization

Figure 4.21 presents the power consumption as a function of network utilization for both geographical and ownership groupings.



(a) EON geographical (fixed) node grouping scheme Power consumption as a function of network utilization.



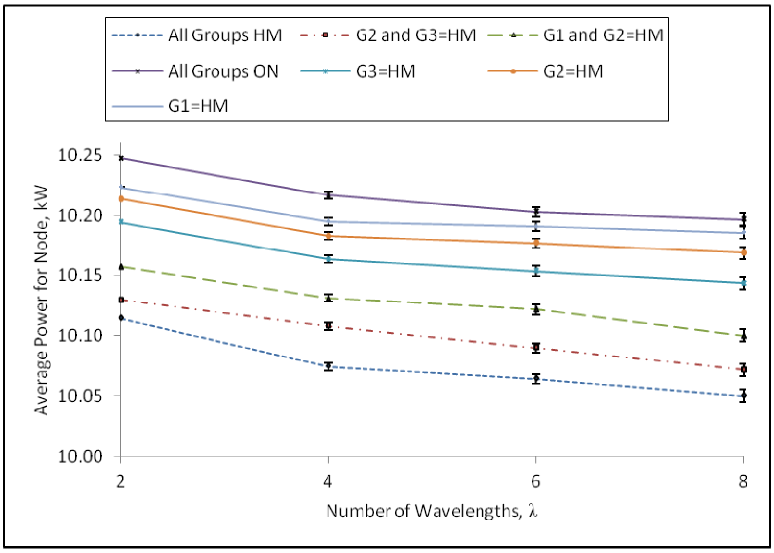
(b) EON ownership (random) node groupings power consumption as a function of network utilization.

Figure 4.21: Power consumption as a function of network utilization for EON.

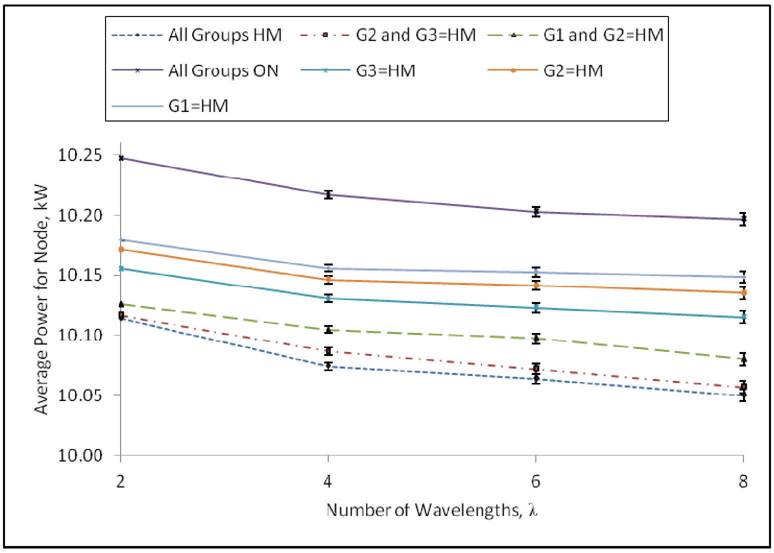
All values are recorded at the same network load. As expected all groups ON provide the highest degree of utilization while for all groups HM although dissipating lower power levels, provide the lowest levels of utilization. Power consumption decreases and network utilization improves for ownership compared to geographical grouping, expected since less network equipment is used in hibernation. A power saving of 10.07kW at 10% network utilization is attained at low offered network loads of 2 Erlangs. Grouping nodes reduce the processing overhead at low network traffic load (10% at 10.07kW). For “All-Group-ON” at low load (10%), the power consumption is 10.22kW.

4.9.2.2 Wavelengths

Figure 4.22 depicts a power consumption comparison between different groups with respect to the number of wavelengths. A slight improvement in power consumption of ownership grouping is observed; 10.13kW with ownership compared to 10.22kW with geographical at 8 wavelengths. Optical bypass at intermediate nodes reduces the number of required router electrical ports. In contrast, all-light paths incident at a node must be terminated viz. all the data carried by the light paths is processed and forwarded by IP routers [116].



(a) EON geographical (fixed) node grouping power consumption as a function of the number of wavelengths for peak and minimum traffic loads.

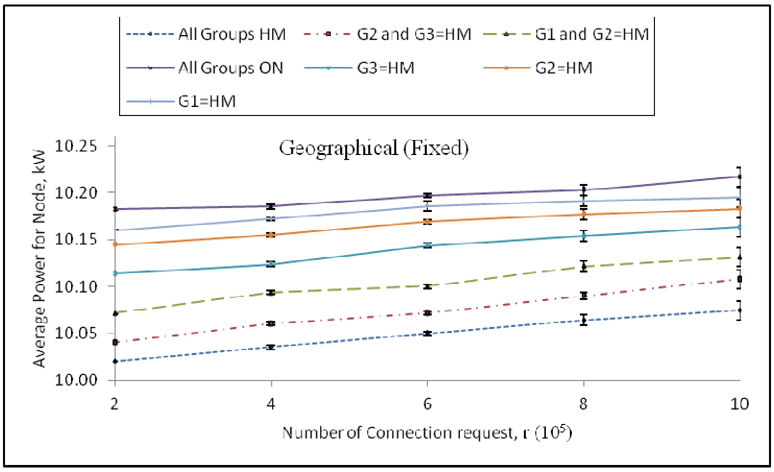


(b) EON ownership (Random) node grouping power consumption as a function of the number of wavelengths for peak and minimum traffic loads.

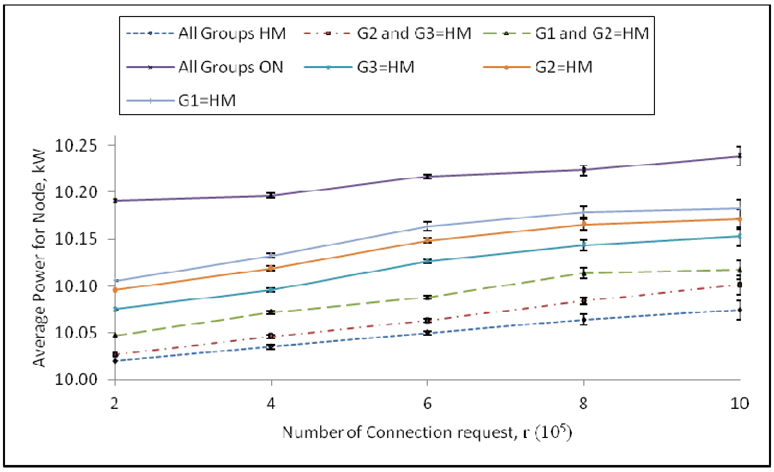
Figure 4.22: EON node grouping power consumption as a function of the number of wavelengths for peak and minimum traffic loads.

4.9.2.3 Connection Requests

Figure 4.23 illustrates the power consumption as a function of the number of connection requests for both geographical and ownership grouping. The connection requests are dynamically provisioned by the GMPLS control plane.



(a) EON geographical (fixed) node grouping node efficiency as a function of the number of connections.



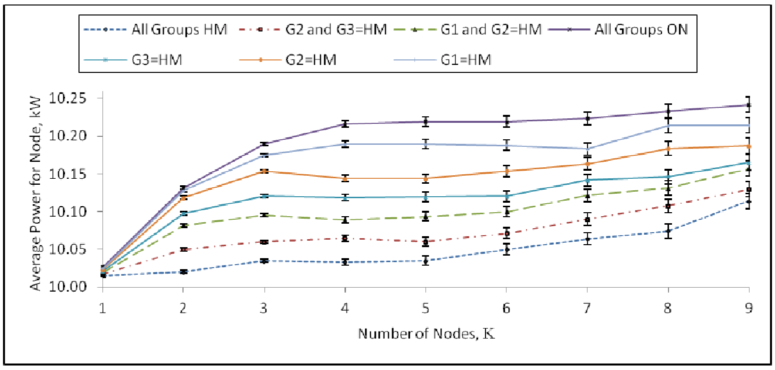
(b) EON ownership (Random) node grouping node efficiency as a function of the number of connections.

Figure 4.23: EON node grouping node efficiency as a function of the number of connections.

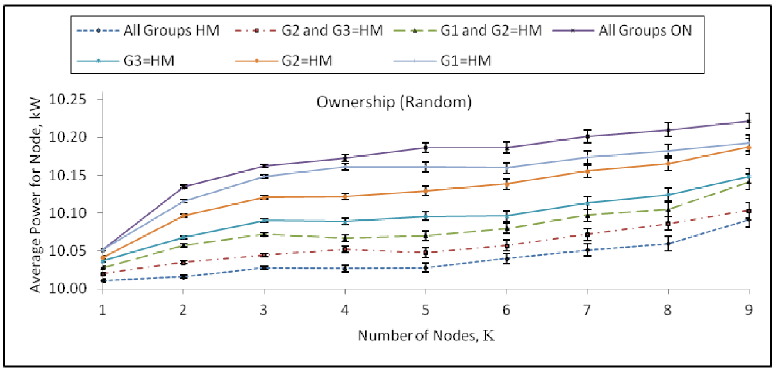
Increases in connection requests increase the power consumption. Again, ownership grouping achieves higher power saving (10.11kW) when compared to geographical grouping (10.16kW) since connection requests result in an increase in the number of ports in use at nodes.

4.9.2.4 Network Size

Figure 4.24 illustrates the power consumption as a function of the number of nodes. Pre-setting of nodes was used for geographical (fixed) grouping and a set of randomly selected nodes for ownership grouping. The results show that both the geographical and ownership groupings suffer increased power consumption as the number of nodes increases; more power is required to route an increased number of connection requests as the number nodes increases. The results demonstrate clearly that the ownership node grouping yields a higher level of power saving than the geographical node grouping.



(a) EON geographical (fixed) node grouping power consumption as a function of the number of nodes.



(b) EON ownership (Random) node grouping power consumption as a function of the number of nodes

Figure 4.24: EON node grouping power consumption as a function of the number of nodes.

4.10 Summary

The Chapter presents an evaluation of an approach to energy saving in IP/GMPLS-based optical networks based on hibernation. The impact of the grouping of nodes following the principles of hibernation on network performance as a function of energy saving was examined and quantified for two representative network topologies. The approach was implemented through two grouping network node strategies - Geographical and Ownership-based. Results show that hibernation has the potential to deliver energy savings at the expense of reduced network performance. Results show that the “Ownership-based node groupings for “All Groups = HM” (hibernate) and “All Groups = ON” delivers similar performance as the Geographical nodes groupings.

The metrics used in the evaluation were the *power consumption difference per node* and the average *power savings.* Table 4.4 present the comparison between both metrics.

Table 4.4: A comparison between "Average power difference for node" and "Average power saving" metrics.

Average Power Difference for node	Average Power Saving
■ The difference between the maximum power consumption known as reference power to power dissipation of the network node. ■ Used to measure the average power variance of the node.	■ The actual power consumption drained by node. ■ Used to measure the actual power efficiency of the node.

Table 4.5 summarises the analysis for a range of metrics that are most appropriate in the goal of determining the trade-off between power saving and network performance. Table 4.6 summarises the results for partial and full mesh topologies under the geographical and ownership node grouping schemes.

Table 4.5: A comparison between Fixed (geographical) and Random (Ownership) in different topologies.

Group-Nodes		*Geographical*		*Ownership*	
Group	Metric	Partial	Full Mesh	Partial	Full Mesh
G1 = HM	Power Difference	0.031 kW	0.045 kW	0.031 kW	0.06 kW
	Blocking Probability	3%	2%	1%	1%
G2 = HM	Power Difference	0.049 kW	0.053 kW	0.054 kW	0.067 kW
	Blocking Probability	4%	3%	3%	2%
G3 = HM	Power Difference	0.055 kW	0.063 kW	0.053 kW	0.076 kW
	Blocking Probability	6%	5%	5%	4%
G1 & G2 = HM	Power Difference	0.097 kW	0.101 kW	0.098 kW	0.114 kW
	Blocking	10%	8%	8%	7%

	Probability				
G2 & G3 = HM	Power Difference	0.108 kW	0.123 kW	0.108 kW	0.133 kW
	Blocking Probability	47%	34%	43%	30%
All Group=HM	Power Difference	0.130 kW	0.134 kW	0.130 kW	0.134 kW
	Blocking Probability	74%	50%	74%	50%
All Group=ON	Power Difference	0.002 kW	0.002 kW	0.002 kW	0.002 kW
	Blocking Probability	0.1%	0.1%	0.1%	0.1%

Table 4.6: Results summary for the full mesh optical networks. ***’HM”*** *signifies the group is operated in hibernation mode providing minimum network operation.*

Group-Nodes			*Number of Wavelength*	*Number of Nodes*	*Number of Connections*	*Network Utilization*
G1 = HM	Power Dissipation	Geographical	10.223 kW	10.025 kW	10.160 kW	10.190 kW
		Ownership	10.179 kW	10.052 kW	10.106 kW	10.145 kW
G2 = HM	Power Dissipation	Geographical	10.214 kW	10.023 kW	10.145 kW	10.175 kW
		Ownership	10.171 kW	10.042 kW	10.095 kW	10.134 kW
G3 = HM	Power Dissipation	Geographical	10.194 kW	10.021 kW	10.1137 kW	10.154 kW
		Ownership	10.155 kW	10.037 kW	10.075 kW	10.111 kW
G1 & G2 = HM	Power Dissipation	Geographical	10.157 kW	10.019 kW	10.071 kW	10.126 kW
		Ownership	10.126 kW	10.028 kW	10.047 kW	10.090 kW
G2 & G3 = HM	Power Dissipation	Geographical	10.130 kW	10.017 kW	10.040 kW	10.090 kW
		Ownership	10.117 kW	10.020 kW	10.026 kW	10.081 kW
All Group =HM	Power Dissipation	Geographical	10.114 kW	10.015 kW	10.020 kW	10.070 kW
		Ownership	10.114 kW	10.011 kW	10.020 kW	10.070 kW
All Group = ON	Power Dissipation	Geographical	10.247 kW	10.027 kW	10.182 kW	10.205 kW
		Ownership	10.247 kW	10.052 kW	10.191 kW	10.205 kW

Chapter 5

Hibernation Mode: Segmentation-Link

5.1 Introduction

Current core networks are over-dimensioned in terms of switching capacity, the number of deployed links and nodes to meet network growth and reliability constraints. The introduction of novel low-consumption silicon technologies is on its own not sufficient for migrating the current network towards greener operation. There are opportunities therefore to explore the possibility of adapting network energy requirements to the actual traffic profiles saving network operational costs as well as reducing the carbon footprint [115].

5.2 Hibernation Mode with Segmentation-Link Mechanism

Figure 5.1 presents the Segmentation-Link structure of the hibernation strategy. In this architecture, nodes are interconnected by point-to-point optical fibre links and a control plane link is used to propagate IP-based control messages, including routing and signalling. A reduction in power consumption is implemented by re-configuring fibre links to segment traffic flows e.g. re-routing all traffic to light paths at segment 1 (active wavelengths) while re-routing the inactive wavelengths to segment 2 (idle wavelengths). Power consumption can be distributed based on fibre link selection and re-routing the traffic via the OSPF-TE extension, already used to advertise the hibernation mode.

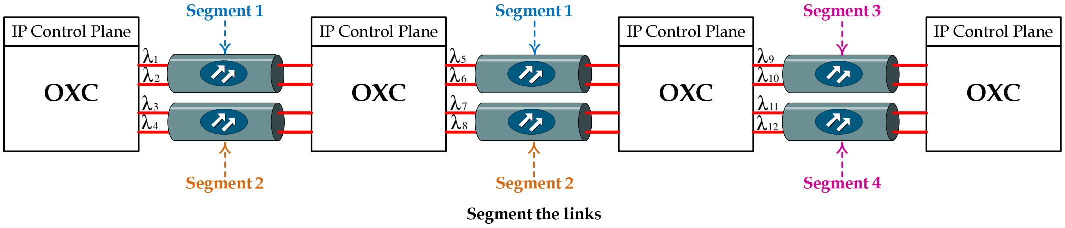


Figure 5.1: Segmentation-Link Hibernation Mode Structure.

5.2.1 Power Saving with Wavelength Converters

Optical switching has integrated wavelength conversion capability so that input wavelength channels of a node can be converted into different output wavelength channels enabling routing flexibility, improving the utilisation of WDM channels, resolving contention and minimizing the blocking of traffic [6][25]. In optical IP networks, minimizing power consumption can be implemented by placing unused wavelength converters at the OXC to sleep. Figure 5.2 shows an Ingress Node with two request message; Request 1 and Request 2. When Request 1 transmits traffic from core router to OXC (Ingress Node), the input light path using wavelength λ_4 converts to wavelength λ_2The light path will flow from Ingress Node through an intermediate node to Egress Node and wavelengths are converted via active wavelength converters. Others unused wavelength converters are placed in sleep mode. Similarly, when Request 2 transmits traffic from Ingress to Egress, the same wavelength converters operation applies as for Request 1.

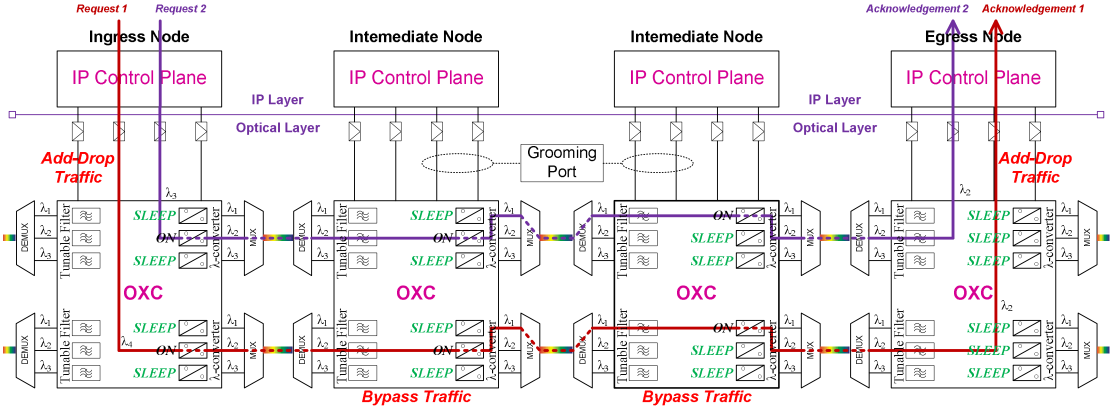


Figure 5.2: Wavelength converter mechanism for providing power saving in optical IP networks.

5.3 Energy Efficient Core Optical Fibre Links

In this Section two extensions to the hibernation mode strategy are described and evaluated: (1) Link only scheme and (2) Segment-link scheme.

5.3.1 Hibernation Mode: Link Only Scheme

The aim of the *link only scheme* is to minimize power consumption through powering down idle links, in so doing reducing the number of active node ports/interfaces. It is assumed that in order to reduce power consumption, only ports/interfaces can be powered off while nodes and EDFAs are placed into low power modes to maintain key network functions. Moreover, this scheme is executed through legacy routing using the OSPF standard protocol *without* any modification on header message and type-length-value (TLV) object. Operation in the optical and the IP domains are independent of each other.

5.3.2 Hibernation Mode: Segmentation-Link Scheme

Figure 5.3 illustrates the segmentation-link scheme message sequence diagram for the transition from ON state to OFF state. Assuming that network in Figure 5.3 is representative of a full mesh topology (complete network topology connections is not shown for simplicity), a similar light path setup request and signalling reservation process is appropriate as that described in Section 4.5. A connection request will be blocked in a link if and only if, no wavelength is available between ingress node and egress node. For end-to-end provisioning with wavelength conversion, after identifying a complete end to end path, wavelengths are reserved through signalling.

Assume that the optical fibre connection from ingress to egress node traverses the path defined as Link = {1, 2, 3, 4} and the setting of the hibernation mode segment-link scheme as Segment = {3, 5}. The control plane receives hibernation notification messages informing that idle links (Link 2) on segment 5 traverse fibre links between node 2 and node 3. After the nested hold-off timer expires, the hibernation notification message is propagated back along the path to release the reserved wavelengths. Then, the loopback LSP *Resv_Confirm_Link* message is transmitted back along the link until it arrives at the ingress node to request suspension of inactive Link 2. If Node 3 receives a LSP setup request message to place Link 2 in *hibernation* state, it will forward a *Resv_Err* message to acknowledge the ingress node that Link 2 is in powering down state. As a result, the network updates the routing table and TED topology. The ingress node releases a LSP by propagating a *Path_Tear* message to tear down the connection to the idle node. Similar actions occur in Link 4 on Segment 5. If there are any inactive links, then hibernation notifications are propagated back along each section of the path to establish all reserved wavelengths. The egress node will reserve light paths and propagate a confirmation request back to the ingress node informing it of the selected light path and releasing all others.

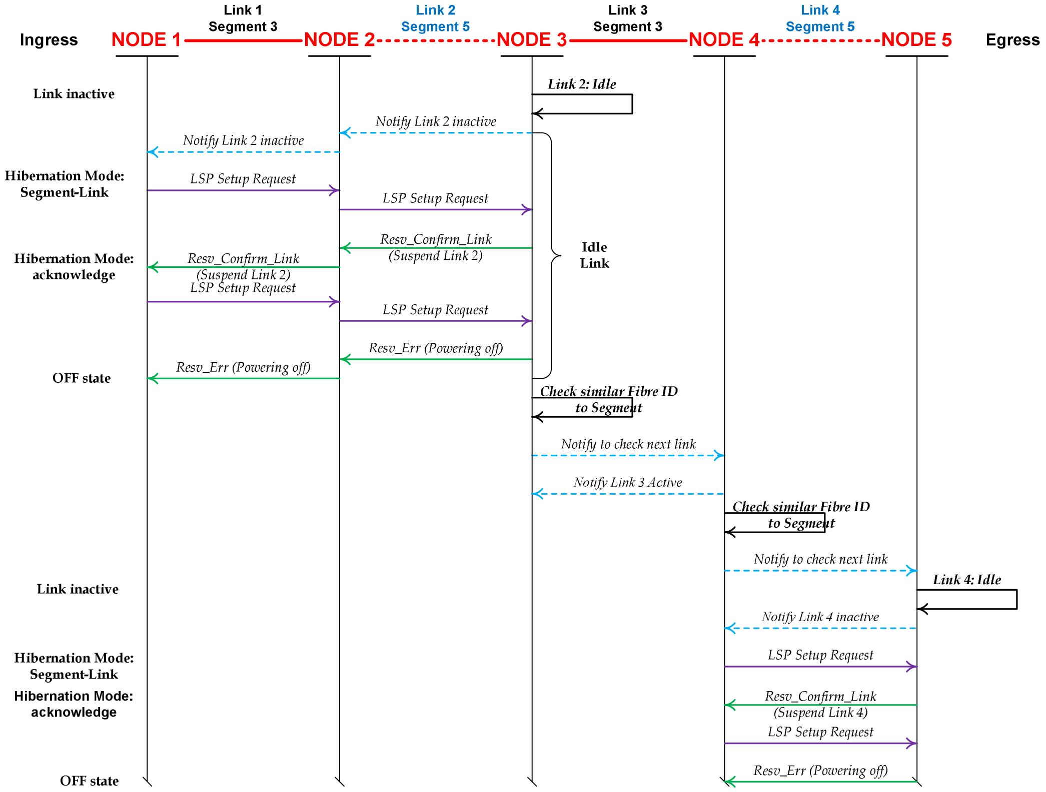


Figure 5.3: Messages Sequence Diagram for transition from ON to OFF of Segmentation-Link scheme.

Figure 5.4 presents a message sequence diagram for the transition from OFF state to ON state. Node 3 detects traffic and changes its state to BUSY (active state) and full power operation is resumed. A confirmation message is sent to inform the adjacent node that it is in the process of powering-up. A *Resv_Tear* message is sent to the ingress node to notify that node is powering to ON state.

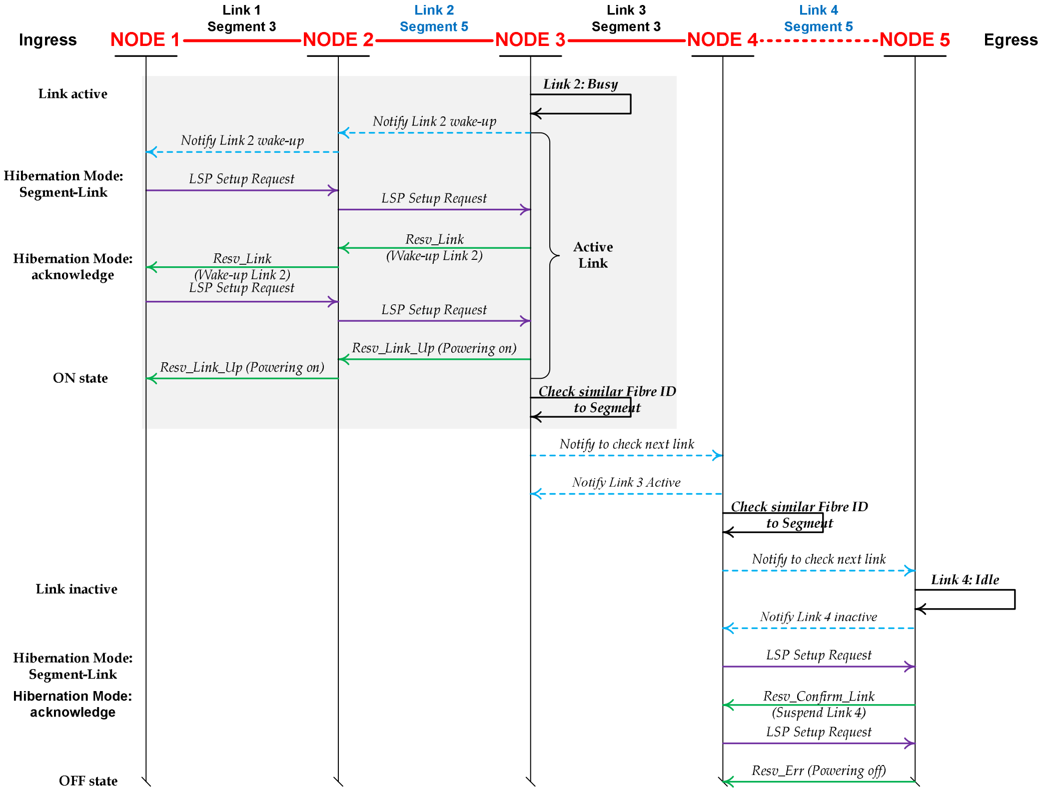


Figure 5.4: Messages Sequence Diagram for the transition from OFF to ON state for the Segmentation-Link scheme.

Figure 5.5 shows the flow diagram of the segment-link scheme algorithm. The proposed algorithm is triggered on the last iteration of the hibernation group procedure. The power level of all network nodes are monitored and recorded. The first fibre link is selected for shut down based on the trade-off between energy conservation and network performance. A check is performed for segmentation for other fibre links so that appropriate links can be bundled. If similar fibre id is identified, then a decision is made whether to utilise separate independent links or bundled for the purpose of hibernation. Note that only connections established on the selected fibre are removed, and then re-routed on the modified network topology. The procedure ends when all fibre links have been inspected and the control plane updates LSA messages and route information into TED.

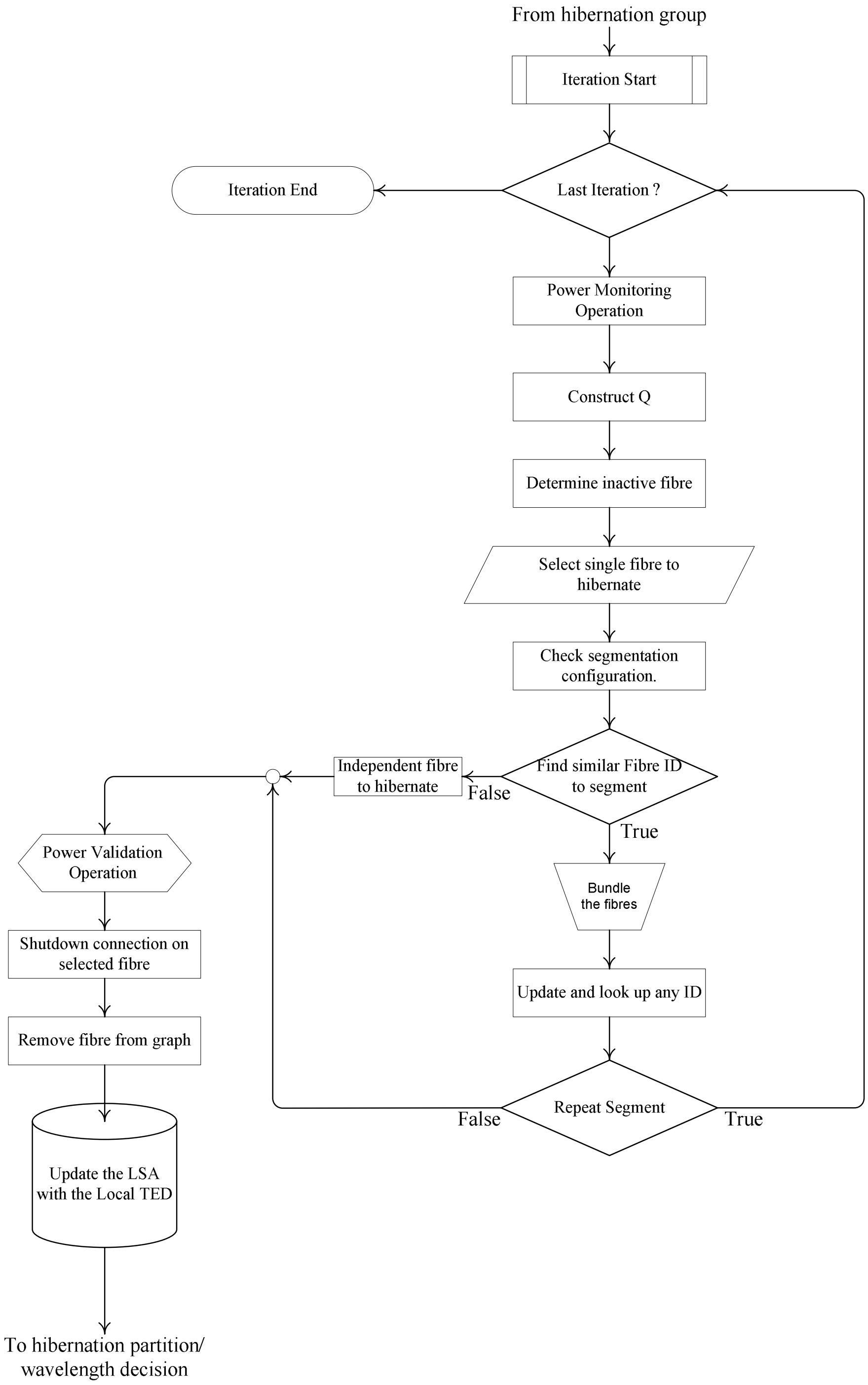


Figure 5.5: Optimization algorithm flowchart of Hibernation Mode for Segmentation-Links Operation.

5.3.3 RWA Heuristic Algorithm

Power consumption for Optical IP networks can be minimised through an ILP formulation. ILP has been identified as a promising candidate to underpin segment-link and wavelength continuity constraints through a heuristic algorithm. Logical IP connections are mapped (or groomed) over multi-hop physical paths. For variable indexing, the following rules are used: *m* and *n* index the nodes in the physical paths in the network, *i* and *j* index the nodes in the virtual light path topology, and *s* and *d* index source and destination nodes (Figure 5.6). The following parameters underpin to formulation [2][4][110][116]:

$G=(N,L)$	A physical topology which consists of a set of nodes *N* and links *L.* The node set corresponds to core routers supporting GMPLS and OXC nodes. At each node, a core router is connected to an OXC. The link set consists of single mode fibre optic links in the network.
Λ^{sd}	A forecast demand matrix (traffic request) Λ^{sd} served by light paths between each node pair (*s,d*)
$R=\theta_k$	Set of available channel rates.
W	The number of wavelength channels carried by each fibre *W* and the capacity of each wavelength *C* Gb/s.
P_A	The power consumption of each in-line EDFA as well as the power consumption of each post- and pre-amplifier pair
P_G	Power consumption of a core router with GMPLS control plane capabilities.
P_T	Power consumption of a transponder (core router in connected to the OXC) with rate θ_k.
P_X	Power consumption of an OXC (optical cross-connect).

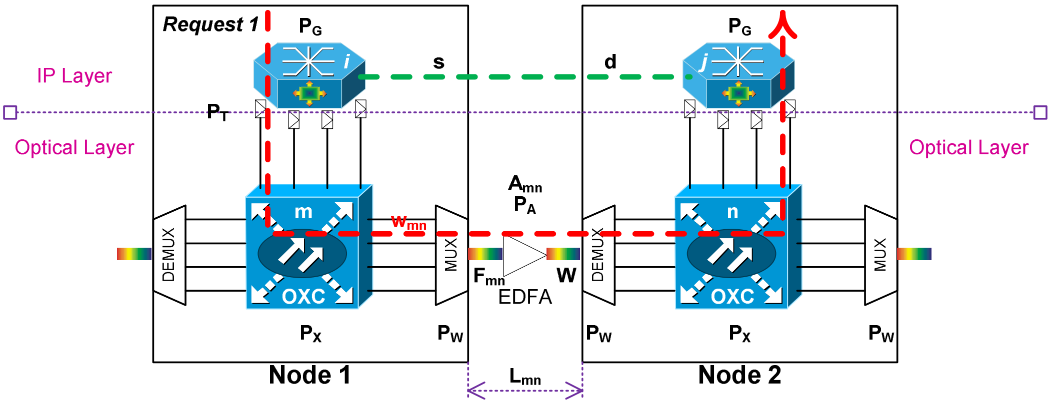


Figure 5.6: Different layers for the transparent optical IP network ILP formulation.

The evaluation of the impact of an energy saving scheme for optical IP network is subject to the following constraints:

1) serving all traffic requests
2) each fibre links is restricted to a maximum number of wavelengths (however, no limit is set on the number of fibres deployed on each physical link)
3) each node is limited to maximum number of IP router ports.

