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Future development trends of optical transport network infrastructure: an infrastructual framework for metropolitan-based optical transport networks - a field test of a Chinese ISP and a case study of a Chinese Electric Power Company

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Future Development Trends of Optical Transport Network Infrastructure

An Infrastructural Framework for Metropolitan-based Optical Transport Networks – a field test of a Chinese ISP and a case study of a Chinese Electric Power Company

A thesis submitted in fulfilment of the requirements for the award of the degree

Master of Information and Communication Technology by Research

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by

SHENG CHEN, MInfoTech *UOW*, B.E. *ECUST*

School of Information Technology and Computer Science

2006

Certification

I, Sheng Chen, declare that this thesis, submitted in fulfilment of the requirements for the award of Masters by Research, in the School of Information Technology and Computer Science, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications as any other academic institution.

Sheng Chen

18 December 2006

Dedication

Dedicated to

my family

and to the memory of my maternal grandfather

Pinxian, Wang (1924-2006)

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Abstract

Optical Transport Networks (OTNs) play a foundational role in current and future telecommunication infrastructure. However, the development and implementation of OTNs have been restrained since the bursting of the dot-com bubble. Many service providers and large companies are confused in the development directions of future OTN infrastructure, as there are several standards organisations with differing positions. On the other hand, there is a lack of large scale testing, as well as practical implementation cases due to the emerging nature of the OTN. Therefore, this thesis develops a framework demonstrating a landscape of current and future development steps of OTN infrastructure from both theoretical and commercial standpoints. The key concept of the framework is the integration of the IP-oriented data transmission layer and the WDM-based optical transport layer. Traditional telecommunication infrastructure focuses on long-haul, point-to-point optical transmission with ultra broadband carrier capacity. Nevertheless, the next generation OTN systems will emphasis the delivery of IP-oriented multifunctional data services, instead of legacy simplex TDM-based services across a metropolitan span with sufficient reliability and efficiency. Thus, this thesis gives a systematic validation of the proposed framework from two angles. Firstly, it provides in-depth research on the evolution of protection technologies in metro core optical networks, along with a MPLS-based network fast recovery field test to validate the framework from the network reliability aspect. The field test was conducted using a large Chinese ISP test bed and demonstrated the practical performance of the advanced OTN protection technology from the perspective of a service provider. Secondly, this research presents a comprehensive case study based on a large commercial metro OTN upgrade project of Shanghai Municipal Electric Power Company (SMEPC). The outcome of the case study is an evolutional roadmap, which illustrates the infrastructural development trends of this ongoing project. The roadmap can be considered as another evaluation of the framework in terms of network efficiency from an industrial-based dimension. The outcome of this research is to clarify future development trends in OTN infrastructure for the purpose of informing the design and implementation of commercial OTN applications.

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Publications

The following papers were published during my candidature at the University of Wollongong. The conferences where these papers appeared were IEEE/IEE sponsored.

1. Sheng Chen, "Evolution of protection technologies in metro core optical networks", *International Conference on Networking and Services (ICNS 06)*, IEEE Computer Society Press, July 16~19, 2006, Silicon Valley, USA.

2. Sheng Chen, "An Overview on the integrated IP Optical data control plane in the Optical Transport Network", *International Conference on Communications, Circuits and Systems (ICCCAS 06)*, IEEE Press, June 25~28, 2006, Guilin, China.

3. Sheng Chen, "A case study based on an optical communication engineering project of the system upgrade for Shanghai Power Telecommunication Network (ShPTnet)", *Advances in Power System Control, Operation and Management (APSCOM 2006)*, Power and Energy section of IEE , 31 Oct~ 2 Nov, Hong Kong, China.

I have also been invited to be a member of the technical committee of *The Third International Conference on Networking and Services (ICNS 07)*.

Chapter 1: Introduction

1.1 Next Generation Optical Networks

This thesis is concerned with the infrastructural issues of the next generation optical network, which is commonly referred to the Optical Transport Network (OTN). It aims to provide a vision for the development orientations of current and future OTN infrastructure, especially within a metropolitan scope. Specifically, this research focuses on demonstrating the evolution of the infrastructural integration between OTN and IP-oriented data networks. This evolution informs the development of an OTN infrastructural framework, which was verified by a field test on a large ISP in Shanghai. The refined framework was then validated by examining a case study of a recent OTN project conducted in Beijing. The results of the Chinese market studies are reported using qualitative and quantitative research methodologies.

1.1.1 Historical Background

Optical fibres, which use light or photonic energy to transmit information through hair-thin strands of glass, are considered as the biggest competitors to satellites and other communications in terms of connection speed and transmission range (Podmore and Faguy, 1986: 341). Optical networks are regarded as both market-driven and technology-driven data communications due to the popularity of the Internet today. The first attempt of optical network communication can be traced back to the Fibre Distributed Data Interface (FDDI), which applies a token-passing dual-ring optical Local Area Network (LAN) structure. The FDDI standard was defined in 1982 by ANSI, and it became more popular in the early 1990s due to its high capacity and redundancy (Mirchandani and Khanna, 1993: 2). FDDI is based on the design concept of the token ring structure, however, it is still relatively expensive and complex for large-scale business implementation (Held, 2001: 110). Actually, with the development of some lower cost and more flexible switching technology, the FDDI has been overtaken by the latest standards such as Gigabit Ethernet (GBE) or even 10-Gigabit Ethernet (10-GBE) within the current LAN environment.

In recent years, however, optical Wide Area Network (WAN) infrastructure has expanded rapidly because the cost and implementation complexity have been continually dropping. Based on a previous investigation of Sato (1996: 118), the data transport evolution of the telecommunications backbone is changing from digital circuit switching to light path switching. Similarly, Whyte (1999: 84) also indicated that the optical network is considered as a core element in building the Next Generation Network (NGN). NGN is defined as a packet-based network able to provide Telecommunication Services with multiple broadband and Quality of Service (QoS) support, and in which "service-related functions are independent from underlying transport-related technologies" (ITU, 2004). Thus, the International Telecommunication Union-Telecommunication (ITU-T) released the recommendation G.872, the "Architecture of Optical Transport Network". The ITU-T (2001a) defines the concept of OTN, as describes "the layered structure of an OTN, including issues such as client/server layer associations, optical signal transmission, multiplexing and routing".

The OTN is designed for transporting ultra-high speed data by utilising optical transport technologies over long distance, especially for the WAN backbone connections. The major part of those optical transport technologies is the Wavelength Division Multiplexing/Dense Wavelength Division Multiplexing (WDM/DWDM), which means the laser signal in one fibre is multiplexed into multiple wavelengths. Traditional multiplexing technologies such as TDM (Time Division Multiplexing) and FDM (Frequency Division Multiplexing) focus on enhancing the transmission bandwidth. However, WDM is capable of presenting more compatibility and flexibility with different types of network services, by implementing the wavelength routing mechanism.

1.1.2 Current Situation

In recent years, IP-based internet services have enjoyed an explosive growth globally. According to a industry forecast, the global consumer Voice over Internet Protocol (VoIP) market will reach 197 million users with a total service revenue of 15 billion US dollars in 2008 (Cisco System, 2005: 8). In addition, Shannon (2006: 49) indicates that about 53 million people will be using the Internet Protocol Television (IPTV) in a worldwide market of 39 billion US dollars in 2009. This requires an unprecedented large amount of data bandwidth, which hits the bottleneck of traditional cable and Public Switched Telephone Network (PSTN) based broadband infrastructure. Furthermore, the latest network transport technologies and various customer demands also accelerate the revolutionary progress in network access methods. On the one hand, by year end-2004, there were already 1.69 million subscribers in the world who had advanced Fibre to the Home (FTTH) technology (Tashiro *et al.*, 2006: 1). On the other hand, enterprises and large organisations are seeking a more cost-effective, IP-oriented packet switching interconnection solution, rather than using inefficient legacy TDM-based circuit switching technologies. One ideal answer to this is the Metro Ethernet (ME), which is to deliver the popular Ethernet data services across a metropolitan area over an optical WAN infrastructure (Alcatel, 2002: 1-2). By comparing the various aspects of service characteristics, including speed, cost and the ease of deployment, there is little doubt that ME will become a cogent competitor of traditional WAN access technologies such as Asynchronous Transfer Mode (ATM) and Frame Relay (FR). Thus, the initiative to build an IP-oriented next generation optical transport infrastructure with sufficient bandwidth and multiple services support, would be considered a crucial topic in the development of the connected business environment and even the whole Internet.

1.2 Previous Research

There is a vast amount of previous research that has been conducted in the optical networking field. In the mid-90s, Ramaswami and Sivarajan (1995) designed the logical topological structure for the wavelength-routed optical networks. Mohan and Murthy (1999) also presented their research achievements on solving routing and wavelength assignment problems for establishing reliable WDM networks. With the rapid development of various IP-oriented network applications and services, network designers and researchers then realised the importance of the convergence of IP and OTN. In a recent research paper, Koga, Morioka and Miyamoto (2004) also demonstrated the latest research progress on optical ultra broadband transmission by utilising OBS and Generalized Multiprotocol Label Switching (GMPLS) technologies from the Nippon Telegraph and Telephone Corporation (NTT) network innovation laboratories. For example, Verma, Chaskar and Ravikanth (2000) proposed a framework on deploying innovative optical burst switching (OBS) technologies for WDM-based terabit level IP backbones.

1.3 The Emerging Gap

Optical transport technologies have developed rapidly over the last few years. The huge carrying capacity and great compatibility of OTNs match the requirements of increasing bandwidth demands and complex services of the present internetwork. Therefore, the OTN is significant in current and future networked business environments, especially for national/international telecommunication infrastructures, large companies and ISPs. As the architecture (ITU-T G.872) is provided for the OTN development, however, a succinct framework to clarify the internal mechanisms and relationships of the latest OTN components, technologies and standards is not readily available.

Although various literature (Ramaswami and Sivarajan, 1995; Mohan and Murthy, 1999; Koga, Morioka and Miyamoto, 2004) presents their achievements on optical transport technologies, such as wavelength routing and optical burst switching, there is a lack of rigorous study on the internal mechanisms of the OTN. Whilst OTN systems have been introduced widely in recent years, widespread deployment has been limited due to immature infrastructural guidelines. The OTN infrastructure takes the responsibility of data and signal transmission for the substratal layers, as well as carrying and maintaining services for upper layers, through an optical-based data transport control plane. Many architectural aspects have been discussed by previous researchers (ITU-T G.871 & G.872; IETF RFC3717 & RFC3945), however, a systematic explanation in clarifying the internal relationships and interactions between optical transport standards, technologies and the OTN business applications have not been presented widely.

Thus, a gap exists between the technological maturity of OTN standards and the lack of infrastructural deployment guidelines targeted at OTN business applications. This research will reduce this gap by providing an infrastructural framework to support implementers, and validate this framework through a field test and a case study.

1.4 Justification

As shown in section 1.3, there is an urgent need to generate an infrastructural solution to allow network planners, such as senior network managers and Chief Technical Officers (CTOs) to access the latest trends of the OTN infrastructure development, for better designing and implementing OTN applications to meet organisations' business demands. Thus, this research is significant in demonstrating the existing situation of OTN systems, infrastructure considerations and their importance within future business solutions.

1.5 Aims and Objectives

OTNs are significant in current and future networked business environments, especially for some national/international telecommunication infrastructure, large companies and Internet Service Providers (ISPs). As with any other engineering field, infrastructure plays a crucial role in the entire expansion of OTNs. Due to the fact that the OTN is still an emerging network industry, it is crucial to amend and optimise the infrastructure of the OTN firstly (Moral *et al*, 2001: 152). Thus, the aim of this thesis is to demonstrate the future trends for development of the OTN infrastructure. In doing so, an infrastructural framework will be developed, along with two systematic evaluations from the network reliability and efficiency aspects.

The main objective of this research is to develop and validate a framework that addresses the lack of infrastructural deployment guidelines targeted at OTN business applications and reduce the gap identified in Section 1.3.

To achieve this objective, it is necessary to address the following stages:

1. Describe the evolution of OTNs and their growing significance within the current and future networked business environment;
2. Identify the weaknesses of the existing infrastructure of OTNs through a detailed literature review, focusing particularly on related business applications;
3. Develop an infrastructural framework that demonstrates future development orientations of OTN infrastructure to address the identified weaknesses;
4. Conduct a network field test with a systematic analysis on the evolution of OTN network protection technologies, so as to verify the proposed framework from the network reliability and survivability aspect;
5. Conduct a comprehensive case study and present a roadmap of OTN infrastructural development through participative observation, to further validate the framework from the network efficiency perspective;
6. Report on the results of the field test and the case study analysis to demonstrate the validity and practicality of the proposed framework.

1.6 Research Methodology

In achieving these objectives, this study developed an infrastructural framework through a qualitative literature review. The literature examined encompasses several dimensions, such as OTN and related industry standards, vendor specifications as well as academic papers. The framework provides readers with a clear presentation on the evolutionary process of the OTN infrastructure. In addition, this research also evaluates the framework to examine its practicability from the aspects of network reliability, survivability and efficiency.

A field test was conducted to illustrate the practical performance of the latest network protection technology in OTN. This test generated a statistical result table, that was compared to relative data of previous and developing protection technologies. This quantitative approach is significant in demonstrating the suitability of the framework for the infrastructural development of OTN reliability and survivability.

Following this, an electric power supplying company, Shanghai Municipal Electric Power Company (SMEPC) was used to conduct an in-depth case study to demonstrate the design and implementation progress of a representative OTN business solution. In particular, this research utilised a qualitative observation to produce an evolutionary roadmap, which demonstrates the development process necessary in improving the efficiency of a large metropolitan business OTN infrastructure. The roadmap can also be used to evaluate the framework in terms of network efficiency.

The field test and the case study results were analysed to demonstrate the validity and practicality of the proposed framework.

1.7 Scope and Limitations

In satisfying the objectives of this research, firstly, an in-depth document analysis on representative literature will be presented in developing the framework. The categories of the literature under review will include OTN related standards, optical transport components and technologies, as well as data transmission technologies and control plane. In particular, this thesis provides specific research on the integration evolution of the IP-oriented data network and the next generation OTN. After providing the infrastructural framework, it is important to evaluate its theoretical accuracy and commercial feasibility. There are many aspects of the proposed framework that would need to be validated in a mature framework before wide spreads deployment. However, this research will provide a representative evaluation from several significant aspects: the network reliability, survivability and efficiency.

Firstly, there will be a detailed analysis on the evolutionary progress of the OTN protection technologies, along with a network fast recovery field testing focusing on metro core optical networks. The test will demonstrate the practical performance of the latest MPLS Fast Reroute (FRR) technology, by utilising pure commercial equipment within a real ISP lab environment. As all test equipment was provided by Cisco Systems and the test environment is within a single ISP lab, the results are not indicative of all real operating environments due to problems such as compatibility issues with other vendors. However, they are a valuable initial benchmark to consider.

Secondly, this study will focus on the implementation of a large scale engineering project by SMEPC, in building business network applications with optical-based infrastructure by utilising interrelated next generation OTN technologies. Nevertheless, due to this ongoing OTN project is managed by both SMEPC and Shanghai state government, the engineering deployment will be executed in several phases and lasts for years. As the OTN is still an emerging topic in the global networking industry, a longitudinal study will be more appropriate in the next steps. Furthermore, this research focuses on a Chinese organisation, which may not be representative of all trends in the OTN development.

1.8 Outcomes and Contributions

The research results in three main outcomes. Firstly, the framework developed can be used in wide spread implementation of metropolitan OTN systems. The analysis of the development of protection technologies and the field test of OTN fast recovery provides existing and future OTN managers with a snapshot of current best practice as well as demonstrating the practicality of the developed framework. Finally the case study and consequent roadmap can be used to optimise existing OTN network service architectures.

Alongside these specific outcomes, several other contributions are made by this research. The literature review with its focus on the evolution of OTN services and deployment provides an historical overview and technological comparison of legacy, current and future core metropolitan OTNs. The diagrams and tables developed in the analysis provide a visual guide for network planners that may inspire current and future network planners and designers.

1.9 Research Outline

Finally the structure of this thesis has been organised to satisfy the objectives clarified in section 1.5.

Chapter two presents a review of the literature associated with several aspects of OTN. The related industry standards, and the technical terms such as WDM and DWDM will be defined and explained. The background information of OTN systems including optical transport components, optical transport technologies and data transmission technologies will also be discussed in detail. The research gap, as well as the significance of the development of the framework will be restated and emphasised.

Chapter three details the methodology used to meet the objectives of the research. The overall research plan is defined along with the techniques that will be used in the process of data gathering and data analysis.

Chapter four develops the infrastructural framework, by providing a more specific analysis inside the IP-oriented OTN data control plane. The framework will demonstrate a landscape of the development of current and future OTN infrastructure, as well as the progress of the integration of IP and next generation OTN.

Chapter five evaluates the practicability of the framework from the angle of network reliability. It gives an in-depth analysis on the network protection technologies in metro core optical networks, together with a network fast recovery field test. The intention here is to show how the framework suits the evolution of OTN infrastructure from the network survivability dimension.

Chapter six provides a comprehensive case study based on a large ongoing OTN upgrade project of SMEPC, which is another validation of the proposed framework. This chapter gives a detailed observation on the legacy network situations of SMEPC, as well as their various increasing business and technical demands. It also designs a roadmap demonstrating the current implementation and future development steps of the next generation OTN infrastructure of SMEPC. The roadmap indicates a representative case of business OTN development in enhancing network efficiency.

Chapter seven, sums up the important findings and conclusions of this research. It also suggests future research directions in the relevant OTN field, including some emerging research discovered during this study. The outcomes and contribution made by this research are further detailed in this chapter.

Chapter 2: Review of the Relevant Literature

2.1 Introduction

This chapter provides a review of the literature relevant to the evolution of Optical Transport Network (OTN). Given that OTN enables greater transport capacity and carrier transparency, addressing the needs of the next generation internetworks in terms of increasing bandwidth and integrated service demands, the over-arching theme of this chapter is to present the current industry infrastructure. The objective of this research project is to develop and validate an infrastructure framework that can be used when designing and implementing OTN business applications within the current and future networked business environment. This review adopts a topical layout. First, the OTN system concepts and measures are defined and considered in the context of the research. Second, studies in the evolution of OTN are critiqued. Third, a gap in research is identified.

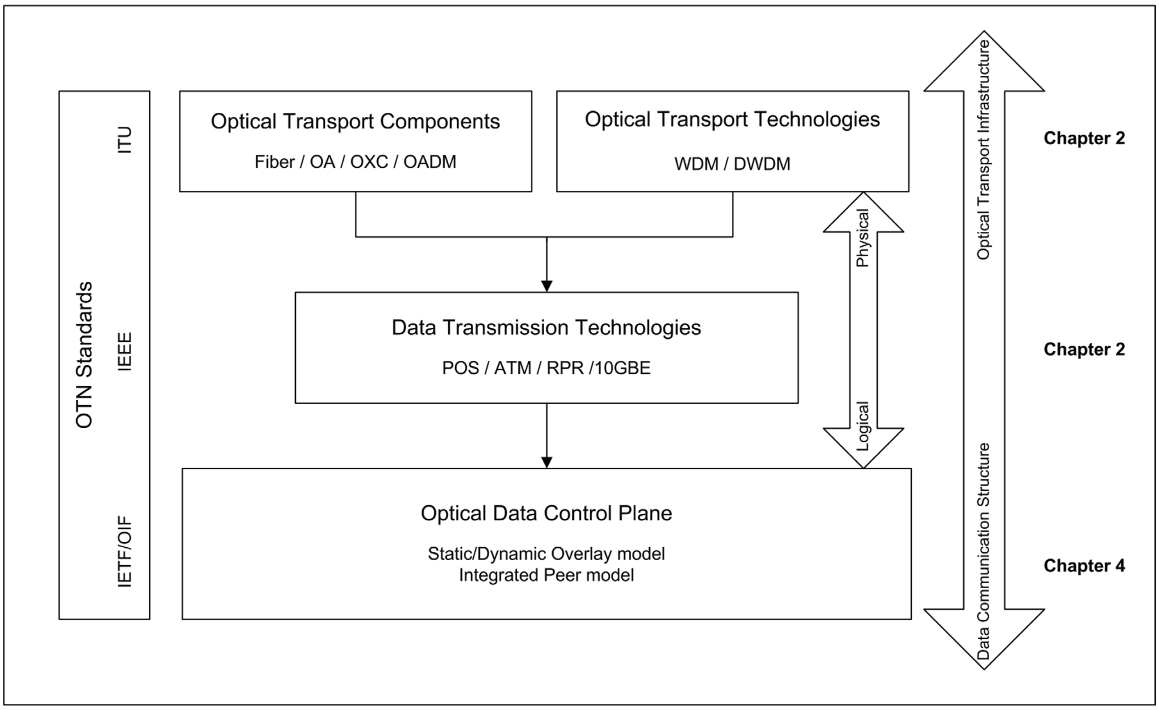

Figure 2.1: Tiered Literature Review Layout

To achieve this, a review of OTN industry standards, their importance, and system structure, including optical transport components and optical transport technologies is presented. This enables an analysis of the OTN infrastructure considerations and requirements, along with an examination of the relevant literatures, including data transmission technologies and data control plane dimensions in terms of OTN business applications to be provided.

Figure 2.1 gives a clear view of the structure of the tiered literature review. In brief, the physical layer of OTN infrastructure consists of optical transport components and optical transport technologies, whereas the data transmission technologies and data control plane compose the foundation of the OTN at the logical layer. The respective chapters are written using an historical approach as this serves the basis for building the foundations for understanding current OTN infrastructure, and predicting its future development.

2.2 OTN Standards

Standards, are prerequisite elements in any industry, however they are extraordinarily significant in the OTN field. The following standards bodies are promoting OTN towards a common aim, such as the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T), the Optical Internetworking Forum (OIF), the Internet Engineering Task Force (IETF) and the Institute of Electrical and Electronics Engineering (IEEE).

There are several standard organisations in OTN industry field and the three main groups are ITU-T, OIF and IETF. The primary objective of the OTN standards is to show how to migrate multiple service layer technologies through an OTN infrastructure. Those tasks involve defining the overall technical architectures for industrial referencing, and unifying the related service platforms inside business applications.

In 1998, the ITU-T released a set of G series (focused on Transmission Systems and Media, Digital Systems and Networks) recommendations focusing on the OTN architecture. Take the pivotal two for example, the G.871, "Optical Networking Standardization Framework" and the G.872, "Architecture of Optical Transport Network". These G series handle the control, development and description of the architecture of OTN (Tomsu and Schmutzer, 2002: 48-50). G.871 and G.872 define the initial fundamentals of OTN, primarily from the substrate (physical) layer perspective, including the specifications of optical transport components and optical transport technologies.

As formed by many optical networking vendors, the mission statement of OIF is to "foster the development and deployment of interoperable products and services for data switching and routing using optical networking technologies" (OIF, 2005). For example, the OIF approved the Optical User-to-Network Interface (O-UNI) 1.0 specification in 2001, which allows clients to establish a dynamic light path connection, through an OTN by utilising a standard type of signaling (OIF, 2001: 1). This specific signaling is also compatible with other common signaling from a typical Traffic Engineering (TE) protocol, named Multiprotocol Label Switching (MPLS).

Inspired by the success of MPLS utilised in IP-based data networks, the IETF has then enhanced optical transport plane by proposing an innovative Multiprotocol Lambda Switching (MPLmS) protocol. MPLmS is an extension of MPLS from the IP to the optical domain. Under the introduction of MPLmS, the OTN can provide an extremely high performance of wavelength routing/switching operation, directly down to the physical light path layer with high availability and durability (Kartalopoulos, 2003: 391-392). In 2004, the proposed MPLmS has been approved by IETF and released as RFC3945, namely the Generalized Multi-protocol Label Switching (GMPLS) architecture.

These standards clarify the technical criterion from the upper (logical) layer perspective, such as data transmission technology and data control plane, which will be investigated thoroughly in chapter four.

2.3 Optical Transport Components

As the relevant OTN standards were highlighted above, it is now necessary to enter a deeper understanding of the foundation of OTN system, including the optical transport components and the optical transport technologies. Thus, this section focuses on optical transport components, which consist of various optical network elements. These pieces of equipment can be interconnected for setting up the physical infrastructure of the OTN.

2.3.1 Fibre Optics

Fibre optics comprise several components, including a core, cladding, buffer coating, strength material and outer jacket (Murthy and Gurusamy, 2002: 3-4). The optical core is a primary element, which contains a hair-thin strand of glass tunnel for light travelling, while the other elements take charge of internal optical reflection and cable strength protection. The carrier light hits the cladding and reflects back into the core, which means it bends around inside the fibre and is capable of travelling "a great distance without having to be repeated" (Bates, 2001: 14). With the inherent carrying capacity, optical fibre provides an extremely high speed of data transmission and a super broad bandwidth for various integrated services such as video, voice and data. In addition, optical fibre offers more reliability and less weight than the conventional copper cable in installation and implementation. For instance, optical fibre weighs 4kg/300m while copper cable usually weighs 36kg/300m, and it has strong resistance to noise and interference due to its natural physical characteristics (Transition Networks, Inc, 2005: 50). As optical fibre carries beams of light, the transmission process is free of electromagnetic radiation and it can protect sensitive information from interception.