The solution aims to determine;

1) optimal light path assignments
2) routing of virtual (light path) links in the physical layer
3) number of wavelengths, fibres and EDFAs required on each physical link.

In addition other relevant sets and parameters are:

N_m	set of neighbouring nodes of node m in the physical topology G_p.
L_{mn}	Length of a physical fibre optic link between nodes *m* and *n*. This distance is used to determine the number of required EDFAs on each fibre link.

A_{mn}	Number of EDFAs that should be deployed on a fibre link (m,n). Specifically, $A_{mn}=[L_{mn}/S-1]+2$, where S is the span distance - 70km - between two neighbouring inline EDFAs and $[L_{mn}/S-1]$ is the number of inline EDFAs required on the link. “2” counts as a post-amplifier and a pre-amplifier respectively at the two ends of a fibre link.
$l_{ijk\lambda}$	Number of wavelength channels on the virtual link between node pair (i,j) (integer).
$\beta_{ijk\lambda}$	Denotes a light path $l_{ijk\lambda}$ between nodes i and j, at rate θ_k and on wavelength λ [4]
F_{mn}	Integer variable denoting the number of fibres on a physical link (m,n)
λ_{ij}^{sd}	Amount of traffic demand between node pair (s,d) that traverses virtual link (i,j) (real).
W_{mn}^{ij}	Number of wavelength channels used for the light path between node pair (i,j) that traverses the physical link (m,n)(integer)
w_{mn}	Number of used wavelength channels on physical link (m,n) (integer)
Z_j	Integer variable expressing the amount of data carried by light paths terminated at node j.
k	Number of nodes.
$Y_{ijk\lambda}$	Integer variable representing the number of light paths $l_{ijk\lambda}$ on link (i,j).

5.3.3.1 ILP Optimization

OXCs with full wavelength conversion are assumed; therefore, there is no need to consider wavelength continuity along a light path. Each node is equipped with a core router connected to a MEMS-based OXC via WDM transponders.

The problem of minimising power consumption can be formulated as:

Objective: minimize

$$\sum_{j} P_G \cdot Z_j + \sum_{\lambda}\sum_{ij}\sum_{k} P_X \cdot \left[Y_{ijk\lambda} + \sum_{mn} w_{mn\lambda}^{ij} \right] + 2\sum_{\lambda}\sum_{ij}\sum_{k} P_T \cdot Y_{ijk\lambda} + \sum_{mn} P_W \cdot Y_{ijk\lambda} + \sum_{mn} P_A \cdot F_{mn} \cdot A_{mn} \tag{5.1}$$

subject to the following constraints:

$$\sum_{\lambda}\sum_{k} \theta_k \cdot Y_{ijk\lambda} \cdot \beta_{ijk\lambda} \geq \sum_{sd} \lambda_{ij}^{sd} \qquad \forall (i,j) \tag{5.2}$$

$$\sum_{ij \in w_{mn}} \sum_{k} Y_{ijk\lambda} \cdot \beta_{ijk\lambda} \leq F_{mn} \qquad \forall (m,n), \forall \lambda \tag{5.3}$$

$$\sum_{i} \lambda_{ij}^{sd} - \sum_{i} \lambda_{ij}^{sd} = \begin{cases} \Lambda_{sd}, & \text{if } s = j \\ -\Lambda_{sd}, & \text{if } d = j \\ 0, \text{otherwise } \forall_j, \forall (s,d) \end{cases} \tag{5.4}$$

$$Z_j = \sum_{sd}\sum_{i} \lambda_{ij}^{sd} \forall_j \neq d \tag{5.5}$$

$$\sum_{n \in N_m} w_{mn\lambda}^{ij} - \sum_{m \in N_n} w_{nm\lambda}^{ij} = \begin{cases} Y_{ijk\lambda}, & \text{if } m = i \\ -Y_{ijk\lambda}, & \text{if } m = j \\ 0, \text{otherwise } \forall_{mij \in N | i \neq j}, \forall \lambda \in L_{mn} \end{cases} \tag{5.6}$$

$$\sum_{\lambda} Y_{ijk\lambda} = Y_{ij} \qquad \forall_{ij \in N | i \neq j} \tag{5.7}$$

$$\sum_{ij} W_{mn\lambda}^{ij} \leq 1 \quad \forall (m,n) \in A, \forall \lambda \in L_{mn} \tag{5.8}$$

The mathematical formulation is implemented using mixed integer linear programming (MILP) [2][4][110][116]. The objective function in Equation (5.1) aims to minimize the energy consumption in both the optical and IP layers. The first term in Equation (5.1) computes the electronic processing power consumption of the core router at each intermediate node for all traffic demands in the IP layer. The total power consumption of core routers includes the chassis, line cards and ports connected to the optical node. The second term of Equation 5.1 represents the power consumption owing to the optical cross-connect (OXC) in which traffic flows in the optical domain and power usage is proportional to the number of wavelengths switched. The third term of Equation 5.1 calculates the power consumption owing to WDM transponders; two transponders are necessary for each source and destination node respectively. The power dissipated by transponder is a function of the total number of established light paths. The fourth term of Equation 5.1 describes the power drained by WDM devices. Finally, the fifth term in Equation (5.1) evaluates the total power consumption of all in-line EDFAs in the network. A_{mn} quantifies the number of amplifiers required on fibre optic links span placed at 70km intervals and F_{mn} denotes the required number of single mode fibre links to carry the traffic demands.

Equation (5.2) represents the capacity constraint within the virtual light path topology limiting the traffic demand traversing a link (i,j) by its capacity. Equation (5.3) ensures that the wavelength-continuity constraint on common physical fibre links with multiple fibres is met; there should not be more than one light path on the same wavelength. Equation (5.4) denotes the flow-conservation constraint ensuring that total output traffic is equal to the total input traffic. Note that electronic processing of the traffic flow is required at node k if an end-to-end traffic flow from i to j is routed using two light paths *(i,k)* and *(k,j)*. The constraint of Equation (5.5) limits the degree of traffic flow aggregation at each node which needs electronic processing.

The constraint of Equation (5.6) treats the *solenoidality constraint* [2] at the logical and physical topologies respectively. The *solenoidality constraint* sets the flow conservation condition for each node and for each connection request in the network; this condition states that the total flow leaving a node must be equal to the total flow incident on that node. Equation (5.6) is slightly modified at the source (destination) node, where the outgoing (incoming) flow must be equal to the generated traffic [2]. Equation (5.7) computes the number of wavelengths required between source and destination nodes. Equation (5.8) represents the constraint dimensioning the physical network capacity. Note that to ensure a feasible resource allocation at all nodes, the sum of flows on each link is smaller than the product of the number of optical fibres by the number of wavelengths per fibre.

5.4 Results

The evaluation is carried out on the EON network topology. Performance is quantified in terms of average blocking probability i.e. probability that setting-up a light path is blocked and average power drained by the optical layer.

Note that, these simulations results are based on *cross-layer optical/IP domain integration* and previous research considered the *optical domain only*. Therefore, results are difficult to compare in terms of power savings and network performance.

5.4.1 The Impact of Energy per Bit Analysis

This simulation evaluates the impact of different energy saving schemes on the power consumption; all analysis is carried out under the same parameters and network load as detailed in Chapter 4.

Figure 5.7 presents the average power consumption for various segment-link settings as a function of offered network load. The average power difference is defined as the difference between the maximum power consumption (reference power) by a node to the power dissipation of the node under the energy saving scheme. When the network utilises the hibernation mode, the power saving for a node is 0.176kW (link-only scheme) and 0.221kW (segment link-scheme) at 2 Erlangs at a corresponding blocking probability of 24% and 40% respectively (Fig. 5.10). The OXC makes use of the all-optical wavelength converters to reduce power dissipation through OFF and ON states; the former de-activates wavelengths and the latter activates wavelengths. The segment-link scheme bundles individual links, in so doing aggregating the available resources and improving routing scalability by reducing the amount of information to be processed by the control plane. Therefore, the number of routing adjacencies in the network is proportional to the number of control planes connected to the nodes and is not governed by the number of data plane links. Consequently, network resources are optimized, reducing the power consumed.

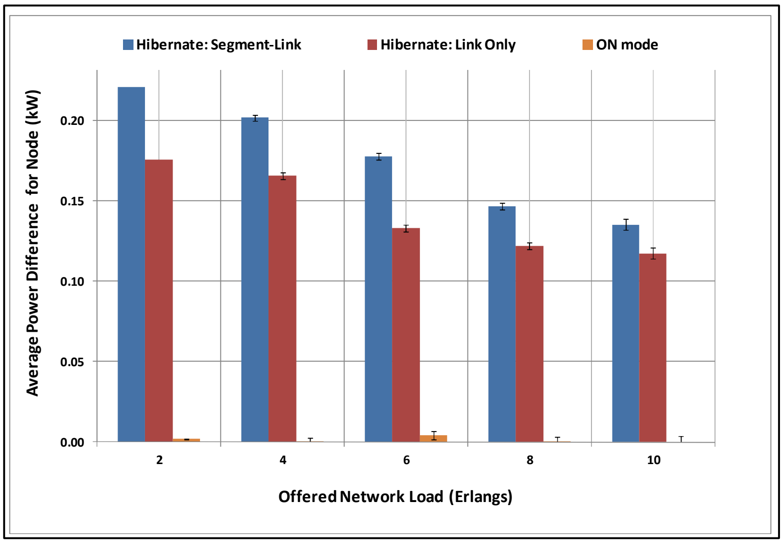


Figure 5.7: Average power difference as a function of different Segment-Links schemes of operation.

Figure 5.8 shows the normalised power consumption of different hibernation segment-link schemes normalised to the reference “ON” state as a function of offered network load. Results indicate that a segment-link scheme can yield a power saving of 67% at 8 Erlangs compared to the link only scheme (55%). Figure 5.9 presents the percentage of power consumed by the Optical and IP domain network equipment respectively when the segment-link scheme is applied. The Power Ratio is the ratio of the number connections under segment-link modes over the number of the active ON state nodes. The results show that both the segment-link scheme and the ‘link only’ scheme in optical domain can yield a power savings of 60% and 50% respectively at a network load of 8 Erlangs.

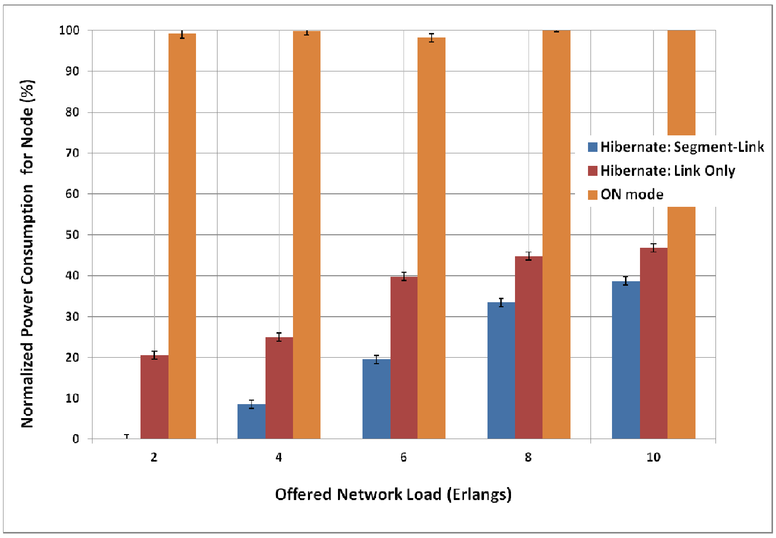


Figure 5.8: Normalized power consumption for various segment-link settings as a function of offered network load.

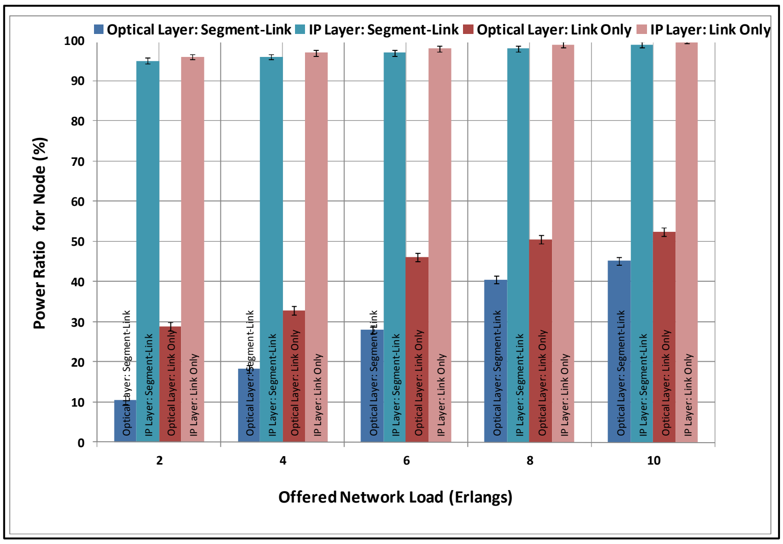


Figure 5.9: Comparison of the power ratio between optical layer and IP layer for segment-link schemes as a function of offered network load traffic.

5.4.2 The Impact of Blocking Probability on Hibernation Mode

The impact on blocking probability of the link-only and segment-link schemes is show in Figure 5.10. In the 'link only scheme' the probability of blocking is below 24% (Figure 5.10) thus delivering a better network performance but the power reduction/savings is minimal at 0.176kW. The segment-link scheme yields a blocking probability of ~40% and offers 0.221kW of power saving. The OXC makes use of all-optical wavelength converters to reduce blocking probability.

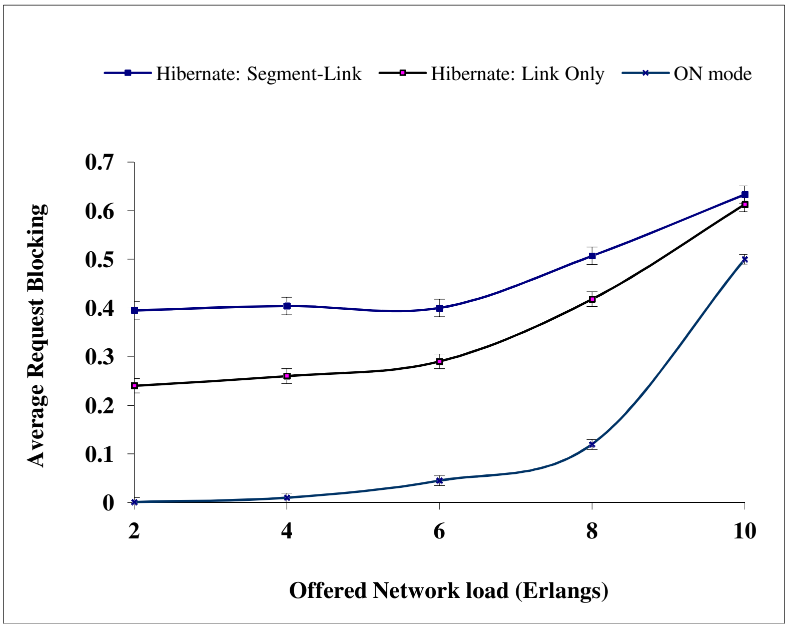


Figure 5.10: Request blocking for different Segment-Links schemes.

5.4.3 The Impact of the Degree of Connectivity and Number of Nodes on Lowering Power Consumption

The following evaluates the link power consumption of segmentation-link as a function of the degree of network connectivity. This parameter indicates the average number of nodes that light paths traverse from source to destination, the link capacity utilization and the number of required fibres on each link; Figure 5.11 presents the link power consumption as a function of the degree of connectivity D. The results shows that the when 8 wavelengths are available and the traffic is at the peak level, D equals to 2 leading to a power saving (normalized) of about 60% and 80% for the link only and segment-link schemes, respectively; values of D greater than 2 do not result in any decrease in the power consumed. It is clear that high values of D lead to a better network capacity utilisation and concomitant lower power consumption.

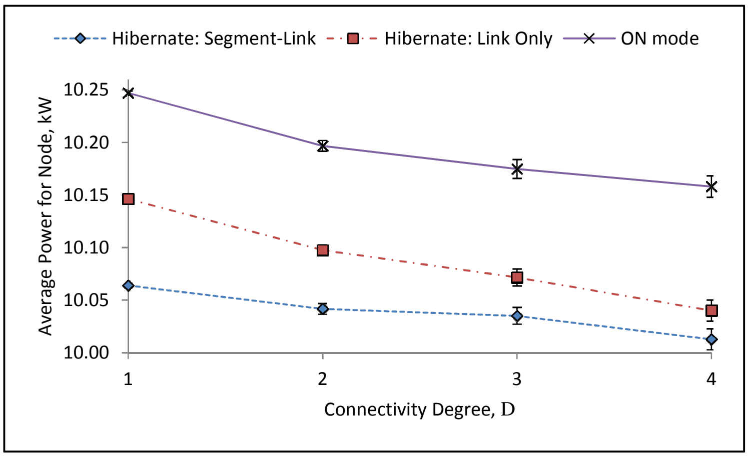


Figure 5.11: Link power consumption as a function of the degree of network connectivity for peak and minimum traffic loads for different Segment-Links schemes.

Figure 5.12 provides the power ratio difference for a node for both the optical and IP layers as a function of the degree of network connectivity when segmentation-link schemes are applied. The power ratio here is defined as the power consumption ratio for nodes of selected light paths to the degree of network connectivity. The results show that in optical domain the segment-link scheme yields a higher power saving ratio (~75%) than the link only scheme (~40%). The reason for this is that the segment-link scheme utilises power-aware-routing based on OSPF-TE standards to re-route light paths as the network connectivity degree escalates. In addition, the results demonstrate that the power savings ratio in the IP domain is slightly increased (5%) as compared to link only scheme (2%); the core routers with segment-link schemes apply traffic grooming and adaptive OSPF-TE routing.

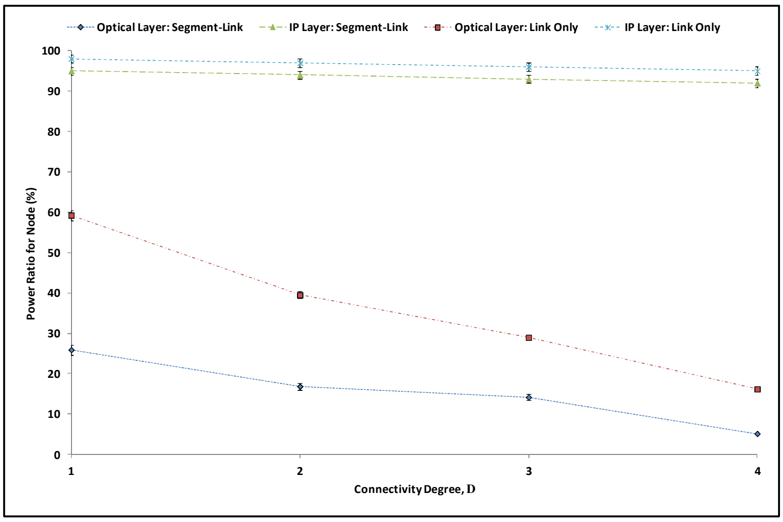


Figure 5.12: Power ratio difference for node as a function of the degree of network connectivity for peak and minimum traffic loads for different Segment-Links schemes.

Figure 5.13 presents the power consumption as a function of the number of nodes for different segment-links schemes. The results demonstrate that the segment-link scheme yields a higher power saving than link only scheme; the latter utilises power-aware-routing based on OSPF-TE standards to re-route the light paths as the network size grows.

Figure 5.14 presents the power ratio for a node for both the optical and IP layers as a function of the number of nodes. The power ratio is defined as the ratio of the power consumption of nodes of selected fibre links to the number of adjacent nodes. The results show that the power ratio at optical layer improves from small to large network sizes when the segment-link scheme is applied and yields a higher power saving ratio (from ~60% up to 95%) than the link only scheme (from ~48% up to 95%). Notice that when the number of nodes is $k=1$ (small network size) the power ratio for both schemes is similar but decreases as the network size grows. Moreover, the results demonstrate that the power saving ratio at the IP layer on the segment-link slightly increases (5%) whilst for the link only scheme declines (2%).

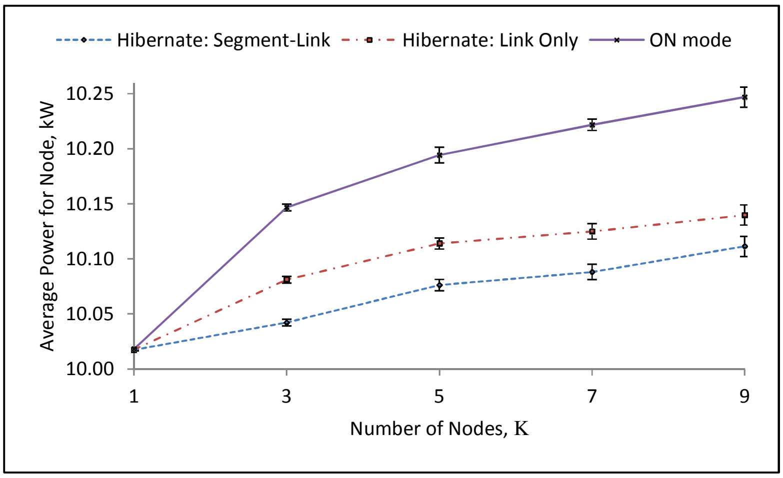


Figure 5.13: Power consumption as a function of the number of nodes for different Segment-Links schemes.

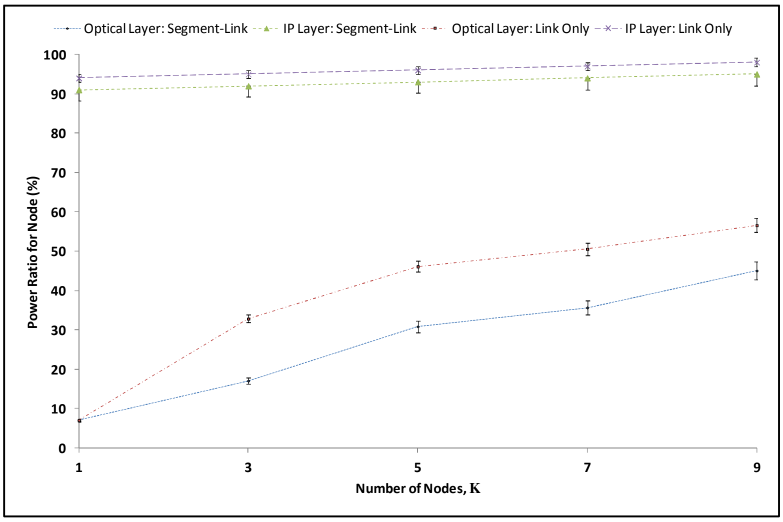


Figure 5.14: Power ratio versus number of nodes for different schemes of Segment-Links Operation.

5.4.4 The Impact of Network Utilization

Figure 5.15 demonstrates the power consumption as a function of network utilization. Results show that the segment-link scheme yields a significant saving in power consumed as network utilization (network offered load) increases; the average power consumption grows with network utilization and network size. The segment-link scheme yields a more marked improvement on average power consumption in proportion to network utilization compared to link only scheme - with ~10.025kW power dissipated - owing to minimal traffic disruption when fibre links are powered down and LSP requests optimized.

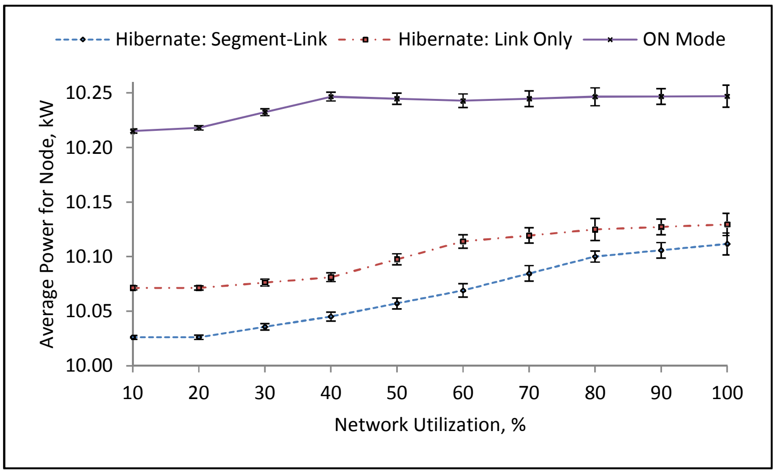


Figure 5.15: Power consumption as a function of network utilisation for different Segment-Links schemes.

Figure 5.16 presents the power ratio for a node for both the optical and IP layers as a function of network utilization. The power ratio is defined as the ratio of the power consumption of nodes of selected hibernation fibre links over the network utilization. The results show that the power ratio at the optical domain improves when the segment-link scheme is applied and yields a higher power saving ratio (from 40% up to ~90%) than the link only scheme (from ~50% up to 71%). Additionally, the results demonstrate that the power ratio at the IP domain with segment-link steadily rises (10%) in contrast to link only scheme (4%). The core routers with the segment-link scheme apply traffic grooming for low-rate traffic; for high-rate traffic, segmentation/link aggregation and adaptive OSPF-TE routing are applied at the IP domain.

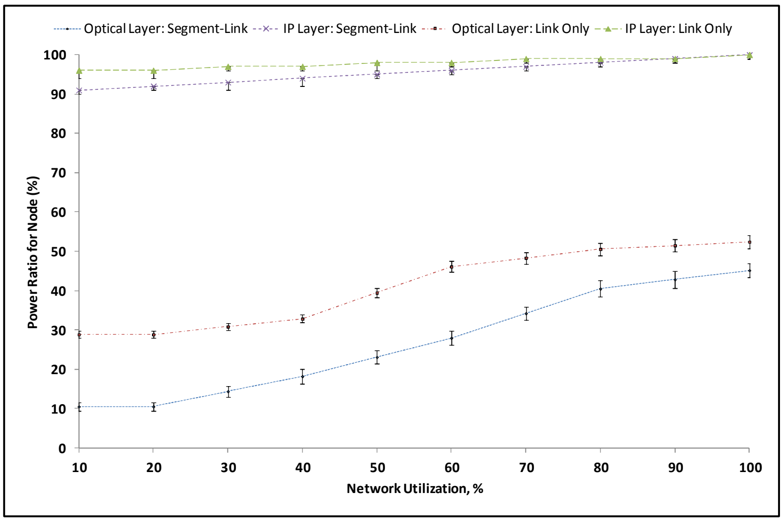


Figure 5.16: Power ratio as a function of network utilisation for different Segment-Links schemes.

Figure 5.17 presents the link power consumption as a function of the number of wavelengths, λ, showing, as expected, that the consumption decreases for increasing number of λ [110]. This is due to the light path rerouting all under-utilized links (links aggregate multi-granular grooming) to a reduced number of fibre links (waveband granularity). Therefore, the fibre is utilised more efficiently, resulting in a decrease in the amount of power consumed within the OXC by reducing the number of ports required. Whilst a noteworthy improvement can be achieved at 8 wavelengths, any further increase in the number of wavelengths deployed λ does not yield a similar decrease in the power consumed. When increasing the number of wavelengths from λ=2 and 4, a power saving of about 50% and 84% can be achieved, while from λ=6 and 8, a further decease of the consumed power of about 70% and 90% for link-only scheme and segment-link scheme respectively is obtained. As the number of available wavelengths per fibre increases, the greater the capacity per fibre and the optimization algorithm has more options to power off a significant number of optical fibres.

Note that, from an energy perspective, the use of an even higher number of wavelengths, despite yielding a further saving of the link power consumption, should be subject to a careful assessment of the corresponding physical impairments associated with multiple signal propagation (out of the scope of this study) [110].

Figure 5.18 provides the power ratio for a node both for the optical layer and IP layer as a function of the number of wavelengths. The power ratio is defined as the ratio of the power consumed by nodes of selected links over the number of wavelengths within the entire set of active light paths. The results show that in the optical domain, the segment-link scheme yields a higher power saving ratio (~75%) than the link only scheme (~35%). The segment-link scheme utilises power-aware-routing based on OSPF-TE to re-route light paths as the number of wavelengths increments. In addition, the results demonstrate that power ratio in the IP domain at the segment-link slightly increases (3%) when compared to the link only scheme (2%).

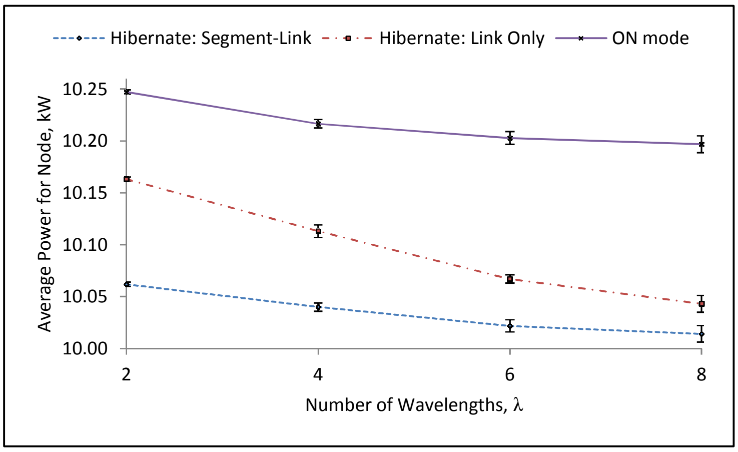


Figure 5.17: Power consumption as a function of the number of wavelengths for peak and minimum traffic loads for Segment-Links schemes.

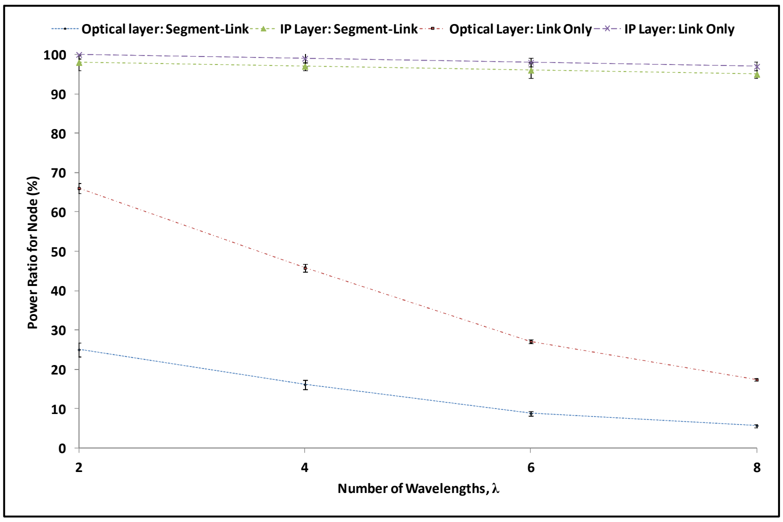


Figure 5.18: Power ratio as a function of the number of wavelengths for peak and minimum traffic loads for Segment-Links schemes.

The power consumed by a node in executing connections requests is presented in Figure 5.19. The results show that the power consumption increases when segmentation-link technique is applied. This result is expected since the dynamic establishment of connections increase due to the scheme at the router stage, increasing the power consumption in core nodes by 80% for a 10Gb/s data rate. Additionally, the power consumption of the OXC becomes high when light path connection requests increase since more add drop port/ports in OXC will be used

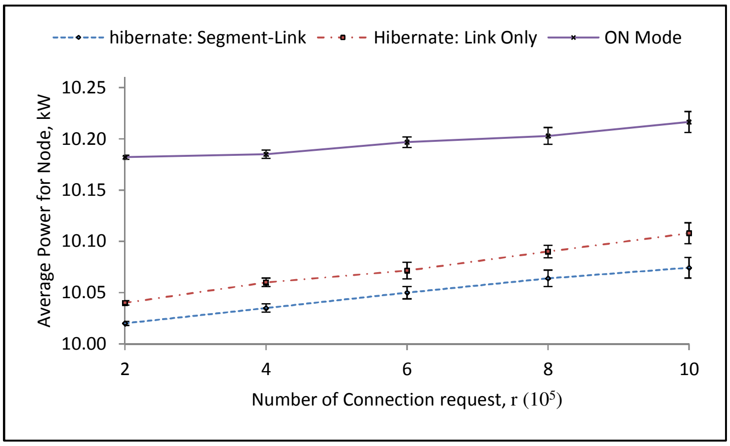


Figure 5.19: Power consumed by a node as a function of the number of connections for Segment-Links scheme.

Figure 5.20 illustrates the power ratio for a node both for the optical and IP layers as a function of the number of connection requests defined as the ratio of the power consumed by a node at the selected number of links used by connections requests over the number of established connections in the network. The results show that in the optical layer the segment-link scheme yields a higher power saving ratio (~92%) than link only scheme (~82%). In addition, the results demonstrate that the power ratio in the IP layer with the segment-link increases (6%) in comparison to the link only scheme (4%).

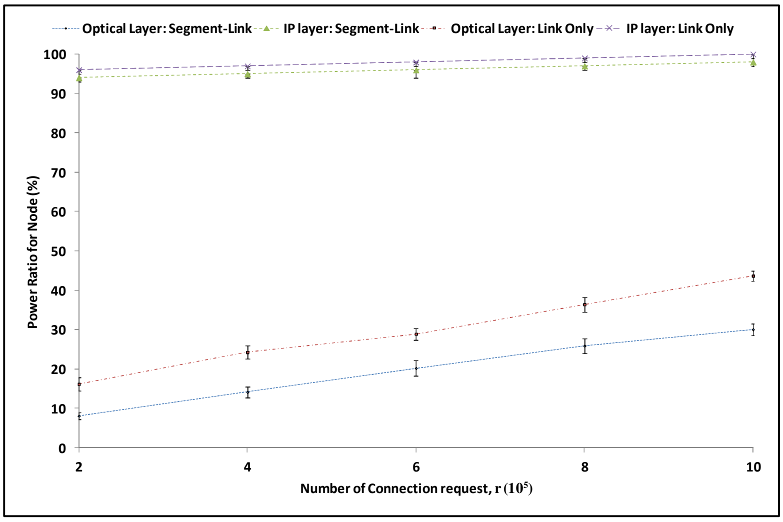


Figure 5.20: Power ratio as a function of the number of connections for Segment-Links schemes.