There are two general types of optical fibre: singlemode and multimode (Held, 2001: 58-60). Singlemode fibre has a very smaller core diametre of 8 to 10μm, and it allows only one mode of light to transport through the core without modal dispersion or pulse spreading. Thus, singlemode fibre provides an unlimited bandwidth carrying capacity in data transmission, especially for the super high speed and long-haul distribution. Multimode fibre has a much larger core size of 50 to 85μm, while it supports hundreds to thousands paths of light from different input angles, and enables the light bouncing continually along the internal optical channel (Held, 2001: 59-61). Based on this design, multimode fibre is more suitable in lower speed and short distance transmission, such as equipment interconnections within an economical cost. In considering the practical deployment, singlemode fibre is preferred to metro or WAN optical transmission whereas multimode fibre is mainly used in local data communication systems. Therefore, the understanding of the fibre system is significant as it is the first step in building the entire OTN infrastructure.

2.3.2 Optical Amplifier (OA)

As other signal transport systems, optical transmission also requires power amplification and signal regeneration for avoiding signal attenuation and ensuring propagating quality. Conventionally, optical regenerators are deployed every 40 km between the transmitter and receiver (Tomsu and Schmutzer, 2002: 74). The regenerators convert the optical signal into the electrical domain for reshaping and retiming, and then remodulate it back to the optical channel with power regeneration. Optical amplifiers (OA), however, are bit rate and modulation independent along with a large-gain bandwidth, which enables the amplification of a multiple wavelength band concurrently and reduces the amount of repeating equipment significantly.

OA involves two types: the semiconductor optical laser type amplifier (SOA) and the fibre-type amplifier, such as erbium-doped fibre amplifier (EDFA) and praseodymium-doped fibre amplifier (PDFA) (Kartalopoulos, 2000: 121). The basic amplification principle is to provide extended energy, which means injecting electrical current in the SOA, or pumping up optical energy in the EDFA/PDFA. Furthermore, there are some physical nonlinear effects inside optical silica fibre, which can be stimulated and utilised in transferring photonic energy from a source pump laser to an objective weak signal. Practically, the amplifying devices such as Brillouin scattering and Raman scattering amplifiers are typical products that are based on the above theories (Laude, 2002: 127-128). The significance of OA is that it improves the operating transparency and efficiency instantly during the signal amplification process. In addition, it has a big impact on reducing the system complexity of the entire fibre communication system.

2.3.3 Optical Cross-Connect (OXC)

Channel cross-connecting is a key function in most communication systems, especially in OTN. In this context, optical cross-connect (OXC) plays a crucial part in building a highly efficient switched optical network. The pivotal principle of the OXC is to reconfigure the optical network at the fibre and wavelength level, for optimising traffic demand and providing flexible services (Ramaswami and Sivarajan, 2002: 419). Moreover, due to the optical channel cross operation is based on the physical layer. OXC allows the system to accommodate and switch various upper layer services, such as IP, ATM and SONET/SDH traffic transparently. Given the capabilities, OXCs are typically deployed in a backbone network of mesh topology.

Generally, there are three models of OXC in terms of different types of switching backplanes, including electrical, hybrid and optical approaches. The conventional electrical OXC transforms the optical wavelengths into electrical signals, and then switches them in the electrical domain, by utilising an electrical nonblocking crossbar-switching fabric (see Figure 2.2 (a)).

The present hybrid OXC, however, consists of both optical and electrical switching fabrics, which enhances the switching processing capacity and enables the whole system to be ready for dense wavelength division multiplexing (DWDM) high-bandwidth multichannel traffic (Laude, 2002: 184). Nowadays, the hybrid method takes most of the proportion in the real engineering cases because of its flexible and scalable design, with an economical cost. As the developmental technical trends, the latest OXC, also referred to a *Wavelength Router*, is based on an advanced absolute optical design (see Figure 2.2 (b)).

Please see print copy for Figure 2.2

Figure 2.2: A Comparison of Electrical OXC and Optical OXC
(Tzanakaki et *al*, 2004: 35)

Wavelength routers are a key component of constructing an all-optical network environment in that there is no internal electrical/optical signal conversion processing, and the switching fabric is purely optical driven (Tomsu and Schmutzer, 2002: 87). The appearance of OXC is a crucial milestone in the development of OTN infrastructure. It not only enhances the intelligence of wavelength assignment and routing operations, but also accelerates the progress in achieving a non-blocking, transparent all-optical network.

2.3.4 Optical Add/Drop Multiplexer (OADM)

An optical add/drop multiplexer (OADM) is a specific device which is designed for the wavelength division multiplexing (WDM) systems, especially in the dense mode wavelength multiplexing (DWDM) network. As shown in the Figure 2.3 (a), OADM aims on providing wavelength add/drop functions, which means that it removes a selected wavelength from incoming fibre and routes its carried content/service to the drop (local) site, bypasses the remaining wavelengths, and then adds the same wavelength with different data content/service on the output optical channel (Kartalopoulos, 2003: 145). This mechanism is momentous as it optimises the transmission architecture of an OTN with ring or end-to-end liner topology, which is a best choice for current metropolitan carrier network structure (see Figure 2.3 (b)). OADM also enables corporations or ISPs to set up a Multiservice Transfer Platform (MSTP), and manages those integrated services including Gigabit Ethernet, SONET/SDH and E-3/DS-3 locally and flexibly, based on the latest WDM technology (Cisco Systems, 1999). Furthermore, traditional electrical ADM, such as used in Time Division Multiplexing (TDM) systems has to terminate entire transmission signals, for converting them into the electrical domain.

Please see print copy for Figure 2.3

Figure 2.3: (a) A Typical OADM Model; (Dods *et al*, 1999: 389) **(b) OADM Deployed in a WDM Ring Topology (Gemelos *et al*, 1999: 349)**

Compared with the electrical ADM, however, OADM boosts the add/drop operational efficiency by only rearranging a selected subset of wavelength paths in a pure optical domain (Goralski, 2001: 187). As the increasing demand from upper layer various

IP-oriented data services, future OTN infrastructure will emphasise the enhanced service transparency between IP data communication and optical transport systems. However, due to the significant cost of OXC, the large commercial deployment has been limited. Thus, OADM plays a decisive role in current OTN implementation, as it gives an excellent solution in migrating various services onto a uniform optical transport infrastructure.

2.4 Optical Transport Technologies: WDM and DWDM

After an analysis focused on optical transport components, this section explores optical transport technologies. Current optical transport technologies mainly focus on WDM/DWDM systems, which aim on maximizing the utilisation of existing optical transport components and network resources, for optimising the physical infrastructure of the OTN on transport capacity and efficiency.

2.4.1 Definition

Wavelength division multiplexing (WDM), is defined as "placing multiple wavelengths over a single strand of fibre optical cable" (Ramaswami and Sivarajan, 2002: 166). It is considered an emerging strength in the field of kernel technologies of optical transmission. Light wavelengths in first WDM system are divided into about 4 to 10 nanometres (nm) apart and operated in both 1310-nm and 1550-nm spectrum windows. As previously defined in ITU-T G.692 "Optical Interfaces for Multi-Channel Systems with Optical Amplifiers", the current dense wavelength division multiplexing (DWDM) systems, which separate light wavelengths by the higher precision level at 0.1 nm to 1 nm, commonly carry signal from 16 to 128 wavelength channels (ITU, 1998) per fibre within the 1550-nm spectrum window. As FDM in wireless/mobile communication systems, WDM dominates the physical layer transport standards of OTN infrastructure.

2.4.2 Operation of WDM and DWDM

Figure 2.4 demonstrates a signal flow process of a simplex end-to-end WDM/DWDM transmission system. Firstly, different data services (electrical bit streams) are converted by Line Terminal Equipment (LTE) into optical signals. Secondly, Optical-Electrical-Optical (OEO) units reshape and regenerate the optical signals into different standard WDM wavelengths (ITU-T G.692), which are then multiplexed by the WDM Mux modules into one single pair of fibre. Thirdly, the multiplexed wavelength channels are amplified by OAs during the long distance transmission. Only the selected wavelengths (services) are de-multiplexed by OADMs at specific relay sites, without any interruption of the transmission for other channels. Finally, the remaining wavelengths are received and de-multiplexed by the other end of the system, and the optical signals are then converted back to original data services by the local LTEs.

Please see print copy for Figure 2.4

Figure 2.4: Basic operations of WDM/DWDM system
(Cisco System, 2002, 102)

Figure 2.5 gives a clear comparison between TDM and WDM systems in a typical 10Gbps transmission link. A conventional TDM transmission system needs four pairs of fibre to transport four sets of 2.5Gbps wavelength signals (running at 1310-nm channel). There are also four electrical amplification sites that are deployed every 40 kilometres. However, a latest WDM transmission system only needs a single pair of fibre to transport four OC-48(2.5Gbps) signals (running on different WDM channels), and only one optical amplification site is required every 120 kilometres. The implementation of wavelength multiplexing significantly increased the whole system efficiency and reduced the cost of deployment, for example, in fibre cables and the number of amplification sites.

Please see print copy for Figure 2.5

Figure 2.5: A Comparison between TDM and WDM transmission system
(Cisco System, 2001a, 14)

2.4.3 Advantages

Compared with the conventional transmission technology such as TDM, WDM and DWDM have their peerless edges on broadening optical propagation power as follows. According to a survey by a major U.S interexchange telephony service provider, it usually costs about $70,000 per mile when a new fibre optical cable is set up (Ramaswami and Sivarajan, 2002: 169). Thus, WDM and DWDM can save existing precious optical resources by maximising utilisation of natural characteristics of optical wavelengths. WDM and DWDM stand at the physical layer which is the foundation level of the network transport system. This structure enables different services such as IP, ATM and SONET/SDH to have a transparent transmission over optical plane without any signal disturbance (Tomsu and Schmutzer, 2002: 40). Within the use of some key components such as OADM and OXC, it is possible to upgrade current telecommunication transport systems into an all-optical network with high flexibility, scalability and survivability (Goralski 2001: 424-425).

2.4.4 Disadvantages

There are, however, some problems associated with WDM systems that need to be solved before commercial scale implementation. Firstly, the control and management of WDM systems, such as accident and alarm trace, are not currently efficient due to immature correlative software. This weak point stifles the progress of optical transmission in a way (Ramaswami and Sivarajan, 2002: 530-531).

Secondly, some core optical components including OADM and OXC are not economically viable because of the current limitation of fabrication techniques (Goralski, 2001: 197). These components usually represent a significant part of the total budget of engineering deployment.

Finally, there is a lack of systematic industry standardization which aims at interface techniques and transport platform of WDM systems between different optical manufacturers (Tomsu and Schmutzer, 2002: 300). This reality, however, will lead to some interconnection problems of WDM systems with traditional carrier network, which is very important for commercial scale implementation of optical transportations.

2.5 OTN Infrastructure Considerations and Requirements

Infrastructure plays a crucial role in the entire expansion of OTN. It not only takes charge of data and signal transmission of the substratal layer, but also provides carrying and maintaining support for multiple services from upper layer, through an optical-based transport platform. OTN is still an emerging network industry field, in other words, there is “a long way to go to realize” (Moral *et al*, 2001: 152) visions such as the optical Internet. The very first step, therefore, is to amend and optimise the infrastructure of OTN. Section 2.3 gave a discussion focusing on the physical construction of the whole OTN system. The next step is to review the data transmission technology and data control plane (see Chapter four), which represent the OTN infrastructural issues from the logical point of view.

Previous researchers have provided various studies on infrastructural development of related optical data communication systems, such as Optical Grid Computing Networks (Simeonidou, Nejabati & O'Mahony, 2004), Optical Storage Networks (DeCusatis, 2005) and Ethernet Passive Optical Networks (Kramer and Pesavento, 2002). However, as discussed in section 1.3, there is a lack of a systematic study inside the infrastructure of OTN itself, especially for the interoperability between IP-oriented data communication and optical transport system.

Table 2.1: Weaknesses in Current OTN Infrastructure Development

Different Parties	Weakness and Limitations
Standard Bodies	Different Standpoints
ISPs and Large Companies	Slow Deployment due to the Unclear Development Trends; Lack of Practical Cases for Further Analysis
Vendors	Lack of Large Scale Simulations and Field Testing; Need for Improvement on Operational Interoperability Between Different Vendor Systems

As illustrated in Table 2.1, there are three main aspects hampering the steps in the evolution and implementation of the OTN infrastructure. Current OTN standard organisations have several different standpoints in the layout of future OTN development. RFC3717 "IP over Optical" architecture in encouraging the whole industry to move forward into an innovative **IP+WDM** peer controlled OTN infrastructure. On the other hand, the ITU places emphasis on optimising the legacy overlayed TDM-based OTN infrastructure at the initial stage. The practical adoption of the latest OTN systems is slow since many service providers and large companies are confused by the proposed future development directions. Due to the emerging nature of the OTN infrastructure, previous research is limited, especially on the limitations of large scale simulations or field tests. There is a lack of practical industry cases for further analysis.

As OTNs will be a foundational carrier of next generation telecommunications, the system interconnections will extend from the metro to national or international scale. There is a strong need for improving the system operational interoperability between various vendors from different regions. However, most of the manufacturers are private companies who do not expect to disclose their latest research achievements due to the intellectual property issues. Thus, the development of an OTN infrastructural framework has more industry wide considerations than the design of a piece of specific network equipment or algorithm.

The guidance of this research is expected to follow the specifications, as the ITU-T G.872 recommendation described that "the layered structure of an OTN, including issues such as client/server layer associations, optical signal transmission, multiplexing and routing" (Tomsu and Schmutzer, 2002: 48-50). Therefore, those technical requirements can be summarised to two main aspects: data transmission technology and data control plane issues. Data transmission technology involves specific physical criteria in signal transmission, various data frame encapsulation and mapping methods, and transport interface technologies for ensuring a high performance data transport tunnel with sufficient efficiency and flexibility and based on the OTN infrastructure.

By contrast, the optical transport data control plane focuses on how the OTN infrastructure adapts and interoperates with the upper data service layer in terms of traffic control and bandwidth management such as network signaling, routing and switching mechanisms as well as optical protection and service guarantee aspects. In brief, data control plane is the key foundation that affects the capability and reliability of the OTN infrastructure in data service transportation. As identified in Section 1.5, a comprehensive description of the development process of the OTN data control plane is a necessary stage in the achievement of the main objective of this research.. This will aid in the development of a detailed framework of future implementation landscape on the OTN, which will boost the step in building the next generation IP-based all-optical (optical switching and routing) network.

2.6 The Evolution of Data Transmission Technologies in OTN

Based on the above discussion of optical transport considerations and requirements, this section provides a detailed review and analysis on the evolution of data transmission technologies in the OTN. Data transmission technologies are the groundwork ensuring a high performance OTN infrastructure with sufficient efficiency and flexibility.

2.6.1 Asynchronous Transfer Mode (ATM)

Asynchronous transfer mode (ATM) was designed for providing powerful layer 2 switching capacity to replace traditional TDM packet switching technologies such as X.25 and Frame Relay (Krupicka, 1994). Originated from the classical virtual circuit principle, it introduces an innovative Virtual Path Identification/Virtual Circuit Identification (VPI/VCI) cell switching operation structure (IEC, 2005). This structure first gives a satisfying solution in processing large throughput of integrated data services with great Quality of Service (QoS) performance instead of conventional complex layer 3 routing mechanisms in carrier core networks. In addition, the optical interfaces have been first largely deployed in WAN data transport along with the integration to the ATM adapter layer (Nortel Networks, 2004: 4-6).

Interestingly, inspired by the succuss of ATM, service provider and network operators are expecting to provide an ATM-based common architecture, namely ATM Passive Optical Networks (ATM-PONs) for various fibre-optic access methods. Those fibre-optic access methods including fibre-to-the-home/building (FTTH/B), fibre-to-the-cabinet (FTTCab), and fibre-to-the-curb (FTTC) will rewrite current narrowband telecommunications while intensifying the utilisation of existing fibre and network resources (see Figure 2.6). Although ATM represents a legacy TDM-based data transmission technology, it is still important in delivering data service across optical infrastructure in the first phase.

Please see print copy for Figure 2.6

Figure 2.6: ATM-PON Architecture
(IEC, 2005)

2.6.2 Packet over SONET/SDH (POS)

Packet over SONET/SDH (POS) is a network interface technology, which enables the network layer to transport IP data packets across the standard physical layer Synchronous Optical Network (SONET)/Synchronous Digital Hierarchy (SDH) frames, by utilising the point-to-point data frame encapsulating and mapping method that lies across the both the data link layer and physical layer (IETF, 1994). It aims at providing a new efficient and cost-effective solution in long-distance data transportation over the existing SONET/SDH architecture, which is the first-generation wide area optical transport infrastructure standard for carrier class networks and ISPs. As the technical details introduced in RFC1619 by the IETF, the overall data transmission efficiency can reach to 96.3% due to its outstanding optimised packet overhead structure (Hay, 2000: 102). Compared with the conventional core transport technology, the ATM cell switching mechanism, the maximum total transmission efficiency is only 86.4% (Tomsu and Schmutzer, 2002: 129). As a consequence, the POS interface is concerned to be one of the most powerful challengers of ATM, which is the ruler in current backbone data transmission field.

2.6.3 Resilient Packet Ring (RPR, IEEE802.17)

The IEEE 802.17 working group has been working in a new multi-Gigabit speed data transmission protocol which is based on a dual-ring architecture, named Resilient Packet Ring (RPR) since 2000 (Lee *et al*, 2003). RPR is mainly a MAC layer protocol (see Figure 2.7) which is developed for implementing data services across the Metro or wide area network (WAN) ranges.

Please see print copy for Figure 2.7

Figure 2.7: Layer Model of The RPR Standard
(IEEE, 2004: 28)

Generally, the ring topology is commonly accepted as a good choice in long-haul data transmission, because it offers more protection mechanisms than hub-spoke structure and is much easier to manager than a mesh network. However, as in the existing SONET/SDH system, there are already some dual-ring designs such as shared protection ring (SPRing), whereas half of the overall bandwidth is merely used for backup means a waste of precious bandwidth resources (Johnson and Gilfedder, 2002: 14). Again, although the POS interface provides a high performance WAN transmission approach within a reasonable cost, it lacks protection and self-restoration capability.

Resilent Packet Ring technology takes advantage of both the resilient functionality of ring topology and the brilliant data transmission capacity of the POS interface. In addition, it supports current SONET/SDH infrastructure as well as future DWDM systems. The most attractive technical aspect of RPR is that it maximally utilises the whole bandwidth of both rings, and improves congestion control of data traffic.

Its bandwidth sharing mechanisms differ from previous MAC control protocols such as Ethernet and token ring, in that RPR uses a revolutionary fairness bandwidth control algorithm. This algorithm (RFC2829) ensures global fairness of total bandwidth allocation, as well as local optimisation that is to reuse the bandwidth for different services between different ring spans independently. Thus, the total operational bandwidth is expanded rapidly.

By utilising the automatic topology discovery and sense mechanism, in addition, RPR is upgradeable to maximum 256 (theoretical) ring nodes instead of the 16 nodes of a conventional SONET/SDH network, with an auto restoration competence that is under 50ms concurrently (Yue *et al*, 2003: 415-416). These features offers excellent scalability and survivability which satisfy the requirements of next generation optical transport infrastructure.

2.6.4 10-Gigabit Ethernet (10-GBE)

Furthermore, the IEEE 802.3ae study group also founded their latest research achievements: the 10 Gigabit Ethernet (10-GBE) in 2002 (IEEE, 2002: 1). Compared with the existing costly ATM and POS interface, the IEEE 802.3ae group facilitates the Internet Protocol (IP) data traffic into an unprecedented high operating speed, and makes the solution acceptable for users in a business Local Area Network (LAN) environment due to its economy and flexibility. Moreover, as the 10-GBE first defines a WAN physical layer interface along with its inherent characteristics from the IEEE 802 family, it is interoperable to be deployed over the above RPR structure in a metropolitan or regional range. As a consequence, it is reasonable to believe that the classic LAN technology Ethernet will set a cost-effective and unified data transmission standard from core to metro to building to desktop. Moreover, in considering various implementation aspects, including bandwidth, service transparency and cost-performance, it is generally accepted (Vaughan-Nichols, 2002; Informa Telecoms & Media Group, 2005) that the 10GBE standard will replace ATM in the IP-based data transmission plane of future OTN infrastructure.

2.7 Conclusion

The key issues about the development of the OTN infrastructure have been highlighted. Many standard organisations are working jointly for clarifying the architecture of OTN systems, as demonstrated by the protocols and recommendations discussed in Section 2.2. This chapter also provides plenty of fundamental literature sources inside the physical infrastructure of the OTN. For the logical infrastructure aspects, there is a detailed investigation focusing on optical-based data transmission technologies. An exhaustive literature search failed to locate any major set of systematic guidelines for the orientation of future OTN infrastructure development. Therefore, the major goal of this research, which is the infrastructure development framework, is crucial. The next chapter will detail the approach taken in building this framework, including the specific methods and techniques for data gathering and analysis.

Chapter 3: Research Methodology

3.1 Introduction

The previous chapter presented necessary and foundational background knowledge in relation to Optical Transport Network (OTN) systems, infrastructure considerations and their importance within future business applications. During the literature review process, a gap in the literature indicated the demand for a systematic infrastructure framework that could be used when designing and implementing the OTN applications within the current networked business environment. The framework, in addition, is also required to enable the OTN interaction with applications based on wavelength division multiplexing/dense wavelength division multiplexing (WDM/DWDM) technical plane.

In satisfying the objectives of this research, it is significant to clarify the approach taken in building this research project. The overall research design is illustrated in Figure 3.1 which shows the overall research design. The major components of the study include a document analysis which is highly descriptive in nature providing the technical background for the study, a field test which is experimental and utilises quantitative data to examine the reliability aspect of the framework, and a qualitative case study that evaluates the efficiency aspect of the framework.

In particular, this chapter gives a comprehensive description of the research methodology, including the detailed research approach taken, data gathering process and data analysis techniques used. In addition, the methodology clarified in this chapter will be used as an important compass in achieving the aims and objectives of this study through the entire research process. Above everything else, it is necessary to restate the purpose of the study.

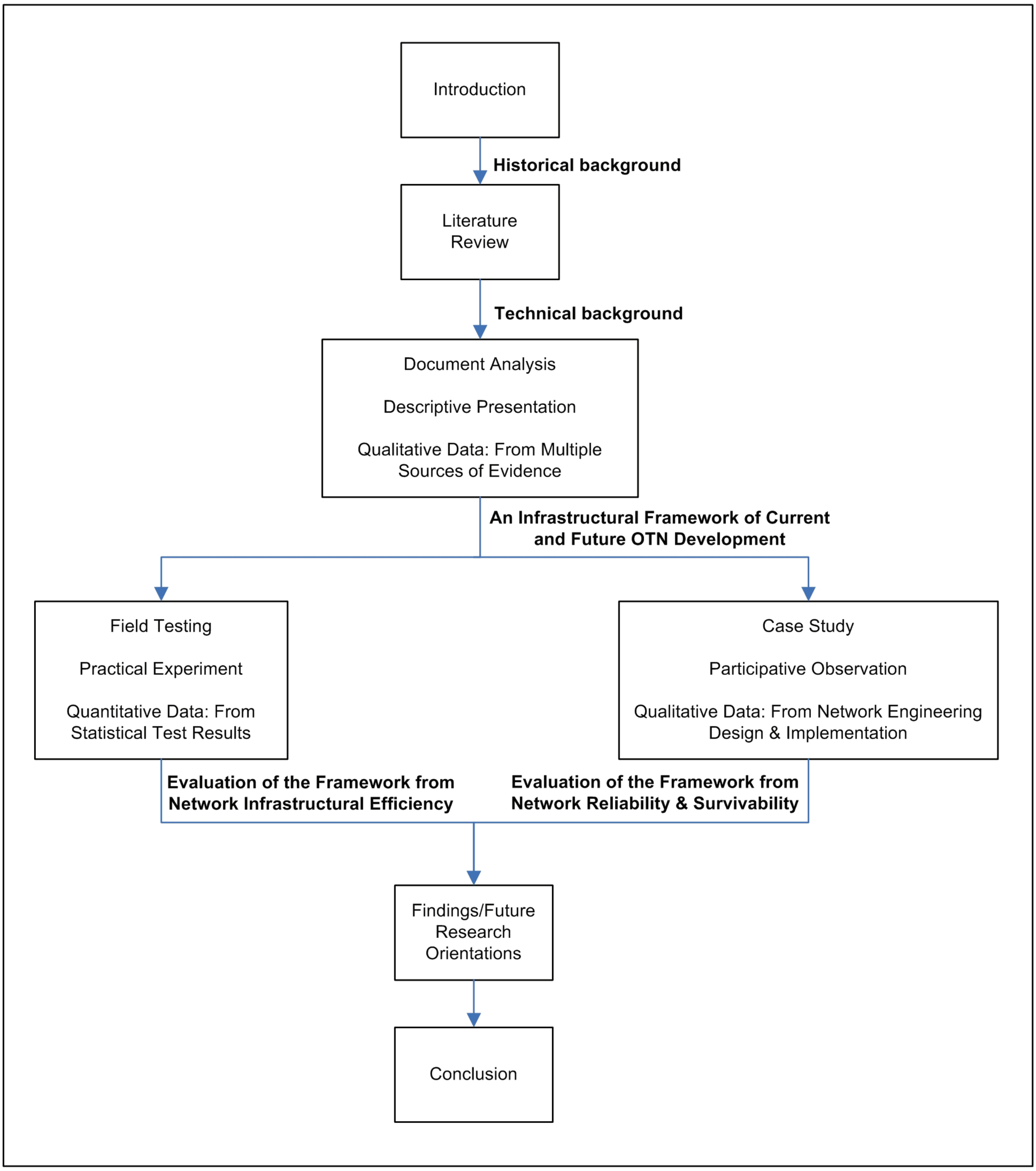

Figure 3.1: Overall Research Design

3.2 Purpose of the Study

Infrastructure plays a crucial role in the entire expansion of the OTN. In the previous chapter, a number of technologies and standards have been discussed for promoting the progress of constructing and enhancing the OTN infrastructure. The aims and objectives of this study are to:

1. Describe the evolution of OTNs and their growing significance within the current and future networked business environment;
2. Identify the weaknesses of the existing infrastructure of OTNs through a detailed literature review, focusing particularly on related business applications;
3. Develop an infrastructural framework that demonstrates future development orientations of OTN infrastructure to address the identified weaknesses;
4. Conduct a network field test with a systematic analysis on the evolution of OTN network protection technologies, so as to verify the proposed framework from the network reliability and survivability aspect;
5. Conduct a comprehensive case study and present a roadmap of OTN infrastructural development through participative observation, to further validate the framework from the network efficiency perspective;
6. Report on the results of the field test and the case study analysis to demonstrate the validity and practicality of the proposed framework.