5.5 Conclusions

This Chapter presents energy saving concepts which deliver improved network power management through Segment-Link schemes. The average power consumption as a function of several network performance metrics is evaluated on the European Optical

Network full mesh topology. Results show that a significant amount of energy can be saved if an appropriate “Hibernation mode” configuration is invoked.

Segment-link is a technique that identifies and powers down idle optical fibre links for the purposes of energy conservation. The mechanism aims to minimise power consumption in both the optical and IP domains; the former utilises optical bypass at intermediate OXC with light path-rerouting while in the latter traffic grooming and low-rate traffic aggregation is used.

With segment-link, the energy saving is based on the generic “Hibernation Mode” in tandem with “Routing and Wavelength Assignment”. The former can be further broken down as segment-links and link only schemes. The latter harnesses heuristic algorithms to underpin power consumption minimization taking into account segment-link and wavelength continuity constraints.

The results for each evaluation are summarised in Table 5.1.

Table 5.1: Link usage for the energy aware Hibernation mode techniques.

Hibernation Scheme			***Link Only***	***Segment-Link***
Power Consumption	Power Difference for a node		0.176 kW	0.221 kW
	Normalized Power Saving		53%	61%
	Power Ratio	IP Layer	4%	5%
		Optical Layer	49%	56%
	Blocking Probability		24%	40%
Number of Wavelength	Power Dissipation		10.16 kW	10.06 kW
	Power Ratio	IP Layer	2%	3%
		Optical Layer	35%	75%
Number of Nodes	Power Dissipation		10.14 kW	10.10 kW
	Power Ratio	IP Layer	2%	5%
		Optical Layer	48%	60%
Number of Connections	Power Dissipation		10.04 kW	10.02kW
	Power Ratio	IP Layer	4%	6%
		Optical Layer	82%	92%
Number of Connectivity Degree	Power Dissipation		10.15 kW	10.06 kW
	Power Ratio	IP Layer	2%	5%
		Optical Layer	40%	75%
Network Utilization	Power Dissipation		10.07 kW	10.02 kW
	Power Ratio	IP Layer	4%	10%
		Optical Layer	71%	90%

Chapter 6

Hibernation Mode: Partition-Lightpath

6.1 Hibernation Mode: Partition-Lightpath

The Partition-Lightpath scheme within the hibernation mode strategy is illustrated in Figure 6.1. In this architecture, the node consisting of a core router and OXC is connected by optical fibre links and a control plane is responsible for managing the delivery of IP-based messages, through OSPF-TE routing and RSVP-TE signalling. Full wavelength conversion is employed at all OXC nodes to manage the wavelength-continuity constraint and more efficient use of the wavelength resource. In this scheme, power consumption is reduced by link re-routing, traffic engineering and traffic grooming.

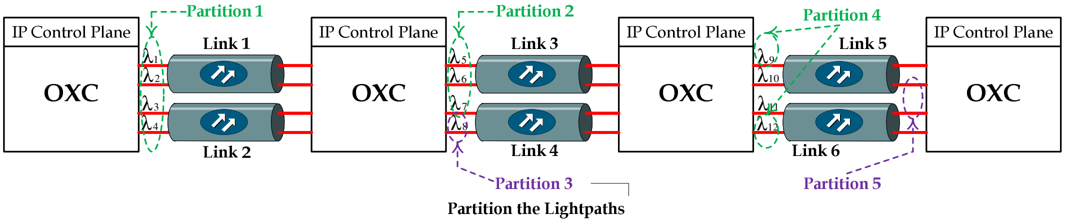


*Figure **6.1**: Partition-Lightpath Hibernation Mode.*

The light path set and parameters are given in Table 6.1; each light path connection is assigned appropriate wavelengths within a fibre link. Table 6.2 presents the partitioning setting of the hibernation mode in relation to light path establishment.

Table 6.1: Lightpath set and parameters.

Lightpath	*Wavelength*
1	λ_1, λ_5, λ_9
2	λ_2, λ_6, λ_{10}
3	λ_3, λ_7, λ_{11}
4	λ_4, λ_8, λ_{12}

Table 6.2: Lightpaths associated with link parameters.

Partition	***Lightpath***	***Wavelength per Node***	***Link***
1	1, 2, 3, 4	λ_1, λ_2, λ_3, λ_4	1, 2
2	1, 2, 3	λ_5, λ_6, λ_7	3, 4
3	4	λ_8	4
4	1, 4	λ_9, λ_{12}	5, 6
5	2, 3	λ_{10}, λ_{11}	5, 6

Although, light paths and fibre links for network partitioning result in network topology changes, this mechanism can lead to significantly reduced power consumption.

6.2 Hibernation Mode support in the Control Plane

The introduction of a link hibernation mode raises two issues in relation to the control plane: (1) when to trigger the mode transition especially from active to sleep mode (and vice-versa) and (2) how to manage the integrity of light paths during such transitions [158]. Here the modification of OSPF-TE routing and RSVP-TE signalling is executed to efficiently trigger the transition while preventing loss of data.

New light paths have to be established owing to hibernation on the transition from OFF state to Active state. As a result, resources are re-allocated by means of the control plane which sends RSVP-TE *Resv message* to the terminating node to execute the link transition from OFF state to Active state; the control plane then updates the link status information into the TED.

For the transition from Active to OFF state, light paths to be re-routed are still active whilst new paths are being established. Once all new light paths are completely established, the traffic flows on new light paths and the ingress nodes can tear down existing light paths by propagating the RSVP-TE *Tear_Down message* to Egress nodes. The approach must prevent data loss during the re-routing process. After all *Tear_Down* messages have been received by the link terminating node and all wavelength resources of the selected links are powered down, the link is placed in the OFF state and the control plane updates the TED.

6.2.1 Intelligent Control Plane in Wavelength Routed Networks

The control plane functionalities include light path routing and signalling. The former provides facilities to route traffic flows based on a link-state routing protocol executed by OSPF with extensions for optical and traffic engineering (TE) - OSPF-TE. At each node, OSPF-TE distributes link state advertisements (LSA) to perform path computation and LSA information is stored in the traffic engineering database (TED). The TED is maintained and updated by the underlying routing protocol. In the case of the optical layer, dynamic routing is based on constrained-shortest path first (CSPF) routing, implemented using the RSVP-TE signalling standard.

The control plane has been extended to support hibernation mode mechanisms by modification to the LSA messages of OSPF-TE used to determine the status of individual fibre links viz. active or off. The TED links attribute database is updated as appropriate and this information is the basis with which to process incoming light path requests through the path computation algorithm. OSPF-TE is responsible for distributing and advertising LSA messages to establish the topology. The information present in TED is broadcast to all network nodes (including the links terminating node) advertising all fibre link states so that any new routing light path requests can be processed.

6.2.2 Energy Aware Routing

Energy Aware Routing (EAR) minimizes the number of active links in the network i.e. reducing the number of physical and virtual links to be used to route traffic. The goal is achieved by forcing a subset of routers to assume routes different from those indicated in their short path tree (SPT) [119]. The key challenge in the implementation of energy aware routing in relation to optical IP network design is mainly on providing the solution for the problem of determining resources that are under-utilized and consequently are options to place into hibernation to save energy consumption. The constraint is addressed and formulated using the Integer Linear Programming (ILP) heuristic approach.

Two parameters are of importance; specifically inactive fibre links and unused light paths. From the inactive fibre links perspective, the goal is to determine idle power dissipation with the ultimate objective of reducing the amount of lightly loaded light paths. From an unused light path perspective, the goal is to implement path bypass as much as possible in which appropriate traffic flows directly bypass intermediate core routers via a cut-through mechanism. Additionally, traffic grooming is a route to effecting energy saving at core routers as aggregate traffic flow connection requests demand fewer routes in the IP domain.

Figure 6.2 summarises the process flow in implementing an energy aware routing strategy.

The Energy Aware Routing Algorithm

- **Initialization**
  - Assign initial capacity as residual capacity for a given physical topology link (i,j).
- **Link State Advertisement (LSA)**
  - Let P_{ij} be the set of paths that connect node pair (i,j) in graph $G(N,L)$.
  - For each link (i,j) from node i, advertise periodically the residual capacity C_{ij} as link weight and time stamp to other nodes.
  - Find the shortest path of node pair (i,j) in $G(N',L')$.
- **Link weight Assignment**
  - Update network topology and the link weight found from the LSA by adding Hop Offset (HO) for a given link (i,j).
- **Path Computation**
  - Find the lowest residual capacity path between source and destination.
  - Update residual capacity of links on the selected path.

Figure 6.2: Energy aware routing procedure.

6.2.3 Energy Aware Multi-layer Traffic Engineering

In general, the term traffic engineering (TE) refers to any effective solution to control network congestion in traffic flows and optimize network performance. Practically, this means choosing routes taking into account traffic load, network state, and user requirements such as Quality of Service (QoS), and moving traffic from more congested to less congested paths. The key features in TE focus on efficient routing algorithms for load-balanced, fault-tolerant networks, traffic scheduling, queue management, resource optimization, and QoS. The basic function of network services is to deliver traffic requested by users from source to destination in an integrated manner. As the routing function of the network determines the paths to be followed by traffic flows, one of traffic engineering's targets is directed to control and optimize the routing mechanism [159][160].

In a multilayer environment, TE involves various approaches to handle issues of traffic demand variations, traffic performance, resource optimization and failure scenarios in a network. Furthermore, TE in optical networks is one method for managing traffic changes in a cost effective manner. As a result of changes of traffic volume in a network, a virtual topology is dynamically configured by establishing the light paths through OXCs. The light path is considered as a directly connected high-capacity fibre link for core/metro routers in the IP layer. The traffic flow between two routers is conveyed over a virtual topology by link state routing protocols. GMPLS-TE is a candidate for managing and controlling the paths; the traffic route and virtual topology in optical IP networks are controlled and computed by the GMPLS control plane. The virtual topology can be re-configured to adapt current traffic in which TE manages significant traffic variations and mitigates the congestion caused by traffic changes.

From the perspective of energy efficiency, the term *energy aware traffic engineering* takes energy consumption into account while optimizing low link utilization and high aggregate transmission rate through spreading the load amongst multiple paths. The aim is to dynamically power down network portions during light utilization periods, in order to minimize the energy consumption, while meeting the operational constraints and current switching workloads [111][115]. In this work, traffic engineering has been applied to aid the decision on which fibre links with low loads (bandwidth under-utilized) and unused light paths can be placed into hibernation. Traffic is re-routed on fibre links with spare capacity and partitioning (bundling) of links to minimize the number of fibre links/light paths used is possible while maintaining the required number of connections. For example, link (light path) power consumption can be reduced by powering -down during off-peak hours and through re-configuration of under-utilized light paths to common partition-lightpath links.

6.3 Energy Efficient Optical Connections (Light path Establishment)

Messaging initiation and termination can be described by a sequence diagram. Figure 6.3 illustrates the messages sequence diagram for the transition from the ON to the OFF state assuming that the network is a full mesh topology (complete network topology connections are not shown for simplicity). A similar light path setup and signalling reservation process is applied to that described in Section 4.5. For end-to-end provisioning from ingress to egress node with wavelength conversion, after mapping the available resources the wavelength are reserved by signalling.

Consider the optical fibre connection from ingress to egress node traverses links with light path 1= {λ1, λ5, λ9, λ13}, light path 2= {λ2, λ6, λ10, λ14}, light path 3= {λ3, λ7, λ11, λ15} and light path 4= {λ4, λ8, λ12, λ16}. Dynamic wavelength provisioning assigns particular wavelengths to light paths on fibre links between adjacent nodes and can be bundled for hibernation to form Partition 1 and Partition 2. The former consists of a set of active wavelengths (λ1, λ2, λ3, λ4, λ9, λ10, λ11, λ12) forming a light path whilst the latter comprises a set of idle wavelengths (λ7, λ8, λ15, λ16) and active wavelengths (λ5, λ6, λ13, λ14). The Control plane receives hibernation notification messages indicating that idle wavelengths (λ7, λ8) of light path 3 and light path 4 respectively on partition 2 on fibre links between node 2 and node 3. At Node 3, after the hold-off timer expires, hibernation notification messages are transmitted back to the ingress node to release the reserved wavelengths. The loopback LSP *Resv_Confirm_Lightpath* message propagates back along the link until it arrives at the ingress node to request the inactive wavelengths. If however, Node 3 receives a LSP setup request message to place the node in an *OFF* state, a *Resv_Err* message is sent to acknowledge the ingress node that wavelengths (λ7, λ8) are in power-down state. As a result, the network updates the routing table, local updated wavelength availability information and network topology into TED. The ingress node releases a LSP by propagating a *Path_Tear* message to tear down the connection to idle wavelengths.

If no idle wavelengths are available along the path, then Node 3 will check for similar light path ID and partition ID to place the link into sleep. Node 3 will then propagate messages to adjacent nodes to check available light paths. In this case, the control plane detects other inactive wavelengths (λ15, λ16) on the fibre linking Node 4 and Node 5. Again, a similar process as previously described at Node 5 is initiated, after the hold-off timer expires, with hibernation notification messages transmitted back to the node to release the reserved wavelengths. A loopback LSP *Resv_Confirm_Lightpath* message propagates back along the link until Node 4 to request the suspension of the idle wavelengths. Based on this information, the shortest path distance to re-route the selected light path (in this case light path 3 and light path 4) and re-configure the idle wavelengths to power-down partition 2 (under-utilized capacity) and to assign (move) the light paths on available wavelengths on partition 1.

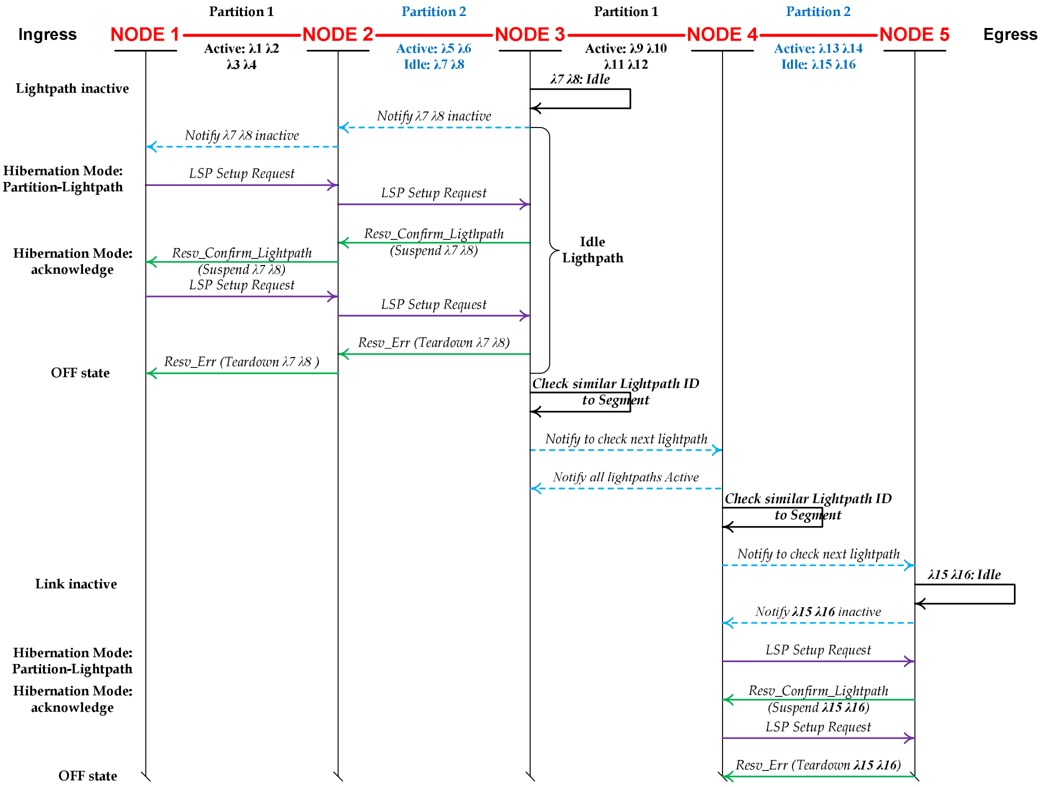


Figure 6.3: Message Sequence Diagram for transition from ON to OFF of Partition-Lightpath Scheme.

Figure 6.4 presents an example messages sequence diagram for the transition from the OFF to the ON state. Node 3 detects traffic on wavelengths (λ7, λ8) and changes its state to BUSY (active state) and full power operation is resumed. It then transmits the confirmed notify message to inform the adjacent node that it is in the process of powering-up. A *Resv_Lightpath* message is sent to the ingress node to notify that the node is powering up, switching to the ON state. The node issues requests for the establishment of a light path connection to adjacent nodes; the control plane propagates the signalling and routing messages to corresponding nodes. Lightpaths re-route to the shortest path and the control plane sends messages to update the topology information into TED. Similar actions occur in Node 4 and Node 5. If any inactive wavelengths are changing to active state, then the wake-up notifications will be sent back along each section of the path to establish all reserved wavelengths. All light paths return to active and full power consumption is resumed.

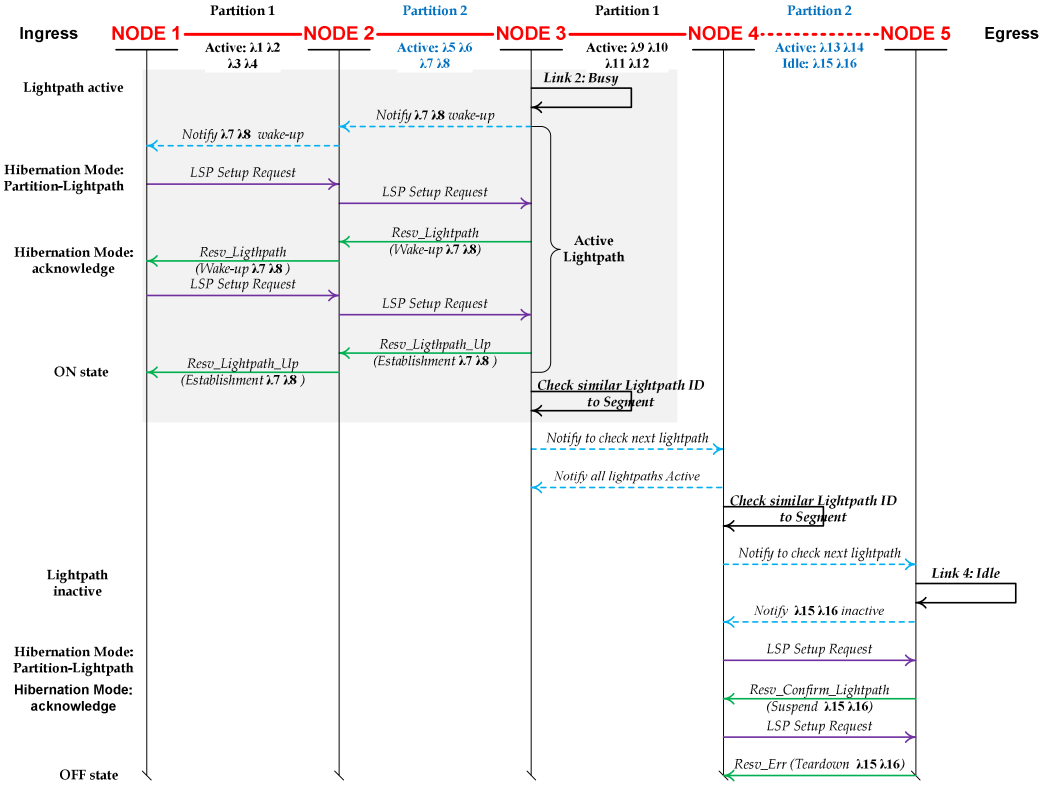


Figure 6.4: Message Sequence Diagram for transition from the OFF to the ON state for the Partition-Lightpath Scheme.

6.4 Wavelengths Only Scheme

The wavelength only scheme provisions light paths without optical bypass at intermediate nodes, wavelength converters always in active state and no traffic engineering. Additionally, this scheme is performed without GMPLS control, applying the existing (original) routing strategy [38][39]. Operation in the optical and IP domains is independent of each other. This scenario represents the reference against which the proposed energy saving schemes is compared.

6.5 Partition-Lightpath Scheme

In this section, the principles of the partition-lightpath scheme together with its mathematical formulation will be given.

6.5.1 Lightpath Re-routing

A Path Computation Element (PCE) is an entity capable of calculating a network path or route based on a network graph, and of applying computational constraints during the computation. It is an application that can be located within a network node (operating on the TED) [161][165]. For routing with distributed wavelength assignment, PCE is only responsible for routing but not for wavelength assignment and resource reservation. Wavelength assignment is performed through signalling, and the assigned wavelength is reserved by a resource reservation protocol [161]. Light path re-routing is an effective way to conserve power in optical IP networks. In this strategy, priority is given to route continuity constraints so that the light path routing complies with the OSPF-TE standard. Some extensions have been proposed in order to establish and maintain LSP connections; Appendix C presents aspects of these extensions in more detail.

6.5.2 RWA Heuristic Scheme

The Path Computation Element (PCE) triggers the active-to-sleep mode transition and is responsible for light path routing. Traffic Engineering within the PCE stores all information about network topology (no wavelength information is available). Also, the TED stores the information about the operating status of the links and their power consumption [162].

The partition-lightpath dimension of the hibernation mode aims to minimize the power consumption for optical IP networks by implementing wavelength assignment and routing at the PCE generated by solving an integer linear programming formulation (ILP). The PCE calculates the best path within a link and updates the network status. The former is implemented according to a *make-before-break-procedure* at the PCE [141][142] in which the light path on the selected link is placed into hibernation after the re-routing procedure is completed. The latter provides information on the link terminating at a node and sends out an updated message to the PCE regarding any change in the status of any of its links, network topology as well as wavelength availability.

The ILP formulation for selecting the link and light path to be placed into hibernation uses the following parameters and variables in the decision making [103][162]:

$G=(N,L)$	A physical topology which consists of a set of nodes N and links L. The former is a node set corresponding to core routers supporting GMPLS and OXC nodes. At each node, a core router is connected to an OXC. The latter is a link set consisting of bidirectional single mode fibre optic links.
Λ^{sd}	A forecast demand matrix (traffic request) Λ^{sd} served by a light path between each node pair (s,d)

$\pi^{\mathrm{sd,k}}$	K^{th} pre-computed path from *s* to *d*.
$y^{sd,k}$	The number of light paths established along $\pi^{\mathrm{sd,k}}$ before the switch-off, i.e., $\sum_k y^{sd,k} = \Lambda^{sd}, \forall_s, d$
w^l	Number of wavelengths on link *l*
P^l	Power drained by link *l*
α	Percentage of link utilization (i.e., $\alpha \in (0,1])$
H^{Ω}	Partition-lightpath hibernation mode.

$\lambda^{\mathrm{sd,k}}$	Indicates the number of light paths along $\pi^{\mathrm{sd,k}}$ after the link switch-off;
Binary q^l	Indicates whether link *l* is selected for being set to sleep ($q^l=0$) or ($q^l=1$)

The objective is to minimize;

$$\sum_{sdk:l\in\pi^{sdk}} \left[1-q^l\right] + \sum_{sd} P^l \cdot q^l + \sum_{ijl\in L_{mn}} \sum_{ij} P_{WC} \cdot w_{mn}^{ij} + \sum_{ij}\left(P_G^D C_{ij} + \sum_{sd} P_G^U \cdot \lambda_{ij}^{sd} \right) + \sum_{ij} H^{\Omega} \qquad (6.1)$$

subject to the following constraints:

$$\sum_{l\in L} q^l \geq L-1 \qquad (6.2)$$

$$\sum_k \lambda^{sdk} = \Lambda^{sd} \quad \forall_s, d \qquad (6.3)$$

$$\sum_{sd,k:l\in\pi^{sd,k}} \lambda^{sdk} \leq w^l \cdot q^l \quad \forall l \in L \qquad (6.4)$$

$$\lambda^{sdk} \geq y^{sd,k}\left(1-\sum_{l\in\pi^{sd,k}}\left(1-q^{l}\right)\right) \quad \forall_{sdk} \tag{6.5}$$

$$\sum_{sd,k:l\in\pi^{sd,k}}\left(\lambda^{sdk}-y^{sd,k}\right) \leq \max\left(0,\alpha w^{l}-\sum_{sdk:l\in\pi^{sd,k}} y^{sd,k}\right) \quad \forall l\in L \tag{6.6}$$

$$\sum_{sj\in N}\lambda_{sj}^{sd}=\lambda^{sd},\sum_{sj\in N}\lambda_{js}^{sd} \quad \forall sd\in Z \tag{6.7}$$

$$\sum_{sd\in Z}\lambda_{ij}^{sd}\leq w^{ij}\leq\sum_{sd\in N}\lambda_{ij}^{sd}+1 \quad \forall ij\in Z \tag{6.8}$$

$$\sum_{l\in L}w_{l}^{ij}=w^{ij}, \qquad \sum_{sd\in N}w_{l}^{ij}=0 \quad \forall ij\in Z \tag{6.9}$$

with the following integrality constraint;

$$x^{l}\in\{0,1\} \quad \forall l; \qquad \lambda^{sd,k}\in\mathbb{Z} \quad \forall_{sd,k} \tag{6.10}$$

The objective function of Equation (6.1) aims to minimize the total energy consumption in terms of the selection of idle fibre links and assignment of idle light paths to form a partition configuration within the hibernation mode. The first term of Equation 6.1 treats the control plane executed network discovery to select idle fibre links and to re-assign idle light paths to form a partition. The second term calculates the selection path through re-routing of the fibre links to realise a fewer number light paths on the link. The third term treats wavelength conversion capability so a light path traversing a link can use different wavelengths. In order to manage power consumption, the wavelength converter can switch off when a light path is not required and switch on to establish a light path. The fourth term treats traffic grooming in which traffic flows are aggregated and groomed at every IP router node so as to share a light path. Finally, the fifth term in Equation (6.1) calculates the energy saving owing to the partition-lightpath hibernation scheme.

Equation (6.2) treats the power aware routing constraint executing on the re-routing process and preventing excessive perturbations of the traffic flow. The constraint of Equation (6.3) ensures that all requested light paths are routed on any of the pre-computed paths whilst the constraint of Equation (6.4) limits the number of wavelengths on light paths traversing active fibre links. Therefore, when the hibernation mode is enabled, this constraint only allows certain light paths to be established on the link.

Equation (6.5) constrains the re-routing of light paths only to selected fibre links; all other light paths remain. Equation (6.6) limits the wavelength occupancy to α of the number of wavelengths on the links supporting re-routed light paths. If the link utilization before re-routing already exceeds the threshold ratio α, then the constraint does not have any effect and the link cannot be used for re-routing light paths. Such constraints are introduced to limit link load and avoid blocking of the re-routing procedures owing to the wavelength continuity constraint [162].

6.6 Energy Consumption Evaluation

The goal is to reduce the power consumed by active optical devices through managing the fibre links to support the minimum number of light paths. The hibernation partition-lightpath scheme is based on *make-before-break* procedure [141][142] that re-routes lightpaths whilst preventing data loss during the transitions.

Note that, these simulations results are based on *cross-layer optical/IP domain integration* and previous research focussed on the *optical domain only (power saving of ~45% [162] at optical layer by using green routing approach).* Therefore, results are difficult to compare in terms of power savings and network performance.

Figure 6.5 presents the power consumption difference from the 'ON' mode compared to partition-lightpath scheme for a node as a function of offered network load; the results show a noteworthy improvement in power consumption of ~0.25kW. The power consumption follows an approximately linear relationship with network traffic demand. This is because the networks employ traffic grooming and optical bypass; the former creates an aggregation of low-rate IP traffic (data) in IP layer into a few of high speed light paths in optical layer thus reducing the number of active electrical ports. The latter balances the traffic load and manages the power distribution variance amongst nodes.

Figure 6.6 shows the normalized power consumption of different hibernation schemes to the case of the reference "ON mode" state as a function of offered network load. Results show that the *partition-lightpath scheme* can achieve a power saving of 74% at 8 Erlangs compared to the *lightpath only scheme* (63%);the previous work claims that achieved a 40% power saving [162] using green routing technique. Figure 6.7 presents the power efficiency ratio between the Optical domain and IP domain network equipment. The Power ratio is defined as the ratio of the number of segment-link connections over the number of the active (ON state) network equipment. Results show that for both the partition-lightpath scheme and the lightpath only scheme, a power saving of 66% and 60% respectively at a network load 8 Erlangs can be achieved.

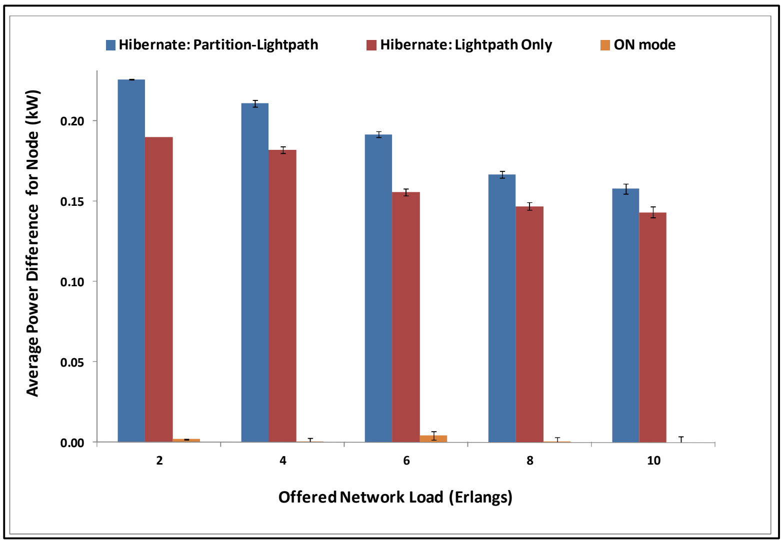


Figure 6.5: Average power difference between the ON state and different Partition-Lightpath Schemes as a function of offered load.

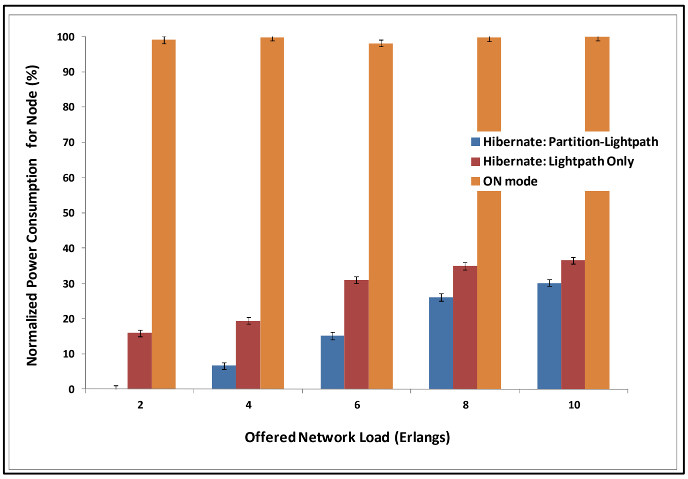


Figure 6.6: Normalized power consumption for different Partition-Lightpath schemes as a function of offered network load.

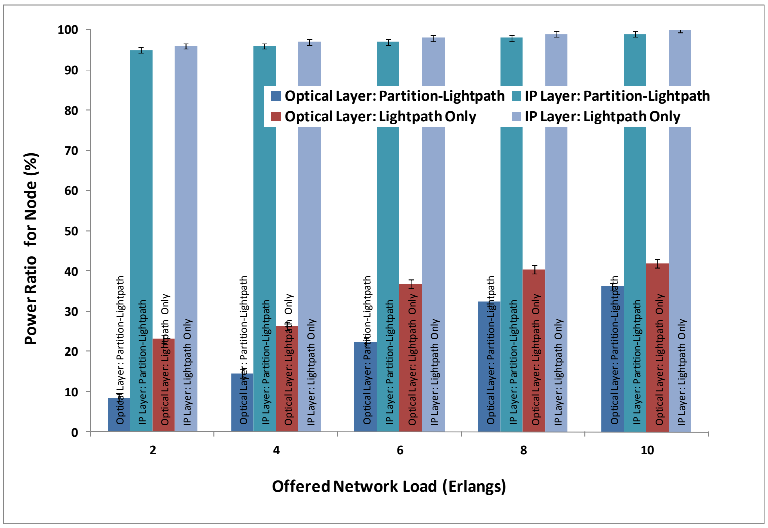


Figure 6.7: The power ratio between the Optical layer and IP layer for partition-lightpath schemes as a function of offered network load.

Figure 6.8 presents the impact on the blocking probability for partition-lightpath and lightpath only schemes. For the ‘lightpath only scheme’, the probability of blocking falls below ~23% thus delivering a better network performance but the power reduction/savings are minimal at 0.18kW (Figure 6.5). However, when segment-link scheme is set the blocking probability falls to ~32% and offers 0.25kW (Figure 6.5) of power saving. Here, the OXC makes use of all-optical wavelength converters to reduce blocking probability. The results show that the hibernation modes approach permits power savings at low loads.

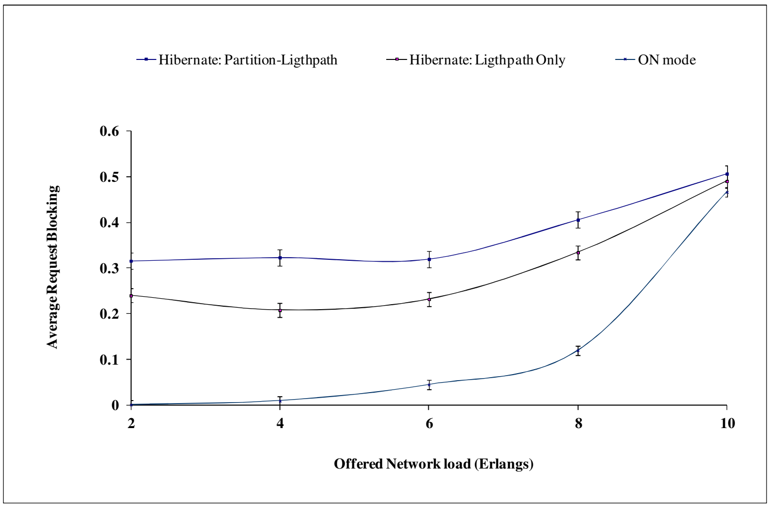


Figure 6.8: Request blocking for different Partition-Lightpath Scheme as a function of offered network load.