3.3 Approach Taken

Based on the overall purpose, a summary of the research approach taken is given in Table 3.1. Firstly, a framework for future development trends of OTN infrastructure will be provided based on a document analysis. For ensuring the reliability and accuracy, this study will select correlative data by analysing the content within published resources such as research journals and conference papers from industry and academic literature databases. These documents will inform the development of the framework. Secondly, with the rapid development of OTN infrastructure, many upper layer data services are completely dependent on substrate wavelength communications. The survivability and reliability issues in the optical domain are now becoming crucial topics. Hence, a detailed study focusing on the evolution of OTN protection technologies, including a field test on network recovery will be implemented as a practical evaluation of the framework from the network reliability and survivability aspects. Thirdly, a comprehensive analysis based on a commercial OTN engineering project of SMEPC will also be used as another effective validation of the framework from a network infrastructural efficiency aspect. Thus, the following steps in defining the research approach are to clarify the type of research strategy, the unit of analysis and the research time horizon.

Table 3.1: Research Approach

Chapter	Research Style	Data Collection	Data Analysis	Outcome
4	Qualitative	Document Analysis	Descriptive/Narrative Presentation	Infrastructural Framework
5	Quantitative	Field Testing	Statistical Summary	Test Results
6	Qualitative	Case Study (Observation)	Network Design and Implementation	Evolutional Roadmap

3.3.1 Overview of Research Strategy

There are three types of main research strategies in general: the experimental or hypothesis-testing research, the exploratory research and the descriptive or diagnostic research (Chaudhary, 1991: 47-52). Firstly, the main objective of the experimental/hypothesis-testing research method focuses on illustrating the existence of causal relationships between variables (Colorado State University, 2005). Secondly, the exploratory research is to find out "what is happening; to seek new insights; to ask questions and to access phenomena in a new light" (Robson, 2002: 59). Thirdly, the descriptive research, which can be considered as a forerunner or an extension of the exploratory research, aims to demonstrate the accurate profiles of an event or situation (Saunders, Lewis and Thornhill, 2003: 98). The research methodologies cited here are expanded in detail in sections 3.4 and 3.5 which cover data collection mechanisms, and the approach to data analysis.

As clarified in section 3.3, the major outcome of this research, which is the infrastructural framework, will be developed based on a variety of previous research, such as industry standards. It aims to give a clear presentation on the existing and current situation to demonstrate the future trends of the development of the OTN infrastructure. The main concept of this research is more likely to portray the legacy and existing infrastructure issues rather than to explore a new future or to test a hypothesis in the OTN industrial field. However, the achievements of this research could be utilised as a crucial resource in exploring the future orientations in OTN infrastructural development. Thus, the research strategy of this thesis can be considered as a descriptive style.

The proposed OTN infrastructural framework is validated by the use of a field test experiment of a large ISP in Beijing (section 3.4.2), and by a case study of a power company located in Shanghai (section 3.4.3). The collection of data from two separate entities in the Chinese market, one being an ISP and the other a power company, provides clear evidence of the robustness and applicability of the framework.

3.3.2 Unit of Analysis

The unit of analysis is significant because it defines the universe and the objects of research taken and the sample size (Misra, 1989: 44-45). Firstly, the unit of analysis in developing the framework will be adopted from multiple aspects, which influence the evolution of the whole OTN infrastructure. A more comprehensive discussion will be given in section 3.4.1. Secondly, the field testing of the OTN network protection will concentrate at various technical parameters, such as protection types, packet loss and restoration time. Thirdly, the unit of analysis of the case study will point at the organisational level due to the inherent characteristics of this case study. In particular, the size of sample is converged at one organisation, namely the Shanghai Municipal Electric Power Company (SMEPC). This enables a detailed analysis of the organisation’s business applications in terms of OTN infrastructure and its future development.

3.3.3 Time Horizon

When determining the research time horizon, some methods are longitudinal where as others are cross-sectional (Cavana *et al*, 2000: 122). The longitudinal study stands for a repetitive collection of same specific data and usually consuming more time, while the cross-sectional study involves a snapshot of data gathering in a specific research process. Thus, it is obvious that the field test would be a typical cross-sectional research, as the experiment data will be gathered within a very short (milliseconds to seconds level) network recovery process. Conversely, as the case study focuses on a large ongoing OTN engineering project, the data collection could be accomplished during a longitudinal approach, usually along with the project schedule. However, this research will only provide an in-depth analysis centring on the first stage of this project, which was the OTN infrastructure construction completed by June 2004.

3.4 Data Gathering Process

During the data gathering process, quantitative and qualitative methodologies are used as two common techniques. The quantitative technique utilises statistical research methods for measuring the quantity of the phenomenon. The qualitative technique, on the other hand, provides a detailed analysis for in-depth understanding on a specific qualitative phenomenon (Locke *et al*, 2004: 147-150). As given in Table 3.1, this research will use a hybrid style in gathering various data from different objectives. In particular, the document analysis and the case study will focus on qualitative data whereas the field testing will collect quantitative data.

3.4.1 Framework Development

In developing the framework, this research will utilise the document analysis method as a qualitative technique. The document analysis involves gathering data by analysing the content of former research achievements (Carney, 1972: 23-26). Those data already gathered from previous research for related or other purpose can be considered as a set of secondary data, which are principally used in descriptive research (Saunders, Lewis and Thornhill, 2007: 248).

Table 3.2: Secondary Data Gathered from a Variety of Online/Offline Literature Sources

Industrial Standards	Vendor Whitepapers	Technical Books/ Journals	Academic Papers/ Presentations
IEEE IETF ITU OIF	Acatel Cisco Systems Fujitsu Networks Lucent Technologies Nortel Networks	Alwayn (2004) Gemelos et al (1999) Goralski (2001) Gumaste & Antony (2003) Halabi (2003) Hay (2000) Tomsu & Schmutzer (2002)	Ahmad (2002) Hong (2002) Lee et al (2003) Liu (2005) Mohan & Murthy (1999) Yue (2003)

In this research, a group of a variety of resources (see Table 3.2), including industry standards, vendor whitepapers technical books/journals as well as academic papers/presentations will be utilised in building this framework. The data gathered here will also include various formats, such as plain text, figures and tables, which are significant in demonstrating a qualitative overview of the evolution of the OTN infrastructure.

3.4.2 Field Testing

The field test is expected to give a performance comparison between different metro OTN protection technologies from the quantitative angle. The nature of this field testing is a network traffic simulation, which is a common technique used in measuring the performance of a network model or algorithm (Flood, 1995: 113-114). Generally, network traffic simulations utilise a simulation language or a software package to generate a simulated telecommunication environment on a computer-based platform. However, there are increasing numbers of researchers focusing on using commercial telecommunication equipment to develop or analyse their specific systems. For instance, Hof *et al* (2003) used a Motorola C-5 Network Processor to implement and verify the actual performance of the RPR technology in a commercial SDH network environment. In addition, Hossam and Čičak (2006) utilised the Cisco

1760 router to design and evaluate their new model in Wireless Mobile-IP registration. Similarly, this research will adopt Cisco 7600 and 12000 series optical service routers as a commercial platform for analysing the practical performance of two MPLS-based metro optical network protection technologies.

Furthermore, as the "field experiments undertaken in natural organisational settings have greater external validity than laboratory-based experiments" (Veal, 2005: 190), this field test aims to give the readers a more reliable result from a real ISP test environment, which is the NGN network fast recovery test bed of China Netcom. The statistical data gathered will include the network packet loss percentage and restoration time from different service level agreements (SLAs) and protection types. By comparing the testing results with previous research achievements, these primary data is crucial in providing an evolutionary landscape on metro OTN protection technologies. In addition, the field testing could also be utilised as a practical evaluation of the framework from the network reliability and survivability in the OTN infrastructural development.

3.4.3 Case Study

According to Leedy and Ormrod (2005: 135), the case study is a common qualitative research design, which intends to give in-depth research on "a particular individual, program or event" within a defined time or period. In addition, the case study method also has a distinctive place in evaluation research, as it can explain, describe and illustrate the causal links between certain topics within a real-life environment (Yin, 1994: 15). Thus, the case study is an ideal solution in evaluating the proposed framework from a practical perspective of OTN business project. In doing so, it is significant to clarify the case study protocol at the initial stage. The case study protocol is a research instrument which also "contains the procedures and general rules that should be followed in using the instrument" (Yin, 1994: 63). Figure 3.2 gives an overall design of the case study protocol of this research.

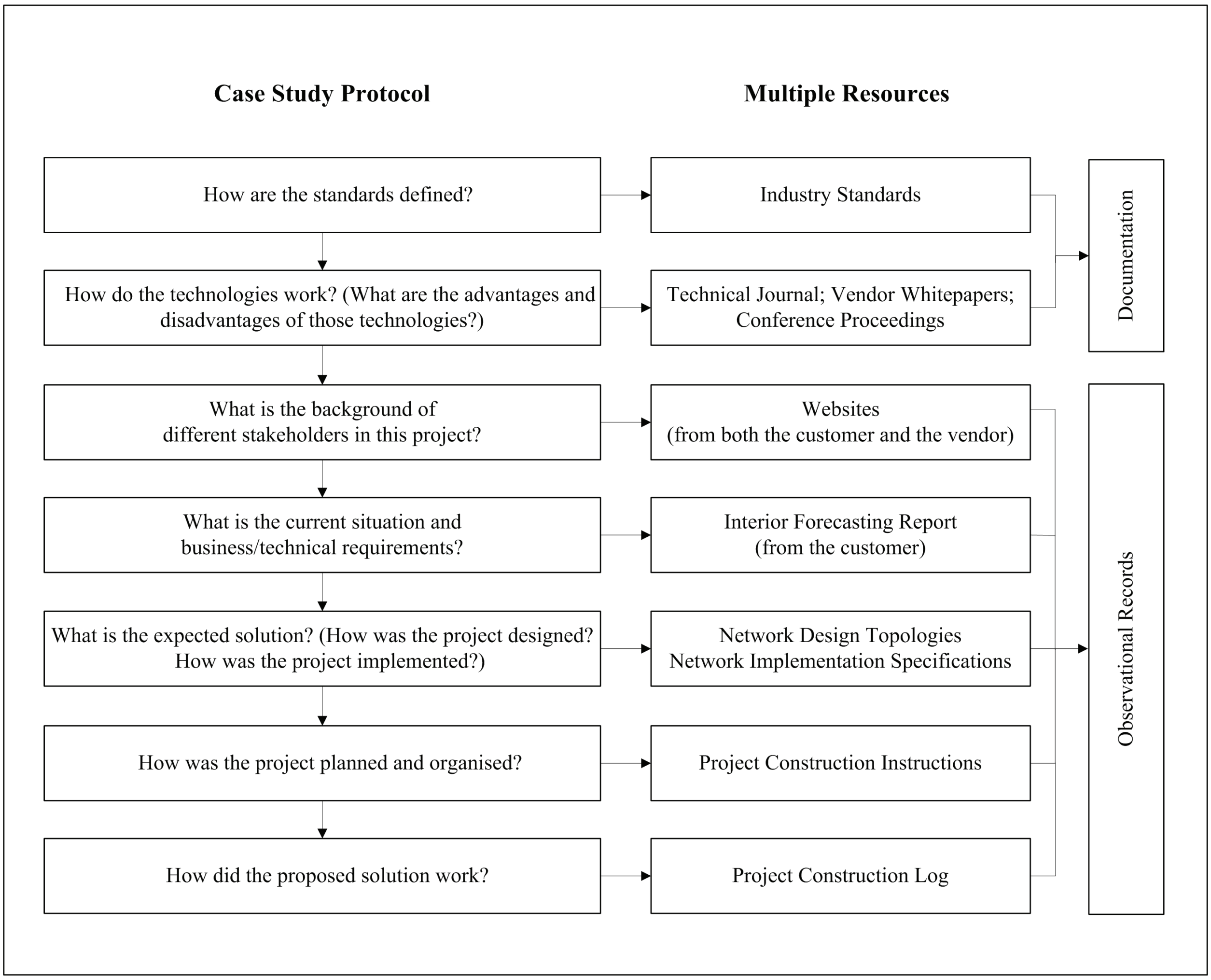

Figure 3.2: The Case Study Protocol

This research will use an observation method to collect another set of primary data from multiple sources, including the related industry documentation and the observational records. The observational methods are a natural and obvious technique in describing, analysing and interpreting a phenomenon (Robson, 1993: 190-191). In particular, if the observer "seeks to become some kind of member of the observed group" (Robson, 1993: 194-195), the research method here can be described as a participant observation. As the researcher has been engaged as an associate engineer in this OTN application case, in terms of system design and implementation, this observation is suitably described as a participative one. In addition, the proposed case study protocol will help the researcher to build up a roadmap demonstrating the evolutional process in the OTN infrastructure of SMEPC. The roadmap, which is the major outcome of the case study, can be utilised as observational evidence in validating the framework in terms of the development of network efficiency from real OTN business applications.

3.5 Data Analysis Techniques

After the data is collected, the next phase is to conduct data analysis. Firstly, in building the framework, the qualitative data gathered will be categorised into several aspects. This research is mainly based on the related industry standards, however, it will also consider various resources from vendors and academia to demonstrate a more accurate landscape of the existing situation of the development in OTN infrastructure.

Secondly, in setting up the field testing environment, this research will utilise the Cisco Internet Operating System (IOS) 12.2(18)SXF (12000 series) and 12.0(31)S2 (7600 series), as the latest ISP level software platform in ensuring the test accuracy from a service provider perspective. In addition, this research will also utilise specialized teletraffic analysis equipment, namely the Sprint **Smartbit** network flow testing system, to give the precise performance evaluation during the network fast recovery period. The logged packet loss in a specific time window is then translated to the network restoration time. In addition, the collected statistical data will also be summarised into a table in comparing the differences between two network protection types with different service priorities.

Thirdly, during the stages of the case study, this research considered the business and technical requirements based on an internal forecasting report of SMEPC. Those demands were converted into a comprehensive solution, including the network topology and construction design, network management platform, network security and protection mechanisms. In producing the solution, it utilised the Microsoft Visio vector drawing system to demonstrate specific network topologies and system structures of different technical topics, in terms of IP-oriented data networking system and the WDM-based OTN infrastructure. By comparing the legacy OTN infrastructure of SMEPC and the proposed solution, which was already implemented during the project, the case study lastly provides an evolutional roadmap presenting the trends for future OTN development of SMEPC. The roadmap considers significant domains for common industrial based OTN applications, such as the development orientations of the backbone bandwidth, system reliability and the network service architecture.

3.6 Conclusion

This chapter restates the purpose and objectives of this research, and clarifies the approach taken as a hybrid design, including both qualitative and quantitative methods. For developing the infrastructural framework, this research utilises a document analysis technique, as for further processing of the qualitative data collected from previous research achievements. Statistical data is also collected through a field test as a practical evaluation of the proposed framework from network reliability. In addition, this research will also use a participant observation technique to develop an evolutional roadmap, which can be considered as another validation of the framework from network efficiency. The methodology offered in this chapter will become a helpful guideline for the following chapters, where the remaining objectives of this thesis will be completed. In particular, the next chapter will develop a framework demonstrating the evolution of the OTN infrastructure, by providing a comprehensive analysis on the development of the OTN data control plane.

Chapter 4: An Overview of the Development of the OTN Data Control Plane

4.1 Introduction

Chapter three has provided a systematic analysis on the research methodology of this study, including the clarification of the approach to be taken, data gathering process and data analysis techniques. The preceding chapter also indicates that the main outcome of this research will be an infrastructural framework. Thus, this chapter presents research on the evolutional process of the OTN data control plane, which has a major impact on the OTN infrastructural development. In particular, this chapter presents a detailed study on three infrastructural models of the OTN, including the current static IP optical overlay control plane, the future dynamic IP optical overlay control plane, and the ultimate integrated IP optical peer control plane. After a comprehensive analysis of the three representative models, a framework is then derived and shown. The framework is developed to demonstrate the future development trends of the OTN infrastructure.

4.2 Background

Basically, the data control plane decides the capability and reliability of the OTN infrastructure, in terms of data service transportation from logical functional layer. Based on the existing IP-oriented multiservice architecture, the first phase for deployment of the Optical Transport Network (OTN) is to set up a static optical layer (physical layer) under the IP layer (Network Layer). As the light paths utilised in the model are assigned manually and statically, this structure is also called *Static IP Optical Overlay Control Plane* (Tomsu and Schmutzer, 2002: 189). Basically, the data traffic here are usually converged at the IP network edge and encapsulated and modulated into optical wavelengths, and simply transferred along the appointed optical route.

With the diffusion of advanced optical transport technologies such as WDM (Wavelength Division Multiplexing)/DWDM (Dense WDM), existing classical optical network topologies such as ring and point-to-point will move forward into a mesh type. In this step, when the upper layer IP traffic converges at the WDM/DWDM junction point, it is capable to be divided and switched by Optical Add/Drop Multiplexers (OADMs) and Optical Cross-Connects (OXCs) dynamically into multiple wavelengths with different types of service, which can be also referred as optical routing or wavelength routing. Most of the network traffic is routed and switched on the physical wavelength plane rather than by upper IP equipments. Hence, this data traffic control method, which is based on *Dynamic IP Optical Overlay Control Plane* (Tomsu and Schmutzer, 2002: 226), enhances the OTN with further efficiency, scalability and survivability.

Given the complex service architecture including the integration of data, voice and video from future network requirements, the service providers and the corporate network operators are seeking a more flexible and dynamic solution on setting up connections, assigning bandwidth upon the OTN system. Therefore, future trends of the OTN control mechanism will centre on the convergence of the dynamic OTN wavelengths (services) distribution and the intelligent IP traffic routing. Based on this principle, the Optical layer is expected to communicate with the IP networks at the same control plane, namely *Integrated IP Optical Peer Control Plane* (Tomsu and Schmutzer, 2002: 244), which offers the network control complete transparency between the two layers.

When comparing the three types of control plane (see Figure 4.1), it is easy to find that the static IP overlay and the dynamic IP overlay optical control plane are similar in several aspects. For instance, the optical layer in both models is opaque to the IP layer, which means the OTN a merely provides basic connection basement for upper layer IP networks. In particular, the lightpath selecting and assigning mechanism in these overlay control structures is not under the control of the IP layer, however, there is no internal relationships between wavelength routing and IP routing. By contrast, the peer model aims on providing a more efficient and flexible control method, to establish an intermediate uniform control platform between the optical layer and the IP layer. In this ideal approach, an optical channel connection and bandwidth allocation are managed by IP routing components.

Please see print copy for Figure 4.1

Figure 4.1: IP/Optical Overlay Model IP/Optical Peer Model

(Tomsu and Schmutzer, 2002: 188)

4.3 Static IP Optical Overlay Control Plane

4.3.1 Evolution of IP-based Service Architecture in the OTN

For more than 20 years of research and development, IP has settled its absolute position in this industry as a uniform internetwork protocol. Current and future corporate intranets and ISP backbones are following the trends to the efficient and cost-effective IP-based integrated multiservice architecture (Teledvance Communications, 2004). In the first place, the whole networking industry, and even the Internet are built on the TCP/IP protocol stack, which is an efficient and compact 4-layer model originated from the classical 7-layer OSI model. Secondly, due to the standardized and connectionless characteristics, IP is capable of being deployed over almost all kinds of network access modes, from traditional X.25, frame relay and popular ATM to the latest 10-Gigabit Ethernet, as well as the wireless network transparently. This attraction feature, which also can be referred as **IP over anything**, is crucial for the present complex and changeful business network environment (Christian, 2004: 15). Most of the current telecom transport infrastructure, however, is based on TDM technology, which is optimised for the synchronous and connection-oriented traffic such as conventional telephony operations. Thus, current technique to transport various connectionless IP services across legacy TDM-based backbone has been proved inefficient and inappropriate.

Since SONET/SDH infrastructure has been introduced into the telecom world, conventional ISPs used to provision WAN connectivity by deploying their TDM-based SONET/SDH optical networks all around the country, especially in the US and European markets (Halabi, 2003: 14-16). Those SONET/SDH networks have consisted of diverse equipment such as add/drop multiplexer (ADMs) and digital cross-connects (DXCs) that usually form into an optical ring topology.

Please see print copy for Figure 4.2

Figure 4.2: TDM-based (deployed with ADM) and WDM-based (deployed with OADM) Data Transport Infrastructures (Cisco Systems, 2000a: 8-9)

Nevertheless, according to the increasing demands of connectionless operations such as IP-oriented services, the data transport network infrastructure will choose WDM/DWDM technology to replace TDM optical foundations (see Figure 4.2). In using this approach, network designers and operators utilise advanced optical components such as OADMs and OXCs (instead of ADMs sand DXCs) to build up a wavelength layer connection based on legacy dark fibre groundwork. Unlike the TDM pattern, a WDM-based infrastructure offers pure applicability with IP services, which exactly matches the requirements of future network service architecture. In addition, due to the endless bandwidth from the theoretical angle, multiple wavelength transmission technologies lead the ideal full-mesh topology network connection, both logically and physically possible within a reasonable cost.

Based on a TDM-oriented design model, traditional SONET/SDH network provides plenty of efficiency and redundancy for general telecom services such as voice traffic. However, this SONET/SDH structure shows itself an obvious gap on QoS and bandwidth management mechanism, which is a significant disadvantage within current popular network environment full of IP data services. Although the ATM system is able to provide a powerful traffic queue mechanism, it faces the problems of the lower payload during the cell switching, and the bottleneck on development of interface bandwidth. In this case, network architects first suggested combining SONET/SDH and ATM together, to achieve both goals including high transport efficiency as well as adequate bandwidth control in IP-oriented WDM network, namely **IP over ATM over SONET/SDH over WDM** (see Figure 4.3). In the meanwhile, they also realised that this composite model would lead to considerable wastage of spare network resources between the layers, and increase the management and maintenance tasks. With the latest transport technologies such as Packet over SONET/SDH (POS) and Gigabit Ethernet (GE), and advanced layer 3 control mechanisms such as IP QoS and VPN developed, next generation OTN will eliminate ATM and SONET/SDH equipment and concentrate on building a simple and efficient two-layer **IP over WDM** architecture.

Please see print copy for Figure 4.3

Figure 4.3: A Complex "IP over ATM over SONET/SDH over WDM" Architecture (Cisco Systems, 2001b)

4.3.2 The Two Layer "IP over WDM" Architecture

Because the IP is a layer 3 standard whereas the optical signal is running at the layer 1, there is a need to encapsulate IP packets into defined layer 2 frames of common optical interface for transporting IP traffic onto a wavelength (Gumaste and Antony 2003: 238).