6.6.1 The Impact of Number of Wavelength on Energy Saving

Figure 6.9 presents link power consumption as a function of the number of wavelengths; results show similar trends for all λ. Energy consumption improves when the partition-lightpath scheme is applied, from 10.05kW to 10.01kW at the expense of a higher probability of blocking. The OSPF-TE advertises LSA messages to all fibre links and draws decisions on the most energy efficient way to re-route to connections with the minimum number of light paths; light path requests are updated by TED followed by path computation. In the extreme, a single fibre link can support all traffic while all other fibre links can be powered down.

Figure 6.10 shows the optical layer and IP layer power ratio as a function of the number of wavelengths. The power ratio is defined as the power dissipated by nodes of selected light path against the number of wavelengths within the entire set of active light paths. In the optical domain the partition-lightpath scheme yields a higher power saving ratio (~80%) than lightpath only scheme (~48%).

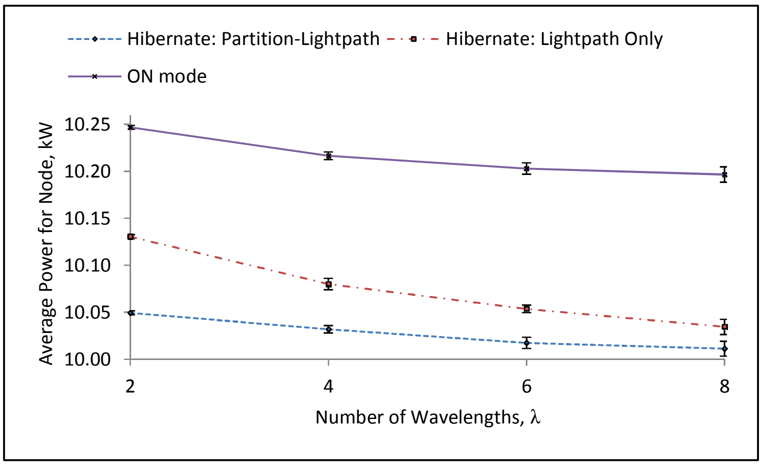


Figure 6.9: Link power consumption as a function of the number of wavelengths for peak and minimum traffic loads for Partition-Lightpath Schemes.

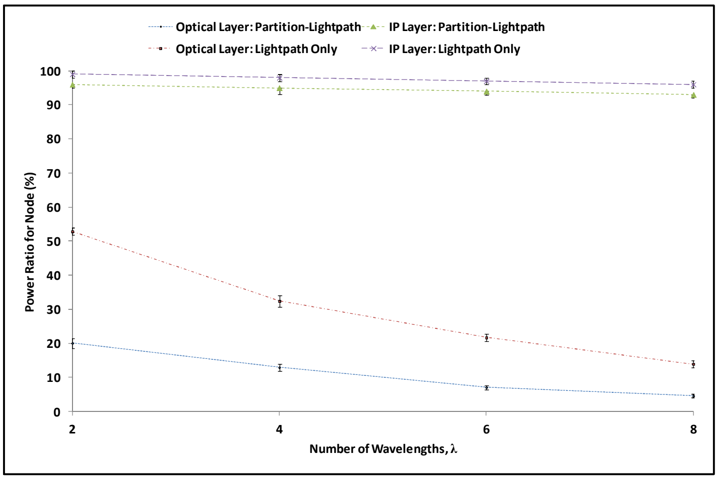


Figure 6.10: Power ratio as a function of the number of wavelengths for peak and minimum traffic loads for Partition-Lightpath Schemes.

6.6.2 Power Metric Evaluation

Figure 6.11 illustrates the power consumption as a function of the degree of network connectivity. The results show that connection availability and power saving both improve when the partition-lightpath approach is applied. Additionally, increasing network connectivity lowers the probability of blocking since the paths become shorter via OSPF-TE disjoint paths thereby improving link capacity. Therefore, as the number of wavelengths in the fibre links increases, not only is light path provisioning enhanced but a reduction in energy consumption results.

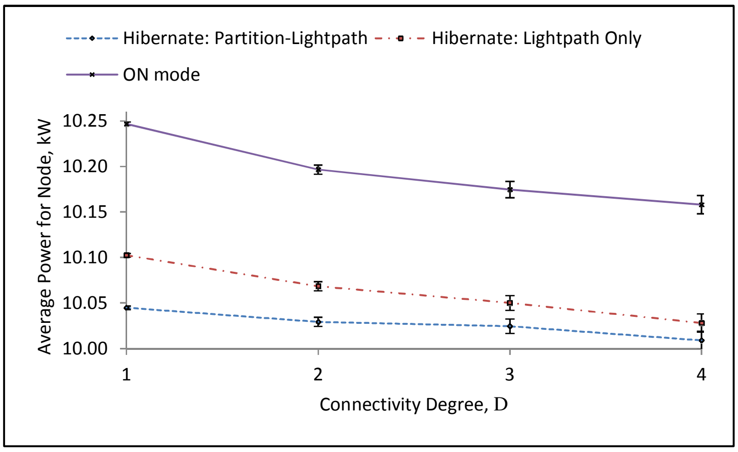


Figure 6.11: Power consumption as a function of the degree of network connectivity for peak and minimum traffic loads for different schemes of Partition-Lightpath Scheme.

The power ratio for a node in the optical and IP layers as a function of the degree of network connectivity is depicted in Figure 6.12. The power ratio is defined as the ratio of power consumption for selected light paths to the degree of network connectivity. In optical layer the partition-lightpath scheme produces a higher power saving ratio (~82%) than for lightpath only scheme (~58%). The reason for this is that the paths become shorter via OSPF-TE disjoint paths and the link capacity improves as the network connectivity degree escalates. In addition to, the results show that power savings ratio in the IP layer via the partition-lightpath increases (6%) when contrasted with the lightpath only scheme (2%).

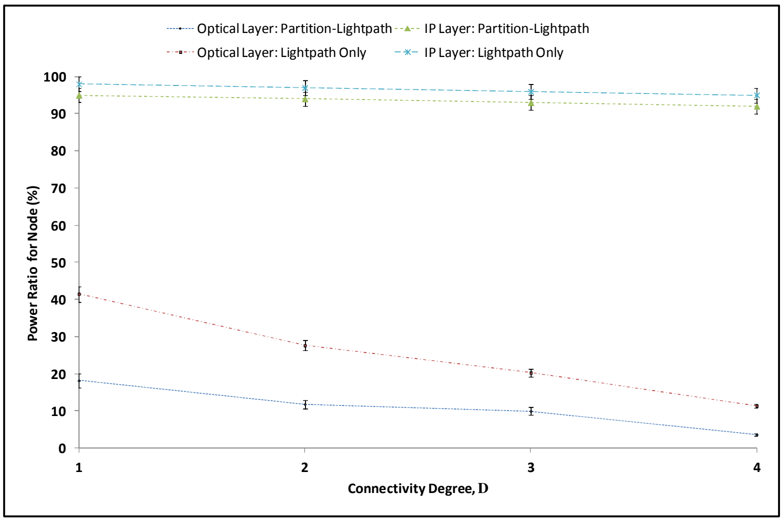


Figure 6.12: Power ratio as a function of the degree of network connectivity for peak and minimum traffic loads for different Partition-Lightpath Schemes.

Figure 6.13 presents the power consumption as a function of the number of nodes. As expected the power consumption significantly increases as the number of nodes increases. Nevertheless, the partition-lightpath scheme yields the most energy saving compared to other schemes. The results demonstrate that when the partition-lightpath scheme is applied, a power saving of ~10.04kW is achieved K=9 (number of nodes) and for the lightpath only scheme (~10.09kW at K=9). Optimised routing and wavelength assignments (RWA) lower the power consumption by using the same fibre link along the same connection as much as possible, thereby, reducing the number of active equipment in the nodes.

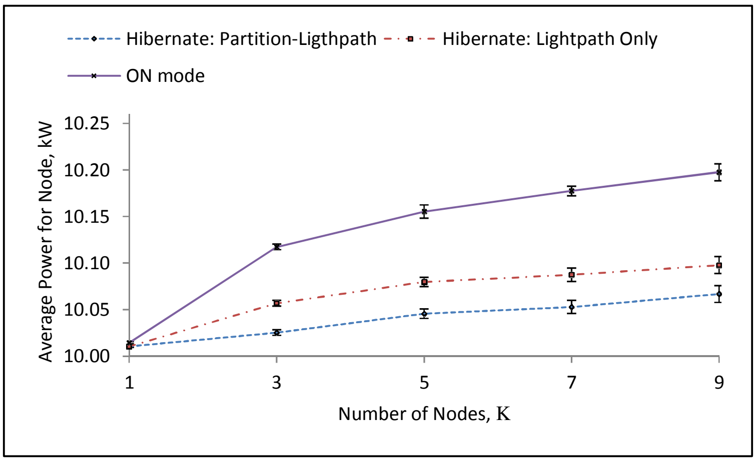


Figure 6.13: Power consumption as a function of the number of nodes for different Partition-Lightpath Schemes.

Figure 6.14 presents the power ratio for both the optical and IP domains for a node as a function of the number of nodes; the power ratio is defined as the ratio of the power consumption generated by nodes of a selected light path to the number of adjacent nodes. The results show that power ratio at the optical layer is improved from small to large network sizes giving a higher power saving ratio (from ~80% up to 97%) than the lightpath only scheme (from ~61% up to 97%). Notice that for *k=1* (small network size) the power ratio for both schemes is similar but the difference is more marked as network size grows. The reason for this is that the partition-lightpath scheme optimises to re-routing of light paths as the network size increases. Moreover, the results demonstrate that power savings ratio at the IP layer with partition-lightpath increases (8%) when compared to the link only scheme (4%).

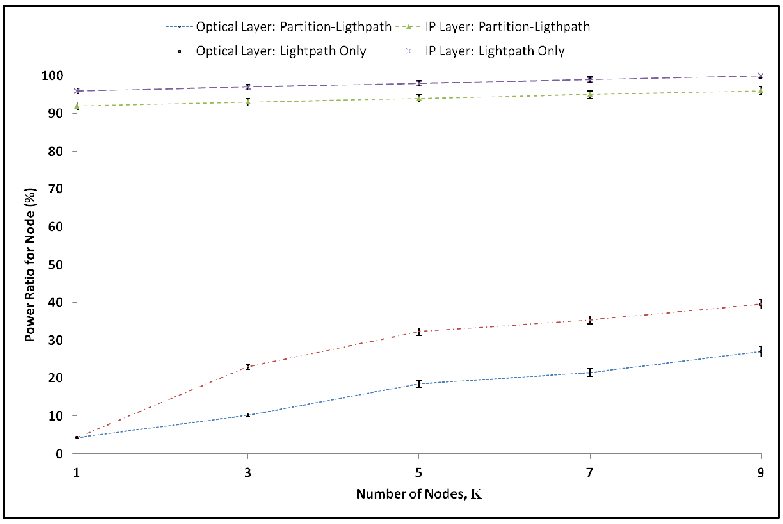


Figure 6.14: Power ratio as a function of the number of nodes for different Partition-Lightpath Schemes.

6.6.3 Energy Saving Evaluation

Depicted in Figure 6.15 is the power consumption as a function of network utilization. In this evaluation, the energy saving is addressed by minimizing the number of wavelengths in the network, while maximizing the number of connections that can be established (minimizing blocking) for a given number of wavelengths and a given set of connection requests. The results demonstrate that the energy saving with partition-lightpath is higher than compared to the “lightpath only scheme”. The dynamic re-routing of light paths over the selected fibre links whilst guaranteeing minimal disruption of existing light paths is worthwhile in terms of energy saving. The approach meets the required transition time between part modes whilst keeping resource utilization within a given threshold.

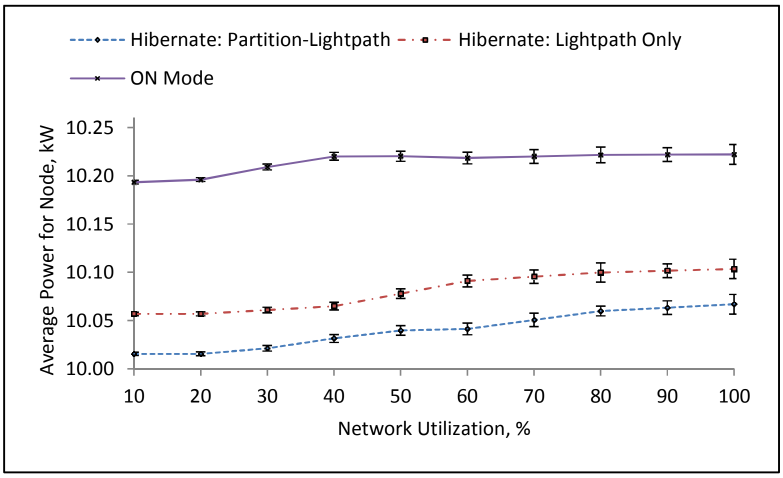


Figure 6.15: Power consumption as a function of network utilisation for different Partition-Lightpath Schemes.

Figure 6.16 presents the power ratio comparison of both the optical layer and IP layer for a node as a function of network utilization; the power ratio is defined as the ratio of the power dissipated by nodes of selected light paths over the network utilization. The results show that power ratio at the optical domain improves producing a higher power saving ratio (from 80% up to ~94%) than the light path only scheme (from ~62% up to 78%). The partition-lightpath scheme minimizes potential traffic disruption on powering down of fibre links, ports/interfaces whilst servicing LSP requests as the network utilization grows. Additionally, the results demonstrate that the power ratio at the IP domain rises steadily to 10% when compared to the lightpath only scheme (4%).

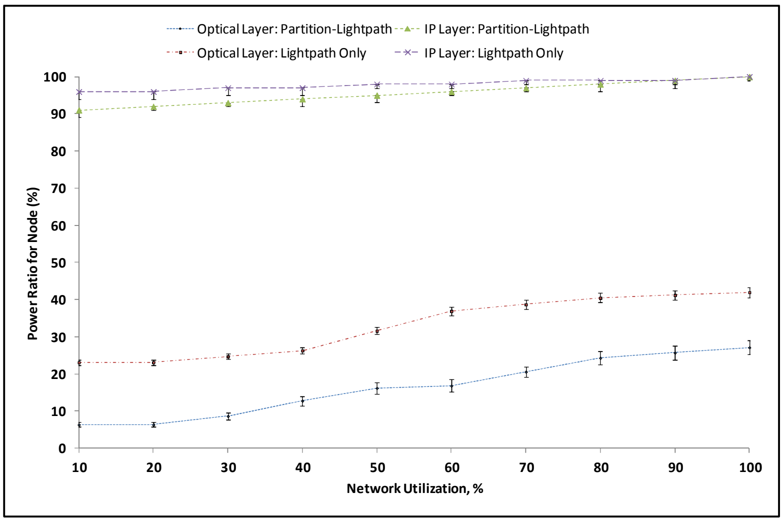


Figure 6.16: Power ratio as a function of network utilisation for different Partition-Lightpath Scheme.

Figure 6.17 presents power consumption as a function of the number of connection requests. The results show that the partition-lightpath scheme improves energy saving (~10.02kW at r=10^5) compared to lightpath only scheme (from ~10.03kW up to (~10.06kW at r=10^5). Light paths are established such that the number of connections established is optimized whilst forbidding the use of the same wavelength in connections that share a common fibre link.

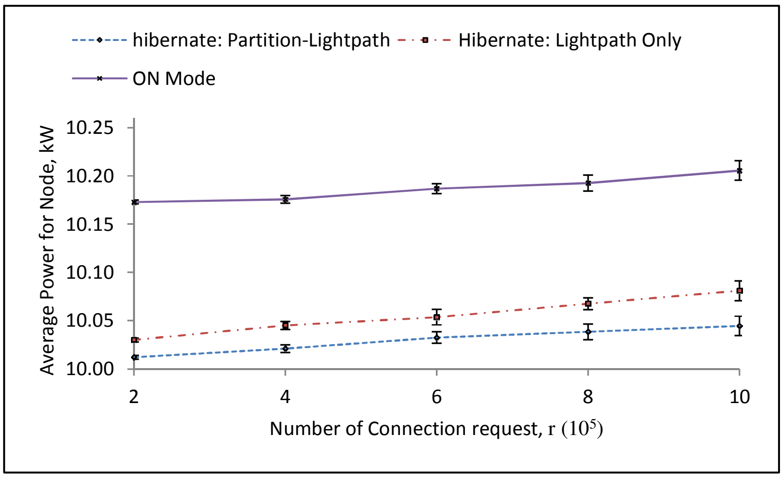


Figure 6.17: Power consumption as a function of connections requests for Partition-Lightpath Schemes.

Additionally, Figure 6.18 illustrates the power ratio for a node of both the optical and IP layers as a function of the number of connection requests; the ratio is defined as the ratio of the power consumed by a node at the selected number of light paths over the number of established light path connections in the network. The results show that at the optical layer the partition-lightpath scheme yields a higher power saving ratio (~95%) than the lightpath only scheme (~88%). The results also demonstrate that the power ratio at the IP layer for the partition-lightpath is higher (8%) than for the lightpath only scheme (4%).

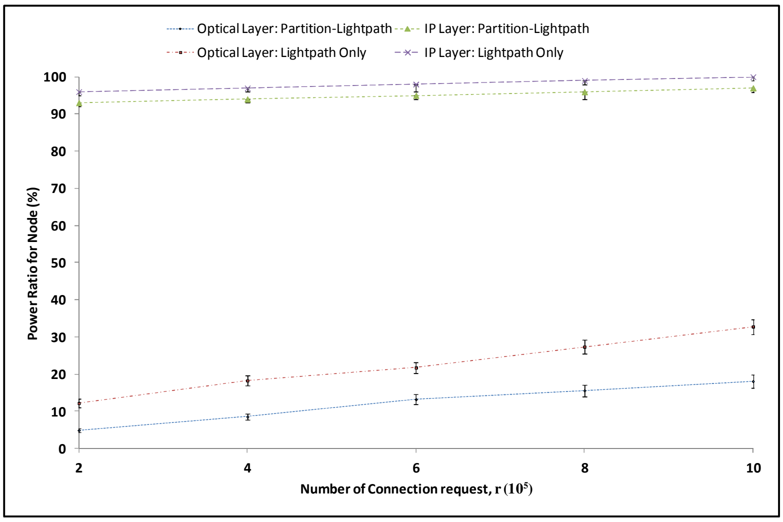


Figure 6.18: The power ratio for a node as a function of the number of connection requests for Partition-Lightpath Schemes.

6.7 Summary

The energy savings owing to partition-lightpath schemes on the European Optical Network (EON) full mesh topology was evaluated. Partition-lightpath optimises energy consumption by tearing down all idle light paths within node link(s) and by sub-clustering based on network activity status. The impact of a proposed approach on energy consumption as a function of the number of wavelengths, the degree of network connectivity, the number of nodes and connection requests was analysed. The proposed path provisioning strategy reduces network power consumption by forming network topologies through the selective partitioning of the wavelength within connections to enable a hierarchy of "suspended" states. The impact of the approach on blocking probability was also investigated. Results show that, the hibernation mode exhibits a trades-off between energy savings and crucial network performance parameters.

The mechanism minimizes power consumption in both the optical and IP domains. The former provides energy savings through optical bypass at intermediate OXCs, control of wavelength converters, traffic engineering and lightpath re-routing. The latter provides energy savings through traffic grooming and low-rate traffic aggregation, traffic engineering and routing.

The results for each evaluation are summarised in Table 6.3.

Table 6.3: Summary of perfromance evaluation of the partition-lightpath and lightpath only schemes.

Hibernation Scheme			***Lightpath Only***	***Partition-Ligth path***
Power Consumption	Power Difference for node		0.18 kW	0.25 kW
	Normalized Power Saving		62%	70%
	Power Ratio	IP Layer	4%	5%
		Optical Layer	58%	65%
	Blocking Probability		23%	32%
Number of Wavelength	Power Dissipation		10.13 kW	10.05 kW
	Power Ratio	IP Layer	2%	4%
		Optical Layer	48%	80%
Number of Nodes	Power Dissipation		10.09 kW	10.04 kW
	Power Ratio	IP Layer	4%	8%
		Optical Layer	61%	80%
Number of Connections	Power Dissipation		10.03 kW	10.01 kW
	Power Ratio	IP Layer	4%	8%
		Optical Layer	88%	95%
Number of Connectivity Degree	Power Dissipation		10.09 kW	10.04 kW
	Power Ratio	IP Layer	4%	8%
		Optical Layer	61%	80%
Network Utilization	Power Dissipation		10.06 kW	10.02 kW
	Power Ratio	IP Layer	4%	10%
		Optical Layer	78%	94%

Chapter 7

Conclusions and Future Work

In this Chapter, results from the evaluation of a number of energy saving schemes are summarised and discussed in detail and the major contributions are highlighted. Further extensions of the research are suggested. The Chapter is organised as follows; Section 7.1 provides the thesis structure; Section 7.2 presents an analysis of the results obtained; a statement of the research contributions are given in Section 7.3; and Section 7.4 provides suggestions for future research directions.

7.1 Thesis Structure

The research centred on the development of energy saving schemes that support the evolution of greener core optical IP networks. The cornerstone of the adopted strategy is various schemes underpinned by the hibernation state implemented through a modification of the control plane, in particular for opaque network architectures under different scenarios. The research evaluated the impact and constraints that arise under this strategy, to provide useful insights on the viability of the approach for practical energy efficient savings.

The Thesis is organized into three main parts. The first part, Chapter 3, is devoted to defining the structure and implementation of an extensive simulation-based environment to evaluate a distributed core optical IP network. This environment was developed using the OMNeT++ simulation platform. A number of initial simulations validated model behaviour and assumptions in terms of signalling and routing protocols, to ensure that the subsequent analyses emulated as far as possible, the operation and performance of realistic networks.

Chapter 4 proposes an approach to energy saving in core optical IP networks with roots in sleep modes. The impact of “Group-Nodes hibernation mode” on energy saving/network performance trade-off was examined. The schemes were evaluated a following two network node grouping strategies - Geographical and Ownership-based and evaluated on a representative network, the NSFnet topology. Results show that group-nodes approach, when properly implemented, can deliver energy savings but at the expense of network performance.

Chapter 5 describes the “Segmentation-Link hibernation mode” which delivers improved network power management through traffic engineering and adaptive routing. In this chapter, several issues were considered. To demonstrate its effectiveness, the method was applied to selected optical fibre links and the average power consumption as a function of network performance was evaluated for the European Optical Network topology. Results show that a meaningful level of energy can be saved using these schemes.

In Chapter 6, an enhanced multi-level operational hibernation mode through partition-lightpath was defined including functionality, structure considering its implementation issues. Through the use of appropriate design parameters the impact on blocking probability, wavelengths assignment, LSP connection requests, degree of node connectivity and network utilization can be minimized while also achieving energy savings.

7.2 Discussion of Results

The key distinction between the sleep mode and hibernation mode is that in the former energy savings are performed manually, for instance by pre-setting configuration or through the manual selection of switch off states for nodes, whilst the latter is a dynamic approach where network equipment or links are placed into sleep modes automatically governed by the state of the traffic flows within the network. Furthermore, previous research has not developed / evaluated hibernation mode techniques for power conservation in core optical IP networks under wavelength continuity. Hibernation modes are proposed based on group-nodes, segment-link, and partition-lightpath schemes to invoke a family of energy conservation options. Table 7.1 present the benefits and drawbacks of reported energy savings techniques in optical IP networks.

Table 7.1: Summary of advantages and disadvantages of energy savings techniques in optical IP networks.

Energy Savings Approach	*Advantages*	*Disadvantages*
Re-engineering	• Space switching: The energy efficiency is improved by setting or self-enabling SOAs (low power sensitivity and intergrability) to idle when unused and exploiting a totally passive technique for generating WDM packets using a wavelength-striped approach [168]. • Re-engineering required fewer network reconfigurations and re-routing due to energy mechanism is embedded in hardware [117]. • Reduce complexity of the switching fabric may lead to a smaller attenuation and smaller power consumption of the optical gates [122]. • Intelligent power management strategies use multi-chassis multi-line cards equipment which consolidate traffic from underloaded ports to reduced power [122].	• Modification of energy mechanism can be done on Hardware based implementation only [117]. • The passive wavelength-striped implementation is challenging and limits the maximum number of wavelengths (and thus of ports per card) [168].
Sleeping Mode	• Switch-off scheme: traffic load in backbone networks follows a stable daily pattern with significantly lower demand during the night. In this way, the network' capacity can be reduced during the night by shutting down idle resources, which in turn saves power on the corresponding interfaces [167]. • Selective switch-off idle network elements when traffic load	• Switch-off scheme: shutting down parts of the IP topology presents several challenges to network operators. First, any switching OFF of the IP links can cause rerouting of a large number of IP flows, which not only leads to service disruptions but also requires reconfiguration of the provider's tools for operation, administration and maintenance. Second, with decreasing number of links the average hop increases, which may increase the end-

	decreases still maintaining the vital functions of the network in order to support the residual traffic [67]. • Smart/Automatic sleeping mode mechanism via control plane implementation provides dynamic/intelligent energy efficient [162].	to-end packet delay and lower the network connectivity, and hence its resilience [167]. • Network performance decreases and higher blocking probability. • Primitive/manual sleeping mode technique such as switch ON/OFF network elements in which for certain circumstances are not practical specifically large scale network sizes [110].
Green Routing	• Uses energy consumption of network equipment as the optimization objective by considering line card/chassis reconfiguration in node to utilized routing scheme [67]. • Green routing is easy to manage, administration and maintenance. This is because routing protocol is based on existing OSPF-TE standard in which the lightpath can reroute the traffic and save energy according to shortest path first algorithm [67].	• The route maintenance mechanism does not locally repair a broken link. State route cache information could also result in inconsistencies during the route reconstruction phase. Thus required retransmission of Link State Advertisement (LSA) that causes more power consumption [117]. • OSPF-TE based routing is very network resources intensive that decreases the performance and energy consumption. For example, OSPF-TE maintains multiple copies of routing information thus increasing the amount of memory needed and changes the network topology (keep updates) [119].
Traffic Engineering (Energy aware)	• Enable device operating at lower frequency and/or voltage can achieve a significant reduction in energy consumption [111]. • Energy aware Traffic Engineering support multilayer network to reduce energy at both optical layer and IP layer [67]. • Utilize and reallocate the bandwidth resources by re-route under-utilized links of low bandwidth rate to single fibre link.	• Traffic engineering obtains best amount of energy savings but largest number of re-routings and reconfigurations causes network topology and database changes [111].
Green Provisioning	• Dynamic green provisioning improves efficiency of power management performance since avoid delay, error and minimized power consumption via algorithm during network operational [122]. • Long-reach WDM transceivers and low attenuation low dispersion fibres increase transmission efficiency such that the metric J/(b.km) can be reduced	• Access networks (PON) does not play significant role in green provisioning connection since users also get a relatively large data rate in case of a low number of users [70].

	by aggregate mixed-line rate technology on single fibre-subchannel connections at lower rates with less energy [122].	
Dynamic Link Rate Adaptation	• Uniformly distributed rates perform better than the exponentially distributed ones, in terms of added delay and average rate reduction (hence, achieved energy saving) [169]. • An increase in the number of supported rates is also shown to result in better performance, at the price of an increased management complexity [169]. • Rate adaptation improves energy saving significantly at access and metro networks due to link aggregation can be applied at these domains [169].	• Rate adaptation not appropriate to applied at core networks. This is because this domain has no significant impact on low speed. • Link adaptation via traffic grooming typically end up with longer routes which requires more transmission power (e.g. more in-line amplifiers) [122].
Time-aware energy optimization	• Scheduling packet transmission reduces the complexity problem, leading to reduction in the latency experienced by incoming packets in large size networks with respect to a single-step scheduler [168]. • Allows for parallelization of the scheduling operations leading to faster computation and higher scalability [117].	• Performance degradation due to suboptimality when applied to realistic traffic and high port counts [168].
Heuristic (ILP)	• It is intuition and simplicity algorithm [116]. • The lightpath bypass design can also equalize the geographical distribution of power consumption, which is helpful to a network that is subject to a maximal electricity power supply at each network node [116]. • Heuristic problem solution decease energy consumption by applied optical bypass via cut-through lightpath that reduced number of ports on the routers/OXCs [123].	• A virtual (lightpath) link must be established no matter how much traffic demand is required between a pair of nodes, so long as there is any. This may lead to low capacity utilization under some circumstances [116]. • Optical bypass unable to support excessive overhead due to bandwidth fragmentation, which may drastically degrade the performance of the direct lightpath strategy in which causes of higher bandwidth blocking ratio [122].

The key advantage of simulation studies and theoretical analysis is to provide implementation-independent results, as compared to prototype, hardware or real development based approaches. The evaluations were carried out using the OMNet++

simulator as an evaluation platform because it provides the best functionality for optical IP modelling with a number of key advantageous features; it is a public-source simulator with generic and flexible architecture, reliable and flexible on a component-based simulation package, class library, graphical network editing and animation, data collection, graphical presentation of simulation data, and random number generator Furthermore since the tool is workable with varieties of operating systems and C++ compilers, it has become a popular simulation platform in both the scientific and industrial communities.

The performance of the energy saving techniques was evaluated through extensive simulations. A summary comparison between group-nodes, segment-link and partition-lightpath scheme is shown in Table 7.2. Based on results, the partition-lightpath scheme provided a higher normalized power saving (~70%) but the network performance degrades with blocking probability of ~32%.

Note that, these simulations results are based on *cross-layer optical/IP domain integration* and previous research focussed on the *optical domain only*. Therefore, results are difficult to compare in terms of power savings and network performance.

The results obtained in Chapter 4, Chapter 5 and Chapter 6 show that implementation of hibernation mode techniques have promise for implementing different levels of energy conservation. Table 7.3 summaries the outcome of analyses of a range of metrics that are most appropriate in comparing the characteristics of Fixed (Geographical) Nodes and Random (Ownership) nodes. Results show that the performance in terms of the power consumption difference between the reference and node grouping improves but at the expense of a significant increase in blocking probability; 0.134 kW and 53% respectively with the group-nodes ownership scheme for all group hibernate in a full mesh topology. Similarly, the power consumption difference improves - 0.133 kW - and blocking probability degrades to 30% when mixed groups G2 and G3 hibernate.

Table 7.3 summaries the selected metrics when geographical and ownership schemes are applied in partial and full mesh topologies. The results show that, the highest power savings for all metrics occur for a mixed hibernate grouping of “G2 and G3” and “All-Group” with the ownership scheme; power saving from 10.117kW to 10.114kW as a function of the number of wavelengths; power saving from 10.020kW to 10.011kW as a function of the number of nodes; power saving from 10.026kW to 10.020kW as a function of the number of connections; and a power saving from 10.081kW and 10.070kW as a function of network utilization. Table 7.4 summaries the corresponding power consumption reduction for the different schemes.

Table 7.2: Comparison of hibernation mode efforts in core optical IP networks.

Energy Saving Mechanism/Attributes	*Group-Nodes*	*Segment-Link*	*Partition-Lightpath*
Normalized Power Savings	~9% (optical layer and IP layers)	~61% (optical layer and IP layer)	~70% (optical and IP layer)
Previous Work (Power Saving)	~50% [118] at optical layer only.	~15% [162] at optical layer only by using green routing approach.	~45% [162] optical layer only by using green routing approach.
Network Energy Model Structure	Cluster based Architecture	Node and link Architecture	Node, Link and lightpath Architecture
Green Routing	OSPF-TE standard	Adaptive OSPF-TE	Adaptive OSPF-TE
Energy Aware Traffic Engineering	None	None	Lightpath re-routing
Traffic Grooming	None	Link aggregation at IP layer.	Link aggregation and waveband granularity at IP layer.
Wavelength Converter	Always ON	▪ ON/OFF ▪ ON: present of wavelengths. ▪ OFF: absent of wavelengths.	▪ ON/OFF ▪ ON: present of wavelengths. ▪ OFF: absent of wavelengths.
Optical Switching Bypass	▪ Geographical: Indirect bypass (or non-bypass). ▪ Ownership: Direct bypass.	Direct bypass	Direct bypass
Heuristic Algorithm	None	RWA algorithm with optimization of node equipments.	RWA algorithm with TE, routing, traffic grooming and wavelength converters
Network Performance	Performance degradation and higher blocking probability (~50%) at	Performance steadily declined and higher blocking probability	Performance decreases and slightly higher blocking probability

	optical and IP layers compared to previous work 50% [118] blocking probability at the optical layer only.	(~40%)	(~32%)

Table 7.3: A summary of power saving evaluation that facilitates comparison between Fixed (geographical) and Random (Ownership) node grouping in partial and full mesh network topologies.