Please see print copy for Figure 4.4

Figure 4.4: Protocol Stacks for Achieving "IP over WDM" (Lucent Technologies, 1999: 8)

This approach requires each known specific encapsulation format to match their correlative optical interface standard respectively (Lucent Technologies, 1999: 8). Based on this principle, it is able to integrate those encapsulation combination mechanisms in future IP and Optical transport equipments (see Figure 4.4), which empowers network planners and engineers to build up a simplified two-layer **IP over WDM** architecture.

Based on this principle, IETF released a framework for "IP over Optical Network" architecture, namely the RFC3717. This draft has a comprehensive description of the technical details such as connection models, routing approaches and signaling-related issues on the system interconnection between IP-based data networks and WDM-based optical networks. It defined a detailed scheme of the IP-based optical data control plane, including the addressing system, neighbour and topology discovery, as well as the protection and restoration models. It also provided a specific discussion on the convergence of WDM and TDM networks under the IP control plane. Other practical engineering issues are also detailed such as the set up of light paths and the conversion of wavelengths. This draft can be considered as an initial milestone in the infrastructural development of the IP-based optical networking field. Therefore, the proposed framework will be developed according to this documentation for ensuring the orientation of future trends in OTN infrastructural development.

Figure 4.5 demonstrates a typical next generation two-layer OTN system. In this phase, IP routers at the edge of service layer take charge of merging over layer data traffics from various access types such as ADSL, cable or leased line services and multiplexing those traffics onto optical transport layer. The optical layer simply provides raw bandwidth under the vision of IP layer, and the legacy network environments such as ATM and SONET/SDH nodes can be seamlessly migrated onto the optical basement (Lucent Technologies, 2004). Due to the lower layer optical connections are unknowable for the upper layer IP routers, it is flexible in setting up different topologies as different engineering requirements. The ring topology is preferred by metro scale service provisioning whereas the point-to-point topology is usually utilised to implement long-haul carrier transportation. The latest POS and GE, or even 10GBE interface can be utilised to distribute optical link up to OC-192 (10 Gbps) speed. With the release of the first mature single 40-Gbps Application-Specific Integrated Circuit (ASIC) which is a core processor in router optical interfaces (Cisco Systems, 2004a), it is easy to upgrade the infrastructure bandwidth onto terabits level by implementing DWDM system. For example, a typical implementation method is to transport 40 channels of OC-768 (40 Gbps) wavelengths, which means finally a 1.6Tb throughput per fibre.

Please see print copy for Figure 4.5

Figure 4.5: Next Generation "IP over WDM" Service Backbone Network (Milinkovich, 2000)

As the existing SONET/SDH infrastructure are commonly designed on metropolitain optical ring topology, the first step to deploy DWDM is to simply replace those SONET/SDH equipments with OADMs and form into ring structure (Alwayn, 2004: 183). With the implementation of DWDM technologies, organisations and ISPs can easily upgrade the utilisation ratio of single fibre and transport various types of service across legacy dark fibre resources by provisioning multiwavelength trunk connection. Although the physical connection is mainly based on ring topology, it is capable to carry multifarious logical connection types such as point-to-point, ring, hub+spoke, or meshed topologies as above mentioned (see Figure 4.6). On the one hand, the reason for this is because all the light paths transported are assigned manually via fibre patch-panels within the optical control domain. This offers great flexibility and compatibility for upper previous service architecture such as ATM and SONET/SDH connections to move onto the new optical transport platform while keeps their existing structure. On the other hand, this new optical infrastructure not only broadens the physical layer bandwidth, but also provides strong logical reliability such as RPR 50ms restoration mechanism. In summary, the simple and efficient two-layer architecture demonstrates that the Static IP Optical Overlay model enhances the raw optical connectivity, and first uniforms Optical and IP control platform together which significantly decreases the operation costs and management tasks.

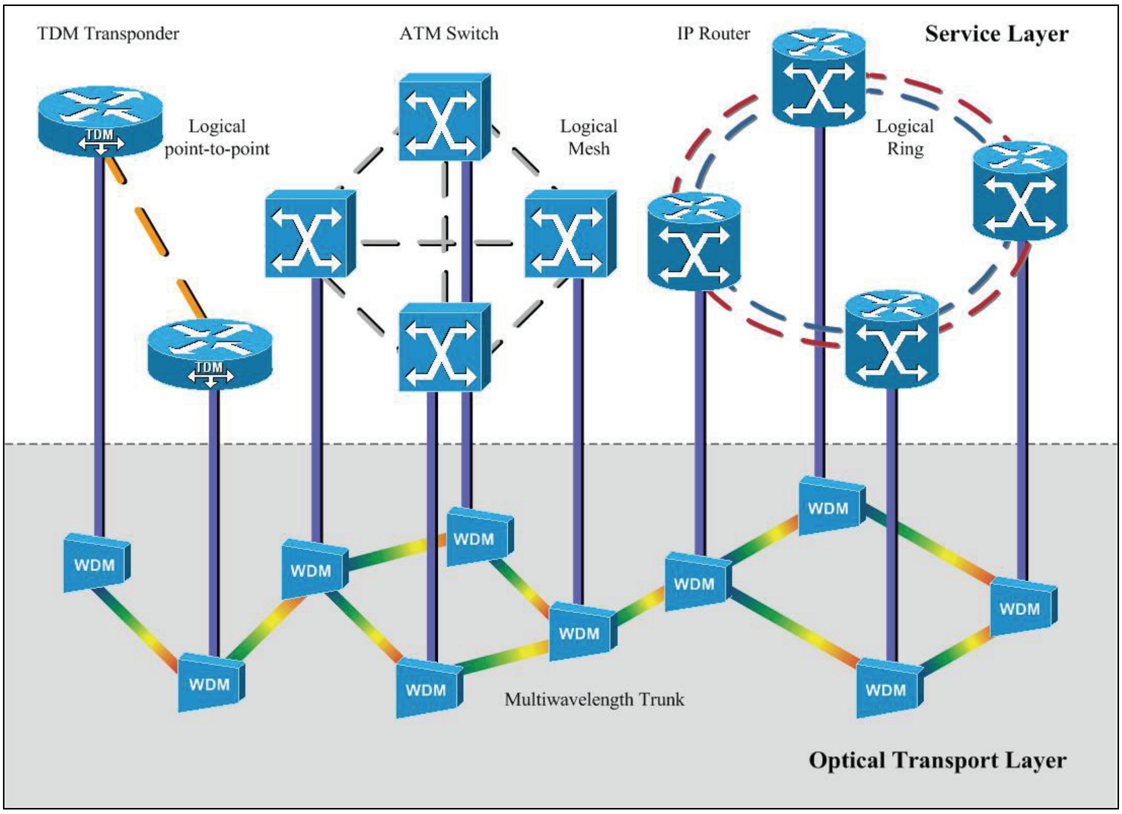

Figure 4.6: A Scalable and Flexible Optical Service Deployment of Static Overlay Model

4.4 Dynamic IP Optical Overlay Control Plane

4.4.1 The Basic Principle of Wavelength Routing

With the increasing and changeful demands of business operations, the static assigned optical domain faces the problem of a considerable amount of manual tasks such as adding new wavelength channels with new services or reconfiguring the light paths when the network fails. Thus, a dynamic wavelength routing approach combined with the classical IP routing concept (see Figure 4.7) is required for fulfilling the future requirements of intelligent optical internetworking. The wavelength channel selection, connection and drop mechanisms are generally accomplished by the OXC and the *wavelength routing controller*, or the combination of both modules, namely the *wavelength router* (WR). Currently, most of the existing commercial OXCs are designed based on electrical cross fabric, which means the wavelength signals are terminated at the incoming interface, switched within the electrical domain and then converted back to accurate outgoing wavelengths. Due to the mature technics in the electrical manufacture field, this design provides a cost-effective solution involving full wavelength conversion and *3R regeneration* (reshaping, retiming and reamplification). However, the rapid growth of market demand, is pushing the industry to develop all-optical processing components, which aims to perform at an extremely high capacity (up to 100 Gbps), nonblocking and transparent wavelength routing and switching tasks inside pure optical domain (Nolting, 2003: 1).

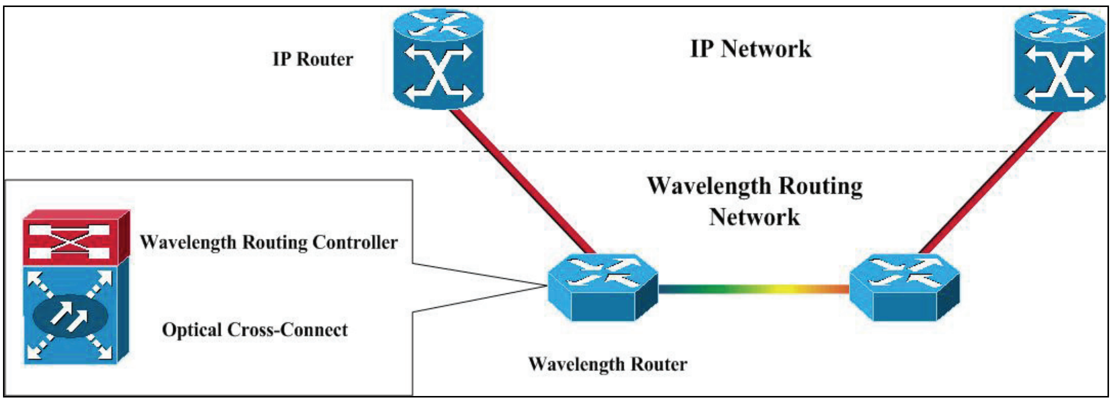

Figure 4.7: IP Optical Dynamic Overlay Model

As opposed to the static overlay OTN model, a wavelength routing network prefers the meshed interconnection type rather than ring or point-to-point topology. An ideal operating environment is that all the OTN nodes are connected within one hop, which enables the WR to achieve an independent wavelength routing process without the participation of IP routers. Generally, classical IP routing protocols such as Open Shortest Path First (OSPF, RFC1131) and Intermediate System to Intermediate System (IS-IS, RFC1142) are applied to generate a wavelength routing protocol that assists the WRs to dynamically connect IP routers or other upper layer service equipments (Cisco Systems, 2000b). The WRs take charge of maintaining a cross-connect table consisting of information about the input fibre port and output fibre port, and input channel and output channel with DWDM modules, which is similar to the functions of the IP routing table inside IP routers (see Figure 4.8). Furthermore, each of the active optical interfaces must have a valid IP address with appropriate subnet information for the WRs to communicate with optical layer neighbors and upon layer IP devices. As described in RFC3717, the IP routers and wavelength routers interact as in the client/server architecture and this also can be referred as the overlay model (IETF, 2004a).

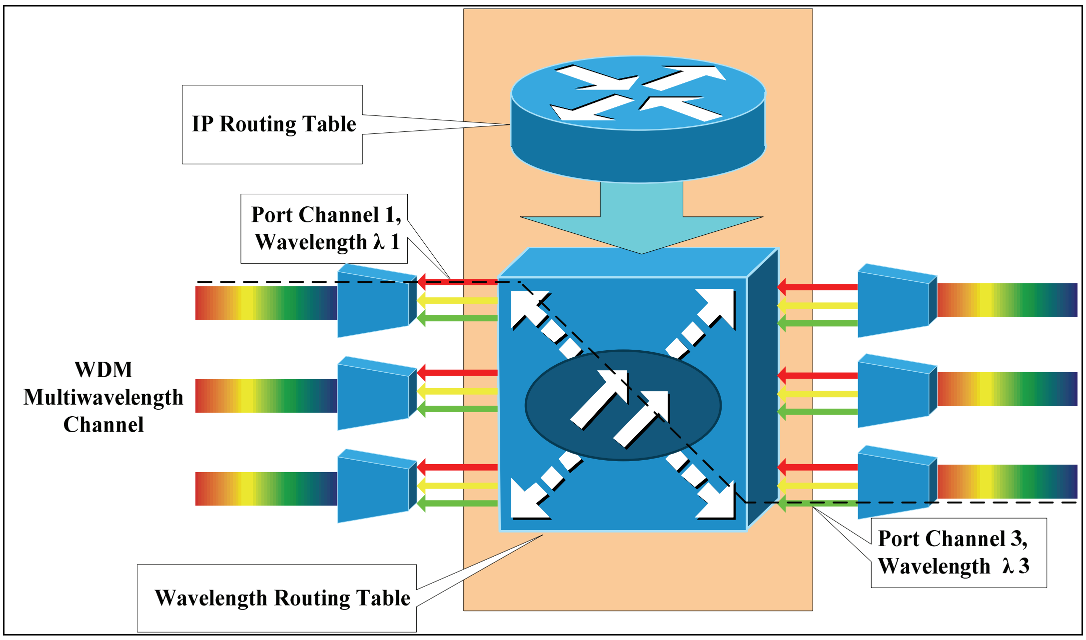

Figure 4.8: Basic Operations of Wavelength Routing Mechanisms

From the description of ITU G.872, when an optical channel trail (OCH trail) consists of an original wavelength throughout the whole connection, it is called a *wavelength path* (WLP). In most cases, however, the data traffic is transported across a unidirectional *virtual wavelength path (lightpath)*, which contains different converted wavelengths from all the individual network segments. In managing the provision of those service lightpaths, there are two common methods. The first method relies on a centralized management server that maintains a database, including all the wavelength routing elements such as topology, network devices and other resources. Although this gives a clear view of the connection status and bandwidth allocation, it has a lack of management scalability and reliability. Thus, the second method aims on providing a distributed wavelength routing mechanism for those large scale OTN projects. Similarly to the distance vector IP routing approach, each WR keeps a local wavelength routing table and exchanges the database with their neighbours, which allows all the routers to see the entire topology and to calculate a best lighthpath independently and locally. In addition, with the high flexibility of wavelength allocation, the dynamic wavelength routing model is capable of providing bandwidth control mechanisms such as traffic classification and congestion management by assigning different Service Level Agreements (SLAs) into specific wavelengths. For instance, it is not difficult to find that traditional TDM-based layer 2 virtual private services such as VPI/VCI parameters from ATM systems, are very similar to the functionalities of wavelength (VPI) and wavelength channel (VCI), which makes the extension of Optical Virtual Private Networks (OVPNs) possible (NEC, 2002).

4.4.2 The Development of Data Transport Protection in the OTN

Since the upper layer services are completely relying on the substrate physical connection, the optical layer protection technique is another crucial topic in optimising the future OTN. When considering a dynamic wavelength routing OTN environment, as mentioned in the above section, the network topology will move from ring to part-meshed or full-meshed types, and the network coverage range will extend from local area to metro core to even long-haul transportation. In addition, with the large scale deployment of DWDM transmission links, there is a hundred times more data traffic than before, as well as the increasing connectivity and service guarantees.

Under these complex circumstances, the system is expected to utilise the “resilience” layer 3 restoration mechanisms such as fast wavelength routing convergence, rather than the simple and direct under layer optical protection methods. For an intra-domain routing system, some well-known IGP routing protocols such as OSPF and IS-IS can “help in route discovery and collecting reachability information” (Durresi *et al*, 2001: 2146). In the meanwhile, the classical “1+1” and “1:1” protection concepts can also be utilised in building the lightpath protection inside local network neighbours, depending on the different network protection requirements. By contrast, in an inter-domain routing system, an Optical Border Gateway Protocol (OBGP), which originates from the classical BGP, is preferred to set up adjacency relationships between border WRs (Hong, 2002). In case of an inter-domain network failure, a border WR will notify the inbound WR to update the routing tables and to reroute the data traffic at the edge of the local area, possibly by multi-hop routing convergence across a third party OTN autonomous system. In doing so, the protection tasks are scaled into multiple wavelength routing network areas, which further ensures the normal OTN operations.

4.5 Integrated IP Optical Peer Control Plane

4.5.1 The Integrated IP/MPLS Peer Control Model

Both the static and the dynamic overlay control models have a common point that the network components from the IP layer cannot communicate with that from the OTN layer directly, in terms of the *routing and wavelength assignment* (RWA) tasks under the two layer “IP over Optical” architecture (Ahmad, 2002: 155-157). However, the end phase of the OTN development process is to achieve the ideal integrated peer model, which means the IP network and the OTN share and exchange control information at an identical plane. The concept of "peer model" can trace backward to the popular age of the TDM-based ATM system. As ATM first provides the powerful cell switching capacity with an outstanding QoS mechanism, it has been deployed in backbone networks a base transport technology. In the meanwhile, with the rising demands of various IP data services, large companies and ISPs have to move their IP networks onto the ATM infrastructure. In connecting the two different networks, IP packets are routed and terminated at the intermediate network edges, and then encapsulated into cell formats for entering into the ATM switching domain. It is important to note that the lower layer ATM switching is opaque for the upper layer IP routing, which means the IP routers have a lack of understanding about the particular ATM path assignment information such as the detailed PVC and SVC structures (Alwayn, 2002). Thus, an advanced transport control technology named Multiprotocol Label Switching (MPLS) is produced for fulfilling the gap and to enable a complete transparent communication between IP and ATM as peer neighbours (IETF, 2001). According to this optimisation principle, it is reasonable to extend the MPLS control plane to the optical domain, and to integrate the IP network with OTN based on a concentrated single layer IP/OTN architecture.

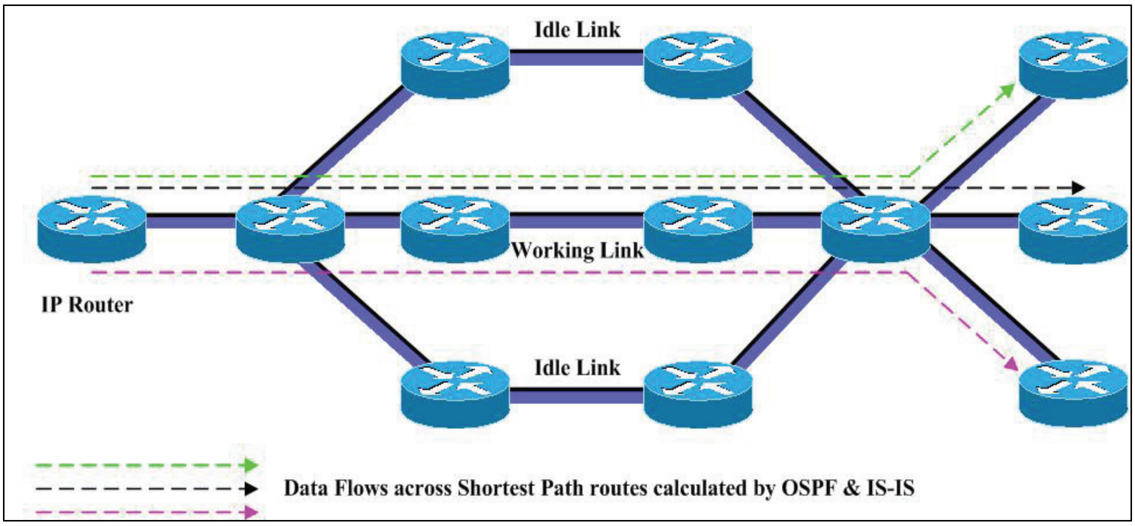

Figure 4.9: Standard IP Routing Causes Wastage of Network Link Resources

The MPLS is a typical QoS technology that functions between the network layer and the data-link layer, ordinarily in an IP-based core network. Generally, MPLS utilises conventional link state IGP such as OSPF or IS-IS, to generate an optimised IP routing table at the edge of the core network. Besides, it operates a simple and efficient label switching mechanism instead of complex routing-based data forwarding, inside the entire core network (Stavdas, 2001: 66-67).

Under this approach, routers running MPLS are called label-switched routers (LSRs), which set up several label-switched paths (LSP) around the interior backbone network (RFC3031). The packet label is a substitute for the IP-header for implementing traffic trunk oriented switching. As a rule, classical IP-based routing algorithms only select a lowest metric path as a best route (see Figure 4.9). Thus, it usually wastes other available link resources and bandwidth. Interestingly, MPLS not only performs traffic loading balance, but also intelligently prevents a link from becoming congested (see Figure 4.10) whereas some other routes are idle (Laude, 2002: 392-393).

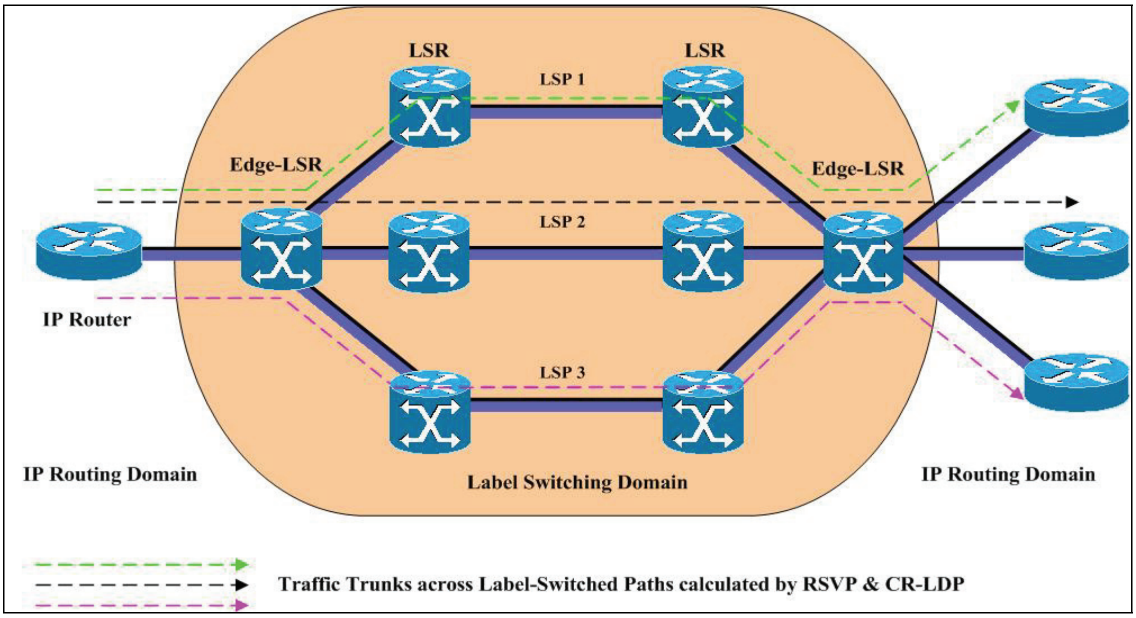

Figure 4.10: MPLS Optimises Network Utilisation with Specific QoS Guaranteed

4.5.2 Advanced Topics in QoS and Network Efficiency of the OTN

The notion of Quality of Service (QoS) is to differentiate and guarantee specific network services by granting network resource and usage control, including "a set of techniques necessary to manage network bandwidth, delay, jitter, and packet loss

(Tamrat et *al*, 2001)". Basically, in operating QoS mechanisms, the first task is to find a path across the network to provide the offered service, which is usually completed by Shortest Path First (SPF) algorithm-based IGP routing protocols such as OSPF and IS-IS. The second step is to ensure and enhance that service with appropriate quality as previously negotiated. In doing so, there are two optimisation engineering methods; one is *network engineering (NE)* which focuses on handling the network to suit the traffic, whereas another one is *traffic engineering (TE)* which emphasises the manipulation of traffic to suit the network (Osborne and Simha, 2003: 6-7). As an early choice, the NE makes an evaluation about how the traffic condition will be, and then orders the required equipments and establishes the adequate network connections through a long time scale. At the mercy of the ever-accelerated updating of the whole internetworking industry, however, the traffic growth rate exceeds all forecasting, which means it is arduous to upgrade the network as changes in time.

As discussed above, MPLS introduces an innovative bandwidth control mechanism in IP-oriented data network. However, existing telecommunication core infrastructures involve a very complex network environment, including IP routers, routers with TDM (ATM/FR) interfaces, OADMs and OXCs. Under this circumstance, how to optimally utilise the existing network structures and resources to achieve connection-oriented TE is becoming the limelight of the advanced network QoS topics.

Previously, the network operators are used to put different metrics on specific IP network interfaces or ATM VCs as the basic traffic engineering implementations. Currently, the idea of combing MPLS with TE (MPLS-TE, RFC2702) improves every aspect of TE functionalities including optimising network utilisation, handling unexpected congestion as well as link and node failure. For setting up the LSPs in MPLS-TE network at first, Label Distribution Protocols (LDPs) such as the Resource Reservation Protocol (RSVP, RFC2205) and Constraint-Routing Label Distribution Protocol (CR-LDP) are applied to seek and establish end-to-end guaranteed bandwidth tunnels for various high performance services. Those services involve real-time multimedia applications such as audio/video conferencing, online multicasting as well as unicast traffic from the Network File System (NFS) and VPN and so on. For ensuring guaranteed network services, it is significant to introduce two QoS architectures: the Integrated Service (Interserv) architecture and the Differentiated Service (Diffserv) architecture.

The Interserv model pays more attention to detailed end-to-end, host-to-host bandwidth reserve control, such as RSVP signaling mechanism, for specific application data flows individually (Srinivas, 2001: 21). The Diffserv model, on the other hand, converges and classifies all the data traffic at the network edge, and then only administers ultra high performance data switching inside the core area without any per-flow state reservation. Therefore, Diffserv is more scalable for large-scale implementations, especially for strategy level QoS planning (Flannagan *et al*, 2003:16).

According to RFC2475, the Differserv architecture takes charge in traffic conditioning such as data flow marking, policing, shaping mechanisms, and the execution of per-hop behaviours (PHBs) such as traffic queuing, scheduling and dropping approaches (IETF, 1998). In a MPLS-TE core network environment, every hop holds and shares the information with their neighbours about a set of policy labels, which differentiate all data packets with particular QoS behaviors.

After receiving the packets from upstream nodes, local LSRs pop out the labels and implement various queuing and dropping activities as defined in the PHBs, by utilising integrated specialized software. Besides this, the LSRs also push their own policy settings (PHBs) into the label stacks and send them with the packets to the downstream neighbours (see Figure 4.11). Hence, a comprehensive TE approach ensures a global QoS strategy with sufficient efficiency, and fairness is achieved.

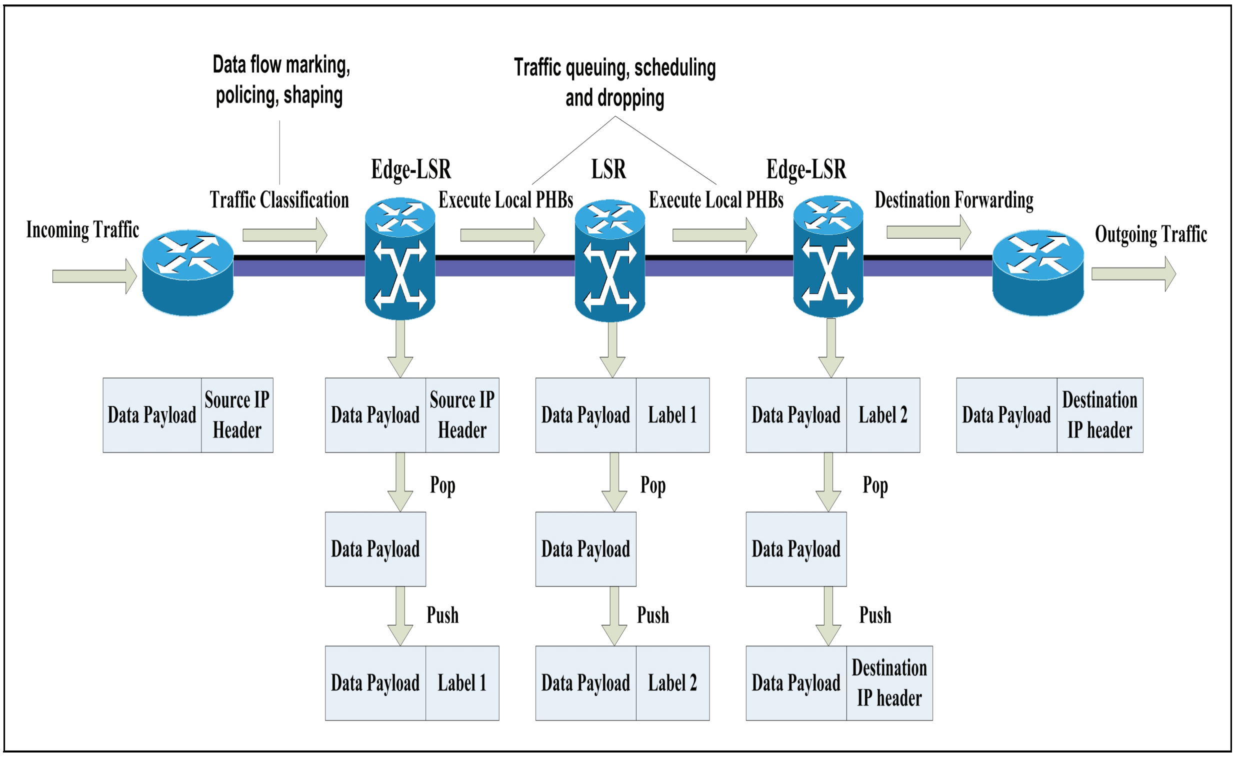

Figure 4.11: Internal Processes of MPLS with Traffic Engineering (MPLS-TE)

According to this traffic optimisation principle, it is reasonable to extend the MPLS-TE into the optical domain. Thus, there was an innovative concept named Mutiprotocol Lambda Switching (MPLmS) extending label switching functionality from electrical to the wavelength control plane. MPLmS was proposed to assign a wavelength to the optical channel in the WDM-based core network, similarly as MPLS assigns a label to a LSP in the circuit-based IP backbone.

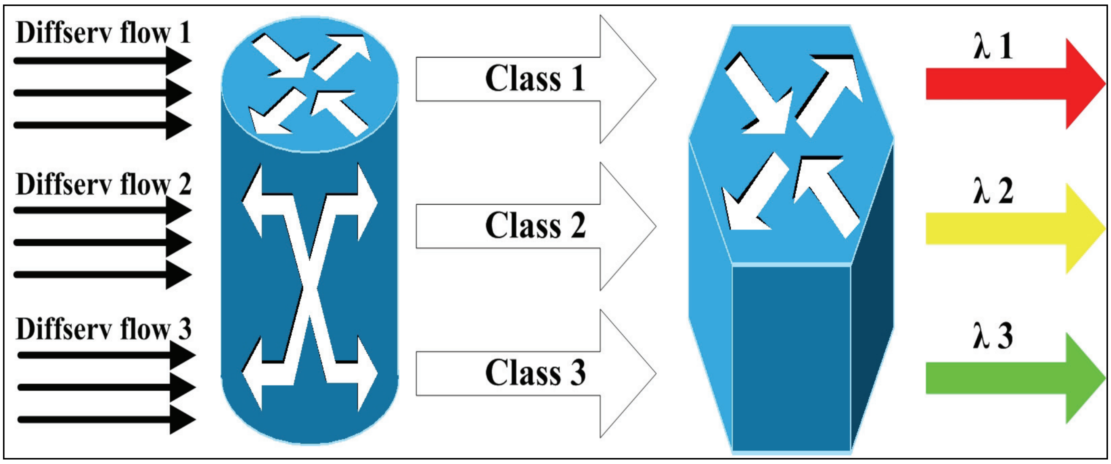

Figure 4.12: TE Implementation from the IP to the Optical Domain

This approach not only enhanced network resource control and management in the OTN, but also expanded the TE implementation from the IP to the optical domain. For instance, a practical deployment method is to label different clusters of Diffserv flows with different wavelengths at the edge between the IP network and OTN (see Figure 4.12). Thus, the internal TE characteristics can be seamless inherited.

4.5.3 The Integration of IP/MPLS and the OTN

According to a worldwide core router market forecast, the IP/MPLS router will keep an average 17.6 percent increasing rate in the next 5 years since 2003 (Bieberich, 2004). As MPLS was so successful on QoS administration in terms of TE implementation, the IETF has subsequently generated the Generalized Multiprotocol label Switching (GMPLS) as an actualization of the concept MPLmS. GMPLS is indeed an extension of MPLS from the IP to the optical world, and it first enables the control and management of the Packet Switch Capable (PSC) layer, Time Division Multiplexing Switch Capable (TDM) layer, Lambda Switch Capable (LSC) layer as well as Fibre Switch Capable (FSC) layer within a common environment (IETF, 2004b).

The basic operation principle of GMPLS is very similar as that of MPLS, however, there are still some distinctions on the way of provisioning the LSPs between them. For supporting the future demands of the OTN, GMPLS introduces an innovative label assignment architecture. As Figure 4.13 shows, the PSC layer labels are exchanged within all IP routers that stand at the outmost edge of the whole GMPLS domain; the TDM layer labels are exchanged between SONET/SDH and ATM equipment in the middle area; and the LSC/FSC layer labels are only exchanged between interfaces of OADMs and OXCs in the core. In brief, the GMPLS LSP architecture is in a position to convert and allocate different types of services from external IP networks into different time slots in TDM infrastructure into different wavelengths/fibres at the core optical plane. As a consequence, this generalized label provisioning method provides a scalable TE solution with excellent management configuration of diversified network resources including time slots, wavelengths and fibres.

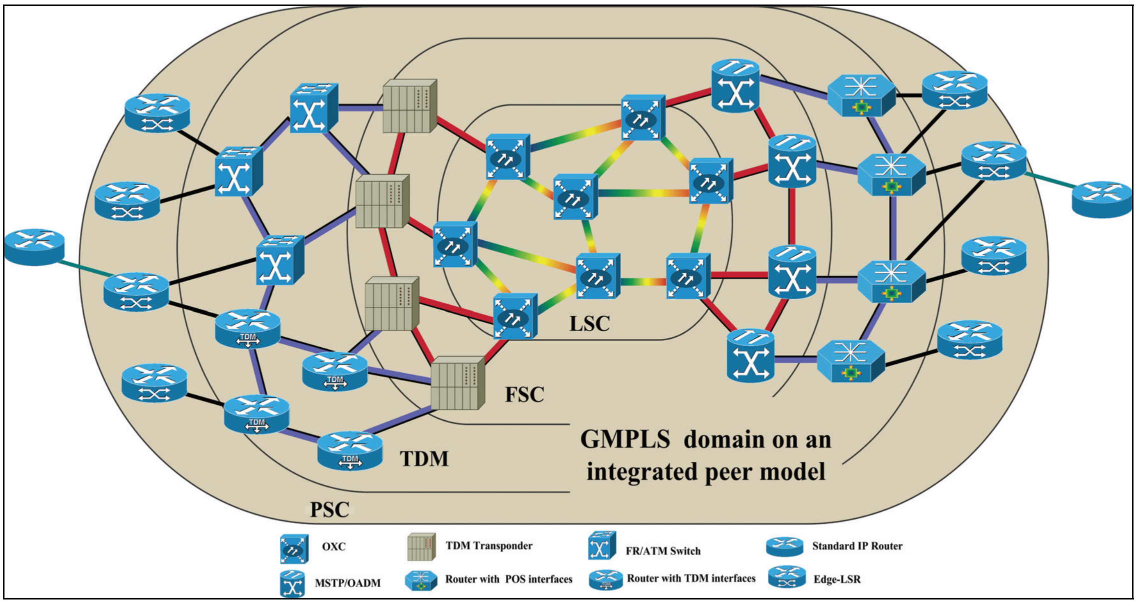

Figure 4.13: GMPLS Domain on an Integrated Peer Model

In satisfying OTN-oriented considerations such as bi-directional communication of fibre links, GMPLS also indicates a bi-directional label distribution structure. Previously, the path selection in bi-directional OTN links is calculated separately, which increases the complexity and potential maintenance problems. Thus, there is an increasing demand of developing the optical LSP assignment mechanism, especially for those optical ISPs and optical intranet operators. In doing so, GMPLS utilises a uniform signaling message structure for establishing bi-directional optical LSPs on both downstream and upstream, which reduces the setup latency and control overhead. This important feature, in addition, ensures both directional LSPs with symmetric TE requirements "including fate sharing, protection and restoration, LSRs, and resource requirements" (IETF, 2003).

Furthermore, as GMPLS is technically designed for OTN-based TE, it empowers the system to stretch QoS capacity to the basement of optical domain, such as the further security feature--Optical Virtual Private Networks (OVPN) solutions. Last but not least, GMPLS supports all convergence forms of IP and optical: both the overlay model and the integrated peer model, which is flexible and scalable for deploying on different OTN environments.

4.6A Framework for OTN Infrastructure Development Trends

Based on the resources and evidences offered, a framework for the OTN infrastructure development orientation is finally achieved (see Figure 4.14). In describing this framework, the first phase is related to the conventional optical network, which only offers basic optical connectivity such as FDDI and legacy SONET/SDH architecture. This model of an optical network is typically layered in three levels that lead to the lowest cost performance.

Secondly, the existing OTN implementation represents the static IP optical overlay control mode, which offers tremendous raw bandwidth in a simplified **IP over Optical** architecture. This logical two layer architecture enhances the efficiency and flexibility in terms of multiple data service integration and the infrastructural migration from traditional TDM to the next generation WDM.

Thirdly, the dynamic IP optical overlay control principle aims on providing intelligent and strong RWA solutions for further ensuring optical infrastructure with sufficient elasticity and reliability. The model is also a logical two layer structure and is expected to largely apply in the near future. Fourthly, an OTN implementation named integrated IP optical peer model is given to facilitate the convergence of IP and optical onto a uniform plane with the elimination of other intermediate transport standards and equipment. By deploying advanced data transport/control technologies such as the IP/GMPLS architecture, this single layer model will be an ideal solution for achieving the final stage of the all-optical network environment.

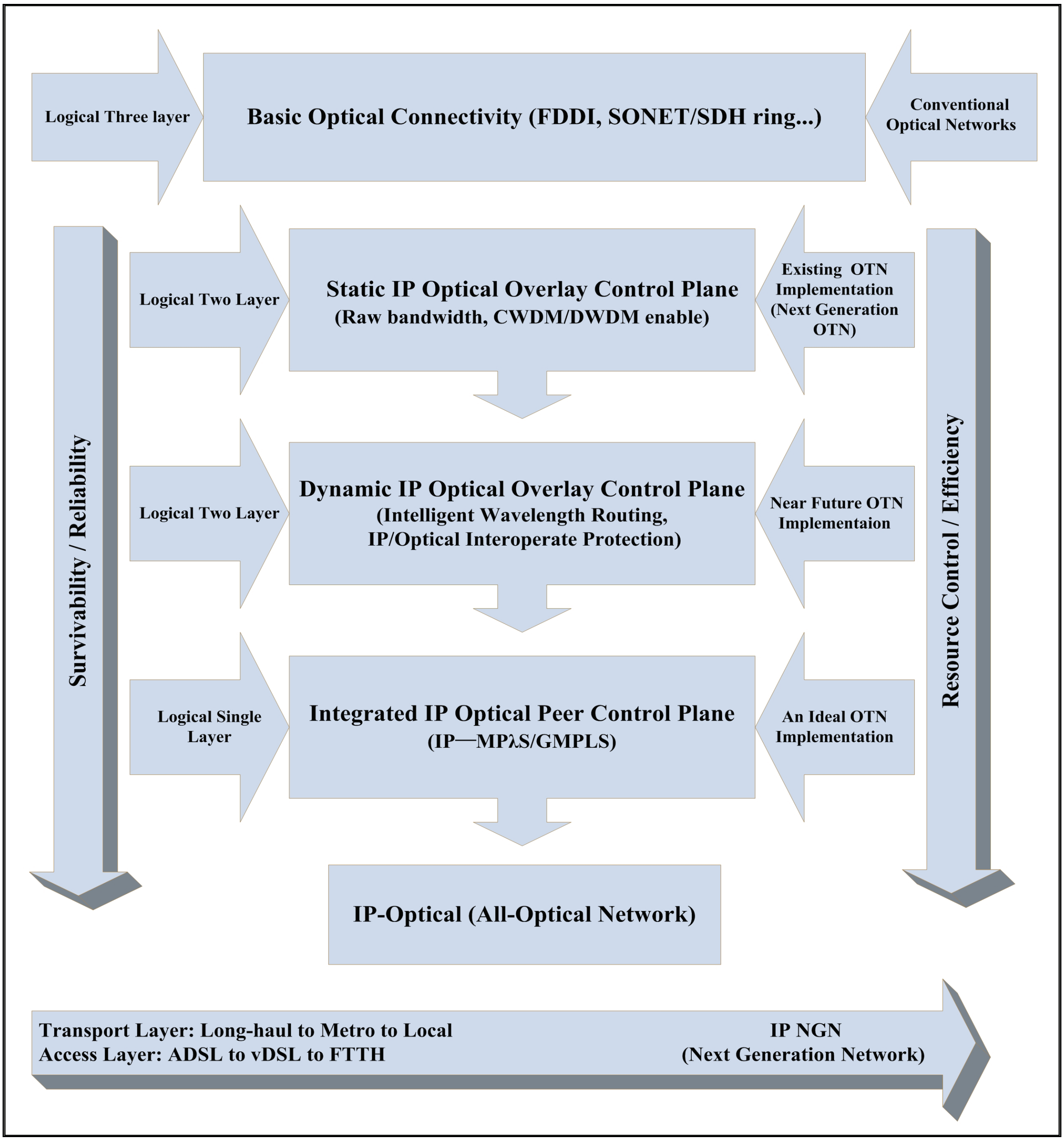

Figure 4.14: A Framework for the OTN Infrastructure Development Orientation

In the meanwhile, the framework also indicates that the infrastructural survivability and reliability with resource control and efficiency will be two key branches throughout the development landscape of the OTN. Firstly, as various upper layer network services are migrating onto the standard OTN infrastructure, the system resilience is becoming more a critical issue. Traditional optical network protection technologies are mostly relying on the TDM restoration and the IP routing recovery. However, there is little internal connection between these two protection mechanisms.

By introducing the **IP over WDM** control plane, the development of future OTN survivability will emphasise on the interoperate protection of the IP and Optical layers. Secondly, current OTN infrastructure carries a complex combination of different network services, including legacy TDM operations, audio, video and IP-oriented data traffic. Thus, how to optimise the network service architecture and consequently improve the network efficiency is another crucial topic. Given the IP/GMPLS peer control model will assist the network designers and implementers to achive the integrated **IP+Optical** OTN infrastructure with unprecedented network efficiency and system cost-performance.

In addition, it is reasonable to believe that the OTN system will be commercially expanded from the long-haul to metro to local area in the transport layer of large enterprises and ISPs. Accordingly, the network access mode will migrate from current standard ADSL to vDSL to FTTH in the future. The term vDSL is an advanced DSL technology that utilises cable or fibre as access media to provide high performance (up to 52Mbps) broadband connection, where as the FTTH is defined as “serves one home per fibre” (Goralski 2001: 403). The reason for these trends is because a fibre link is the only means that satisfy future bandwidth requirements on the convergence of various high quality network applications such as HDTV, digital broadcast, IP telephony and 100Mbps Ethernet access (opticalsolutions.com, 2005), namely the “full-service” network. This is also the essence of IP Next Generation Network (NGN) towards providing an all-inclusive IP-based internetwork solution over a single fibre link, instead of the complexity of traditional information and telecommunication network systems including radio, TV, telephony and data services.

4.7 Conclusion

This chapter provided a comprehensive study on the OTN data control plane, which had a major influence on the OTN infrastructure development, in terms of the capability, efficiency and reliability of the OTN. Based on the document analysis, this chapter presents a framework showing the detailed orientations and steps of the OTN infrastructure development. The framework, which is the main outcome of this chapter, is expected to become an effective guideline in design and implementation of future OTN projects for ISPs and large enterprises. The next two chapters then focus on the research for the development trends on network survivability and efficiency of the OTN, as two key branches presented in the framework. In addition, the following research tasks, including a field testing on OTN network protection and a case study based on a real OTN engineering project of SMEPC, can be considered as significant practical evaluations on this framework.

Chapter 5: The Evolution of Protection Technologies in Metro Core Optical Networks

5.1 Introduction

Chapter four provided a comprehensive analysis of the OTN data control plane, which has a significant influence on the performance of the OTN infrastructure. The main outcome of the previous chapter, therefore, was a framework demonstrating current and future development orientations of the OTN infrastructure, including the aspects of network efficiency and reliability. Thus, the next two chapters will verify the proposed framework on theoretical accuracy and commercial feasibility aspects. This chapter focuses on the infrastructural development of the OTN survivability and reliability, by presenting research on the evolutionary progress of the protection technologies in metro core optical networks.

5.2 Background

The metro optical networking market has increased rapidly over the last few years. Traditional telecommunication infrastructure has an emphasis on long-haul optical transmission with ultra broadband capacity, relying mostly on large pure Dense Wavelength Division Multiplexing (DWDM) systems. Today, however, metro core optical networks have the major role in provisioning local access services and interconnecting service points of presences (POPs) with long-haul transmission. This represents a pivotal point in business operations of data communication services for service providers and large enterprises. In addition, the upper layer data services completely depend on the substrate wavelength communication, and hence the survivability and reliability issues in the optical domain are now becoming crucial topics.

This chapter presents a research of the recent history and likely future of optical protection technologies in metro core areas. Current data communication services are moving towards the efficient and cost-effective IP-oriented multiservice architecture. The concept of **IP over WDM** (Lucent Technologies, 1999) is recognised as an ideal solution for supporting IP-oriented Next Generation Network (IP NGN) architecture. Therefore, the development of metro optical protection technologies is also extending from the single Time Division Multiplexing (TDM) plane to **IP over WDM** to the unitive **IP+WDM** domain. In addition, future research will centre on the interoperability between steady optical protection and intelligent IP restoration technologies.

5.3 Ring Protection Technologies in Modern SONET/SDH Systems

Since the SONET/SDH architecture was first deployed in TDM-based infrastructure, the metro ring topology with "1+1" has been chosen as a simple redundant solution. For instance, a Unidirectional Path Switched Ring (UPSR) network transport two ways of optical signals through a pair of fibres. One channel is called the working ring while the other is referred to as a protection ring (see Figure 5.1).

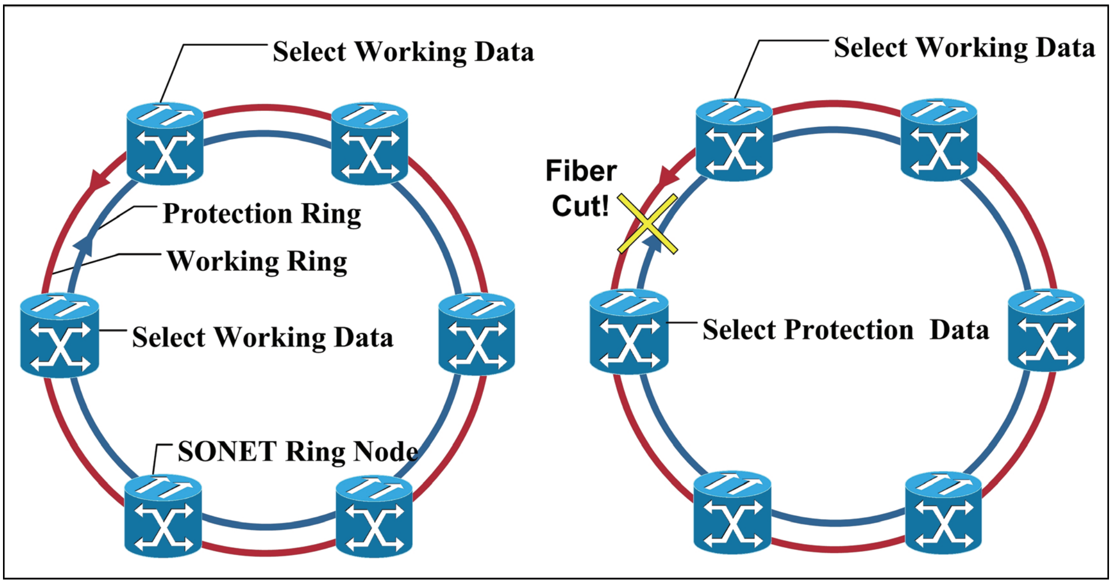

Figure 5.1: "2-fibre" UPSR with "1+1" Path Protection

Each ring carries the same traffic (i.e. “1+1”) throughout the entire SONET network which doubles the transport reliability. The protection ring will automatically switch the traffic within 50 ms in case of a failure. Moreover, a Subnetwork Connection Protection (SCNP) structure also delivers identical protection mechanism in the SDH network. This kind of protection approach provides a very fast response to network faults but 50% of bandwidth is wasted (Warren and Hartmann, 2004: 89-93), and the significant disadvantage is that when both rings are disconnected at different ring sections, the network operations are totally suspended.

Thus, a more flexible “1:1” protection approach was then developed. This scheme also utilises 2N (N in courier) fibre-ring topology, however, the bandwidth in each fibre is respectively divided fifty-fifty for both working and protection purposes. For example, in a Bidirectional Line-Switched Ring (BLSR, defined in SONET) or a Multiplex Section Shared Protection Ring (MS-SPRing, defined in SDH) architecture (see Figure 5.2), the optical signals are exchanged and terminated between each node, and the bandwidth from every single network span can be reused if necessary.