Group-Nodes		*Geographical*		*Ownership*	
Group	Metric	Partial	Full Mesh	Partial	Full Mesh
G1 = HM	Power Difference	0.031 kW	0.045 kW	0.031 kW	0.06 kW
	Blocking Probability	3%	2%	1%	1%
G2 = HM	Power Difference	0.049 kW	0.053 kW	0.054 kW	0.067 kW
	Blocking Probability	4%	3%	3%	2%
G3 = HM	Power Difference	0.055 kW	0.063 kW	0.053 kW	0.076 kW
	Blocking Probability	6%	5%	5%	4%
G1 & G2 = HM	Power Difference	0.097 kW	0.101 kW	0.098 kW	0.114 kW
	Blocking Probability	10%	8%	8%	7%
G2 & G3 = HM	Power Difference	0.108 kW	0.123 kW	0.108 kW	0.133 kW
	Blocking Probability	47%	34%	43%	30%
All Group=HM	Power Difference	0.130 kW	0.134 kW	0.130 kW	0.134 kW
	Blocking Probability	74%	50%	74%	50%
All Group=ON	Power Difference	0.002 kW	0.002 kW	0.002 kW	0.002 kW
	Blocking Probability	0.1%	0.1%	0.1%	0.1%

*Table 7.4: The outcome of simulation for each group in full mesh optical networks. **"OFF"** signify group is operated in hibernation mode with minimum network operation.*

Group-Nodes			*Number of Wavelength*	*Number of Nodes*	*Number of Connections*	*Network Utilization*
G1 = HM	Power Dissipation	Geographical	10.223 kW	10.025 kW	10.160 kW	10.190 kW
		Ownership	10.179 kW	10.052 kW	10.106 kW	10.145 kW
G2 = HM	Power Dissipation	Geographical	10.214 kW	10.023 kW	10.145 kW	10.175 kW
		Ownership	10.171 kW	10.042 kW	10.095 kW	10.134 kW
G3 = HM	Power Dissipation	Geographical	10.194 kW	10.021 kW	10.1137 kW	10.154 kW
		Ownership	10.155 kW	10.037 kW	10.075 kW	10.111 kW
G1 & G2 = HM	Power Dissipation	Geographical	10.157 kW	10.019 kW	10.071 kW	10.126 kW
		Ownership	10.126 kW	10.028 kW	10.047 kW	10.090 kW
G2 & G3 = HM	Power Dissipation	Geographical	10.130 kW	10.017 kW	10.040 kW	10.090 kW
		Ownership	10.117 kW	10.020 kW	10.026 kW	10.081 kW
All Group =HM	Power Dissipation	Geographical	10.114 kW	10.015 kW	10.020 kW	10.070 kW
		Ownership	10.114 kW	10.011 kW	10.020 kW	10.070 kW
All Group = ON	Power Dissipation	Geographical	10.247 kW	10.027 kW	10.182 kW	10.205 kW
		Ownership	10.247 kW	10.052 kW	10.191 kW	10.205 kW

The results for each evaluation of link usage for the segment-link technique metrics are summarised in Table 7.5. The results show clearly that the segment-link scheme provides a normalized power saving of 61%, the power ratio of Optical layer and IP layer being 56% and 5% respectively. However, network performance degrades with a blocking probability of up to 40%. The *segment-link scheme* provides improves energy efficiency compared to *link only scheme* in terms of the power metrics as a function of the number of wavelengths (power dissipation of 10.06 kW, optical layer power ratio of 75% and IP layer power ratio of 3%), network size (power dissipation of 10.10 kW, optical layer power ratio of 60% and IP layer power ratio of 5%), number of connections (power dissipation of 10.02 kW, optical layer power ratio of 92% and IP layer power ratio of 6%), of the degree of connectivity (power dissipation of 10.06 kW, optical layer power ratio of 75% and IP layer power ratio of 5%) and network utilization (power dissipation of 10.02 kW, optical layer power ratio of 90% and IP layer power ratio of 10%). In summary, the most significant power savings can be attributed to the *segment-link scheme* (~61%) whereas the best network performance occurs with the *link only scheme* with ~24% blocking probability.

Table 7.5: *Summary of the evaluation of the power savings attributed to the segment-link and link-only scheme.*

Hibernation Scheme			***Link Only***	***Segment-Link***
Power Consumption	Power Difference for node		0.176 kW	0.221 kW
	Normalized Power Saving		53%	61%
	Power Ratio	IP Layer	4%	5%
		Optical Layer	49%	56%
	Blocking Probability		24%	40%
Number of Wavelength	Power Dissipation		10.16 kW	10.06 kW
	Power Ratio	IP Layer	2%	3%
		Optical Layer	35%	75%
Number of Nodes	Power Dissipation		10.14 kW	10.10 kW
	Power Ratio	IP Layer	2%	5%
		Optical Layer	48%	60%
Number of Connections	Power Dissipation		10.04 kW	10.02kW
	Power Ratio	IP Layer	4%	6%
		Optical Layer	82%	92%
Number of Connectivity Degree	Power Dissipation		10.15 kW	10.06 kW
	Power Ratio	IP Layer	2%	5%
		Optical Layer	40%	75%
Network Utilization	Power Dissipation		10.07 kW	10.02 kW
	Power Ratio	IP Layer	4%	10%
		Optical Layer	71%	90%

The results for each evaluation of lightpath only and partition lightpath hibernation mode metrics are summarised in Table 7.6. The results show that partition-lightpath scheme provides a normalized power savings of 70% and higher power ratio of optical layer and IP layer of 65% and 5% respectively. However, network performance degrades with a blocking probability of up to 32%. The *partition-lightpath scheme* provides improved energy savings compared to *lightpath only scheme* as a function of the number of wavelengths (power dissipation of 10.05 kW, optical layer power ratio of 80% and IP layer power ratio of 4%), network size (power dissipation of 10.04 kW, optical layer power ratio of 80% and IP layer power ratio of 8%), number of connections (power dissipation of 10.01 kW, optical layer power ratio of 95% and IP layer power ratio of 8%), of the degree of connectivity (power dissipation of 10.04 kW, optical layer power ratio of 80% and IP layer power ratio of 8%) and network utilization (power dissipation of 10.02 kW, optical layer power ratio of 94% and IP layer power ratio of 10%). In summary, the most significant power savings occur with for the *partition-lightpath scheme* (~70%) whereas the best network performance is provided by the *link only scheme* with a ~23% blocking probability.

Table 7.6: A summary of the evaluation of the power savings owing to Lightpath only and partition lightpath schemes.

Hibernation Scheme			***Lightpath Only***	***Partition-Lightpath***
Power Consumption	Power Difference for node		0.18 kW	0.25 kW
	Normalized Power Saving		62%	70%
	Power Ratio	IP Layer	4%	5%
		Optical Layer	58%	65%
	Blocking Probability		23%	32%
Number of Wavelength	Power Dissipation		10.13 kW	10.05 kW
	Power Ratio	IP Layer	2%	4%
		Optical Layer	48%	80%
Number of Nodes	Power Dissipation		10.09 kW	10.04 kW
	Power Ratio	IP Layer	4%	8%
		Optical Layer	61%	80%
Number of Connections	Power Dissipation		10.03 kW	10.01 kW
	Power Ratio	IP Layer	4%	8%
		Optical Layer	88%	95%
Number of Connectivity Degree	Power Dissipation		10.09 kW	10.04 kW
	Power Ratio	IP Layer	4%	8%
		Optical Layer	61%	80%
Network Utilization	Power Dissipation		10.06 kW	10.02 kW
	Power Ratio	IP Layer	4%	10%
		Optical Layer	78%	94%

These findings suggest that in general, the partition-lightpath scheme is the preferred power savings (~70%) option compared to other schemes. Potential further reductions in power consumption are possible if a combination of both segment-link scheme and partition-lightpath scheme are employed. However, this combination scheme requires new energy modelling solution and complex simulation computation that require more hardware computer resources (high-end servers) as well as being time consuming; thus, we best leave it for future research works.

7.3 Achievements

In summary, the major achievements of the research are:

1. A network energy model that executes hibernation mode mechanisms based on an intelligent control plane supporting *smart sleep* was developed. The key feature of the proposed strategy is to identify network conditions amenable to implementing hibernation modes to save power, operations that suspend inactive nodes or elements of nodes by disabling unnecessary functionalities such as ports/interfaces, Mux/Demux capabilities, signalling gates, unused wavelengths. Nodes in the HM state represent the minimum mode maintaining core network capabilities.
2. The Group-Nodes hibernation mode that invokes cluster based architectures was evaluated and investigated. By dividing the nodes into several disjoint sets, as well as providing each node with geographical and ownership topology settings, produces clusters adopting sleep cycles to reduce power consumption.
3. The Segmentation-Link hibernation mode relying on an intelligent routing and traffic engineering strategy, providing power savings through identifying and powering-down a subset of inactive links.
4. The Partition-Lightpath hibernation mode relying on balancing energy consumption across network while maintaining wavelength connectivity was proposed and evaluated. The approach lowers power consumption at the expense of a slight increase in blocking probability; maintaining network performance by enhanced traffic utilisation through efficient lightpath establishment.

7.4 Future Work

In this Section future research direction are presented.

7.4.1 Energy Saving of Core Network Survivability: Protection, Restoration and Recovery

In the core network, future research issues on energy-aware network survivability consist of path/link protection, restoration and recovery mechanisms. Such mechanisms are amenable to an intelligent control plane implementation supporting survivability schemes under different failure conditions. In [163], the author suggests a new strategy to reduce the carbon footprint by considering network survivability in the context of the energy saving. In traditional optical transport networks, many network survivability techniques such as 1+1/1:1, p-Cycle, and shared backup path protection (SBPP) have been widely investigated [163]. In green core optical networks, the energy saving results in fewer network resources and longer network equipment power-up times. It is thus necessary to re-evaluate different network protection techniques in the context of the energy saving. An understanding of how operational modes or restoration can be changed driven by energy-saving goals. Specifically, can a subset of network resources or equipment allocated to protection be allowed to partially sleep under normal network conditions; and when a failure occurs, how quickly can the powered-down network resources be activated to recover the failure. In addition, the depth and extent of the powered-down network resources need to be defined so as not to disturb network continuity. Further, different levels of network resources can be powered-down dependent on the types of network services and different types of protection requirements. For example, a low priority service can cope with a significant level of network resources powered-down, whilst a service at a critical priority would be underpinned with a high level of always-on network resources.

Another potential approach to energy-aware network survivability is implementing pre-allocated restoration techniques under full single and dual-link failure recovery, covering issues on spare capacity allocation/optimisation, multi-layer cooperation, and differentiated survivability [163][166].

7.4.2 Renewable Energy Sources of Core Optical IP Networks Design.

Renewable energy (viz. solar, wind) is being harnessed to replace traditional hydrocarbon energy generation. This not only reduces the carbon footprint, but also paves the road towards a sustainable and environment-friendly societal evolution [67] [163]. Therefore, the strategy can be extended to evaluate energy saving mechanisms through the use of alternative energy sources in powering core optical IP networks.

Power consumption aware network designs using renewable energy sources approaches are proposed in [171]. The authors evaluate the approach for energy minimization in IP over WDM networks, using renewable energy to further reduce the CO_2 emissions by developing a Linear Programming (LP) model for improving renewable energy utilization. In addition, the authors investigated the energy savings that can be gained through Adaptive Link Rate (ALR) techniques developing routing algorithm with renewable energy sources as an input parameter. The authors in [163] suggest that considering renewable energy during network planning and operation viz. knowledge of the capability of each node to harness renewable energy achieves the greenest network operation. Particularly, if a network node can easily access renewable energy; plan to locate a core node that supports a large amount of traffic demand to take advantage of the energy source; in contrast if a node is unable to access renewable energy, its switching capability can be controlled to be sufficient to carry its local add/drop traffic.

It is also desirable that energy saving strategies be evaluated in relation to the modification of the GMPLS control plane incorporating energy aware traffic engineering and supporting renewable energy aware traffic load redistribution. Therefore, the research can be extended by adapting RSVP-TE signalling and OSPF-TE routing protocols, promoting more innovative networks based on renewable energy sources. The challenges are that the evaluation is not only time consuming but also requires complex simulation environments, and sophisticated simulation software resources.

7.4.3 Energy Minimization on Enhancement of Traffic Engineering and OSPF-TE Routing

Energy aware routing and Traffic Engineering are potential candidates to improving the power drained by core routers and optical devices. By optimizing algorithm modifications of both mechanisms not only reduce energy consumed but improve network utilization, in particular path convergence time, topology updates and efficiently re-routing unused/idle fibre links.

In [115], the authors suggest that routing and traffic engineering aim at dynamically turning network portions off during light utilization periods, in order to minimize energy requirements, while meeting the operational constraints and current switching workloads. The authors in [122] proposed power aware provisioning by means of service provisioning following a Traffic Engineering approach in which service provisioning is schematically decomposed as multiple serial operations, and power efficiency is analysed for both optical bypass and traffic grooming. In future, these approaches may be designed and developed to be adopted in control plane.

Appendix A

Network Topologies

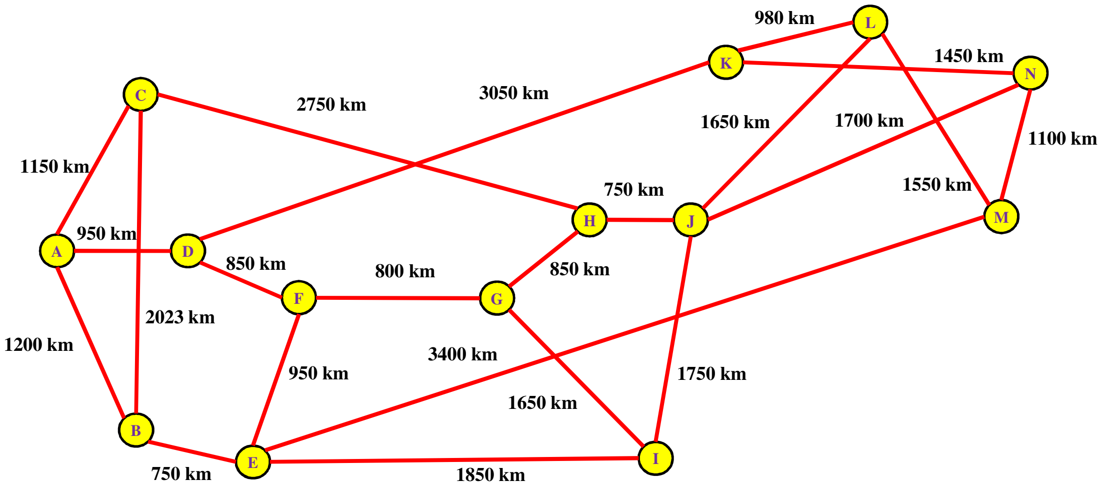


Figure A.1: National Science Foundation (NSFnet) Network Topology.

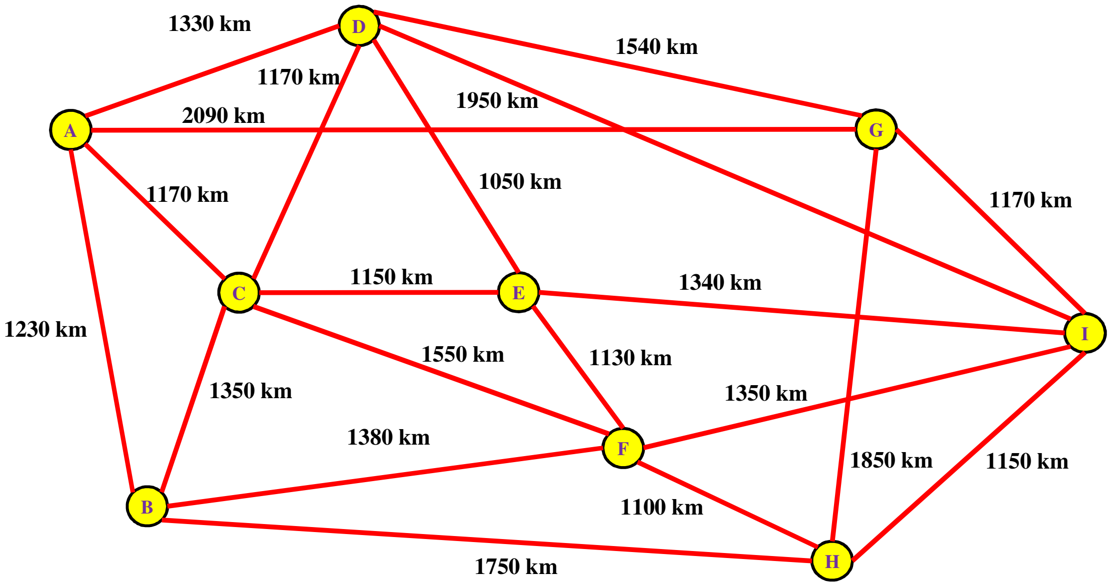


Figure A.2: European Optical Network (EON) Network Topology.

Appendix B

Simulation Model Structure

1. Introduction

This appendix presents the network simulation modelling design in terms of architecture and implementation using the OMNeT++ software platform. These core network simulation model has been described in different references and sources [132][133][135][136][137][138][164]. This Appendix provides an illustration of the structure and functionality of the optical IP network as a platform for the evaluation of the impact of different energy saving schemes presented in this work.

2. Network Modelling

OMNeT++ is an extensible, modular, component based C++ simulation library and framework with an integrated development and graphical runtime environment. Its provide a generic component architecture, and it is up to the model designer to map concepts such as network devices, protocols or optical channels into model components. Model components are terms modules, and, if well designed, modules can be used in a variety of different environments and can be combined in various ways as blocks. Modules primarily communicate via exchanges of messages, either directly or via predefined connections. Messages may represent events, packets, commands, jobs or other entities depending on the model domain. Figure B.1 through to Figure B.16 depict screen shots of the different elements of the modelling environment emulating an optical IP network used throughout the research.

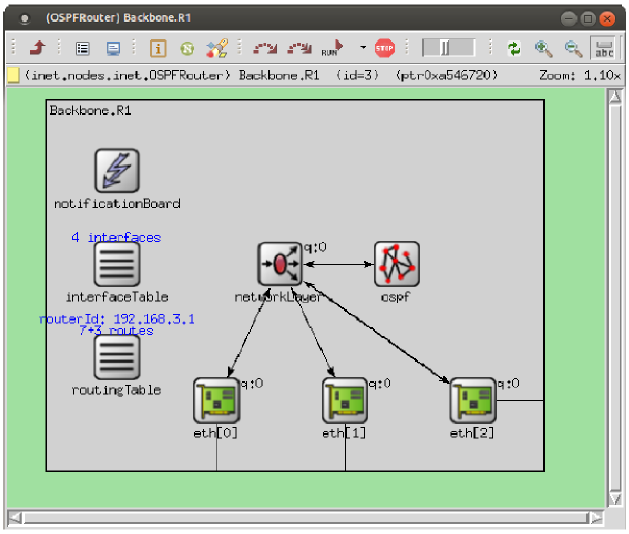


*Figure **B.1**: OSPF-TE routing.*

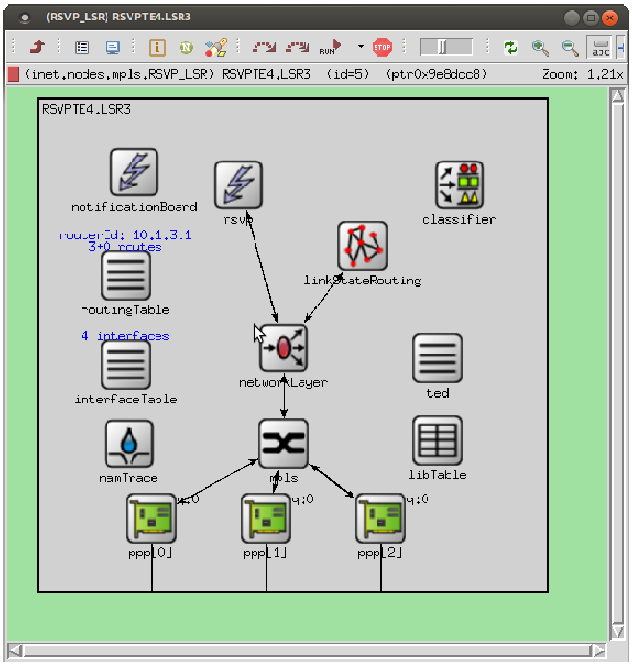


Figure B.2: RSVP-TE signalling.

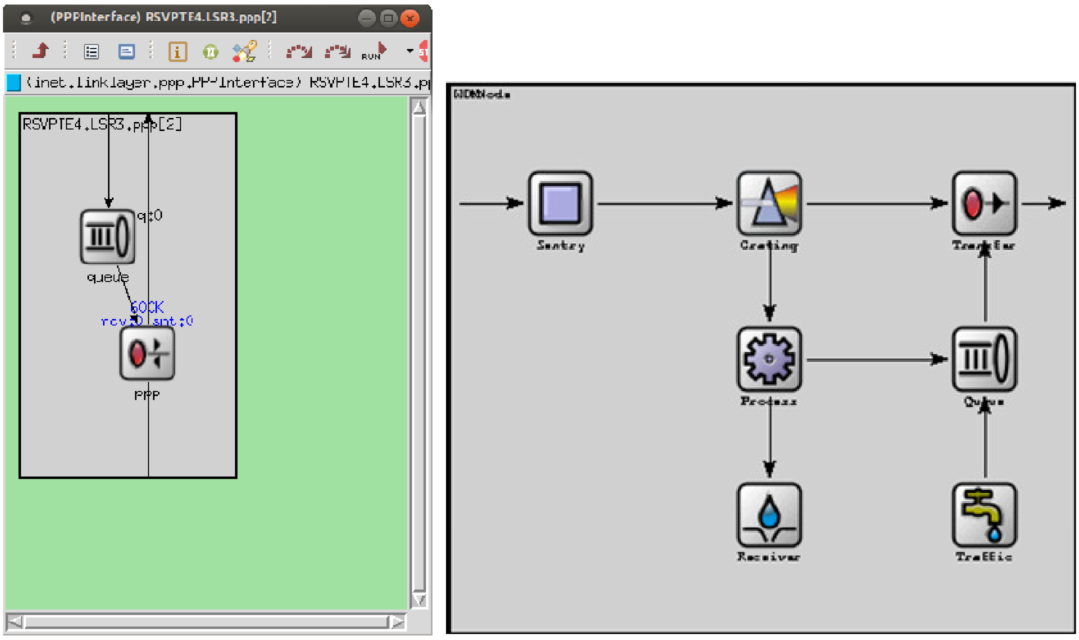
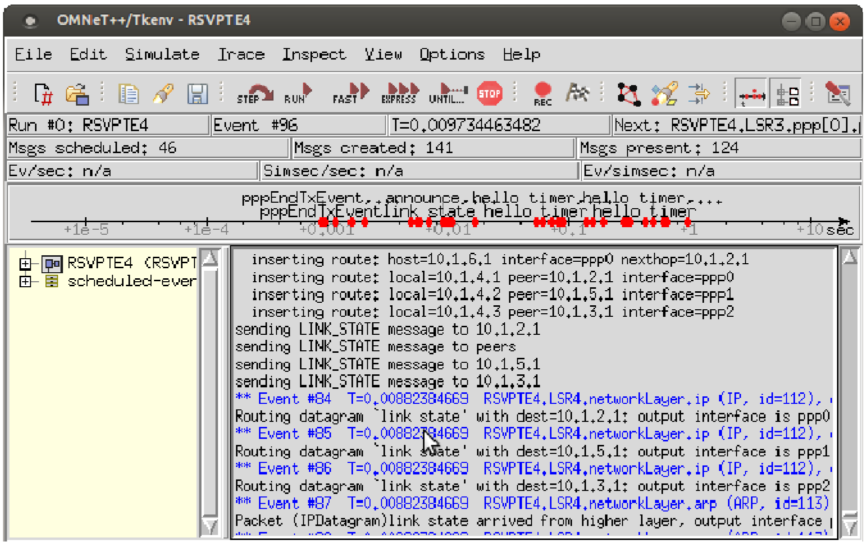


Figure B.3: Node Model.



Run #0: RSVPTE4 | Event #96 | T=0.009734463482 | Next: RSVPTE4.LSR3.ppp[0].

Msgs scheduled: 46 | Msgs created: 141 | Msgs present: 124

Ev/sec: n/a | Simsec/sec: n/a | Ev/simsec: n/a

```
  inserting route: host=10.1.6.1 interface=ppp0 nexthop=10.1.2.1
  inserting route: local=10.1.4.1 peer=10.1.2.1 interface=ppp0
  inserting route: local=10.1.4.2 peer=10.1.5.1 interface=ppp1
  inserting route: local=10.1.4.3 peer=10.1.3.1 interface=ppp2
sending LINK_STATE message to 10.1.2.1
sending LINK_STATE message to peers
sending LINK_STATE message to 10.1.5.1
sending LINK_STATE message to 10.1.3.1
** Event #84  T=0.00882384669  RSVPTE4.LSR4.networkLayer.ip (IP, id=112),
Routing datagram `link state' with dest=10.1.2.1: output interface is ppp0
** Event #85  T=0.00882384669  RSVPTE4.LSR4.networkLayer.ip (IP, id=112),
Routing datagram `link state' with dest=10.1.5.1: output interface is ppp1
** Event #86  T=0.00882384669  RSVPTE4.LSR4.networkLayer.ip (IP, id=112),
Routing datagram `link state' with dest=10.1.3.1: output interface is ppp2
** Event #87  T=0.00882384669  RSVPTE4.LSR4.networkLayer.arp (ARP, id=113)
Packet (IPDatagram)link state arrived from higher layer, output interface
```

Figure B.4: OMNeT++ messaging.

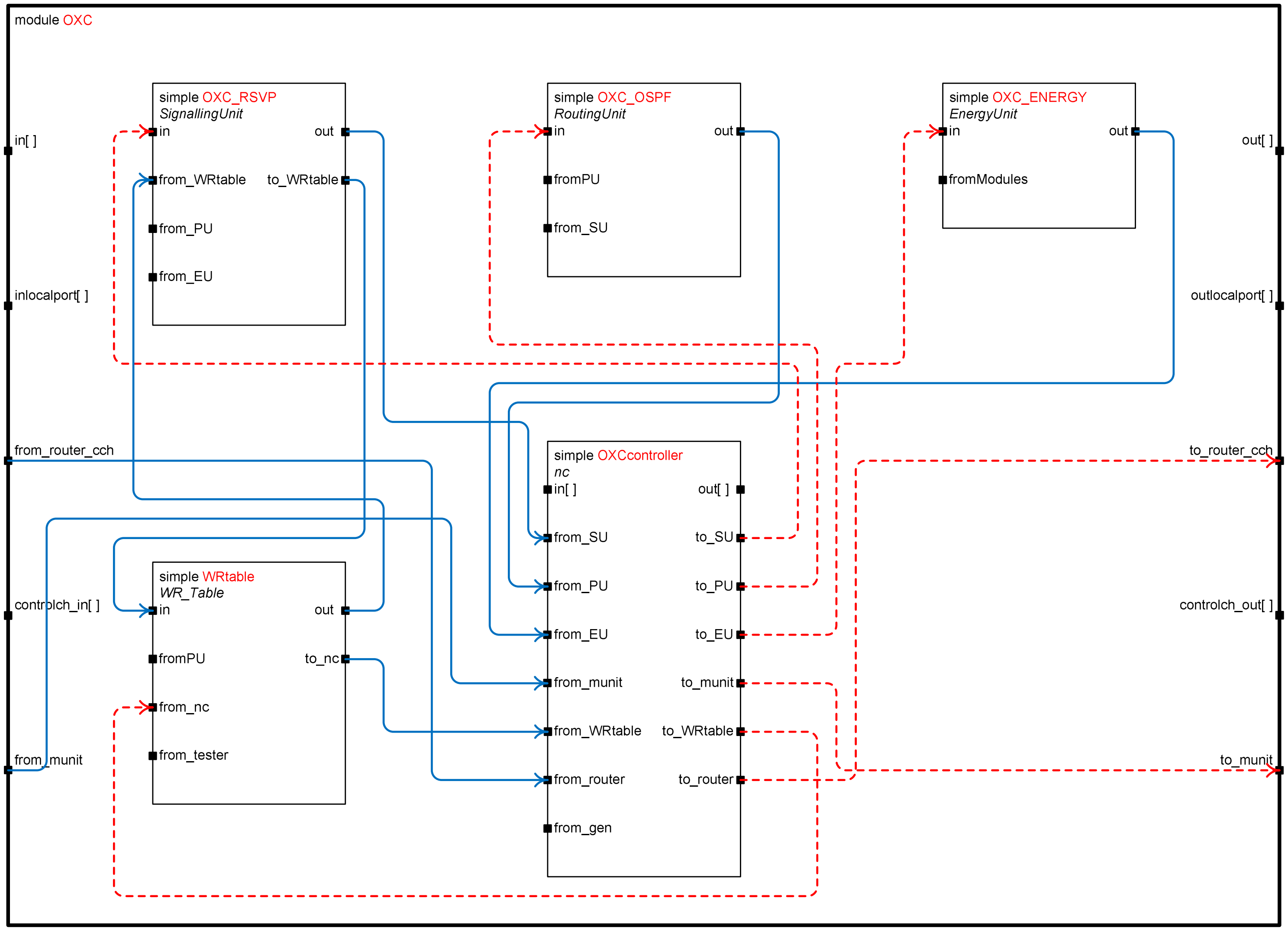


Figure B.5: OXC model implementation.

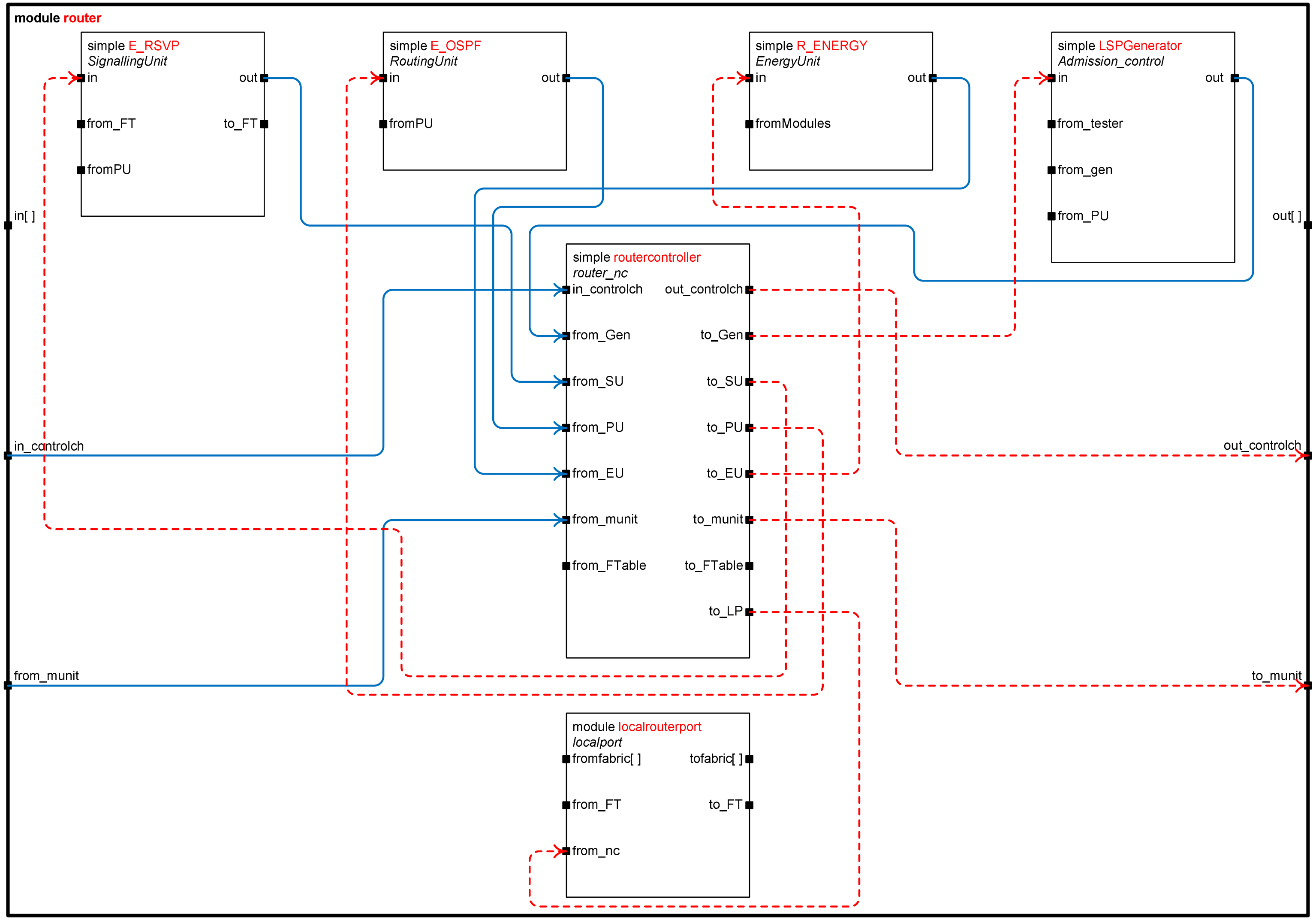


Figure B.6: Core router model implementation.