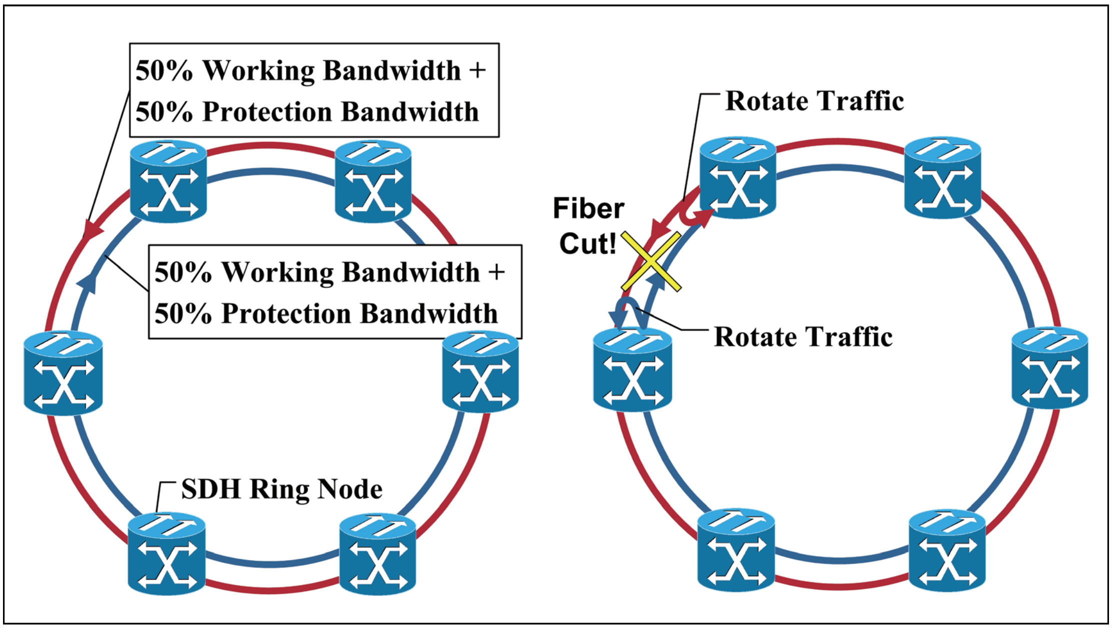

Figure 5.2: “2-fibre” MS-SPRing with “1:1” Line Protection

Once a failure occurs, the data traffic from one fibre is rotated at the error place and switched into another fibre. As a result, the normal network operations are not affected even if both fibres are ruptured, while the available bandwidth in each individual span is also increased due to the resource reuse mechanism from the "1:1" protection principle. Due to the high efficiency and strong survivability, a four-fibre BLSR structure is the most popular deployment solution in the current SONET metro backbones.

5.4 Resilient Packet Ring (IEEE 802.17)

To satisfy the requirements of next generation optical transport infrastructure, the latest layer 2 transport interfacing technologies such as Packet over SONET/SDH (POS) and 10-Gigabit Ethernet (10-GE) were developed to achieve the **IP over Optical** data service architecture. Since traditional optical protection techniques are mostly based on the legacy TDM circuit plane, there is a distinct lack of protection and restoration mechanisms for ensuring the reliability of data packet services. Hence, the IEEE 802.17 work group has released a fibre-ring based transport architecture, the Resilient Packet Ring (RPR), which is established on an innovative layer 2 MAC structure, named Spatial Reuse Protocol (SRP, RFC2892). The significance of SRP is that it allows re-encapsulating Ethernet frames into RPR frames, also referred to as "MAC in MAC", which first empowers service providers to directly deliver the simple and efficient Ethernet services from LAN to WAN area. Based on this feature, RPR is also recognised as a key transport technology in the emerging access service Metro Ethernet (ME) architecture (Halabi. 2004: 35-39).

In addition, RPR provides a superior restoration performance by implementing an Intelligent Protection Switching (IPS) approach, which is similar to that in BLSR or MS-SPRing structure (see Figure 5.3). Previously, the basic protection principle in conventional SONET/SDH networks relied on the pre-reserved protection bandwidth, which reduced the actual transport efficiency. However, the RPR architecture has its natural gift in bandwidth control and allocation which overcomes this technical gap while still keeping the restoration time under 100ms (IETF, 2000).

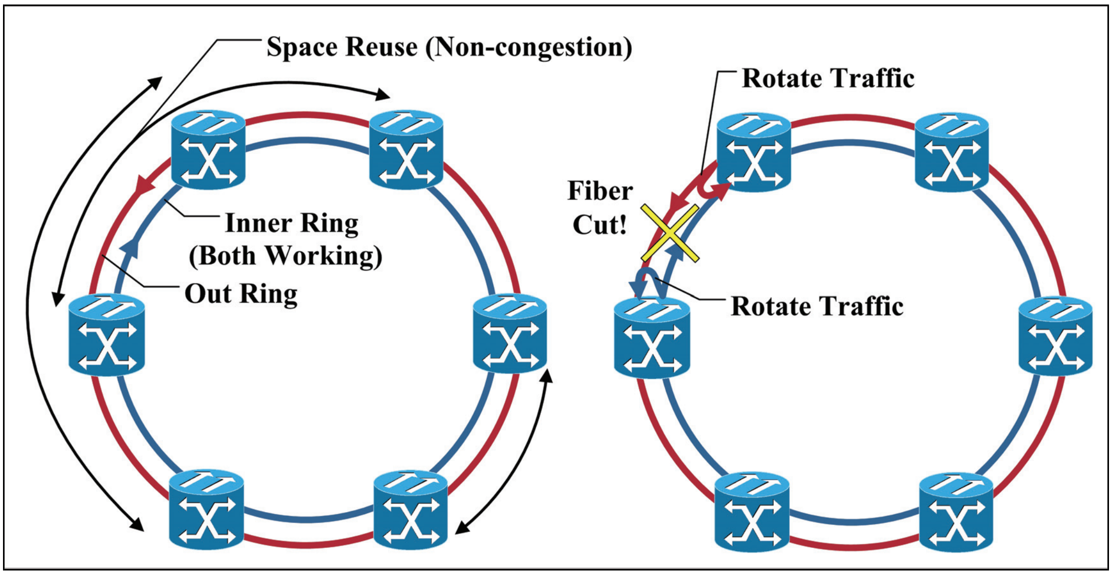

Figure 5.3: Spatial Reuse Algorithm and Intelligent Protection Switching

The SRP algorithm utilises a destination stripping data transport mechanism instead of the inefficient method of passing tokens used in traditional ring-based data communication structures such as Token Ring and FDDI. Thus, data traffic is only added and terminated at defined sources and destination nodes, which enable multiple concurrent flows from different parts of the ring. In addition, there is no longer a specific pre-reserved protection bandwidth. As a result, this particular characteristic enhances the effective network operational bandwidth up to 100% (Wang *et al*, 2004: 7-8).

5.5 Fast Reroute (FRR) Technology

Although RPR provides a revolutionary optical ring protection mechanism, it is only dedicated to single-ring protection, which leads to an inborn limitation for protecting traffic across complex topology such as multiple rings or mesh structures.

Please see print copy for Figure 5.4

Figure 5.4: The Restoration Time Gap between IP and Optical
(Chen, 2006, 92)

Moreover, RPR is designed to replace the traditional TDM protection methods in ensuring IP-oriented data transmission over the optical layer. There is still a serious problem on the restoration time gap between the IP routing (Layer 3) recovery and the optical transport (Layer 1) protection (see Figure 5.4). Thus, a more flexible protection solution, the Fast Reroute (FRR) technology has been introduced from the IP/MPLS (Multiprotocol Label Switching) domain into metro core optical transport systems. FRR is an emerging protection scheme based on the Traffic Engineering (TE) feature of the mature IP/MPLS architecture (Alcatel, 2004: 2). The basic principle of FRR is to establish one or more bandwidth protection TE-tunnels along pre-specified Label Switching Paths (LSPs) to enable temporary bypassing of traffic in case of a link or node failure (IETF, 2005). As demonstrated in Figure 5.5, when an IP packet comes to the head-end router, it simply encapsulates the whole packet with a pre-specified label header, which leads the packet across the working tunnel under normal circumstances.

However, once the second node senses a link failure, it will directly switch traffic to the protection tunnel without any route recalculation. Given the original IP payloads and the label of working tunnel are wrapped again with the protection tunnel label header, the data traffic is rapidly shifted to protection tunnels (LSPs). Due to the intelligent protection mechanism, the frontal failure situation will be transparent to the head-end node, with almost no effect to the protected traffic in the working tunnel. Simultaneously, the second node also sends a path error message to notify the head-end node and to grant it time to recalculate a new, optimal route.

Please see print copy for Figure 5.5

Figure 5.5: FRR Implementation in MPLS-TE Domain
(Chen, 2006, 91)

Moreover, by utilising TE techniques such as the Resource Reservation Protocol (RSVP) or Constraint-based LDP (CR-LDP) signaling, FRR is able to provide end-to-end bandwidth reservation functionalities for TE-tunnels, which guarantees a strict restoration delay level for those specified key services in the event of network failures. A recent field test (Chen, 2006, 91) utilising current commercial equipments, connected with pure GE fibre links is able to demonstrate the practical protection performance of the MPLS-TE FRR model. The test used Cisco 7600 and Cisco 12400 carrier level routers as customer edge (CE) routers, provider core routers and provider edge (PE) routers, to simulate a field operating environment of a metro optical backbone network in a large ISP. The test also utilised a Sprint “Smartbit” performance analysis system (a dedicated flow analysis equipment) to continually generate three sets of representative data flows (see Table 5.1), for simulating a real condition of network traffic as the daily business running circumstance in that ISP.

Table 5.1: Simulated Network Traffic

Traffic Types	Time	Frame Size	Load
Key VPN traffic	**60s**	**68 Bytes**	**20% GE line rate**
Normal VPN traffic	**60s**	**68 Bytes**	**30% GE line rate**
Public VPN traffic	**60s**	**68 Bytes**	**30% GE line rate**
Total traffic	**60s**	**68 Bytes**	**80% GE line rate**

In particular, the test was designed to simulate two common network failures, by manually shutting down an intermediate network node or link. In addition, all network traffic status, including the total data frame transferred, received and lost within a specific time window (60 seconds) was monitored and logged during the simulation process. The test results demonstrate the network recovery time (performance), which is also equivalent to the network outage time:

$$\text{Outage Time} = (\text{Lost Frame \%} * \text{Test Time}) \text{ sec} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

whereas Test Time = 60 sec.

As shown in Figure 5.6, PE1 and PE2 were simulated as two head-end provider edge routers connected with two customer edge routers (CE1 and CE2). For the network link recovery simulation, there was a pair of bidirectional RSVP-based TE-tunnels established between P4, P2 and P5, as for protecting the main trunk between P4 and P5. At the same time, the FRR functionality was enabled at PE1 and PE2 for ensuring the key layer 3 VPN traffic between the two branch sites. However, there were also some simulated bidirectional normal VPN traffic and public traffic injected into the two PE routers, without any specified protection approach. For the network node recovery simulation, the only difference was that the protection TE-tunnels were designed to set up between P4 and P2, as for protecting the intermediate network node P1.

Please see print copy for Figure 5.6

Figure 5.6: Simulations of FRR on Two Common Network Failures
(Chen, 2006, 91)

The simulation has used the **TeraRouting** tester as the associated testing software of the **Smartbit** performance analysis platform. **TeraRouting** tester provides a comprehensive testing mechanism including the support of various standard routing protocols such as BGP, OSPF and IS-IS. Many specific (connection) types, such as Ethernet, POS and ATM can also be categorised and monitored separately in order to show the differences between the performance of each kind of services. In particular, this test only utilised Gigabit Ethernet connection, and the monitored service types are further divided into three sub-categories: the protected MPLS VPN (key NGN) service, the unprotected MPLS VPN (common VPN) service and the unprotected public service. After the simulation data was logged as in Figure 5.7 and 5.8, the results (lost percent of frames, i.e. %Loss) were converted into Table 5.2 by utilising the given equation 1. The summarised results shows that FRR downgrades the maximum restoration time to a few seconds, while most of the existing IP routing recovery solutions usually take tens or hundreds of seconds to achieve re-convergence.

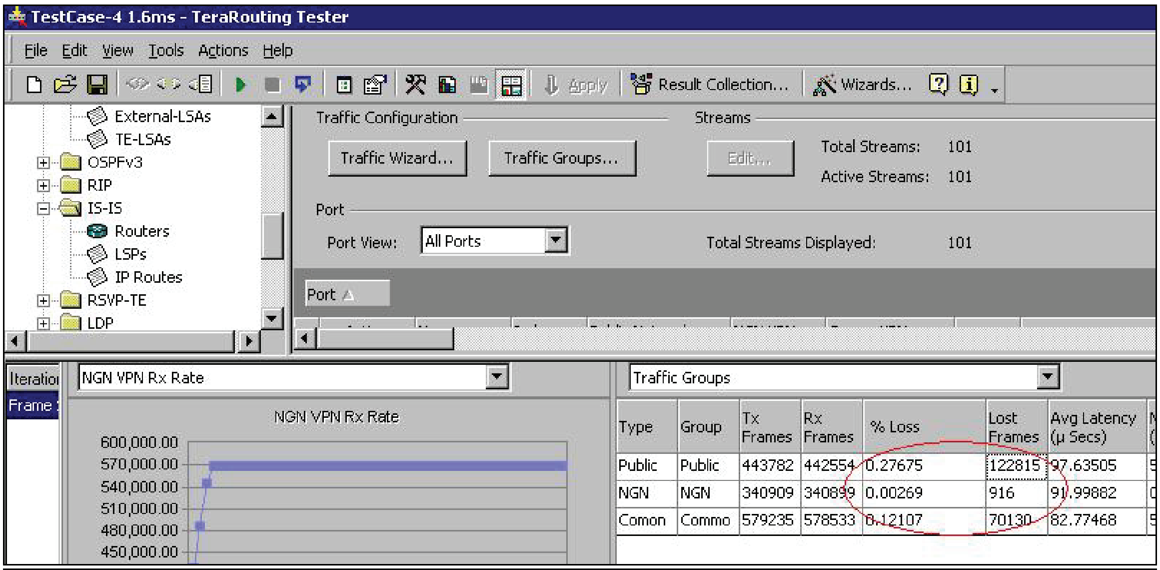

Figure 5.7: Results of the Network Link Recovery Test

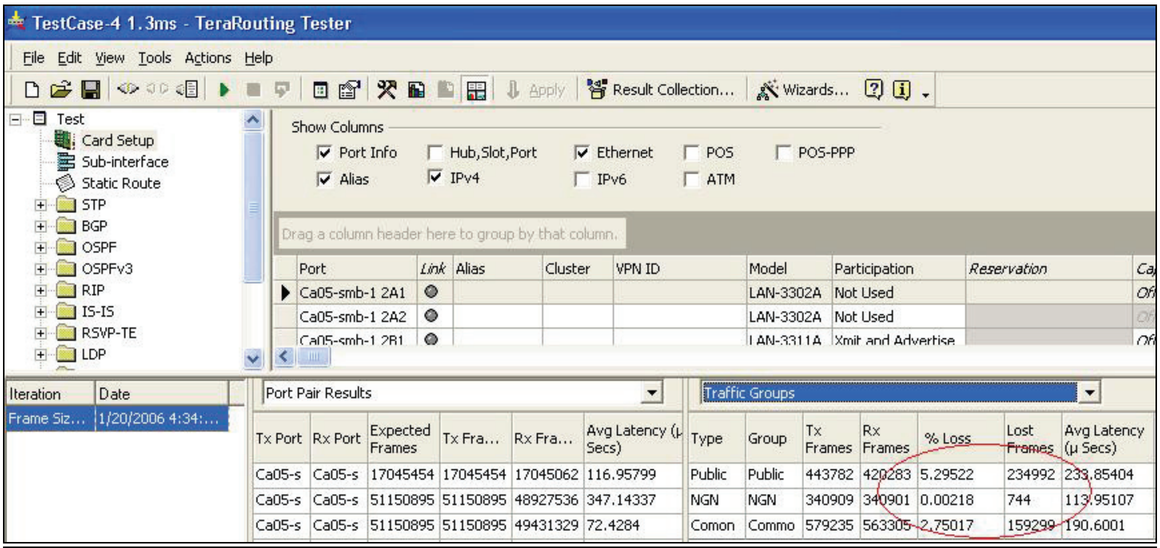

Figure 5.8: Results of the Network Node Recovery Test

Table 5.2: Summary of the Test Results

Restoration Time / Test Type	Key VPN traffic	Normal VPN traffic	Public traffic
MPLS-TE FRR link Protection	<2ms	<80ms	<200ms
MPLS-TE FRR node Protection	<1.5ms	<2S	<3.5S

However, there are noticeable distinctions in the level of restoration time between protected and normal services. For those specialised protected key services, FRR further reduces the restoration time to only one or two milliseconds grade.

5.6 Overall Considerations of Current Metro Core Optical Protection

Based on the above discussion, an overall comparison of existing protection methods in the metro optical transport field is provided as shown in Figure 5.9. Around the optical layer, only SONET/SDH and RPR protection can ensure strict restoration time within telecommunication requirements.

Please see print copy for Figure 5.9

Figure 5.9: Current Metro Optical Protection Solutions
(Chen, 2006, 92)

However, both of them are inherently designed on a ring-based architecture, which means a scalability limitation when facing a complex topology. Although the SRP algorithm brings an attractive bandwidth utilisation while keeping the telecom level restoration time for data services, it is helpless to TDM operation failures. This is due to RPR being designed to carry pure data packet services. Similarly, as MPLS-TE

FRR offers a more comprehensive protection solution, it currently only supports data services such as GE fibre links. Therefore, the protection techniques can be divided into two correlative control planes in the current and near future metro optical networking field. For protection in the optical control plane, a practical approach is to combine RPR and traditional SONET/SDH protection methods together, for ensuring both data services and TDM operations. For protection in the data control plane, MPLS-TE FRR deployment can provide more flexible redundant solutions with guaranteed recovery time, especially for those pivotal services.

5.7 Future Development Trends of Metro Core Optical Protection

5.7.1 WDM Protection

In recent years, WDM protection has emerged as a scheme for first layer protection of metro core optical networks. Unlike fibre restoration of TDM systems, WDM protection focuses on the self-healing of internal wavelength channel connections. However, since the mature SONET/SDH systems are globally adopted, the protection of metro WDM networks is currently developed based on a TDM-based fibre ring architecture. The restoration operations of WDM rings is very similar to that of common TDM rings, such as the Unidirectional Wavelength-Path Switched Ring (UWPSR) and the Bidirectional Wavelength-Path Switched Ring (BWPSR) (Shiragaki *et al*, 1999), whereas the resources of switching are now expanded to both fibres and wavelengths. However, some shortages from TDM systems are inherited by WDM protection such as the resources (wavelengths) wasted for reserved protection use. Network failures such as signal errors or fibre cuts are also detected in the electronic domain back to the TDM layer, resulting in high complexity and low efficiency for the wavelength layer protection. Hence, current WDM protection demands a set of independent and systematic mechanisms in terms of fault detection and service restoration.

Relying on the legacy TDM ring architecture is a primary limitation in the development of WDM protection. For many years metro deployment, using the optical ring architecture has been recognised as an ideal topology for achieving the balance between efficiency and reliability. However, there is little doubt that the mesh design will be an ultimate stable solution, and it has already been approved as an ideal choice for protecting WDM networks (Maier *et al*, 2002: 251-269). ely, present DWDM technology enables the combination of both topologies, which is to build logical wavelength mesh connections above physical fibre ring infrastructure. The latest Supercontinuum light source (Liu and Kordel, 2005: 1-2) and Arrayed Waveguide Grating (AWG) techniques empowers the carrying capacity up to 1000 channel (Koga, Morioka and Miyamoto, 2004: 87-97) wavelengths over 120km (NTT, 2005) on field testing. This actually means the available amount of wavelengths now is sufficient to support about forty branches under full mesh deployment, while most of the existing commercial metro DWDM systems can only support six to nine branches (sixteen to forty channels). In addition, with the global demand for IP NGN data services, it is reasonable to assume that the physical (fibre) mesh will be first deployed in the metro core transport area in the near future. Under this circumstance, WDM protection is an ideal substitute solution for maximizing the system resiliency and survivability at the optical layer.

5.7.2 GMPLS-TE End-to-End Protection

At the data control plane, as discussed in section 5.6, MPLS-TE FRR is currently recognised as a flexible and reliable protection solution, especially for specified data services. Nevertheless, the establishment of TE tunnels requires strict uniform MPLS configuration environment, mostly within a local Interior Gateway Protocol (IGP) domain. Additionally, the FRR functionalities are only supported by high level IP/MPLS routing equipment, which means the protection LSPs cannot drill through in intermediate non-routing environments such as the TDM network connection. Therefore, the concept of FRR has been introduced into Generalized MPLS (GMPLS) architecture (Kumaki, *et al*, 2006). GMPLS is indeed an extension of MPLS from the

IP to optical world, and it first enables the control and management from the IP routing domain to the TDM and WDM optical transport layer within a common environment. Nowadays a metro core telecommunications infrastructure in large ISPs or enterprises may involve various network elements, such as IP routers, routers with TDM (ATM/FR) interfaces, Optical Add/Drop Multiplexers (OADMs) and Optical Cross Connects (OXCs). Inspired by the features of FRR in MPLS, GMPLS then aims to utilise extended TE signaling protocols such as Generalized RSVP and Generalized CR-LDP, to establish non-blocking end-to-end protection tunnels through from packet switching to TDM switching to Lambda/Fibre switching domains (Lang *et al*, 2005). Based on this extended TE architecture, GMPLS is capable of unifying the protection and recovery approaches between data service network and optical transport infrastructure.

Please see print copy for Figure 5.10

Figure 5.10: GMPLS-TE Extension End-to-End Protection

(Chen, 2006, 93)

Figure 5.10 presents a deployment landscape of the future metro optical transport backbone. For the core layer, a WDM mesh architecture is adopted as the steadiest protection solution with the highest system resilience. For the distribution layer, there are many independent protection methods that can be selected for particular services from each autonomous span, such as the SONET/SDH ring protection for TDM operations, RPR ring protection for data services, or the combination of WDM and RPR for ensuring ROADM-based MSTP (next generation SONET/SDH) service transportation.

In this context, however, GMPLS focuses on the holistic stability of extended TE tunnels between every head-end (provider edge) node, regardless of any intermediate network (IP, TDM or WDM) failure within a uniform GMPLS-TE domain. By exchanging standard TE extension signaling, each network element in front of a failure will automatically bypass the protected traffic through a local restoration link, path or tunnel. Concurrently, the network element is also able to notify the head-end nodes immediately and give them time to recalculate for new optimal LSPs. Moreover, there is no conflict for introducing FRR into the GMPLS-TE domain, and FRR can also be referenced as a local restoration technique to enhance the interoperability between MPLS and GMPLS.

5.7.3 Summary

Figure 5.11 gives a summary of protection technologies in future metro core optical networks. Firstly, WDM protection will be gradually adopted at the first layer with the efficient mesh architecture. Concurrently, RPR will also replace the SONET/SDH protection based on the existing metro ring architecture, as IP-oriented data services will soon take the place of legacy TDM operations. In addition, a number of vendors (e.g. Cisco Systems, Alcatel, and Nortel Networks) are now working on embedding the RPR feature into their existing metro transport and core routing systems as a standard configuration, which decreases the potential deployment investment significantly (Chen, 2006, 94).

Secondly, the principle of TE-tunnel protection of FRR will be expanded from MPLS-TE to the uniform GMPLS-TE domain. By implementing standard TE extension signaling between all network (IP, TDM and WDM) elements, future service providers will be able to deliver veritable end-to-end data services with high guaranteed reliability through an entire metro span. By comparing with Figure 5.9, it is not hard to see that the future trends in the research of metro core optical transport reliability will focus on the convergence of WDM protection efficiency and IP/MPLS recovery resiliency.

Please see print copy for Figure 5.11

Figure 5.11: Future Metro Optical Protection Solutions
(Chen, 2006, 94)

5.8 An Evaluation of the Proposed Infrastructural Framework

After providing a comprehensive study on the development process of the protection technologies in metro optical backbones, it is necessary to make a comparison between the research results and the proposed framework. This can be considered as a representative evaluation of the proposed OTN infrastructural framework in terms of the network reliability and survivability. As shown in Figure 5.12, the protection pivot of the metro core OTN centres on the optical transport layer at the initial stage. In this phase, the wavelength connections are mainly set up by static TDM-based configuration, and therefore the network reliability mostly relies on common TDM fibre protection technologies. In addition, RPR is developed for ensuring the transmission of IP-oriented data services over the TDM-based optical infrastructure. However, there is still a distinct restoration time gap between the IP recovery mechanism and the optical transport protection. This is because the limited control communication between the IP layer and the Optical layer, which is the inborn nature of the Static IP Optical Overlay Control Plane.