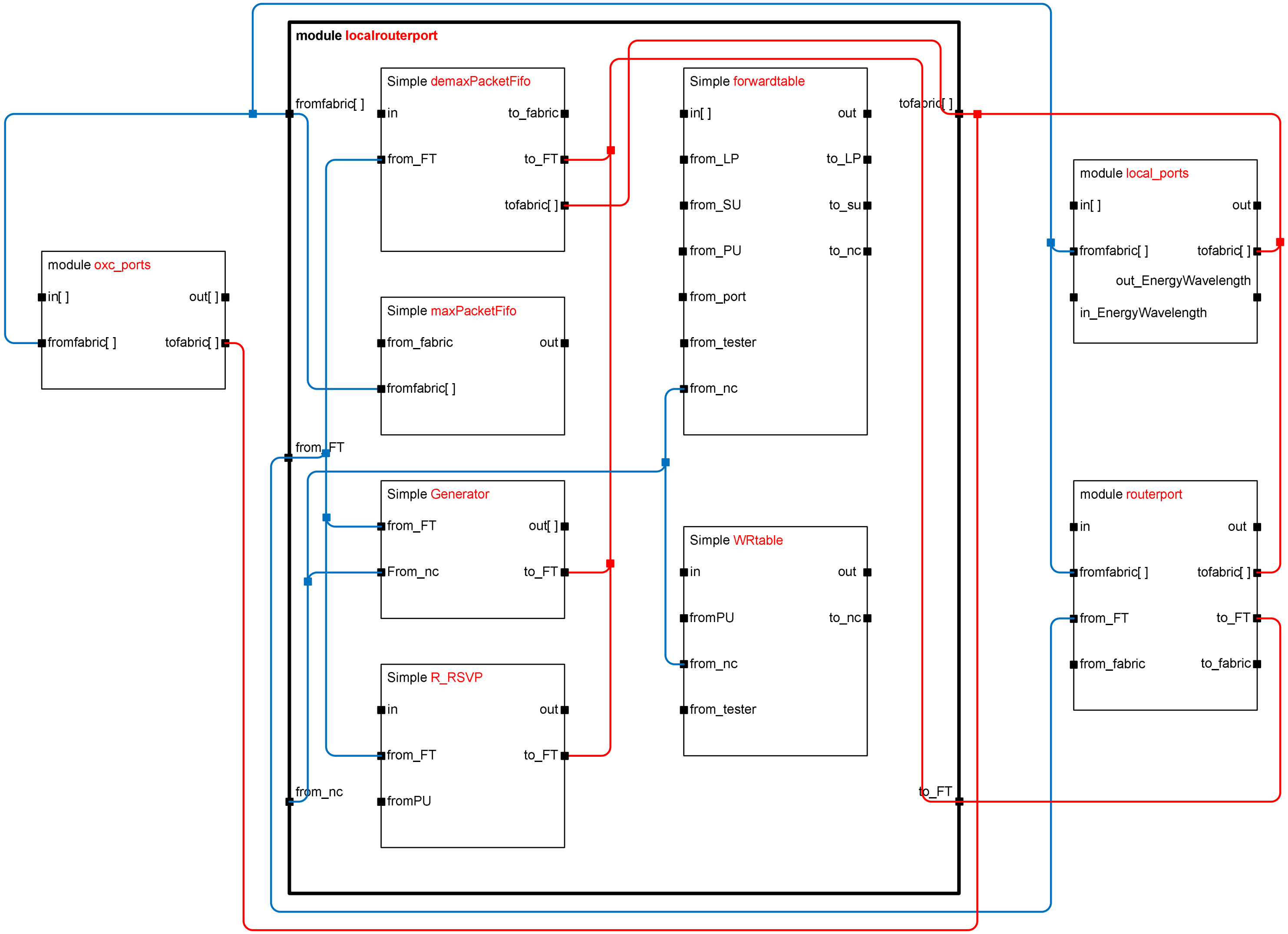


Figure B.7: Local core router port model.

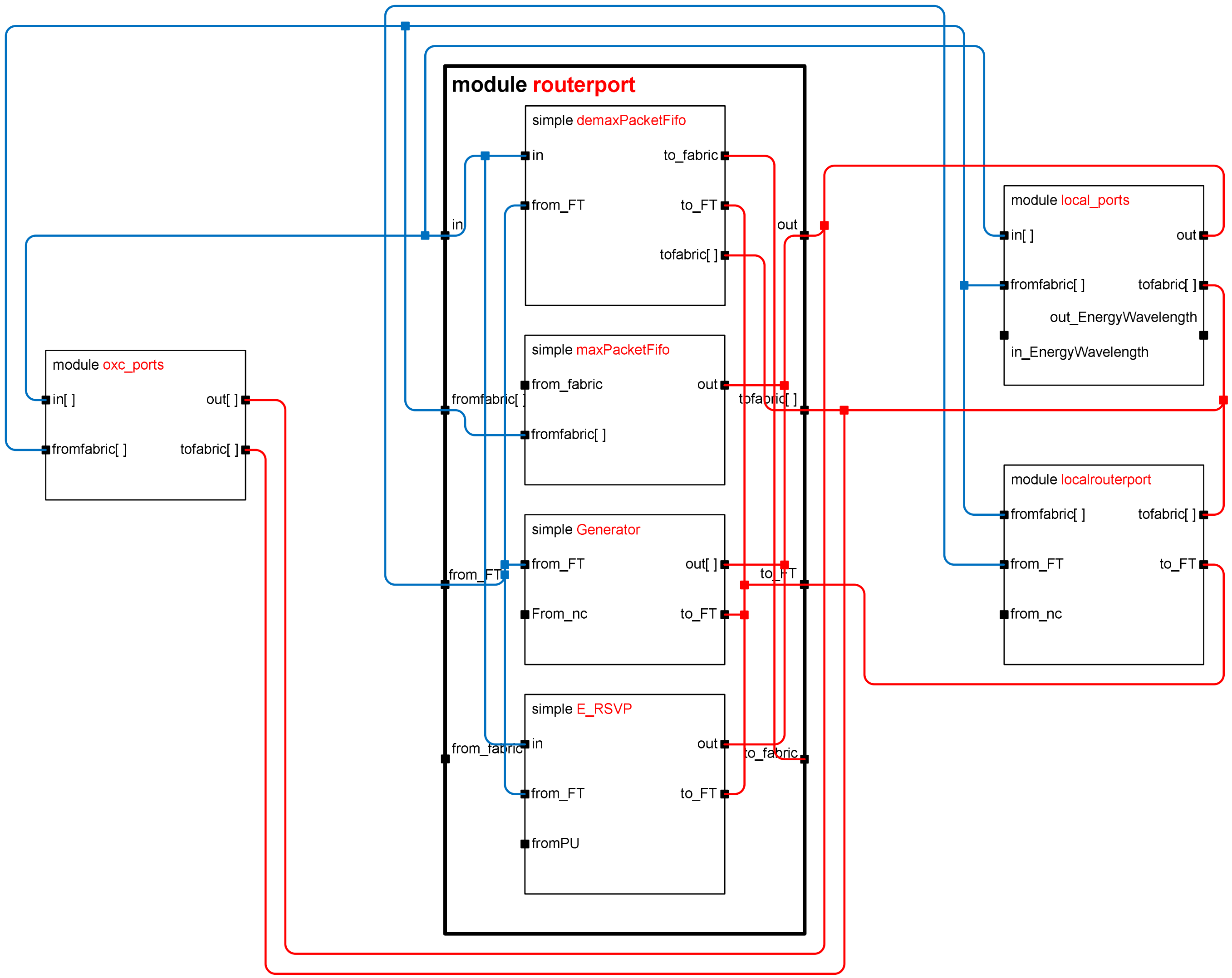


Figure B.8: Core router port model.

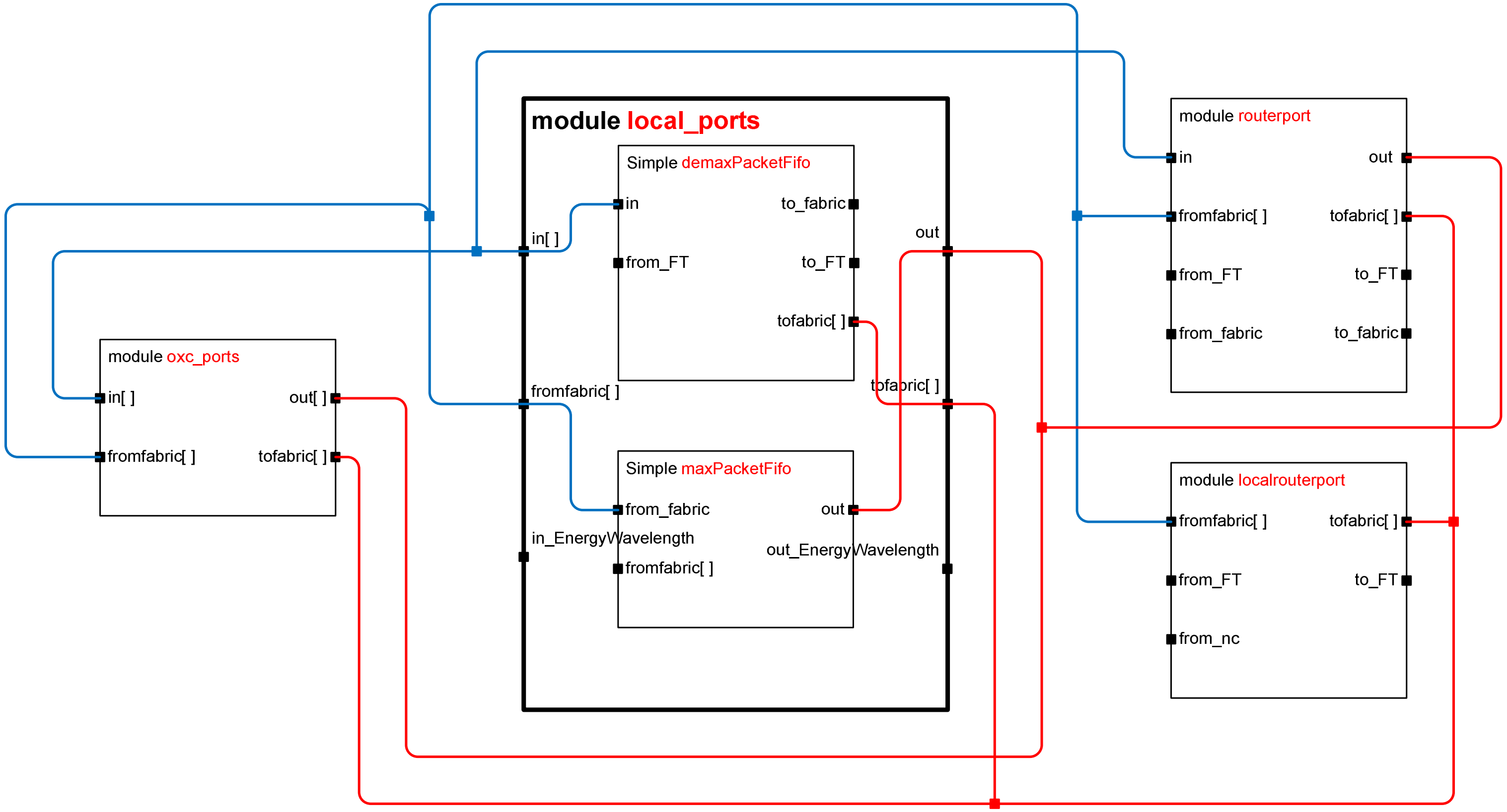


Figure B.9: Local ports model.

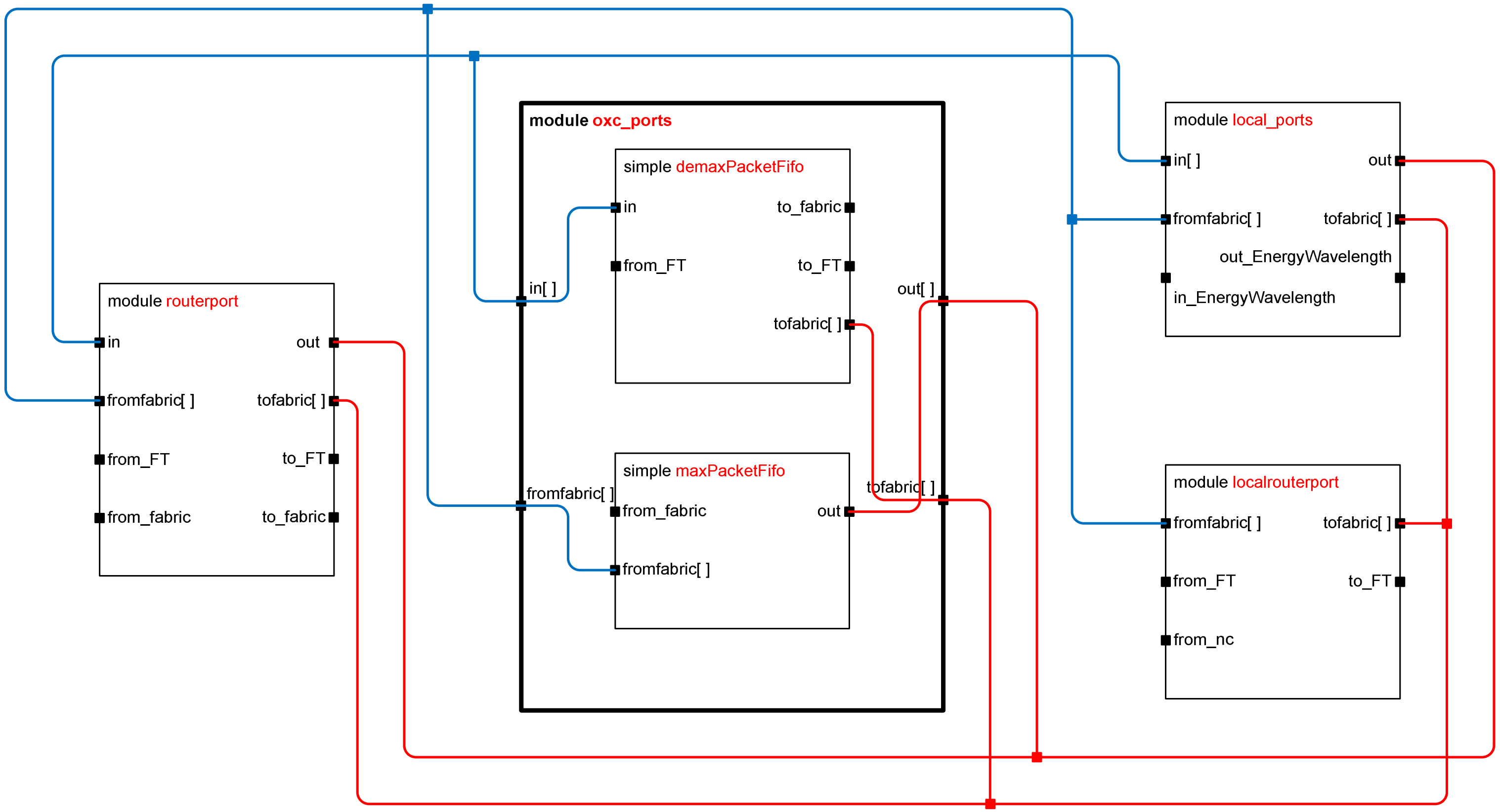


Figure B.10: OXC ports model.

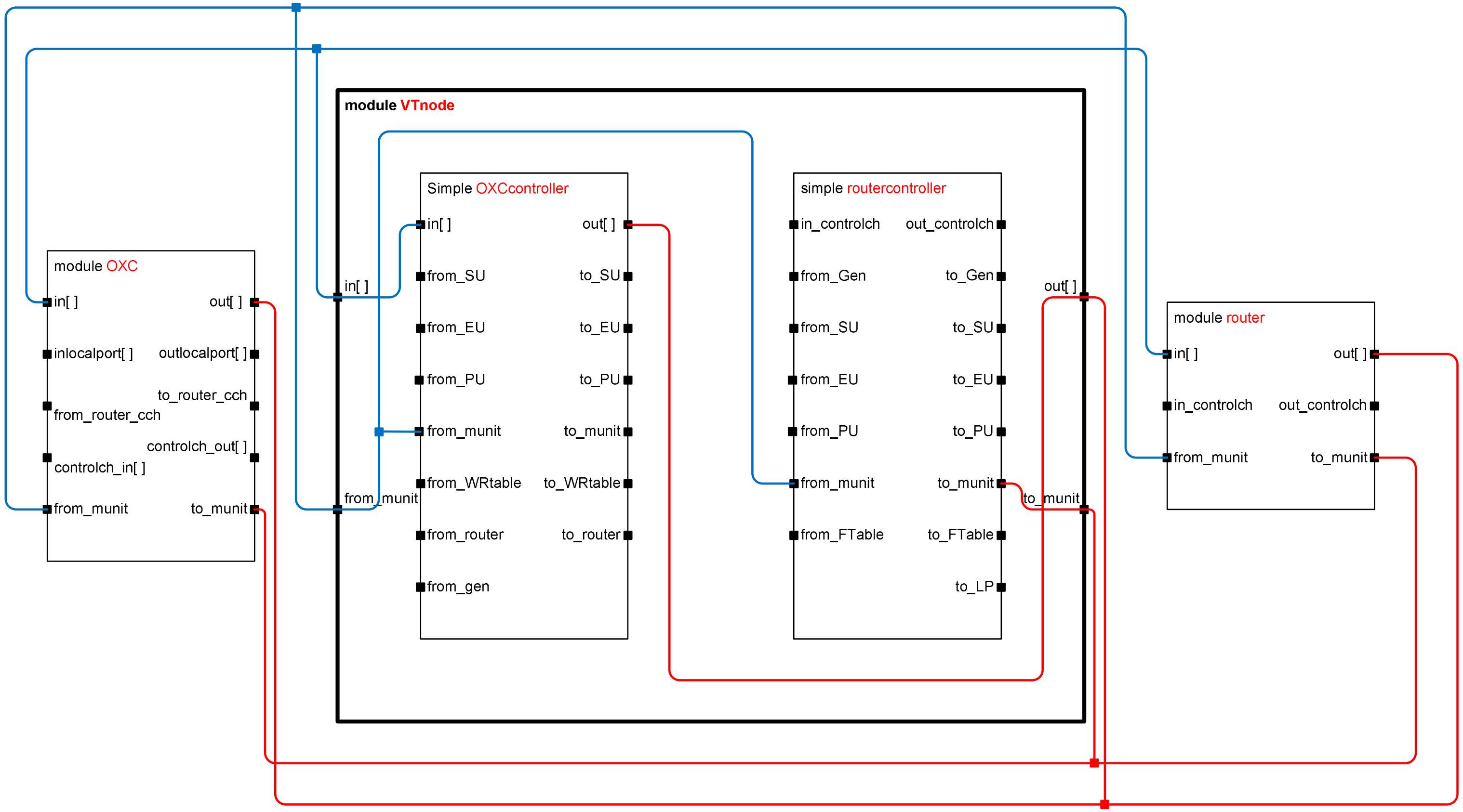


Figure B.11: Virtual Topology (VT) node model.

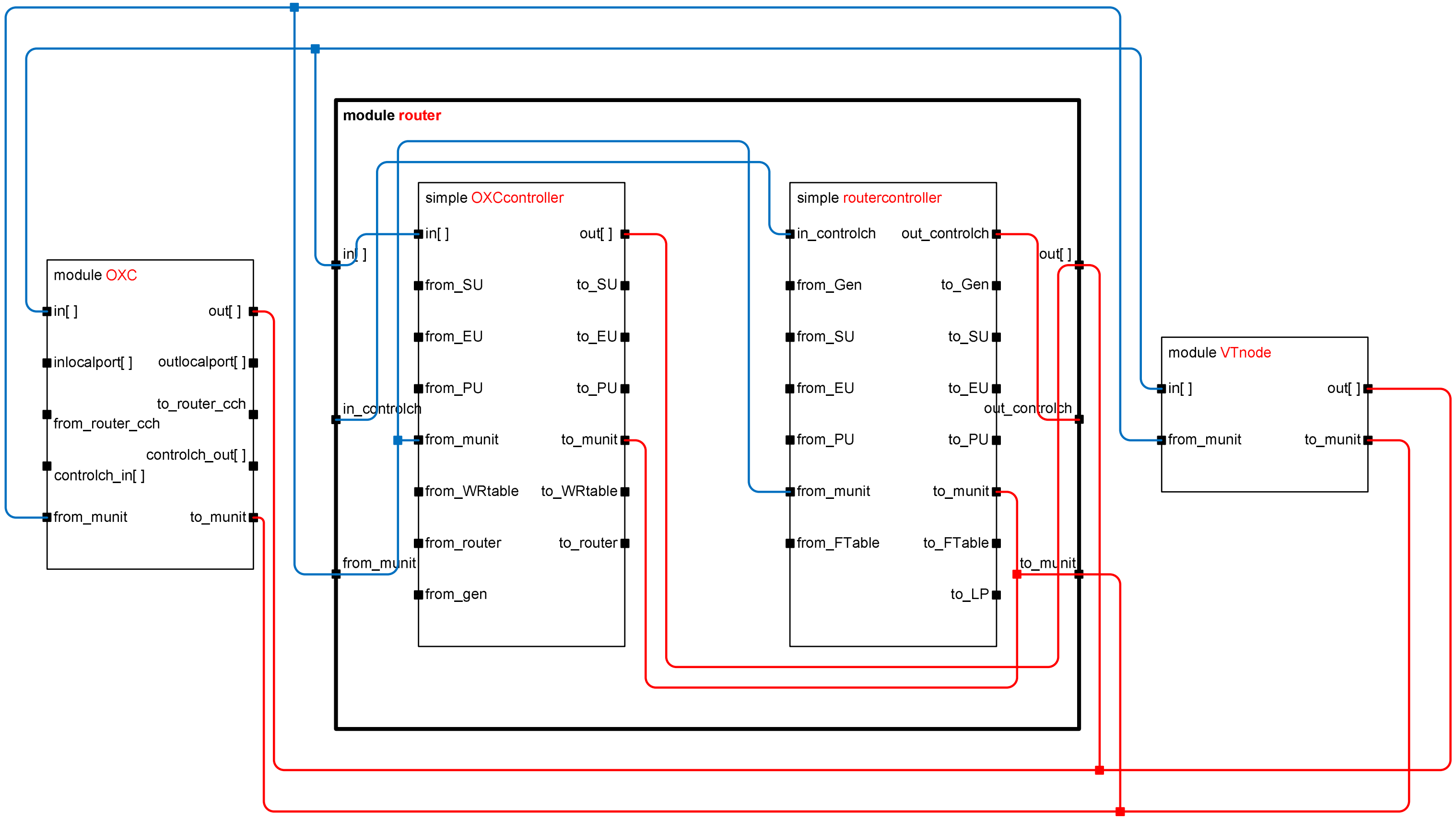


Figure B.12: Module router model.

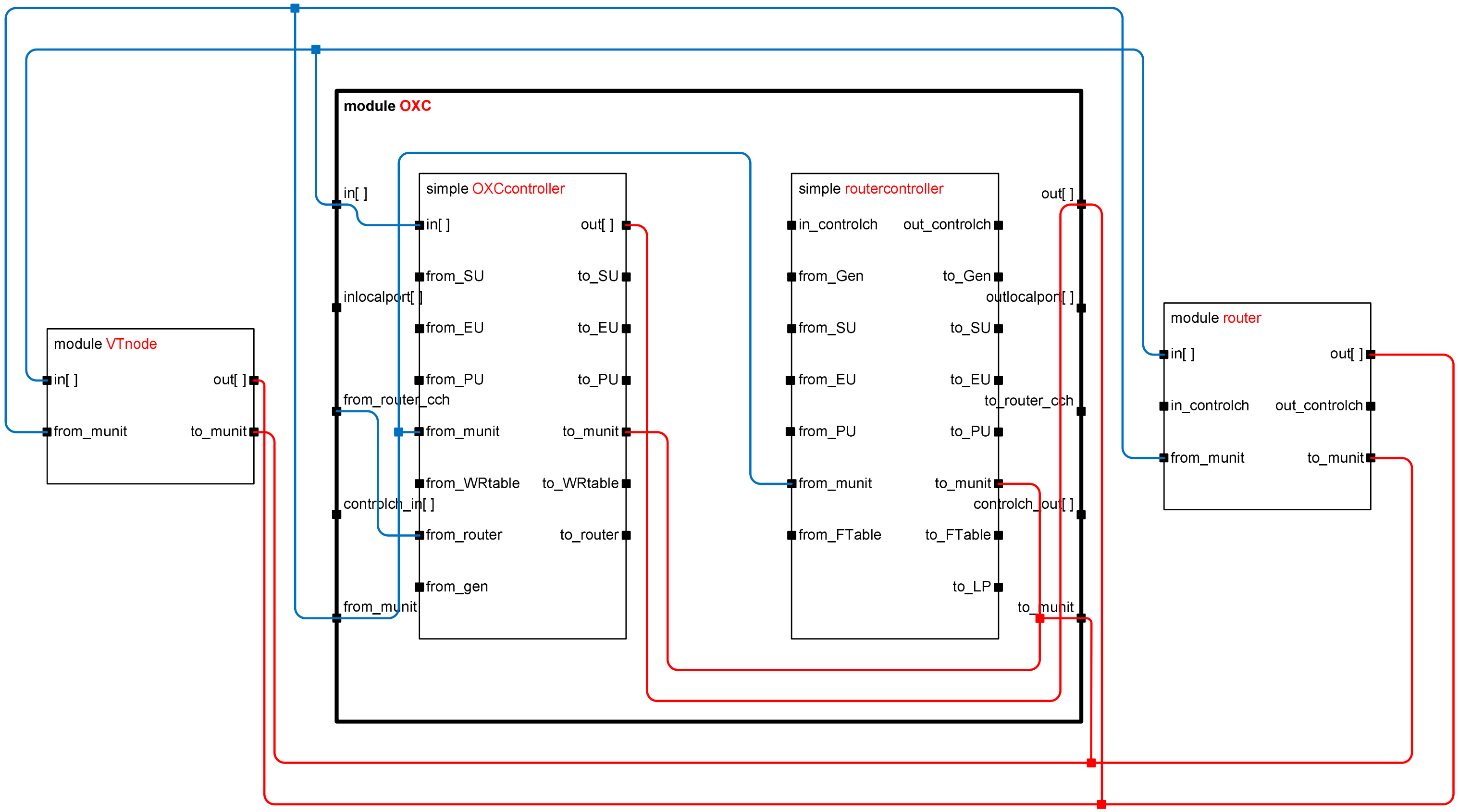


Figure B.13: Module OXC model.

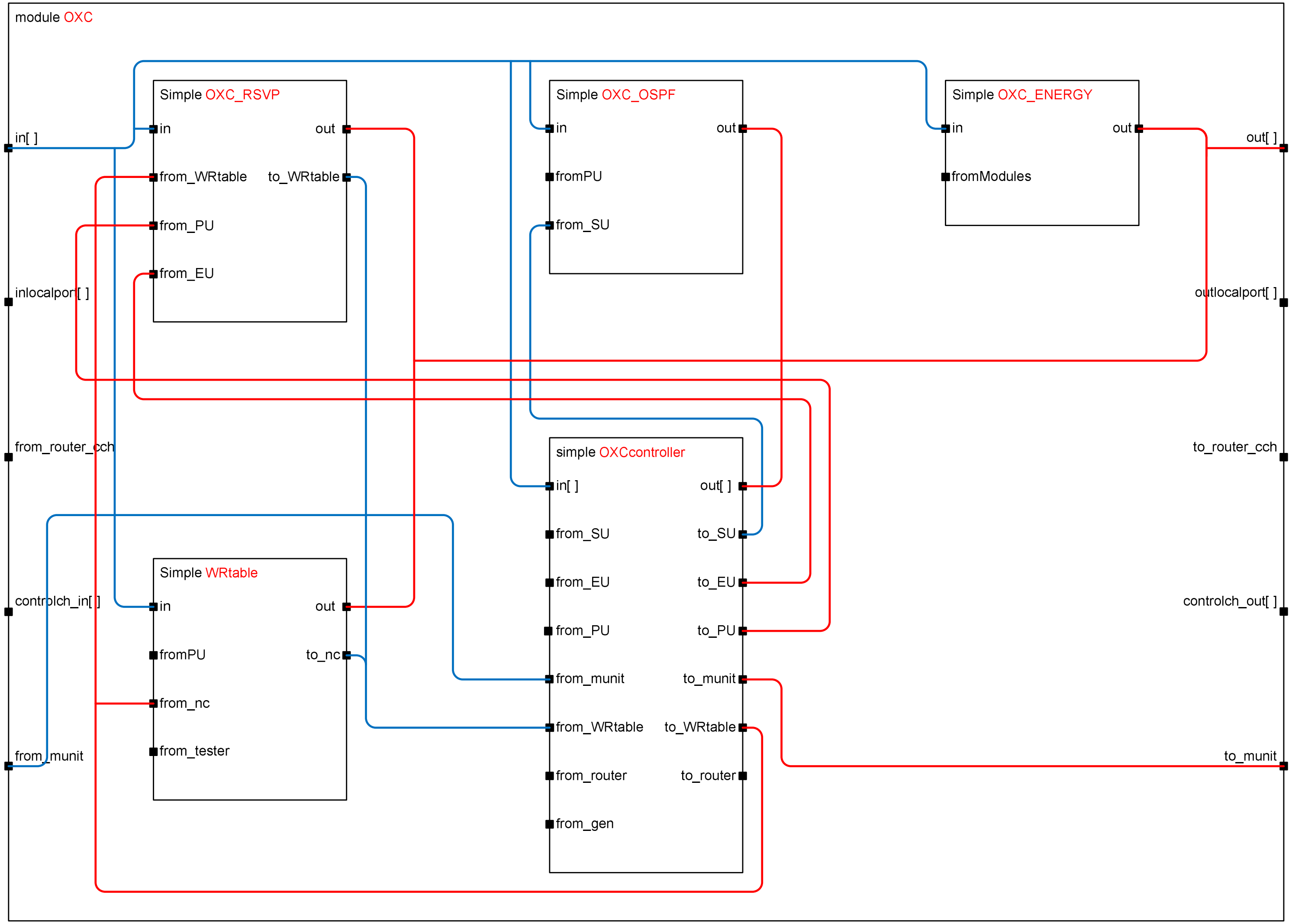


Figure B.14: OXC signalling model.

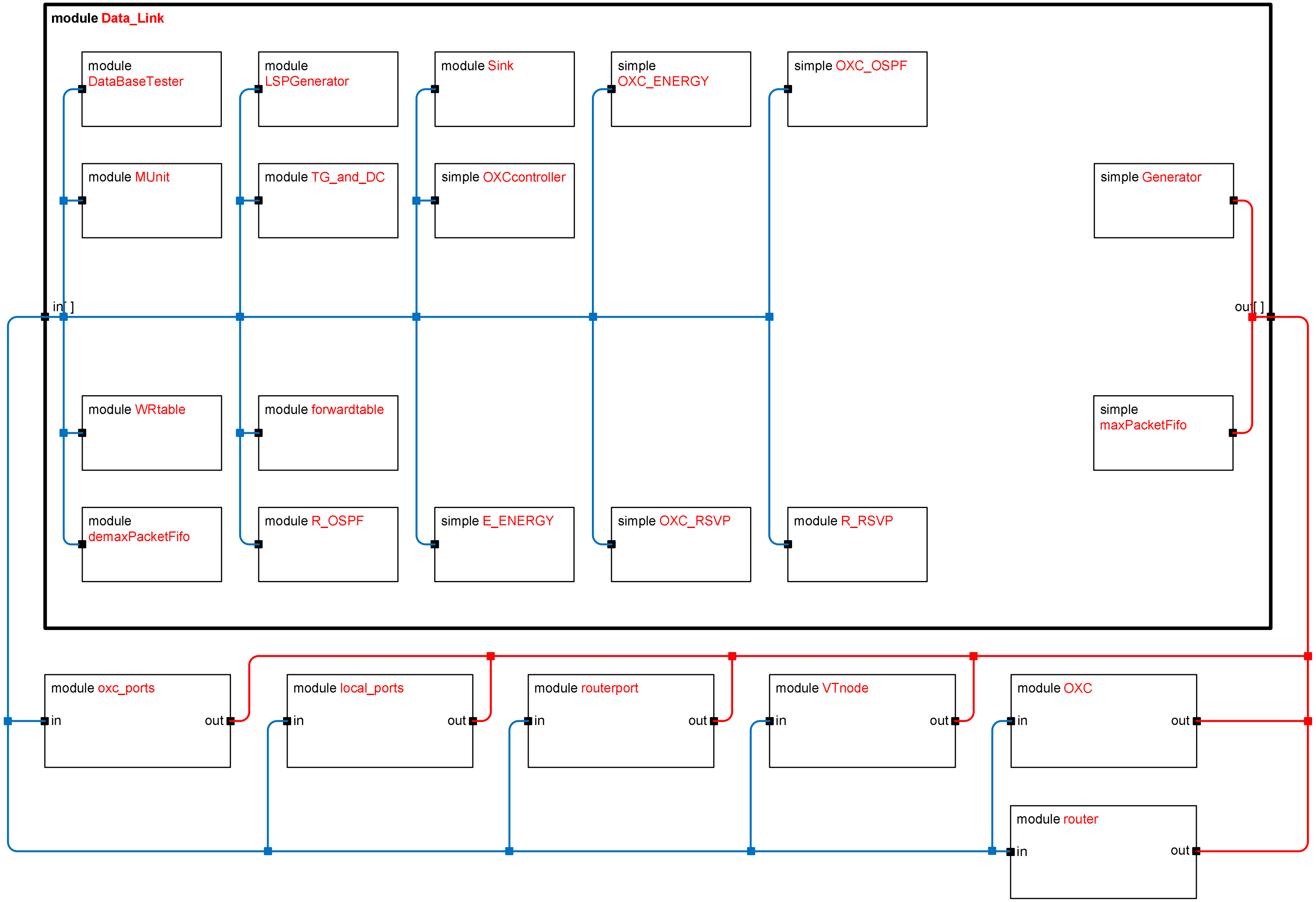


Figure B.15: Data link model.

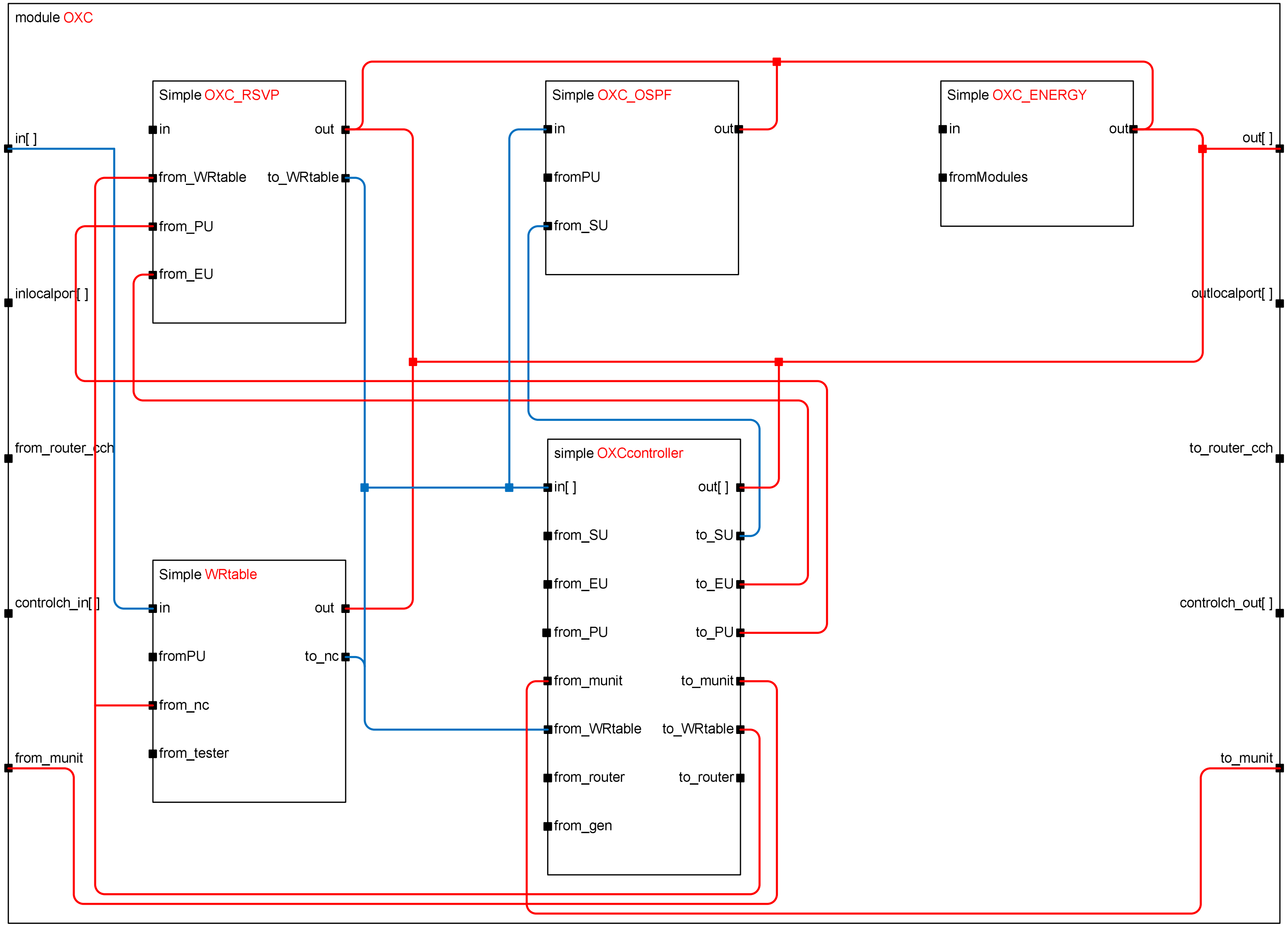


Figure B.16: OXC signalling test schematic.

Appendix C

GMPLS Protocols

1. Introduction

This Appendix presents a summary discussion of GMPLS signalling and routing in terms of architecture and implementation. These protocols have been described in different sources [30][38][39][133][141][142] and here, an interpretation of the structure and functionality of these protocols as a platform for the evaluation presented in this work is provided.

2. Resource Reservation Protocol with Traffic Engineering (RSVP-TE)

The main function of the GMPLS RSVP-TE protocol is to provide communication functionality between network nodes in order to establish traffic engineered Label Switch Paths (LSP). The GMPLS RSVP-TE protocol is an extension of IP RSVP signalling protocol. Table C.1 summarises the enhancement to the IP RSVP when such a protocol is adopted by MPLS- and GMPLS-based networks.

Table C.1: Comparison between IP RSVP, MPLS RSVP-TE and GMPLS RSVP-TE.

	RSVP	**RSVP-TE**	**GMPLS RSVP-TE**
Control Plane	• The control messages are forwarded through the data plane interfaces	• The control messages are forwarded through the data plane interfaces	• Separate the data plane from control plane, so the control messaging is independent of data plane interfaces
Establish connection	• Based on the IP routing table • Unidirectional path	• Based on the Explicit routing • Unidirectional path • Start and end in the IP routers	• Based on the Explicit routing • Bidirectional path • Start and end in any two nodes with the same switching capability
Maintain connection	• Soft state (*Path* and *Resv* refresh messages) • Failure leads to the removal of the *Path* and *Resv* state	• Soft state (*Path* and *Resv* refresh messages) • Failure leads to the removal of the *Path* and *Resv* state	• Remote notification mechanism • Control plane failure does not affect data link and restart procedure can be used
Deletion connection	• *Path* or *Resv* refresh messages are timed out • *PathTear* or *ResvTear* messages are received	• *Path* or *Resv* refresh messages are timed out • *PathTear* or *ResvTear* messages are received	• Apply deletion in progress concept.

The communication between nodes is achieved by means of control messages**.** The structure of such messages consists of two parts; message header and objects (Figure C.1). The header (Figure C.2) includes the required information to identify messages while objects are used to carry certain parameters between nodes.

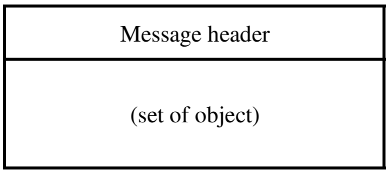


*Figure **C.1**: the structure of RSVP-TE messages.*

Vers	Flags	Msg Type	Checksum
SEND_TTL		reserved	Message length

- Vers: 4 bits, protocol version number.
- Flags: 4 bits, to indicate that a nodal failure has occurred and the control state has been lost.
- Msg Type: 8 bits, to indicate the message type
- Length: 16 bits, the total length of the message in bytes.

Figure C.2: the structure of RSVP-TE messages header.

RSVP-TE messages carry a variable number of objects with a standard header and different contents (parameters) (Figure C.3). Therefore, this structure is a hierarchical approach to improving RSVP-TE functionality. Simply, improvements can be realised by defining new objects.

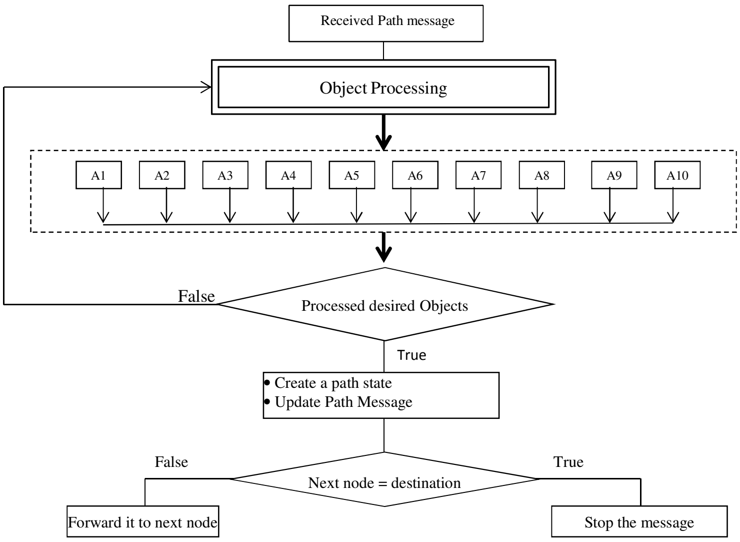
Length	Class Number	C-Type
(Object contents)		

- C-Type and Class are used in order to code the object in a hierarchical way. The Class number identifies a broad class of similar object and the C-Type identifies a specific object within the class
- Length: 16 bits, the total length of the object in bytes

Figure C.3: The structure of RSVP-TE object header.

RSVP-TE messages are processed at each node to setup or modify the reservation state. Such a processing procedure depends upon the type of message and their objects. The most relevant RSVP-TE messages in terms of the research presented are the *Path* and *Resv* messages. Figure C.4 to Figure C.7 present the processing procedure and object descriptions of the *Path* and *Resv* messages respectively.

Once a message reaches any node along its route, the carried objects must be checked and processed. Consequently, based on the objects' parameters the node either updates the objects' parameters and local database and then forwards the message to the next node or sends back an error response to the previous node.

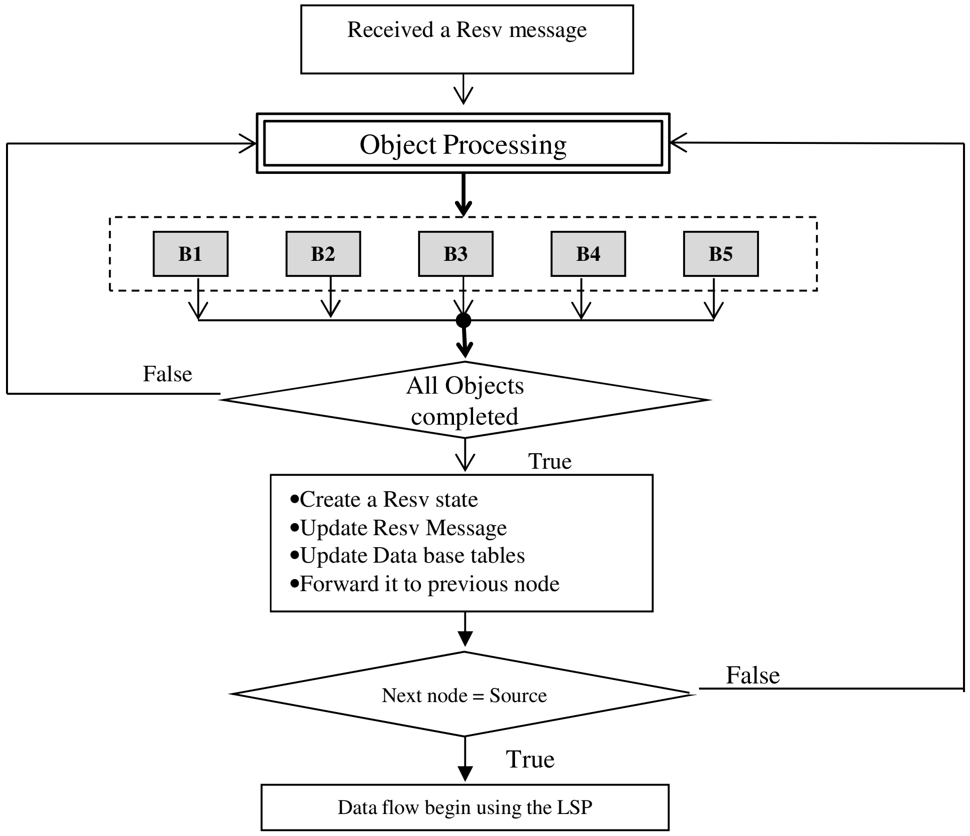


Reference	Object Description
A1	Explicit Route
A2	Label Set
A3	LSP Tunnel Identification
A4	Suggested Label
A5	Generalized Label Request
A6	Upstream Label
A7	Interface Identification
A8	Notification Request
A9	Record Route
A10	Energy Information

Figure C.4: The GMPLS Path message structure.

Object	Procedure
GENERALIZED LABEL REQUEST	➢ Set up by ingress node and may also be updated hop-by-hop ➢ A node processing this object must verify that • The node itself and the interface or tunnel on which the traffic will be transmitted can support the requested LSP Encoding Type • Also support the requested LSP switching Type ➢ The egress must verify that it can support the payload data type.
LABEL SET	➢ Set up by ingress node and may also be updated by hop-by-hop and in case the label set is empty the path must be terminated. ➢ Based in the action field in the label set object, the receiving node may restrict its choice of labels to: • One which is in the label set • One which is not in the label set • One which in the range specified by the label set.
UPSTREAM LABEL (Bidirectional LSP)	➢ In order to establish a bidirectional LSP: • Downstream nodes assign the label for the forward direction at the time the *Resv* message is sent • Upstream nodes assign the label for the reverse direction at the time the *Path* message is sent ➢ The two labels must have the same parameters for both directions.
PROTECTION INFORMATION	➢ It is used to establish both the work and protection paths of an end-end-protected connection as follows: • Indicate whether the path is primary or backup. • Indicate the protection mode (1+1, 1:N, unprotected.) for the primary path which is requested • Only an unprotected mode can be requested for a secondary connection. ➢ Intermediate node must verify that the requested protection can be satisfied by the outgoing interface.
EXPLICIT ROUTE	➢ Routing unit responsible for computing the appropriate explicit routing from the source or any intermediate nodes to the destination. ➢ Set up by ingress node and may also be updated by intermediate nodes. ➢ Determination of the next node to forward the message is based on the kinds of the explicit route, and it is as follows: • Strict explicit route: forward the *Path* message directly to the neighbour. • Loose explicit route: the next node not directly connected and there are two ways : • Forward the *Path* message to the next node toward the remote node according to the IP routing table. • Compute a new explicit route and forward the *Path* message to the next node in the computed route
ADMINISTRATIVE STATUS	➢ It is may be carried by a *Path*, *Resv* or notification messages ➢ In the case of a *Path* message, it is used to indicate the administrative state of a LSP as follows: • The node that received the object must be reflected back in an appropriate message. • Indicates that the connection is being set in the test mode, being taken down, or deletion is in progress.
INTERFACE IDENTIFICATION	➢ A new Hop object is used to associate the control and data channel interfaces. ➢ The node which is going to send the path message set the new Hop parameters which are the node, control channel interface and data channel interface addresses. The latter is assigned as follows: • Numbered link: the data channel interface addresses. • Unnumbered link: using the node local identifiers of interfaces.
LSP TUNNEL IDENTIFCATION	➢ To indicate the LSP egress node at which the LSP tunnel terminates
Suggested label	➢ The upstream node suggests using a specific label.
RECORD ROUTE	➢ Updated at any node receiving a path message
NOTIFCATION REQUEST	➢ To indicate the IP address of the node that should be notified when generating an error message.

Figure C.5: Path Message object descriptions.



Reference	**Object Description**
B1	Flowspec
B2	Filterspec
B3	Generalized
B4	Suggested Label
B5	Generalized Label Request

Figure C.6: The GMPLS Resv message structure.

Object	Procedure

Generalized Label	• Label travels in the upstream direction in *Resv* message.
	• LABEL type may be:
	  • Port or wavelength: the upstream node must verify that the values that are passed are acceptable.
	  • Waveband label: the upstream node must verify that the values that are passed are acceptable.
	The label set, which sends in the path message, may restrict the acceptable label value.

FILTERSPEC	• Set up by the destination to indicate the packet classification in each node (classify packets according to their contents)
FLOWSPEC	• Set up by the destination to indicate the reservation request (bandwidth, buffering requirements)
INTERFACE IDENTIFICATION	• A new Hop object is used to associate the control and data channel interfaces. • The node which is going to send a *Path* message set the new Hop parameters which are the node, control channel interface and data channel interface addresses. The latter is assigned as following: • Numbered link: the data channel interface addresses. Unnumbered link: using the node locally identifiers of interfaces.

ADMINISTRATIVE STATUS	• It may be carried by *Path*, *Resv* or notification messages
	• In case of a *Path* message, it is used to indicate the administrative state of a LSP as follows :
	  • The node that received the back in an appropriate message.
	  • Indicates that the connection is being set in the test mode, being taken down, or that deletion is in progress.

Figure C.7: Resv message object description.

Open Short Path First (OSPF-TE)

As illustrated in Figure C.8, OSPF-TE has three main protocols; *hello protocol* responsible for providing neighbour discovery functions, database exchange protocol to achieve database synchronisation and flooding protocol to flood network change information to neighbours. OSPF-TE is responsible for resolving route competition using the constraint short path first (CSPF) algorithm [30][38].

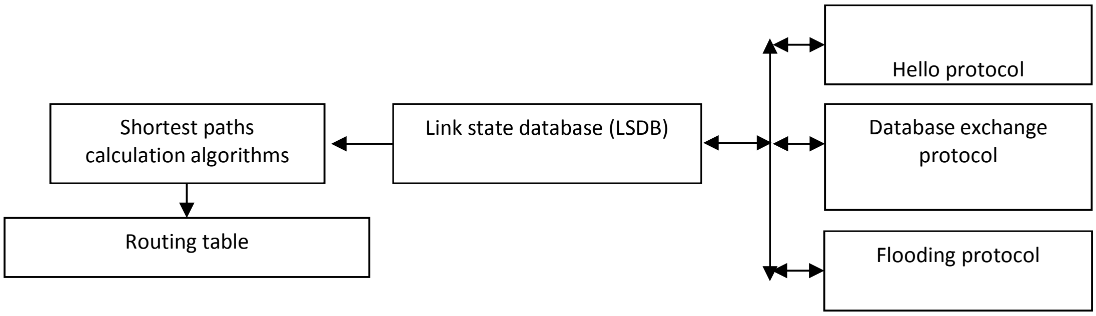


Figure C.8: The structure of OSPF-TE protocol.

OSPF-TE operates independently, managing its functions by the means of control messages. The most important role is to collect global topology knowledge of the network including active links and adjacent neighbours in each router. Such information is maintained in the Link State Database (LSDB). During initialization, a router periodically broadcasts hello messages to discover its adjacencies. Figure C.9 describe the procedure to form adjacencies with neighbours.

Once the neighbour discovery process is done, a router exchanges its LSDB information with its neighbours using data description messages. The aim of link state exchange process is to synchronize all routers' LSDB information. Afterwards, a change of network status or topology will be issued in a Link State Advertisement (LSA) and distributed through the network using link state updated messages. Such a distribution is achieved by the means of a flooding protocol (Figure C.10). Nodes receive and store LSAs in a topology LSDB used to calculate a forwarding table.

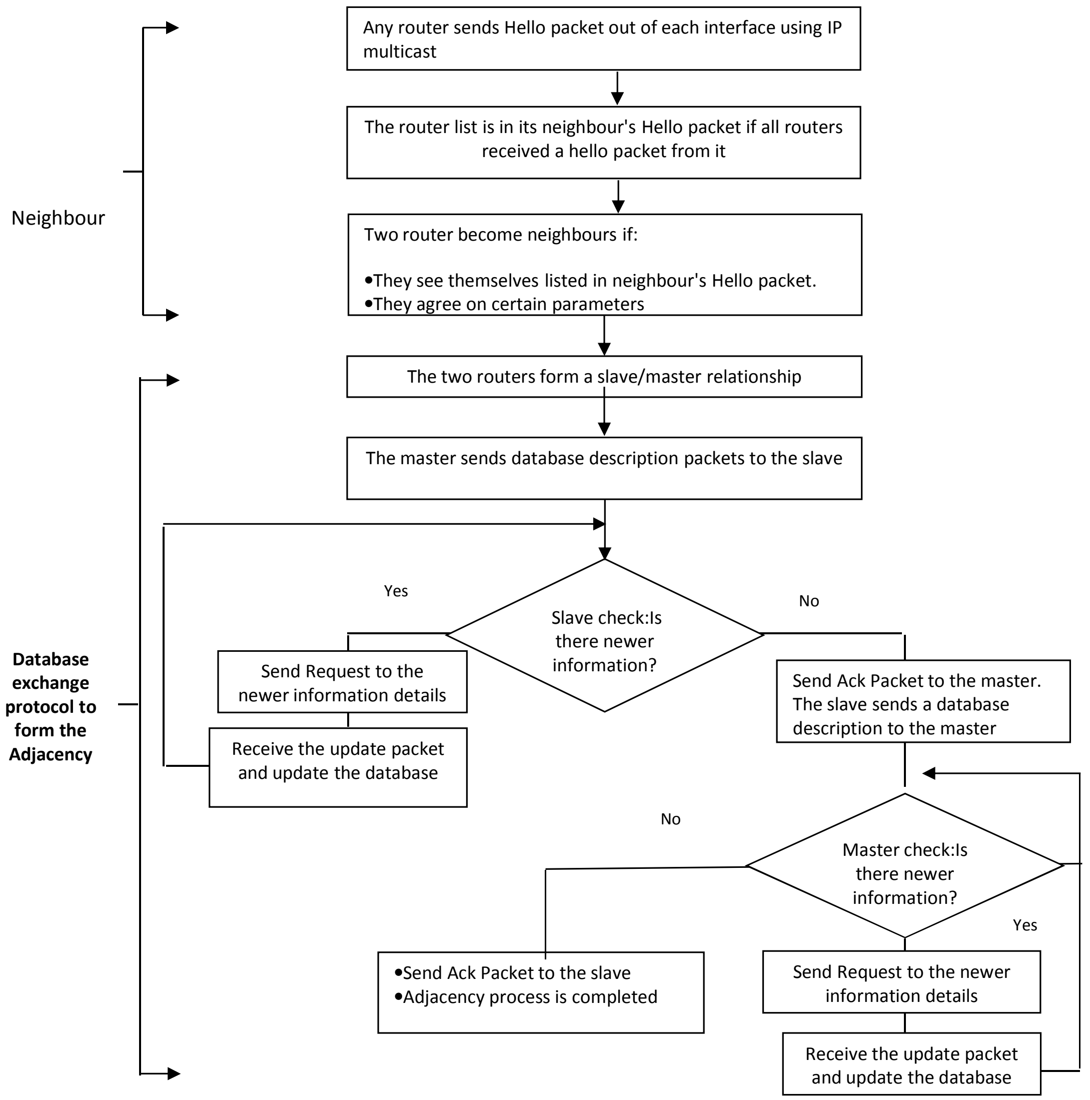


Figure C.9: the flowchart of adjacency procedure.

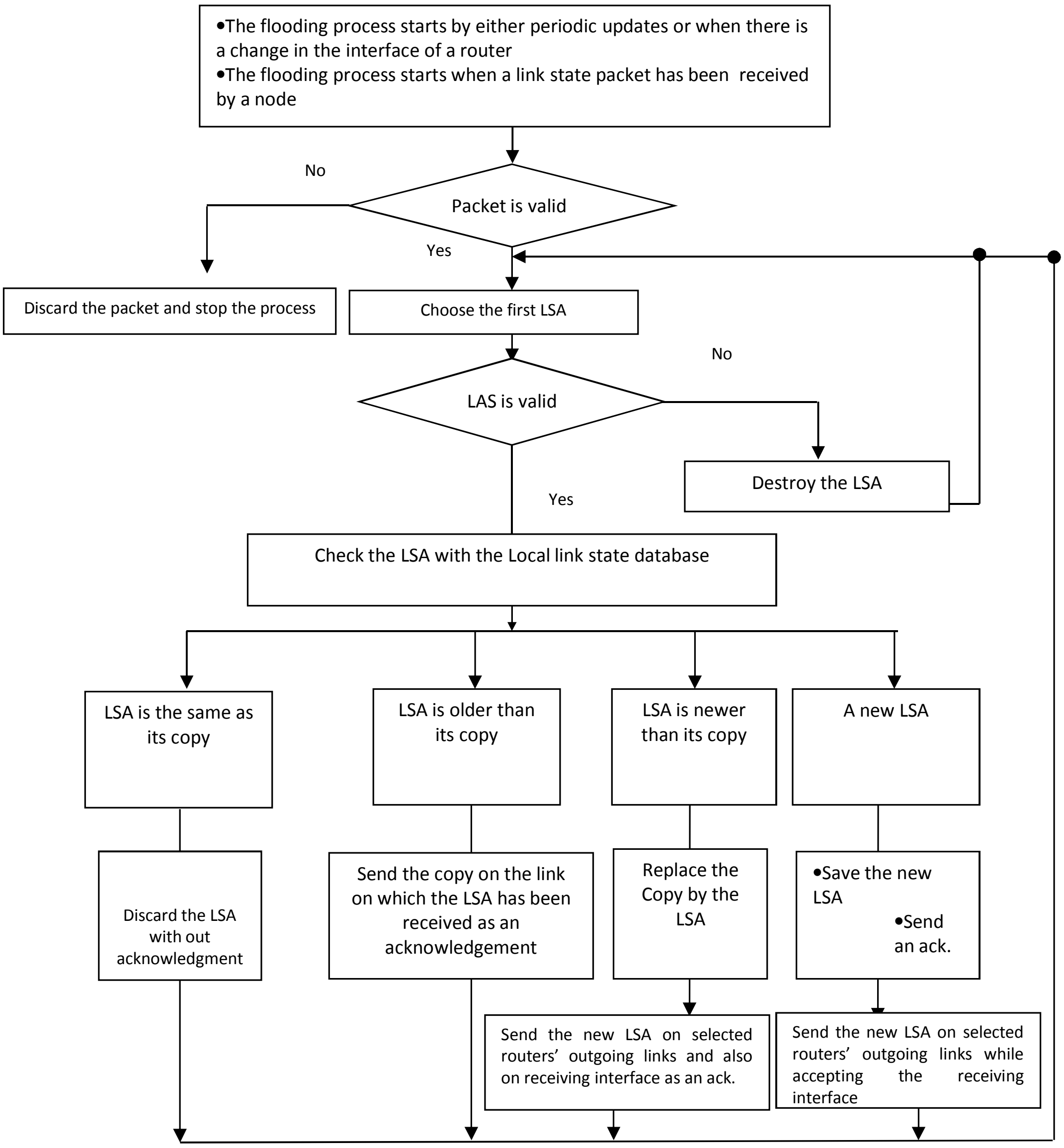


Figure C.10: Flow chart of flooding protocol.

Using the notion of areas illustrated in Figure C.11, the size of the database and number of updated LSAs that exchange through the network will be reduced. This can be achieved by exchanging detailed topology information between nodes that belong to one area or for special multiple area routers, called Area Border Routers (ABRs), exchanging topological information between areas.

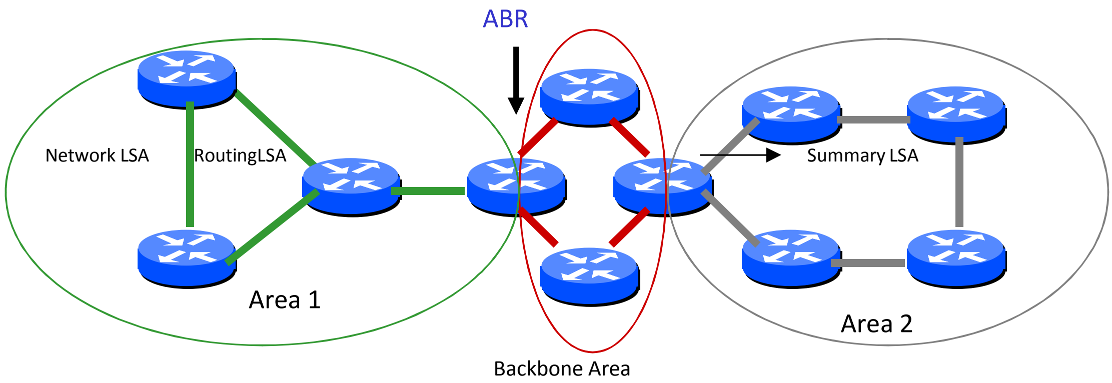


Figure C.11: The network structure based on the notion of areas.

As mentioned earlier, the main role of OSPF-TE is to facilitate the exchange of topology and traffic engendering information between nodes using a messaging system. Therefore, it is worth considering the type and structure of such messages. All OSPF-TE messages share a common header structure (Figure C.12). This header allows certain information to be conveyed in a standard manner such as the type, length, authentication, source router and area of message.

Common header

Version	Type	Packet length
Router ID		
Area ID		
LS checksum	Length	
Authentication		
Message body		

Figure C.12: Structure of OSPF-TE messages header.

Five messages are utilised by OSPF-TE; *hello*, Database Description, Link state request, Link state update and Link state acknowledgment. The structure of these messages is illustrated in Figure C.13.

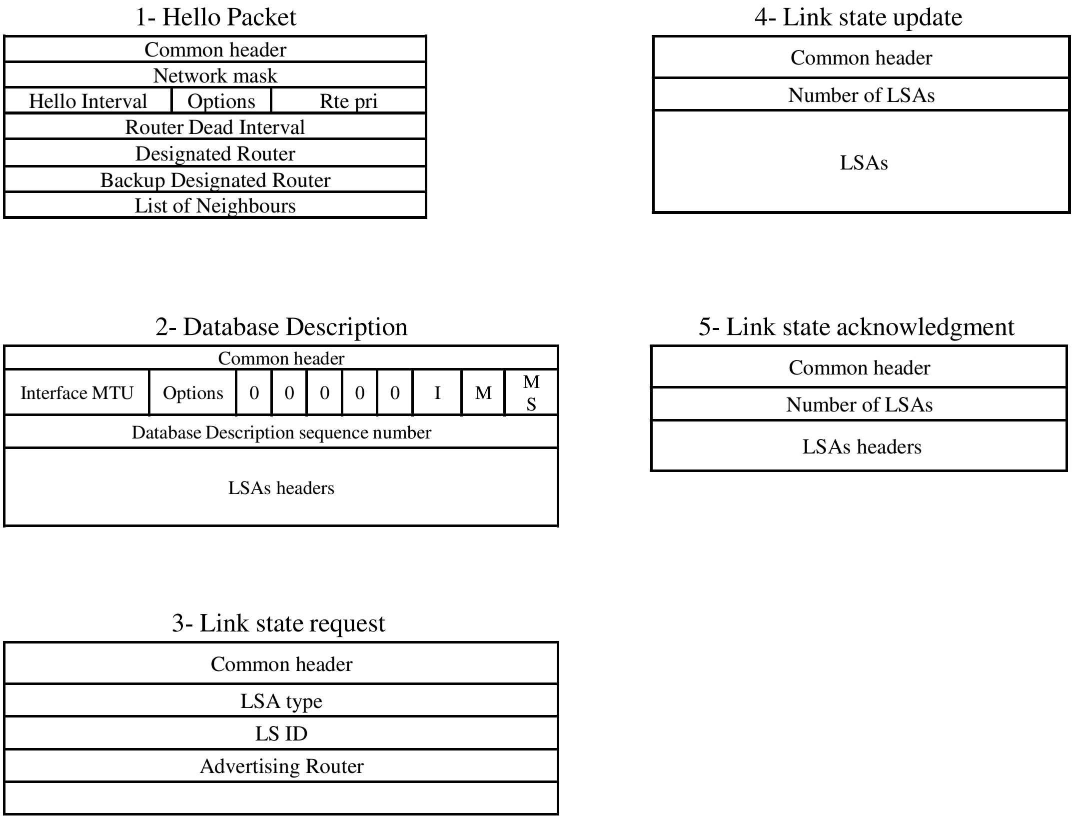


Figure C.13: Structure of OSPF messages.

Link state update messages carry a set of LSAs one hop further away from its point of initiation; there are different types of *OSPF LSAs*. The primary LSAs as listed below and shown in Figure C.14:

1. Router LSA: the state and the parameters of all links that terminated on a node.
2. Network LSA: contains a list of routers connected to the network.
3. External LSA: the route to a destination on another Autonomous Systems.
4. Opaque LSA: provides the standard way to extend OSPF.

Common Header

LS age	Option	LS Type
Link State router		
Advertising router		
LS sequence number		
LS checksum	Length	

1- Router-LSA

Common Header					
0	V	E	B	0	Number of links
Link ID					
Link Data					
Type	#TOS	Cost metric			
TOS	0	TOS metric			
TOS	0	TOS metric			
Repeat again					

2- Network-LSA

Common header
Network mask
Attached router
Repeat again

4- Opaque-LSAs

9-link-local scope, 10-area scope and 11-autonomous system

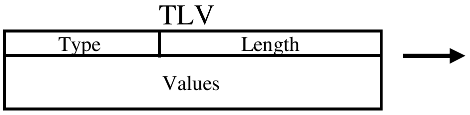
LS age	Option	LS type
Opaque type	Opaque ID	
Advertising router		
LS sequence number		
LS checksum	Length	
Opaque Information		

3- AS-external-LSA

Network mask		
E	0	Metric
Forwarding address		
External Route tag		
Repeat again		

Figure C.14: Structure of OSPF LSAs.

In order to convey the traffic engineering information, GMPLS OSPF-TE, a new traffic engineering LSA-TE has been introduced which has the same format as an opaque-LSA. The Type-Length-Value (TLV) structure (Figure C.15) is used as the payload in the TE LSA. The Type specifies the type of the data; the length specifies the length of the whole TLV structure, and the Value describes the information regarding to Traffic Engineering and GMPLS support.



TLV-type	sub-TLVs name	Length (byte)
1	Router address	4
2	Link type (Point-to-point, multi-access)	1
3	Local interface IP address	4
4	Remote interface IP address	4
5	Traffic engineering metric	4
6	Maximum bandwidth	4
7	Maximum reserveable bandwidth	4
8	Unreserved bandwidth	32
9	Administrative group	4
11	Link local/remote identifiers	8
14	Link protection type	4
15	Interface switching capability descriptor	Variable
16	Shared risk link group	Variable

Figure C.15: A new traffic engineering LSAs introduced by OSPF-TE.

References

[1] *Optoelectronics Industry Development Association.* [Online]. http://www.oida.org.

[2] Francesco Musumeci, Massimo Tornatore, and Achille Pattavina, *A Power Consumption Analysis for IP-Over-WDM Core Network Architecture*, IEEE/OSA Journal of Optical Communications and Networking, vol. 4, no. 2, pp. 108-117, February 2012.

[3] Bala Rajagopalan, James V. Luciani and Daniel O. Awduche, *IP over Optical Networks: A Framework*, RFC 3717, IETF, March 2004.

[4] Pulak Chowdhy, Massimo Tornatore, Avishek Nag, Ezra Ip, Ting Wang and Biswanath Mukherjee, *On the Design of the Energy-Efficient Mixed-Line-Rate (MLR) Optical Networks,* IEEE/OSA Journal of Lightwave Technology, vol. 30, no.1, pp. 130-139, January 1, 2012.

[5] Guangzhi Li, Dongmei Wang, Jennifer Yates, Robert Doverspike and Charles Kalmanek, *IP over Optical Cross-Connect Architectures*, IEEE Communications Magazine, vol. 45, no. 2, pp. 34-39, February 2007.

[6] Byrav Ramamurthy and Biswanath Mukherjee, Wavelength Conversion in WDM Networking, IEEE Journal on Selected Areas in Communications, vol. 16, no. 7, pp. 1061-1073, September 1998.

[7] ITU-T Recommendation G.709/Y.1331, *Interfaces for Optical Transport Network (OTN)*, International Telecommunication Union (ITU), December 2009.

[8] ITU-T Recommendation G.709/Y.1331, *Interfaces for Optical Transport Network (OTN): Amendment 1*, International Telecommunication Union (ITU), November 2001.

[9] ITU-T Recommendation G.872, *Architecture of Optical Transport Networks*, International Telecommunication Union (ITU), November 2001.

[10] Martin Carroll, Josef Roese, and Takuya Ohara, *The Operator's View of OTN Evolution*, IEEE Communication Magazine, vol.48, no.9, pp.46-52, September 2010.

[11] Ashwin Gumaste and Nalini Krishnaswamy, *Proliferation of the Optical Transport Network: A Use Case Based Study*, IEEE Communication Magazine, vol.48, no.9, pp.54-61, September 2010.