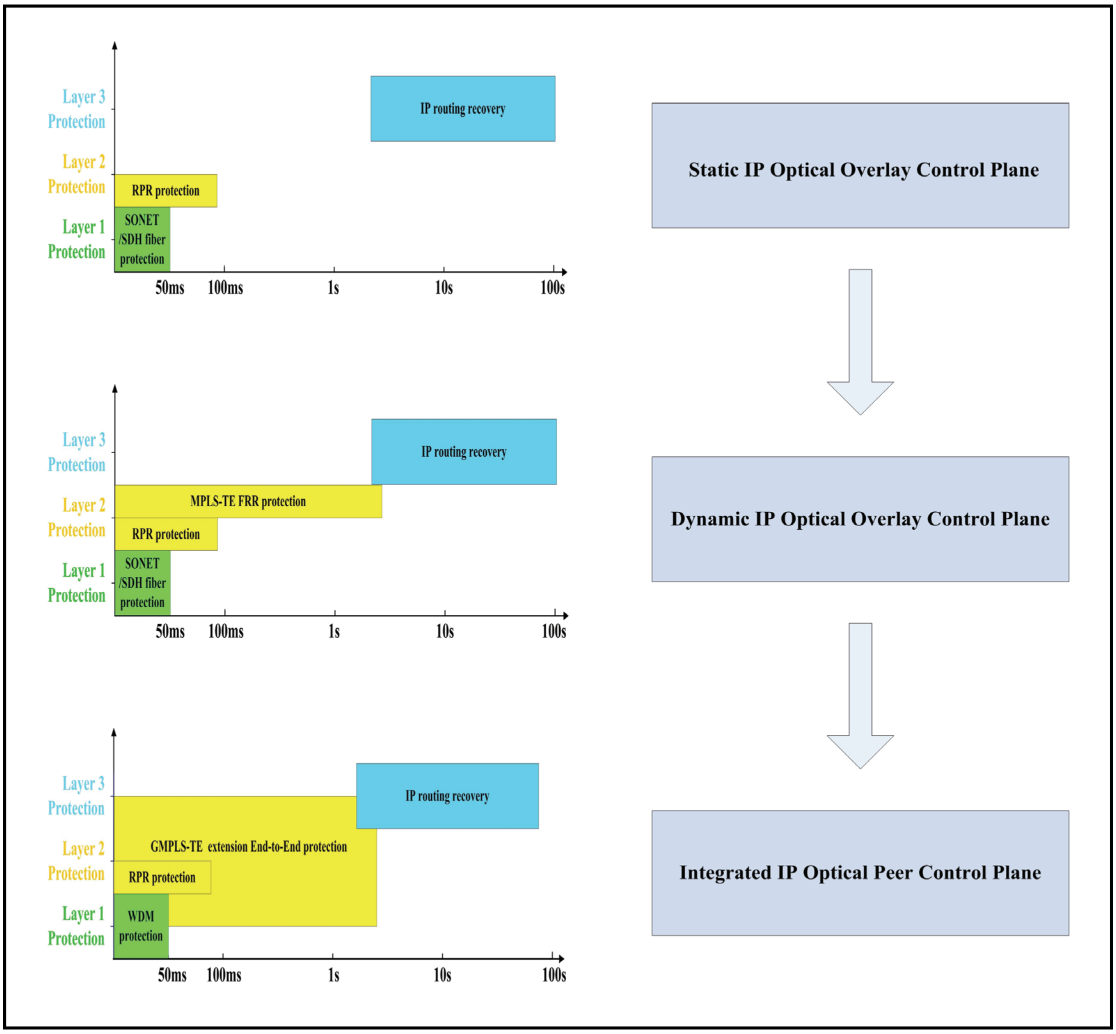

Figure 5.12: A Comparison between the Research Results and the Proposed Framework

Thus, the next phase of OTN protection development will emphasise on optimising the intermediate control layer between IP and Optical. In doing so, the advanced MPLS-TE FRR recovery mechanism is developed to provide a more flexible protection solution. By utilising MPLS-based traffic engineering approach, FRR is able to set up multiple end-to-end LSP protection tunnels for ensuring various service transmissions with differentiated protection level guaranteed. In particular, the restoration time level varies from milliseconds to seconds, depending on the particular priorities of the upper layer data services. Interestingly, the restoration time scope of MPLS-TE FRR ideally fulfils the mentioned protection gap. The FRR technology boosts the protection interoperability between IP and Optical layers, which represents the basic principle of the Dynamic IP Optical Overlay Control Plane.

However, as RPR and FRR are both designed for protecting the IP-oriented data services, they are helpless in guaranteeing other OTN service systems such as the legacy TDM operations. Inspired by the working concept of MPLS-TE FRR, a more comprehensive protection standard, the GMPLS-TE FRR is then developed to overcome above shortcoming. GMPLS enhances the establishment of protection LSP tunnels extending from WDM to TDM to IP domains. By introducing the GMPLS-TE scheme, it is capable of setting up a uniform OTN protection system for various service types with specific restoration levels support. As GMPLS first unifies the OTN control plane between the IP and the Optical layer, it can be considered as a primary instance of the Integrated IP Optical Control Plane.

5.9 Conclusion

The performance of network protection technologies reflects the stability and reliability of the whole carrier system. Present metro optical backbones require extreme operational safety, as they are ensuring various upper layer network services in various geographic contexts. Thus, this chapter provides a comprehensive study on existing metro optical protection technologies, including the evolution from the traditional SONET/SDH system to the emerging RPR architecture. A simulation under the FRR protection model within a MPLS-TE test environment was also supplied to demonstrate the practical performance of this emergent protection scheme.

By providing a comparative analysis on the latest optical protection technologies, this chapter clarifies the potential orientations for future development of metro core optical transport protection. In addition, the outcome is a good fit to the major concept of the infrastructural framework given in the preceding chapter, that is, to simplify the protection operations and optimise the protection structures between IP (MPLS) and the optical (WDM) control plane. Thus, the next chapter will examine the framework from the network efficiency aspect.

Chapter 6: A Case Study Based on an OTN System Upgrade Engineering Project of SMEPC

6.1 Introduction

In chapter four, a framework was presented in demonstrating the future development trends of the OTN infrastructure. Chapter five provided a systematic analysis of the development process of protection technologies in metro core optical networks, along with a practical field test for exploring the practicability of the proposed framework from the angle of network reliability. This chapter, therefore, will verify the framework from the perspective of network efficiency with resource utilisation. In addition, this chapter will illustrate the potential interactions between the OTN infrastructure, WDM/DWDM technologies and modern business data network services, by utilising a real OTN business implementation case study of Shanghai Municipal Electric Power Company (SMEPC).

In recent years, optical communication services have became very important in the field of electricity supply control and management. On the one hand, most existing power manufacture communication, such as control and dispatch, are migrating from analog to digital formation, which requires stable data communication infrastructure with broadband capacity for ensuring upper layer service operation. On the other hand, the latest online business operations of power companies, such as power markets and sales information are transferred and updated instantly, which also demands a scalable data network architecture as business expands. Thus, this chapter presents a case study based on an ongoing engineering project from SMEPC. In particular, it is a system upgrade from the legacy SDH network to the latest Multiservice Transport Platform (MSTP), along with the major goal of broadening the capacity for the metropolitan optical communication infrastructure of SMEPC, namely the Shanghai Power Telecommunication Network (ShPTnet).

6.2 Background Information of SMEPC

Shanghai Municipal Electric Power Company (SMEPC) is a large organisation which takes charge of Shanghai electric power generation, transmission and distribution. The primary missions of this company are focusing on grid formulation, implementation and development, as well as centralized power dispatching in all the districts of Shanghai. The company plays a crucial role in supervising and guiding the electric use for the entire city around safety and saving aspects. The origin of SMEPC, namely Shanghai Electric Company was founded in 1882 with the first electric lamp appearing in China. Currently, SMEPC operates 19 sub enterprises and institutions with over 580 power substations. In 2004, SMEPC has achieved a total grid power generation capacity of 11828.3 MW, and an overall transformer capacity of 61421.7 MVA with annual power sales 61.596 billion kWh (SMEPC.com, 2005), which equates to a production value of 31.411 billion Yuan (AUD 5.149 billion). For more than 120 year development history, the company has insisted on providing top rank services in terms of power supplying for the international metropolis.

6.3 Current Situation and Problems in the ShPTnet

The existing ShPTnet (Zhang et *al*, 2004: 20) of SMEPC has been set up based on optical transport infrastructure since 1993 when the first fibre link was installed. In addition to more than 10 years development, this data communication network provides multifarious business data share and exchange services, which significantly enhances the organisation's productivity in this information age. Working requirements of power telecommunication are moving forward to digital, integrated and broadband operations, which bring more challenges to the network architects and engineers. Conversely, the recent maturity of optical transmission technologies also push the development of data transport infrastructure, to satisfy the increasing and changeful demands of both the intranet and extranet. The overall size of ShPTnet has been expanded from an initial six nodes to over one hundred nodes today. Current ShPTnet plays a role in not only metro intranet, but also as a crucial data communications link between the East China Grid and the National Grid. As a consequence, the major goal of this OTN project is to maximise the utilisation of legacy fibre resources and network resources, for broadening the data communication bandwidth and capacity of ShPTnet with sufficient flexibility and scalability.

Traditionally, the development of ShPTnet was mainly expanded along longitudinal orientation on the same transmission bandwidth trunk. This leads to a complex network configuration consisting of multiple ring and chain topologies. Due to this the network infrastructure has a lack of latitudinal hierarchy and the traffic is frequently exchanged between different segments, causing congestion the central SDH fibre network in terms of data share and dispatch communication. Given the network requirements and bandwidth limitations, the legacy SDH network only provisions traditional TDM services, including stored program controlled (SPC) exchange, dispatch telephony, Remote Terminal Unit (RTU) applications which meet modern power system control and management tasks. However, the present STM-1 (a SDH interface standard, bandwidth: 155 Mbps) connection is not able to afford the increasing demands of IP-based data services for future business operations and expansions.

6.4 The Importance of Increasing Efficiency of ShPTnet

6.4.1 Data Service Considerations in the Current Business Environment

According to an intramural forecast, the total data service throughput of ShPTnet in 2005 will be double that of 2002 (Ren and Shen, 2004: 1-2). The service categories and types, in addition, are also becoming sophisticated. For satisfying the internal business manipulation and administration of SMEPC, ShPTnet provides various IP-based services such as the following systems: Power Management Information

System (MIS) and Power Market Operation System (PMOS), Enterprise Resource Planning (ERP), Decision Support System (DSS), Customer Service Centre and Customer Relationship Management (CRM), Data Warehouse (DW) and Utility Data Centre, Office Automation (OA) and Video Conferencing. Besides, latest specialised communication applications in power system control and management, such as Transmission and Distribution Management, Supervisory Control and Data Acquisition (SCADA), Energy Management System (EMS) and Substation Automation System (SAS), Automatic Metering Reading (AMR) and Load Management also require real-time IP-oriented interconnection. In brief, an IP-based integrated data transmission structure with high bandwidth and ample reliability, is indispensable to current and future online business operations of SMEPC. Thus, it is vital to enhance the infrastructure transport capacity of ShPTnet, for ensuring those mission-critical applications which will affect power supplying issues of the whole Shanghai city and even the entire eastern regional of China.

6.4.2 Towards Advanced Optical Transport Technologies

Firstly, mature commercial DWDM systems represent the impact of the latest optical communication research achievements in today's business world. Those advanced optical transport technologies provide ultra-high transmission bandwidth almost reaching the theoretical high-point capacity of a single fibre. In the initial phase of this long timescale project, however, it is wasteful to deploy DWDM technologies with exorbitant prices in interconnecting specialised power communication systems. A recommendation instead is to introduce a DWDM-ready transport platform at the first instance, and to gradually upgrade the system bandwidth with DWDM on demand in the future, which is an efficient and cost-effective solution for building the next generation ShPTnet. Secondly, some of the latest optical transport platforms are also capable of ensuring basic connectivity while supporting comprehensive interface speed extension, from essential E1 (2 Mbps) and E3 (34 Mbps) TDM connectors to STM-1/4 (155/622 Mbps) ATM interfaces to STM-16/64 (2.5/10 Gbps) POS interfaces, as well as all sorts of 10/100/1000 Mbps Ethernet interfaces. This important feature relies on transporting data services across the optical layer directly, which demonstrates the foundations of the **IP over Optical** concept. Thirdly, current intelligent data transport technologies influence the service principle of network infrastructure. Conventionally, a given service network type only provides a simplex functionality. For example, ISDN provides a leased line service and Frame Relay provides a packet switching service which results inevitably in low efficient commercial operation. To offer merely a single TDM-based service in one network will not suit the requirements of multifarious IP data services in this WDM-dominant age anymore. Nowadays a uniform optical transport infrastructure makes it possible to sustain abundant varieties of services with great flexibility and scalability. In addition, optical data transportation now emphasises more on achieving fast and accurate service provisioning, to minimise the total operating costs and risks.

6.5 Systems Analysis of the Upgrade Project

6.5.1 Technical Requirements of the OTN Project of SMEPC

The next generation ShPTnet orientation was a typical metropolitan (metro) OTN for providing internal business information sharing and exchange services while keeping legacy TDM operations. The pivotal issue of this construction was to import new technologies for improving the bandwidth capacity of the metro transport infrastructure, which is based on the principle of protecting existing investments. Today, there is a capability of optimising the network hierarchy together with a maximum utilisation of crucial fibre resources to achieve a high performance and a cost-effective intranet solution in terms of business data network services. In addition, the new transport foundation will enhance communication efficiency of IP-based data services, and satisfy traditional TDM operation requirements as well. The technical requirements of this engineering project can be summarised as follows:

1. To overcome the inherent low efficiency in transferring IP-based data services across SDH systems, which are naturally designed for traditional simplex voice services.

2. The new transport system is expected to achieve fast service provisioning and ultra high bandwidth expansion in the same chassis of the same platforms.

3. To provide various broadband access services with service-oriented traffic optimisation and aggregation for fulfilling various requirements from different customers.

4. To provide comprehensive optical and data communication protection and restoration mechanisms while ensuring the reliability of the existing SDH system.

In seeking an appropriate solution, Ethernet technology has proved an excellent efficiency with IP-based data services despite that it is not compatible with conventional TDM operations. Although the classical SDH system is framed to the TDM service structure, it faces a bottleneck in providing data packet switching functionalities. Optical routing/switching technologies offer great transport capability and compatibility for both types of services. However, they are currently only suitable for the core segment of the large ISP backbone, due to the expensive and immature OXC equipment which is still not able to provide terminal service interfaces. Thus, a specialised transport platform designed for optical-based metro intranet deployment is needed to overcome the above mentioned technical gaps within an integrated and complicated data communication environment of future ShPTnet of SMEPC.

6.5.2 Next Generation SDH Transport Platform

For delivering data services over a metro span, the practical solution is to encapsulate Ethernet frames into SDH payload, which also can be referred as Ethernet over SDH

(EoS) architecture (Halabi, 2004: 50-51). For instance, the standard frame mapping technologies Generic Framing Procedure (GFP, G.7041) (ITU, 2001b) defines a comprehensive mapping protocol, which allows various types of data packets to be mapped onto a common TDM-based bandwidth pipe transparently with glorious stability and compatibility. However, GFP has the shortcoming that it lacks TDM bandwidth utilisation. In particular, the allocated TDM circuits have a very limited choice due to the discontinuous SDH multiplexing hierarchy, which means the whole system wastes a certain amount of bandwidth in almost every data service provisioning.

Given this limitations, the transport optimisation technologies of virtual concatenation (VCAT, ITU-T G.707) and link capacity adjustment scheme (LCAS, ITU-T G.7042) were then developed to overcome the weaknesses. The VCAT recommendation provides a method in reuse the spare empty payload during the flow mapping process between different levels of SDH fragments, which obtains an increment in total bandwidth utilisation (see Figure 6.1 and 6.2). The G.7042 Link Capacity Adjustment Scheme (LCAS) (ITU, 2001c), in addition, enables the latest system to adjust the bandwidth for individual services gradually as the up-to-date Service Level Agreement (SLA) without breaking off the data flow traffic.

Please see print copy for Figure 6.1

Figure 6.1: A VCAT Example

(Cisco Systems, 2003: 5)

Please see print copy for Figure 6.2

Figure 6.2: A Comparison of VCAT and Standard Concatenations in Bandwidth Utilisation (Cisco Systems, 2003: 6)

Although the VCAT/LCAS structure offers great performance and efficiency in implementing EoS services, it faces a bottleneck in specific QoS deployment over a WAN scale, especially under existing metro SDH ring structures. As Ethernet has an inherent collision problem in the ring-based structure, a possible solution is to utilise the layer 2 loop avoidance protocol, such as the multiple Spanning Tree Protocol (MST, IEEE 802.1Q). However, this is still not an ideal method for a large amount of multipoint to multipoint communication under a metro span.

For this reason, a fibre-ring based data transport protocol, resilient packet ring (RPR) was then released by the IEEE 802.17 group to overcome this limitation. RPR utilises an innovative MAC structure with a spatial reuse mechanism to carry Ethernet frames. The data traffic in the RPR network is only added and terminated at defined source and destination nodes, which enables multiple concurrent flows from different parts of the ring (Tsiang and Suwala, 2000). This approach expands the total operational bandwidth rapidly, by implementing global fairness on total bandwidth allocation, as well as local optimisation. As a result, RPR first empowers service providers to deliver abundant multipoint to multipoint data services in a simple and efficient way over an existing SDH-ring structure. Thus, a mature design of a next generation SDH transport platform is shown in Figure 6.3:

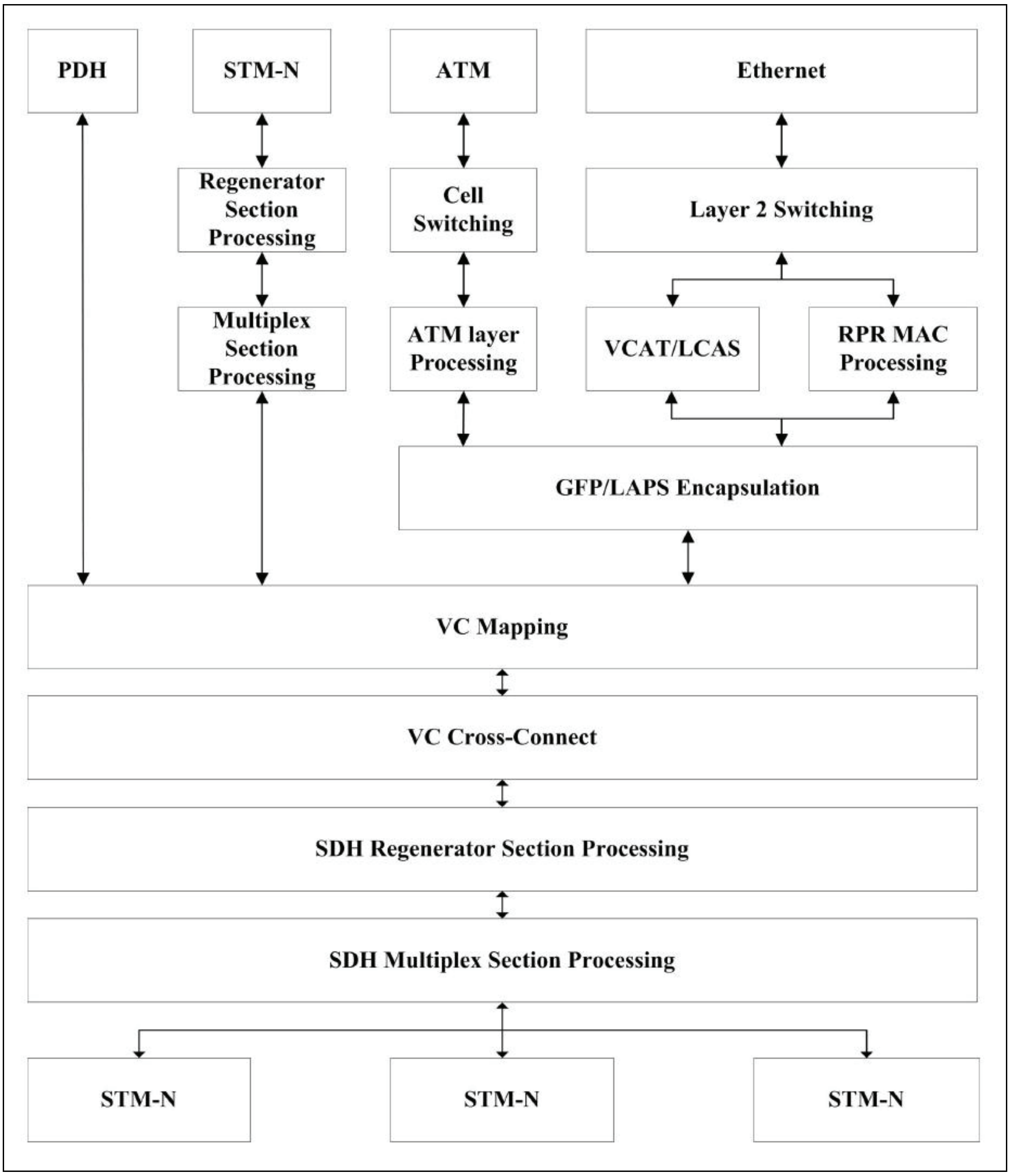

Figure 6.3: Delivering Data Services over Next Generation SDH Transport Platform (Chen, 2006, 3)

6.6 The System Construction of the Next Generation ShPTnet

6.6.1 ShPtnet Network Deployment

In deploying the new network elements, Cisco Systems, which is a leading company in the worldwide internetworking industry, provided a turnkey solution named Complete Optical Multiservice Edge and Transport (COMET) service architecture. The COMET solution includes several series of next generation (TDM and WDM) optical transport platforms, from long-haul transmission to metro core to access edge optical networks. It also introduces an innovative OTN control system, by providing a comprehensive network management application package. In addition, as the legacy ShPTnet already adopted various routing and switching equipments from Cisco, it is reasonably to choose their optical transport platforms for reducing the potential implementation risks such as compatibility issues. Thus, this project selects the Cisco Optical Networking System (ONS) 15454 (Cisco Systems, 2004b) as the optical transport platform Cisco systems for each engineering site deployment. The Cisco ONS15454 is a typical metro MSTP product (see Figure 6.4), which is a combination of the next generation SDH transport platform with DWDM function support (Fujitsu Networks, 2005: 2-4).

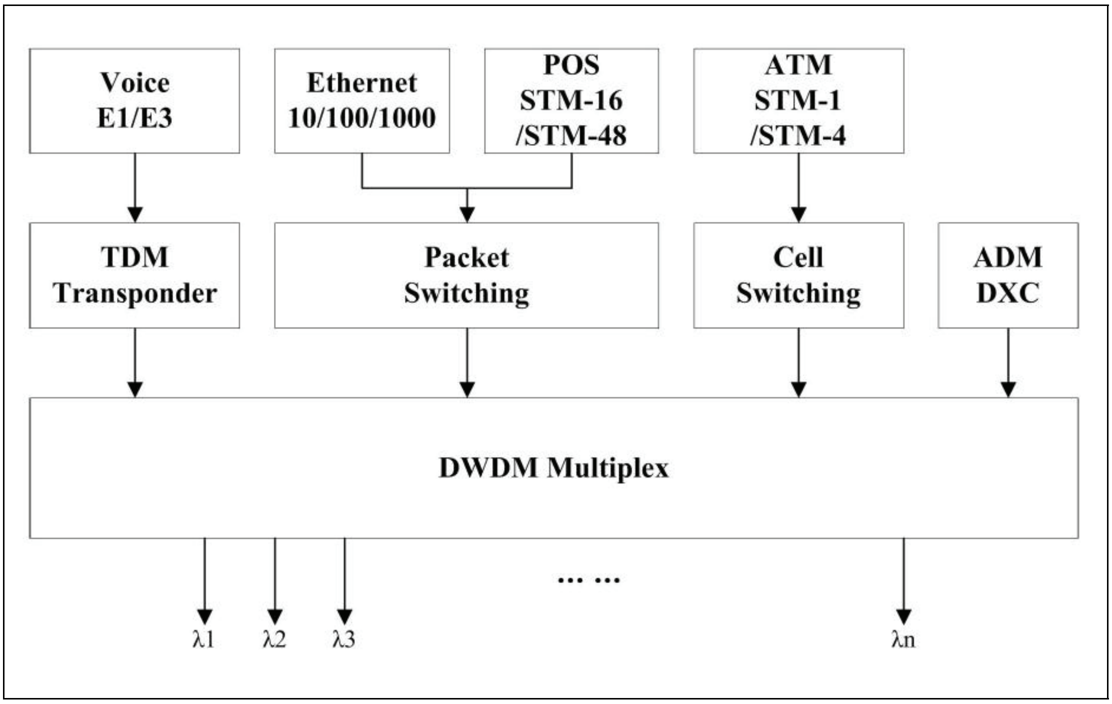

Figure 6.4: System Structure of the Cisco ONS 15454 MSTP

It provides an unprecedented transport capacity from both bandwidth and service types, including a comprehensive set of interface types with various line speed supports, such as essential E1 (2 Mbps) and E3 (34 Mbps) TDM connectors to STM1/4 (155/622 Mbps) ATM ports, and STM-16/48 (2.5/10 Gbps) POS ports. Moreover, this product can provide all types of Ethernet (10/100/1000 Mbps) services with great flexibility based on standard VCAT/LCAS or the latest RPR solutions.

The predominantly TDM-based services for specialised power system applications such as dispatch control and Energy Management System (EMS), security automatics unit and Remote Terminal Unit (RTU), and the power line relay protection system can be seamlessly migrated from legacy SDH equipment onto the raw platform. In the meanwhile, it also offers unprecedented abundant IP-based data services along with both ATM and Ethernet access modes, including e-business and the ERP system, intranet and Internet, video and audio streaming and storage networking. As being the smallest (dimension and power consumption) 10G platform within the whole optical networking industry, the ONS 15454 provides an ideal solution in metro area network transportation by intensifying the utilisation of valuable fibre resources.