[12] Stamatios.V. Kartalopoulus, *Next Generation Intelligent Optical Networks: From Access to Backbone, Springer*, New York, USA, 2008.

[13] Biswanath Mukherjee, *WDM Optical Communication Networks: Progress and Challenges*, IEEE Journal on Selected Areas in Communications, vol. 18, no. 10, pp. 1810-1824, October 2000.

[14] Charles A. Brackett, *Dense Wavelength Division Multiplexing Networks: Principles and Applications,* IEEE Journal on Selected Areas in Communications, vol. 8, no. 6, pp. 948-964, August 1990.

[15] Stamatious V. Kartalopoulos, *DWDM: Network, Devices and Technology,* IEEE Press/Wiley-Interscience, New Jersey, 2003.

[16] R. Ramaswami, K.N. Sivarajan and G.H. Sasaki, *Optical Networks: A Practical Perspective, 3rd Ed.*, Morgan-Kauffmann Publishers, Massachusetts, 2010.

[17] Bala Rajagopalan, James V. Luciani and Daniel O. Awduche, *IP over Optical Networks: A Framework*, RFC 3717, IETF, March 2004.

[18] Kevin H. Liu, *IP over WDM,* John Wiley & Sons, Chichester, 2002.

[19] Marco Listanti, Vincenzo Eramo, and Roberto Sabella, *Architecture and Technological Issues for Future Optical Internet Networks*, IEEE Communication Magazine, vol.38, no.9, pp.82-92, September 2000.

[20] Hui Zang, Jason P. Jue, Laxman Sahasrabuddhe, Ramu Ramamurthy and Biswanath Mukherjee, *Dynamic Lightpath Establishment in Wavelength-Routed WDM Networks,* IEEE Communications Magazine, vol. 39, no. 9, pp. 100-108, September 2001.

[21] Imrich Chlamtac, Andras Farago and Tao Zhang, *Lightpath (Wavelength) Routing in Large WDM Networks*, IEEE Journal on Selected Areas in Communications, vol. 14, no. 5, pp. 909-913, June 1996.

[22] Rajiv Ramaswami and Kumar N. Sivarajan, *Design of Logical Topologies for Wavelength-Routed Optical Networks,* IEEE Journal on Selected Areas in Communications, vol. 14, no. 5, pp. 840-851, June 1996.

[23] Yufeng Xing, George N. Rouskas and Harry G. Perros, *On the Physical and Logical Topology Design of Large-Scale Optical Networks,* IEEE/OSA Journal of Lightwave Technology, vol. 21, no.4, pp. 904-915, April 2003.

[24] Rudra Dutta, and George N. Rouskas, *A Survey of Virtual Topology Design Algorithms for Wavelength Routed Optical Networks,* Optical Networks Magazine, SPIE/Springerlink, vol.1, no.1, pp. 73-89, January 2000.

[25] Rajiv Ramaswami and Galen Sasaki, Multiwavelength Optical Networks with Limited Wavelength Conversion, IEEE/ACM Transactions on Networking, vol. 6, no. 6, pp. 744-754, December 1998.

[26] Asuman E. Ozdaglar and Dimitri P. Bertsekas, *Routing and Wavelength Assignment in Optical Networks,* IEEE/ACM Transactions on Networking, vol. 11, no. 2, pp. 259-272, April 2003.

[27] Rajiv Ramaswami and Kumar N. Sivarajan, *Routing and Wavelength Assignment in All-Optical Networks,* IEEE/ACM Transactions on Networking, vol. 3, no. 5, pp. 489-500, October 1995.

[28] Hui Zang, Jason P. Jue and Biswanath Mukherjee, *A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks,* Optical Networks Magazine, SPIE/Springerlink, vol.1, no.1, pp. 47-60, January 2000.

[29] Alberto Leon-Garcia and Indra Widjaja, *Communication Networks: Fundamental Concepts and Key Architectures,* 2nd Edition, The McGraw-Hill, New York, 2006.

[30] Adrian Farrel, *The Internet and Its Protocols: A Comparative Approach,* Morgan Kaufmann Publishers, Elsevier, San Francisco, 2004.

[31] Raju Rajan, Dinesh Verma, Sanjay Kamat, Eyal Felstaine and Shai Herzog, *A Policy Framework for Integrated and Differentiated Services in the Internet,* IEEE Network Magazine, vol. 13, no. 5, pp. 36-41, September/October 1999.

[32] Paul P. White, *RSVP and Integrated Services in the Internet: A Tutorial*, IEEE Communications Magazine, vol. 35, no. 5, pp. 100-106, May 1997.

[33] Vivek Alwayn. *Advanced MPLS Design and Implementation*. Indianapolis.: Cisco Press. 2001.

[34] Grenville Armitage. *MPLS: The Magic behind the Myths.* IEEE Communications Magazine, Page(s) 124 – 131, January 2000.

[35] Jeremy Lawrence, *Designing Multiprotocol Label Switching Networks*, IEEE Communications Magazine, vol.39, no.7, pp.134-142, July 2001.

[36] Roberto Sabella, Marina Settembre, Gianpaolo Oriolo, Federica Razza, Fabio Ferlito and Giulia Conte, *A Multilayer Solution for Path Provisioning in New-Generation Optical/MPLS Networks,* IEEE/OSA Journal of Lightwave Technology, vol. 21, no.5, pp. 1141-1155, May 2003.

[37] Saha. D, rajagopalan. B, and Bernstein. G. *The Optical Network Control Plane: State of The Standards and deployment.* IEEE Communication Magazine, Vol.41, Issues 8, page(s) S29-S34, August 2003.

[38] Adrian Farrel and Igor Bryskin, *GMPLS: Architecture and Applications,* Morgan Kaufmann Publishers, San Francisco, 2006.

[39] Naoaki Yamanaka, Kohei Shiomoto and Eiji Oki, *GMPLS Technologies: Broadband Backbone Networks and Systems,* CRC Press, Taylor & Francis Group, Florida, 2006.

[40] Khurram Kazi, *Optical Networking Standards: A Comprehensive Guide,* Springer, New York, 2006.

[41] Huub Van Helvoort, *The ComSoc Guide To Next Generation Optical Transport: SDH/SONET/OTN*, IEEE/The McGraw-Hill, New York, 2009.

[42] Jun Zheng and Hussein T. Mouftah, *Optical WDM Networks: Concepts and Design Principles,* IEEE Press/Wiley-Interscience, New Jersey, 2004.

[43] Achyut K. Dutta, Niloy K. Dutta and Masahiko Fujiwara, *WDM Technologies: Optical Networks, Volume III,* Academic Press, Elsevier, London, 2004.

[44] Martin Maier, *Optical Switching Networks*, Cambridge University Press, 2008.

[45] Biswanath Mukherjee, *Optical WDM Networks,* Springer, New York, 2006.

[46] Ivan P. Kaminow, Tingye Li and Alan E. Willner, *Optical Fiber Telecommunications: Systems and Networks, Volume VB,* Academic Press, Elsevier, London, 2008.

[47] Sam Halabi, *Metro Ethernet*, Cisco Press, 2003.

[48] E. Rosen, A. Viswanathan, and R. Callon, *Multiprotocol Label Switching (MPLS) Architecture, RFC 3031*, IETF, January 2001.

[49] M. S. Lebby, *Green Photonics Technology and Markets,* IET Electronics Letters, vol.45, no.20, pp.1007, 24th September 2009.

[50] Juan Camilo Cardona Restrepo, Claus G. Gruber, and Carmen Mas Machuca, *Energy profile aware routing*, in Proceedings of the IEEE 1st International Conference on Communications Workshop Green Communications ICC 2009, Dresden, Germany, pp. 1-5, 14th-18th Jun 2009.

[51] Jayant Baliga, Robert Ayre, Kerry Hinton, Wayne V. Sorin, Rodney S. Tucker, *Energy Consumption in Optical IP Networks*, IEEE/OSA Journal of Lightwave Technology, vol. 27, no.13, pp. 2391-2403, July 1, 2009.

[52] Kerry Hinton, Jayant Baliga, Michael Feng, Robert Ayre and Rodney S. Tucker, *Power Consumption and Energy Efficiency in the Internet,* IEEE Network Magazine, vol. 25, no. 2, pp. 6-12, March/April 2011.

[53] Cisco Systems, Data Sheets. [Online]. Available: http://www.cisco.com, 2011.

[54] Juniper Networks, Data Sheets. [Online]. Available: http://www.juniper.net, 2011.

[55] Alcatel-Lucent, Data Sheets. [Online]. Available: http://www.alcatel-lucent.com, 2011.

[56] Ciena, Data Sheets. [Online]. Available: http://www.ciena.com, 2011.

[57] MRV Communications, Data Sheets. [Online]. Available: http://www.mrv.com, 2011.

[58] Fujitsu, Data Sheets. [Online]. Available: http://www.fujitsu.com, 2011.

[59] ADVA Optical Networking, Data Sheets. [Online]. Available: http://www.advaoptical.com, 2011.

[60] Optilab, Data Sheets. [Online]. Available: http://www.optilab.com, 2011.

[61] NEC, Data Sheets. [Online]. Available: http://www.nec.com, 2011.

[62] Ericsson, Data Sheets. [Online]. Available: http://www.ericsson.com, 2011.

[63] Zhone, Data Sheets. [Online]. Available: http://www.zhone.com, 2011.

[64] Huawei Marine Networks, Data Sheets. [Online]. Available: http://www.huaweimarine.com, 2011.

[65] G. Waterworth, *Power Industrial Solutions for Regional Cabled Ocean Observatories,* in Proceedings of the IEEE International Conference on Ocean 2005 Europe, vol. 2, pp. 1033-1037, Brest, France, 20 - 23 June 2005.

[66] Gary Waterworth, *Connecting Long-Term Sea Floor Observatories to the shore,* Sea Technology Magazine, vol. 45, no. 9, pp. 10-13, September 2004.

[67] Yi Zhang, Pulak Chowdhury, Massimo Tornatore and Biswanath Mukherjee, *Energy Efficiency in Telecom Optical Networks,* IEEE Communications Surveys &Tutorials, vol. 12, no. 4, pp. 441-458, Fourth Quarter 2010.

[68] Daniel C. Kilper, Gary Atkinson, Steven K. Korotky, Suresh Goyal, Peter Vetter, Dusan Suvakovic and Oliver Blume, *Power Trends in Communication Networks*, IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 275-284, March/April 2011.

[69] S. J. Ben Yoo, *Energy Efficiency in the Future Internet: The Role of Optical Packet Switching and Optical-Label Switching*, IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 406-418, March/April 2011.

[70] Slavisa Aleksic, *Energy Efficiency of Electronic and Optical Network Elements,* IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 296-308, March/April 2011.

[71] Maher Ali, Byrav Ramamurthy and Jitender S. Deogun, *Routing and Wavelength Assignment with Power Considerations in Optical Networks,* Computer Networks Journal, Elsevier, vol.32, no.5, pp. 539-555, May 2000.

[72] The Carbon Trust, UK. [Online]. Available: http://www.carbontrust.com, 2012.

[73] Gustavo Sousa Pavani., Luiz Gustavo Zuliani., Helio Waldman., Mauricio Magalhaes. *Distributed approaches for impairment-aware routing wavelength assignment algorithms in GMPLS networks.* Computer Networks. Elsevier. 2008. Vol. 52. Page(s) 1905-1915.

[74] Agrawal B and Sherwood T. *Modelling TCAM Power for Next Generation Network Devices.* IEEE international Symposium on Performance Analysis of Systems and Software. 19-21 March 2006. Page(s) 120-129.

[75] Energy Star, the U.S. Department of Energy and U.S. Environmental Protection Agency. [Online]. Available: http://www.energystar.gov, 2011.

[76] European Codes of Conduct for ICT, European Commission Joint Research Centre, Institute for Energy and Transport. [Online]. Available: http://re.jrc.ec.europa.eu/energyefficiency/html/standby_initiative.htm, 2011.

[77] The European Telecommunications Standards Institute (ETSI). [Online]. Available: http://www.etsi.org, 2011.

[78] The European Committee for Electrotechnical Standardization (CENELEC), CLC/TC 215 Electrotechnical aspects of telecommunication equipment. [Online]. Available: http://www.cenelec.eu, 2011.

[79] The Energy Consumption Rating (ECR) Initiative. [Online]. Available: http://www.ecrinitiative.org, 2011.

[80] The Alliance for Telecommunications Industry Solutions (ATIS). [Online]. Available: http://www.atis.org, 2011.

[81] Verizon NEBS (Telcordia Technologies Inc). [Online]. Available: http://www.verizonnebs.com, 2011.

[82] The Broadband Forum. [Online]. Available: http://www.broadband-forum.org, 2011.

[83] S. Okamoto, *Requirements of GMPLS Extensions for Energy Efficient Traffic Engineering*, draft-okamoto-ccamp-midori-gmpls-extension-reqs-00, The Internet Engineering Task Force (IETF), 27 June 2011.

[84] J. Quittek, B. Nordman and R. Winter, *Reference Model for Energy Management*, draft-quittek-eman-reference-model-03, The Internet Engineering Task Force (IETF), 31 October 2011.

[85] J. Quittek, Ed. R. Winter, T. Dietz, B. Claise and M. Chandramouli, *Requirements for Energy Management*, draft-ietf-eman-requirements-05, The Internet Engineering Task Force (IETF), 1 November 2011.

[86] B. Claise, J. Parello, B. Schoening, J. Quittek, *Energy Management Framework*, draft-ietf-eman-framework-03, The Internet Engineering Task Force (IETF), 31 October 2011.

[87] International Energy Agency. [Online]. Available: http://www.iea.org, 2011.

[88] ITU-T Focus Group on ICTs and Climate Change (FG ICT & CC). [Online]. Available: http://www.itu.int/ITU-T/focusgroups/climate/index.html, 2011.

[89] Gabrielle Giner and Tom Okrasinski, *Greenhouse Gas Protocol ICT Sector Supplement Overview Telecommunications Network Services Chapter Update*, in Proceedings of the ITU-EC Workshop on Methodologies for Accessing the Environmental Impact of ICT, Rome, Italy, 5 Sept 2011.

[90] ASHRAE Special Publication, *Datacom Power Trends and Cooling Application,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta, GA, 2005.

[91] John H. Lienhard, *A Heat Transfer Textbook*, 3rd Ed, Phlogiston Press, Massachusetts, 2008.

[92] Michael C. Parker and Stuart D. Walker, *Roadmapping ICT: An Absolute Energy Efficiency Metric,* IEEE/OSA Journal of Optical Communications and Networking, vol. 3, no. 8, pp. A49-A58, August 2011.

[93] Michael C. Parker and Stuart D. Walker, *Differential Temperature Carnot Heat Analysis Shows that Computing Machines are Thermodynamically Irreversible,* Optics Communications, Elsevier, vol. 281, no.3, pp. 3440-3446, March 2008.

[94] Raffaele Bolla, Roberto Bruschi, Franco Davoli and Flavio Cucchietti, *Energy Efficiency in the Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures,* IEEE Communications Surveys &Tutorials, vol. 13, no. 2, pp. 223-244, Second Quarter 2011.

[95] Rodney S. Tucker, *Green Optical Communications-Part I: Energy Limitations in Transport,* IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 245-260, March/April 2011.

[96] Rodney S. Tucker, *Green Optical Communications-Part II: Energy Limitations in Networks,* IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 261-274, March/April 2011.

[97] Ashok V. Krishnanmoorthy, Keith W. Goossen, William Jan, Xuezhe Zheng, Ron Ho, Guoliang Li, Richard Rozier, Frankie Liu, Dinesh Patil, Jon Lexau, Herb Schwetman, Dazeng Feng, Mehdi Asghari, Thierry Pinguet and John E. Cunningham, *Progress in Low-Power Switched Optical Interconnects,* IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 357-376, March/April 2011.

[98] Banit Agrawal and Timothy Sherwood, *Ternary CAM Power and delay Model: Extensions and Uses*, IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 16, no. 5, pp. 554-564, May 2008.

[99] Jayant Baliga, Robert Ayre, Kerry Hinton and Rodney S. Tucker, Energy Consumption in Wired and Wireless Access Networks, IEEE Communications Magazine, vol. 49, no. 6, pp. 70-77, June 2011.

[100] Lei Shi, Biswanath Mukherjee and Sang-Soo Lee, *Energy Efficient PON with Sleep-Mode ONU: Progress, Challenges, and Solutions,* IEEE Network Magazine, vol. 26, no. 2, pp. 36-41, March/April 2012.

[101] Gang Qu and Miodrag Potkonjak, *Techniques for Energy-Efficient Communication Pipeline Design*, IEEE Transactions on Very Large Scale Integration (VLSI) Systems, vol. 10, no. 5, pp. 542-549, October 2002.

[102] Tilman Wolf and Mark A. Franklin, *Performance Models for Network Processor Design*, IEEE Transactions on Parallel and Distributed Systems, vol. 17, no. 6, pp. 548-561, June 2006.

[103] June-Koo Kevin Rhee, Chan-Kyun Lee, Ji-Hwan Kim, Yong-Hyub Won, Jin Seek Choi and Jung Yul Choi, *Power and Cost Reduction by Hybrid Optical Packet Switching with Shared Memory Buffering,* IEEE Communications Magazine, vol. 49, no. 5, pp. 102-110, May 2011.

[104] Willem Vereecken, Ward Van Heddeghem, Margot Deruyck, Bart Puype, Bart Lannoo, Wout Joseph, Didier Colle, Luc Martens and Piet Demeester, *Power Consumption in Telecommunication Networks: Overview and Reduction Strategies*, IEEE Communications Magazine, vol. 49, no. 6, pp. 62-69, June 2011.

[105] Anna Tzanakaki, Kostas Katrinis, Tanya Politi, Alexandros Stavdas, Mario Pickavet, Peter Van Daele, Dimitra Simeonidou, Mike J. O'Mahony, Slavisa Aleksic, Lena Wosinska and Paolo Monti, *Dimensioning the Future Pan-European Optical Network with Energy Efficiency Considerations,* IEEE/OSA Journal of Optical Communications and Networking, vol. 3, no. 4, pp. 272-280, April 2011.

[106] Vincenzo Eramo, *Effect of ASE Noise on the Power Consumption of MVMC and Benes Optical Packet Switches*, IEEE/OSA Journal of Optical Communications and Networking, vol. 3, no. 9, pp. 692-703, September 2011.

[107] Christoph Lange, Dirk Kosiankowski, Rainer Weidmann and Andreas Gladisch, *Energy Consumption of Telecommunication Networks and Related Improvement Options,* IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 285-295, March/April 2011.

[108] Bernhard Schrenk, Francesc Bonada Bo, Johan Bauwelinck, Josep Prat and Jose A. Lazaro, *Energy-Efficient Optical Access Networks Supported by a Noise-Powered Extender Box,* IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 480-488, March/April 2011.

[109] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang and S. Wright, *Power awareness in network design and routing*, in Proceedings of the IEEE 27th Conference on Computer Communications INFOCOM 2008, Phoenix, pp. 1130-1138, 2008.

[110] Angelo Coiro, Marco Listanti, Alessandro Valenti, and Francesco Matera, *Reducing Power Consumption in Wavelength Routed Networks by Selective Switch Off of Optical Links Trends*, IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 428-436, March/April 2011.

[111] N. Vasic, P. Bhurat and D. Kostic, *Energy-Aware Traffic Engineering,* EPFL Technical Report NSL-REPORT-2008-004, EPFL, Switzerland, 2008.

[112] L. Chiaraviglio, M. Mellia, and F. Neri, *Energy-aware networks: Reducing power consumption by switching off network elements*, in Proceedings of the national Telecommunications and Information Theory Group Meeting, Florence, Italy, pp. 1-5, 16th-18th Jun 2008.

[113] Koen Hooghe and Mamoun Guenach, *Towards Green Cooper Broadband Access Networks*, IEEE Communications Magazine, vol. 49, no. 8, pp. 87-93, August 2011.

[114] Bjorn Skubic, Einar In de Betou, Tolga Ayhan and Stefan Dahlfort, *Energy-Efficient Next Generation Optical Networks*, IEEE Communications Magazine, vol. 50, no. 1, pp. 122-127, January 2012.

[115] Raffaele Bolla, Roberto Bruschi, Antonio Cianfrani and Marco Listanti, *Enabling Backbone Networks to Sleep,* IEEE Network Magazine, vol. 25, no. 2, pp. 26-31, March/April 2011.

[116] Gangxiang Shen and Rodney S. Tucker, *Energy-Minimized Design for IP Over WDM Networks*, IEEE/OSA Journal of Optical Communications and Networking, vol. 1, no. 1, pp. 176-186, June 2009.

[117] Yi Zhang, Massimo Tornatore, Pulak Chowdhury, Biswanath Mukherjee, *Energy Optimization in IP-over-WDM Networks,* Optical Switching and Networking Journal, Elsevier, vol.8, no.3, pp. 171-180, July 2011.

[118] B. G. Bathula, M. Alresheedi and J.M.H. Elmirghani, *Energy efficient architectures for optical networks*, in Proceeding of the London Communications Symposium (LCS), UCL, London, 2009.

[119] Antonio Cianfrani, Vincenzo Eramo, Marco Listanti, Marco Marazza, and Enrico Vittorini, *An energy saving routing algorithm for a green OSPF protocol* in Proceedings of the IEEE Conference on Communications Traffic Management and Monitoring Workshop INFOCOM 2010, San Diego, CA, pp. 1-5, 15th-19th March 2010.

[120] Bart Puype, Willem Vereecken, Didier Colle, Mario Pickavet and Piet Demeester, *Power reduction techniques in multilayer traffic engineering,* in Proceedings of the 11th International Conference on Transparent Optical Networks ICTON 2009, pp. 1-4, Azores, Portugal, 28 June – 2 July 2009.

[121] Ashraf M. Hamad and Ahmed E. Kamal, *Power-Aware Connection Provisioning for ALL-Optical Multicast Traffic in WDM Networks,* IEEE/OSA Journal of Optical Communications and Networking, vol. 2, no. 7, pp. 481-495, July 2010.

[122] Ming Xia, Massimo Tornatore, Yi Zhang, Pulak Chowdhury, Charles U. Martel and Biswanath Mukherjee, *Green Provisioning for Optical WDM Networks, IEEE Journal of Selected Topics in Quantum Electronics,* vol.17, no.2, pp. 437-445, March/April 2011.

[123] Rodney S Tucker, Rajendran Parthiban, Jayant Balinga, Kerry Hinton, Robert W. A. Ayre and Wayne V. Sorin, *Evolution of WDM Optical IP Networks: A Cost and Energy Perspective*, IEEE/OSA Journal of Lightwave Technology, vol. 27, no. 3, pp. 243-252, February 1, 2009.

[124] Xiaowen Dong, Taisir El-Gorashi and Jaafar M.H. Elmirghani, *IP over WDM Networks Employing Renewable Energy Sources,* IEEE/OSA Journal of Lightwave Technology, vol. 29, no. 1, pp. 3-14, January 1, 2011.

[125] A. Leiva, J.M. Finochietto, B. Huiszoon, V. Lopez, M. Tarifeno, J. Aracil and A. Beghelli, *Comparison in Power Consumption of Static and Dynamic WDM Networks,* Optical Switching and Networking Journal, Elsevier, vol.8, no.3, pp. 149-161, July 2011.

[126] Yong Wu, Luca Chiaraviglio, Marco Mellia, and Fabio Neri, *Power-aware routing and wavelength assignment in optical networks* in Proceedings of the 35th European Conference on Optical Communication ECOC 2009, Vienna, Austria, 20-24 September 2009.

[127] Avinash Karanth Kodi and Ahmed Louri, *Energy-Efficient and Bandwidth-Reconfigurable Photonic Networks for High-Performance Computing (HPC) Systems,* Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 384-395, March/April 2011.

[128] Odile Liboiron-Ladouceur, Isabella Cerutti, Pier Giorgio Raponi, Nicola Andriolli and Piero Castoldi, *Energy-Efficient Design of a Scalable Optical Multiplane Interconnection Architecture,* IEEE Journal of Selected Topics in Quantum Electronics, vol.17, no.2, pp. 377-383, March/April 2011.

[129] Matteo Fiorani, Maurizio Casoni and Slavisa Aleksic, *Performance and Power Consumption Analysis of a Hybrid Optical Core Node,* IEEE/OSA Journal of Optical Communications and Networking, vol. 3, no. 6, pp. 502-513, June 2011.

[130] Thomas E. Stern, Georgios Ellinas and Krishna Bala, *Multiwavelength Optical Networks: Architectures, Design and Control,* 2nd Edition, Cambridge University Press, 2009.

[131] Christos G. Cassandras and Stephane Lafortune, *Introduction to Discrete Event Systems,* 2nd Edition, New York, Springer, 2009.

[132] Andras Varga, *OMNet++ User Manual Version 4.1, OMNet++ Community Site*, 2011, [Online] http://www.omnetpp.org.

[133] S. Albarrak, *Failure Recovery in Distributed GMPLS-based IP-over-Optical Networks*, PhD Thesis, University of Strathclyde, UK, 2008.

[134] L. Begg, W. Liu, K. Pawlikowski, S. Perera and H. Sirisena, *Survey of Simulators of Next Generation Networks for Studying Service Availability and Resilience*, Technical Report, University of Canterbury, New Zealand, February 2006.

[135] Varga, Andras, *The OMNeT++ Discrete Event Simulation System*, in Proceedings of the European Simulation Multiconference (ESM'2001), 2001.

[136] Varga, Andras and Hornig, Rudolf, *An overview of the OMNeT++ simulation environment*, Simutools '08: in Proceedings of the 1st international conference on Simulation tools and techniques for communications, networks and systems & workshops, pp. 1-10, 2008.

[137] Ahmet Sekercioglu, *OMNeT++ versus NS2: A Comparison*, Monash University, Australia, 2006 [Online] http://ctieware.eng.monash.edu.au/twiki/bin/view/Simulation/OMNeTppComparison.

[138] Klaus Wehrle, Mesut Gunes and James Gross, *Modeling and Tools for Network Simulation,* New York, Springer, 2010.

[139] Daniel Awduche and Yakov Rekhter, *Multiprotocol Lambda Switching: Combining MPLS Traffic Engineering Control with Optical Cross-connects*, IEEE Communications Magazine, vol. 39, no. 3, pp. 111-116, March 2001.

[140] Guangzhi Li, Jennifer Yates, Dongmei Wang and Charles Kalmanek, *Control Plane Design for Reliable Optical Networks*, IEEE Communications Magazine, vol. 40, no. 2, pp. 90-96, February 2002.

[141] L. Berger, "Generalized Multi-Protocol Label Switching (GMPLS) Signalling Functional Description", RFC3471, 2003 [Online]. Available: http://www.faqs.org/ftp/rfc/pdf/rfc3471.txt.pdf.

[142] J. Lang, "Generalized Multi-Protocol Label Switching (GMPLS) Signalling Resource Reservation Protocol-Traffic Engineering (RSVP-TE) Extension", IETF RFC 3473 [Online]. Available at: http://www.faqs.org/rfcs/rfc3473.html.

[143] Kejie Lu, Gaoxi Xiao and Imrich Chlamta, *Analysis of Blocking Probability for Distributed Lightpath Establishment in WDM Optical Networks,* IEEE/ACM Transactions on Networking, vol. 13, no. 1, pp. 187-197, October 2005.

[144] Theodore. T. Allen, *Introduction to Discrete Event Simulation and Agent-based Modelling: Voting Systems, Health Care, Military and Manufacturing*, New York, Springer, 2011.

[145] Mohammad S. Obaidat and Noureddine A. Boudriga**,** *Fundamental of Performance Evaluation of Computer and Telecommunication Systems,* Wiley, New Jersey, 2010.

[146] William L. Oberkampf, Timothy G. Trucano and Charles Hirsch, *Verification, Validation and Predictive Capability in Computational Engineering and Physics*, in Proceedings of the Foundations for Verification and Validation in the 21st Century Workshop, John Hopkins University, Maryland, pp. 1-74, 22-23 October 2002.

[147] Robert G. Sargent, *Verification and Validation of Simulation Models*, by M.E. Kuhl, N.M. Steiger, F.B. Armstrong, and J.A. Joines, eds in Proceedings of the

37th Winter Simulation Conference, WSC 2005, Orlando, Florida, USA, pp. 130-143, 4-7 October 2005.

[148] Ben H. Thacker, Scott W. Doebling, Francois M. Hemez, Mark C. Anderson, Jason E. Pepin and Edward A. Rodriguez, *Concepts of Model Verification and Validation*, in Proceedings of the Los Alamos National, LA-14167-MS, USA, pp. 1-27, October 2004.

[149] R. Barry, "Wavelength Routing for All-Optical Networks", PhD Dissertation, Dept. Elect. Eng. and Comp. Sci., MIT (1993).

[150] R. A. Barry and P.A. Humblet, *Models of Blocking Probability in All-Optical Networks With and Without Wavelength Changers*, IEEE Journal on Selected Areas in Communications, vol. 14, no. 5, pp. 858-867, June 1996.

[151] A. Sridharan and K.N. Sivarajan, "*Blocking in All-Optical Networks*", IEEE/ACM Transactions on Networking, vol. 12, no. 2, pp. 384-397, April 2004.

[152] Abdelnaser Adas, *Traffic Models in Broadband Networks,* IEEE Communications Magazine, vol. 35, no. 7, pp. 82-89, July 1997.

[153] Victor S. Frost and Benjamin Melamed, *Traffic Modeling for Telecommunications Networks,* IEEE Communications Magazine, vol. 32, no. 3, pp. 70-81, March 1994.

[154] Patricia E. Wirth, *The Role of Teletraffic Modeling in the New Communications Paradigms*, IEEE Communications Magazine, vol. 35, no. 8, pp. 86-92, August 1997.

[155] Krzysztof Pawlikowski, Hae-Duck Joshua Jeong and Jong-Suk Ruth Lee, *On Credibility of Simulation Studies of Telecommunication Networks,* IEEE Communications Magazine, vol. 40, no. 1, pp. 132-139, January 2002.

[156] John Heidemann, Kevin Mills and Sri Kumar, *Expanding Confidence in Network Simulations,* IEEE Network Magazine, vol. 15, no. 5, pp. 58-63, September/October 2001.

[157] Massoud Pedram and Jan Rabaey, *Power Aware Design Methodologies, Kluwer Academic Publishers,* New York, 2002.

[158] Satoru Okamoto, Ko kikuta, Daisuke Ishii, Eiji Oki and Naoaki Yamanaka, *Proposal of the MiDORi GMPLS traffic engineering for energy optimal traffic controlled networks*, in Proceedings of the MPLS2010, 1-2 October 2010.

[159] Paola Iovanna, Roberto Sabella and Marina Settembre, *A Traffic Engineering System for Multilayer Networks Based on the GMPLS Paradigm,* IEEE Network Magazine, vol. 17, no. 2, pp. 28-37, March/April 2003.

[160] Youngseok Lee, and Biswanath Mukherjee, *Traffic Engineering in Next-Generation Optical Networks,* IEEE Communications Surveys &Tutorials, vol. 6, no. 3, pp. 16-33, Third Quarter 2004.

[161] Yongli Zhao, Jie Zhang, Yuefeng Ji and Wanyi Gu, *Routing and Wavelength Assignment Problem in PCE-Based Wavelength-Switched Optical Networks,* IEEE/OSA Journal of Optical Communications and Networking, vol. 2, no. 4, pp. 196-205, April 2010.

[162] Isabella Cerutti, Nicola Sambo and Piero Castoldi, *Sleeping Link Selection for Energy Efficient GMPLS Networks,* IEEE/OSA Journal of Lightwave Technology, vol. 29, no.15, pp. 2292-2298, August 1, 2011.

[163] Gangxiang Shen, Jing Deng, and Pin-han Ho, *Green backbone optical Networks: the way forward*, in Proceedings of the 8th International Conference on Information, Communications and Signal Processing, ICICS 2011, Singapore, pp. 1-5, 13-16 Dec 2011.

[164] W. Colitti, P. Gurzi, K. Steenhaut and Ann Nowe, *Adaptive multilayer routing in the next generation GMPLS internet,* in Proceedings of the 3rd International Conference on Communication Systems Software and Middleware and Workshops COMSWARE 2008, pp. 768-775, 6-10 January 2008.

[165] Adrian Farrel, J. P. Vasseur and J. Ash, *A Path Computation Element (PCE)-Based Architecture*, RFC 4655, IETF, August 2006.

[166] Dongyun Zhou and Suresh Subramaniam, *Survivability in Optical Networks,* IEEE Network Magazine, vol. 14, no. 6, pp. 16-23, November/December 2000.

[167] Marcel Caria, Mohit Chamania, and Admela Jukan, *A Comparative Performance Study of Load Adaptive Energy Saving Schemes for IP-Over-WDM Networks*, IEEE/OSA Journal of Optical Communications and Networking, vol. 4, no. 3, pp. 152-164, March 2012.

[168] Odile Liboiron-Ladouceur, Pier Giorgio Raponi, Nicola Andriolli, Isabella Cerutti, Mohammed Shafiqul Hai and Piero Castoldi, *A Scalable Space-Time Multi-plane Optical Interconnection Network Using Energy-Efficient Enabling Technologies*, IEEE/OSA Journal of Optical Communications and Networking, vol. 3, no. 8, pp. A1-A11, August 2011.

[169] Aruna Prem Bianzino, Claude Chaudet, Dario Rossi and Jean-Louis Rougier, *A Survey of Green Networking Research,* IEEE Communications Surveys &Tutorials, vol. 14, no. 1, pp. 3-20, First Quarter 2012.

[170] Josef Roese, Ralf-Peter Braun, Masahito Tomizawa and Osamu Ishida, *Optical Transport Network Evolving with 100 Gigabit Ethernet*, IEEE Communication Magazine, vol.48, no.3, pp.S28-S34, March 2010.

[171] Xiaowen Dong, Taisir El-Gorashi and Jaafar M. H. Elmirghani, *IP over WDM Networks Employing Renewable Energy Sources,* IEEE/OSA Journal of Lightwave Technology, vol. 29, no.1, pp. 3-14, January 1, 2011.