6.6.2 ShPTnet Network Construction and Topology

This large OTN project of SMEPC has consisted of three engineering layers: the core layer (ring), the edge layer (ring) and the access layer. The objective of this phase was to construct the core layer and the edge layer to be considered as the optical transport infrastructure. With the use of STM-64 line cards, the core layer MSTP equipment can carry a 10 Gbps optical signal for building up a backbone ring topology. The core layer has also taken the responsibility of converging services from edge rings and accomplishing the primary transport mission. The edge layer uses STM-16 MSTP equipment to carry a 2.5 Gbps signal for each ring. With the large deployment of ML-1000 service cards, each site is able to provide Layer 3 switched Gigabit Ethernet data services based on embedded RPR mechanisms. Because the updated system transport bandwidth is abundant for current services, there was no necessity to implement DWDM at this stage. However, by deploying the optional DWDM module in the future, the existing systems are able to gradually upgrade to 32 wavelengths, which means the maximum backbone bandwidth can increase dramatically up to 320 G (32λ x 10 G).

According to the existing situation in terms of fibre resource allocation and network routing, it was decided to build a hybrid structure to combine the ring and linear topologies in the initial engineering phase. The network operations of remaining sites (that which is out of the rings) will be combined into those edge rings and then aggregated onto the core ring as the practical requirements in the future. A detailed network topology with routing description is shown below (see Figure 6.5):

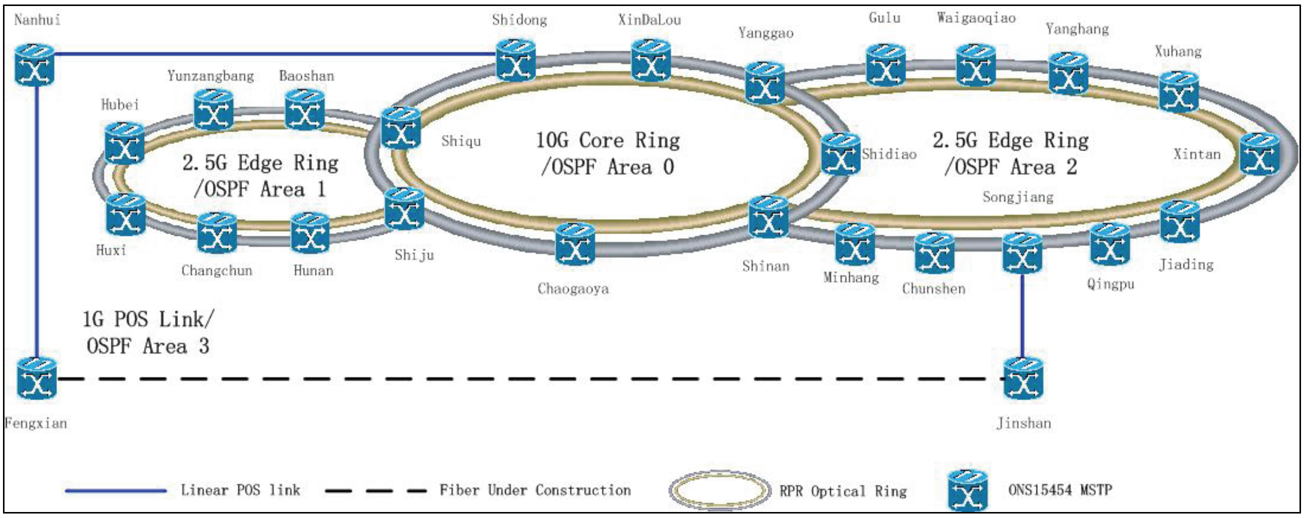

Figure 6.5: Engineering Topology of the MSTP-based OTN of SMEPC

6.6.3 ShPTnet Network Management Platform

In the first place, an innovative Cisco Transport Manager (CTM) is provided by Cisco as a centralized network management application for the whole metro OTN system. CTM gives a comprehensive and uniform subnet management and element management system (EMS) environment to handle all control and maintenance tasks for both MSTP (SDH) and DWDM equipments (Cisco Systems, 2001d), which benefits SMEPC a great deal as they save on further investment of the management system for future metro DWDM system. CTM can be deployed on various network operating systems with a complete set of network management mechanisms in terms of configuration, performance, fault, alarm and security aspects (see Figure 6.6). An additional database system is supported by CTM to enforce strong inventory and log functionalities of system performance and alarm issues. In this project, a network monitor and management platform is established in the central dispatch office of

SMEPC with the following specification (see Figure 6.7):

Please see print copy for Figure 6.6

Figure 6.6: Cisco Transport Manager (CTM)
(Cisco Systems, 2001c: 12)

Network Management Platform	Vendor	Type/Version
Workstation System	SUN	Blade 2000
Operating System	SUN	Solaris 8
Database	Oracle	Standard Edition R8.1.7
Element Management System (EMS)	Cisco	CTM R4.0
Management Interface Support	(Open)	CORBA & SNMP v1/2c
Communication Protocol	(Open)	IP v4

Figure 6.7: Network Management Platform of the SMEPC OTN Project

For the local craft terminal (LCT) management, a control application named Cisco Transport Controller (CTC) is also embedded in the backplane of all MSTP equipment. As the implementation of CTC in the ONS15454 is based on JAVA2 platform, it is convenient to use web browsers to download the applet from the equipment onto local terminals (PCs), which is economical and convenient for daily control and maintenance operations. Contrary to traditional LCT applications, CTC applies a user-friendly Graphic User Interface (GUI) while ensuring powerful management functionalities, including system configuration, circuit/service provision, and performance/alarm/security management. Moreover, a discretional node in the domain is able to discover the entire network topology automatically and represent it as a detailed graph (see Figure 6.8). This important feature allows the network operators to perform node configuration from local to remote, and even to implement end-to-end circuit provisioning across different rings.

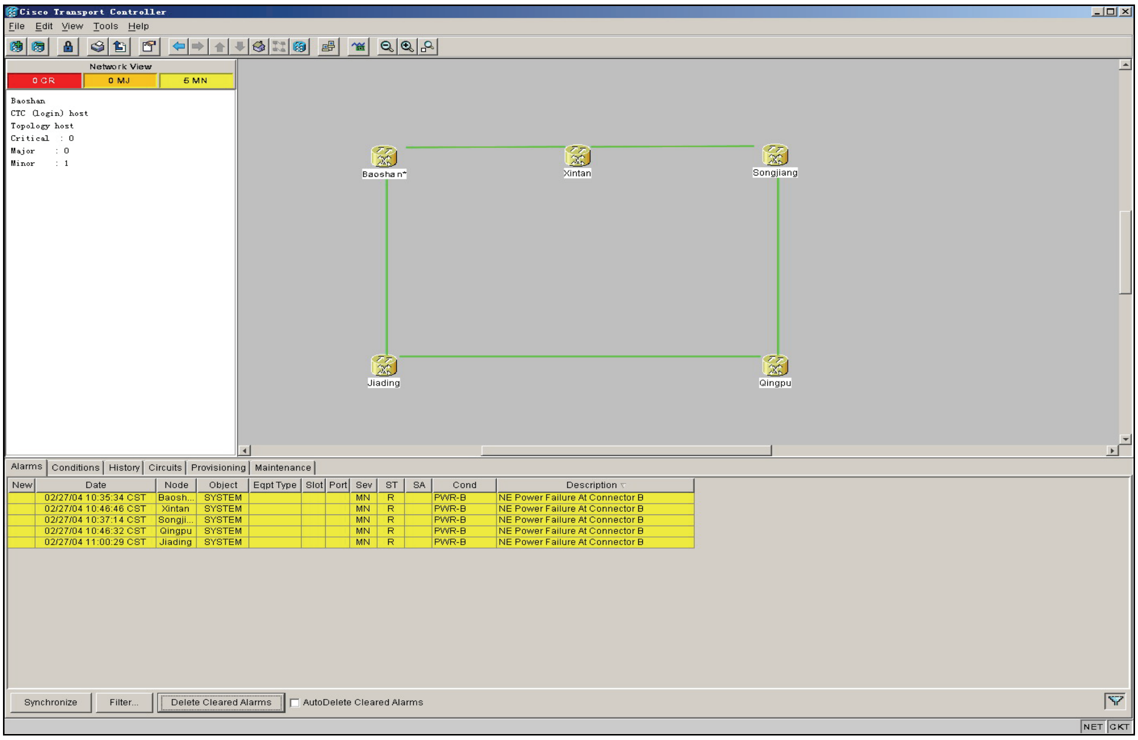

Figure 6.8: A Screenshot of the Cisco Transport Controller (CTC)

6.6.4 ShPTnet Network Protection and Security Mechanism

The ONS15454 transport platform supports diversified optical protection solutions of ring and linear topologies within 50ms carrier level restoration time. Those protection modes include classical "1+1" Subnetwork Connection Protection (SCNP) and 1:1 Multiplex Section Shared Protection Ring (MS-SPRing) (2-fibre STM-4/16/64 and 4-fibre STM/16/64) methods with the ONS15454 internal protection mechanisms from the RPR technology. All the protection tasks implementation can be accomplished by utilising the CTM and CTC management platforms.

Although RPR provides an ideal protection solution for the metro optical backbone, it is only dedicated to pure data services, with a weakness in supporting traditional TDM operations recovery. Furthermore, because RPR is designed for single-ring protection, it has an inborn limitation for protecting traffic across complex topologies such as multiple rings or mesh structures. Thus, the overall optical protection solution depends on the detailed system specification. For those pure data services such as Ethernet connections, RPR can ensure the fastest and most accurate response to any network failure. For those complex hybrid services including previous TDM-operations, the system is suggested to be used with traditional TDM protection method. In particular, this project eventually adopted a 2-fibre SNCP fibre-restoration solution as there were still several key operations, including power system control and dispatch running on TDM service provision across different rings.

6.6.5 ShPTnet Network Bandwidth Expansibility

As the current design of edge rings are based on a 2.5 Gbps line rate, it is sufficient to upgrade those systems to 10 Gbps to cater for future demands, by simply replacing the 15454E-XCVXL-2.5G cross-connect fabric card with the 15454E-XCVXL-10G cross-connect fabric card (Cisco Systems, 2001e), and adding a STM-64 (10 Gbps) optical interface line card on the same chassis of the ONS15454. Moreover, in order to meet the unprecedented increase in bandwidth demand, it is also recommended to introduce the Cisco ONS 15216 series as a specialised metro DWDM platform to broaden the core link bandwidth up to $32\lambda\times2.5/10$ Gbps, by utilising advanced DWDM amplifying/filtering technologies. This robust solution not only solves the issue of bandwidth, but also provides an integrated protection mechanism at the optical transport layers in terms of multiple lambdas.

6.6.6 ShPTnet Data Service Deployment

While ensuring traditional TDM operations, the up-to-date ShPTnet takes high charge of data services transportation. Each branch ONS15454 offers multiple GE level interfaces with core routing mechanisms for interconnecting their office's existing layer 3 switches, which sustain daily intranet, Internet and other online business applications (see Figure 6.9).

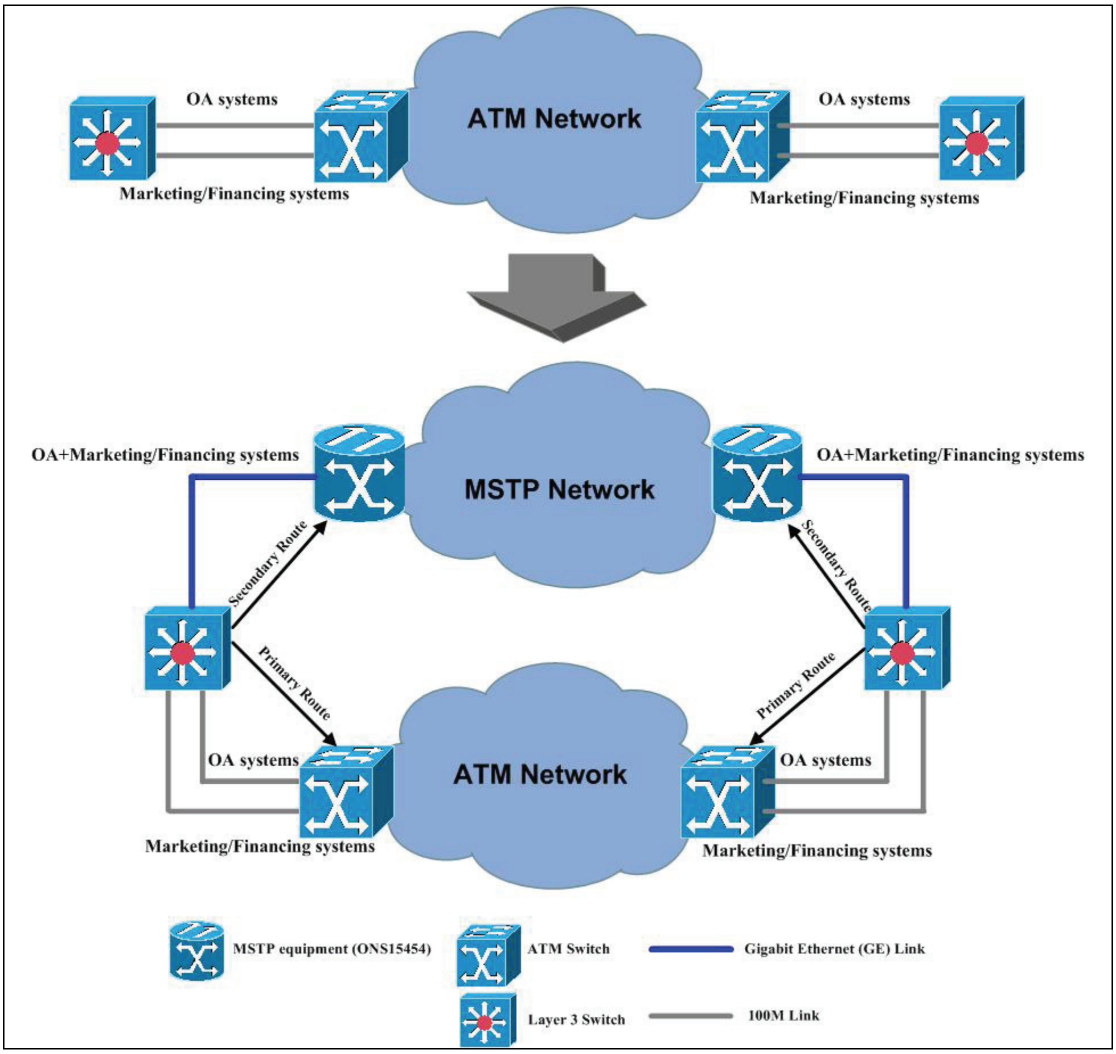

Figure 6.9: Configure MSTP Network as a Backup Route of Legacy ATM Network

For those professional applications of power systems run within the legacy ATM-based Shanghai Power Dispatching Network (ShPDnet), there is also a demand to migrate specialised operations onto ShPTnet. This is primarily due to the obsolesced of the ATM network is becoming the bottleneck of today's high density data service surroundings, especially in transmission speed and capacity. As a consequence, the MSTP network has been configured as a backup route of the existing ATM infrastructure of ShPDnet.

6.7 Future Development and Layout of the ShPTnet

Phase one of this ongoing project has now been implemented, and all TDM and IP-based applications have been in operation since June 2004. The future development of ShPTnet will centre on several key points.

There are currently two remote data centres of SMEPC which are established as disaster backups for each other. For interconnecting and synchronizing both data centres, the carrier MSTP provides a direct support of optical storage networking applications such as fibre channel (FC) and Enterprise Systems Connection (ESCON). Firstly, this solves the potential problems in compatibility and stability between transmission and storage networking systems, as well as reducing the engineering difficulty from operation and maintenance.

Secondly, with the development trends of power system communications moving forward into IP-based broadband applications, future ShPTnet will upgrade the bandwidth of edge ring from 2.5G to 10G and that of the core ring from 10G to 40G to 320G (DWDM). The ONS15454 can also apply a line rate of 10GBE connection with internal layer 3 switches which eliminate the bottleneck in terms of LAN data service aggregation. Thirdly, for present special power system applications, SMEPC will disconnect the primary route to the ATM network, and migrate those applications from ShPDnet onto the next generation ShPTnet until to the product lifecycle decommissioning of ATM equipment in the near future (see Figure 6.10).

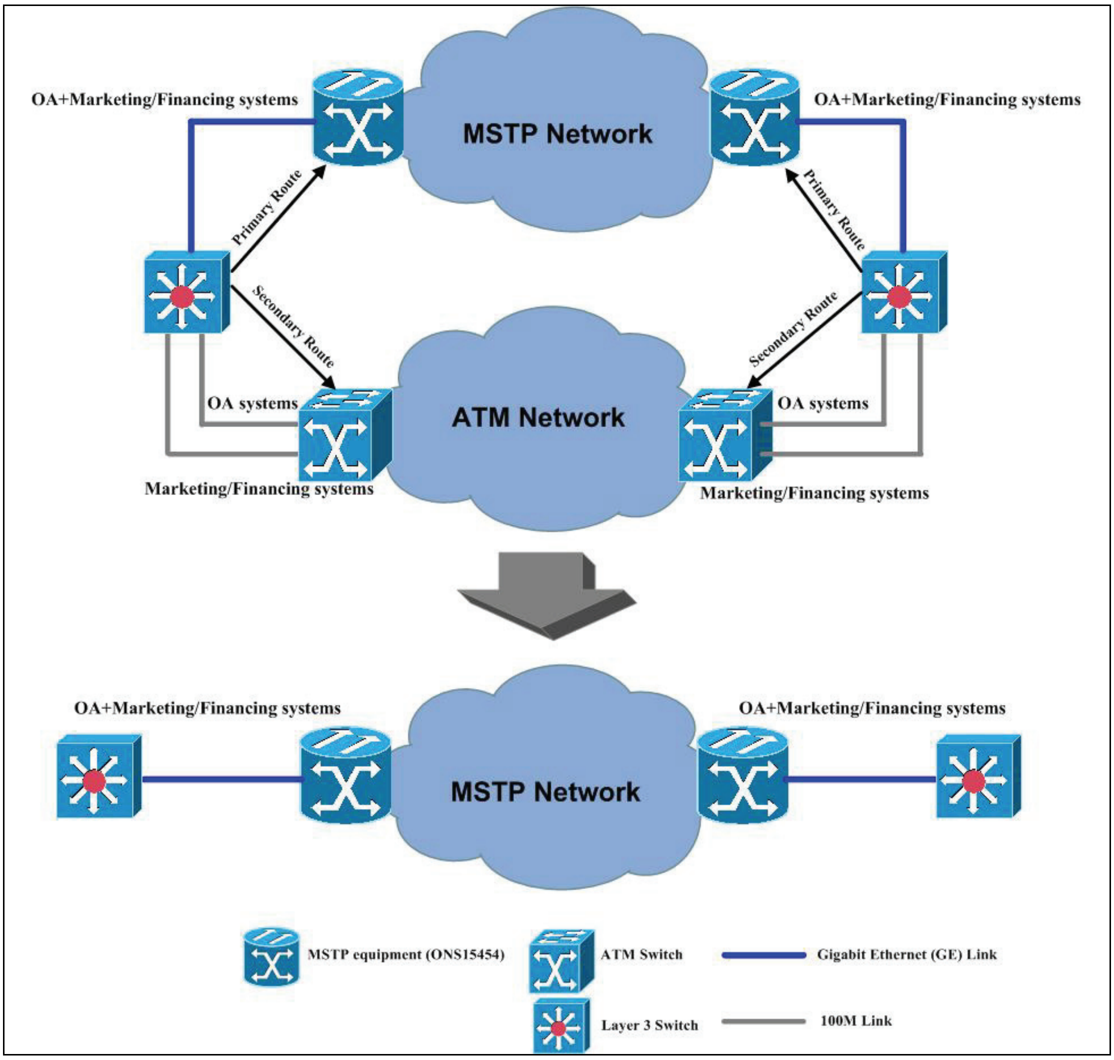

Figure 6.10: Migrate Services from Legacy ATM network onto the Unitive MSTP network

As the present ShPTnet holds multiple autonomous subsystems such as SMEPC online, marketing and financing sections which not only emphasises the need for bandwidth, but also brings strict requirements on network security. In doing so, there are two general security solutions. One solution is to provide physical (layer 2) isolated bandwidth channels with routing mechanisms for individual subsystems based on inherent RPR features of MSTP network. However, to archive flexible intersystem connection and efficient bandwidth control, it needs to apply MPLS technology onto MSTP network for implementing layer 3 Virtual Private Network (VPN) services (MPLS/VPN) (IETF, 1999), which is a mature security technique widely adopted by service providers. In this case, the combination of both solutions will be an accurate answer for SMEPC. In particular, specialised RPR channels can be configured for those pivotal sections to gain maximum safety, whereas the MPLS/VPN architecture is operable to differentiate normal Intranet and OA applications with specific security levels and to provide corresponding VPN services.

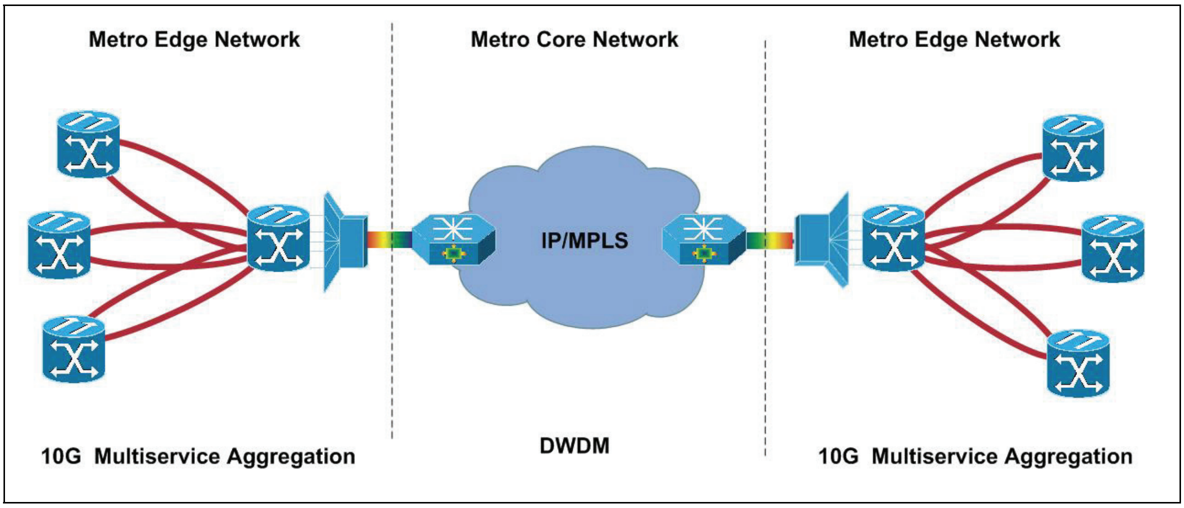

Figure 6.11: A Landscape of the Future ShPTnet Network Infrastructure

According to these development trends, intending ShPTnet continue to extend the core data control plane to an IP/MPLS+DWDM architecture, and provide traditional TDM operations, 10GBE broadband access as well as specialised VPN services with in a standard MSTP-based OTN (see Figure 6.11). This up-to-date optical transport infrastructure is expected to ensure future SMEPC in their fully networked business environment with ultimate efficiency, flexibility and reliability, which maximise their competitive power toward enterprise informatisation.

6.8 A Roadmap of the Development Trends of ShPTnet

After presenting a detailed case observation, a roadmap demonstrating the whole development trends of ShPTnet infrastructure is finally archived. As illustrated in Figure 6.12, firstly, the core bandwidth of ShPTnet expanded rapidly from 155 Mbps to 10 Gbps, and will continually upgrade to 32 x 10 Gbps as the increase of future networked business demands of SMEPC. Secondly, as the ShPTnet is a representative metro core OTN system with DWDM support, it will gradually adopt advanced network protection technologies, from legacy TDM-based SNCP to the latest

IP-oriented RPR and MPLS-FRR, and to the uniform WDM-based GMPLS-FRR with wavelength protection (Chen, 2006: 91-94). Thirdly, the network service architecture will also upgrade from simplex TDM system to multiple IP-oriented data services, and to the MPLS-based VPN data services with maximum efficiency and security. In the meanwhile, the roadmap shows the future development orientations of optical transport infrastructure will migrate from TDM-based to WDM-based, and will emphasise on the convergence of IP and Optical layers, along with more network management flexibility and efficiency. This also reflects the evolutionary steps of OTN infrastructure, which is from the Static IP Optical Control Plane to the Dynamic IP Optical Control Plane and to the Integrated IP Optical Control Plane. In general, the roadmap can be considered as another evaluation of the proposed framework, in terms of the development of network efficiency in real OTN business projects.

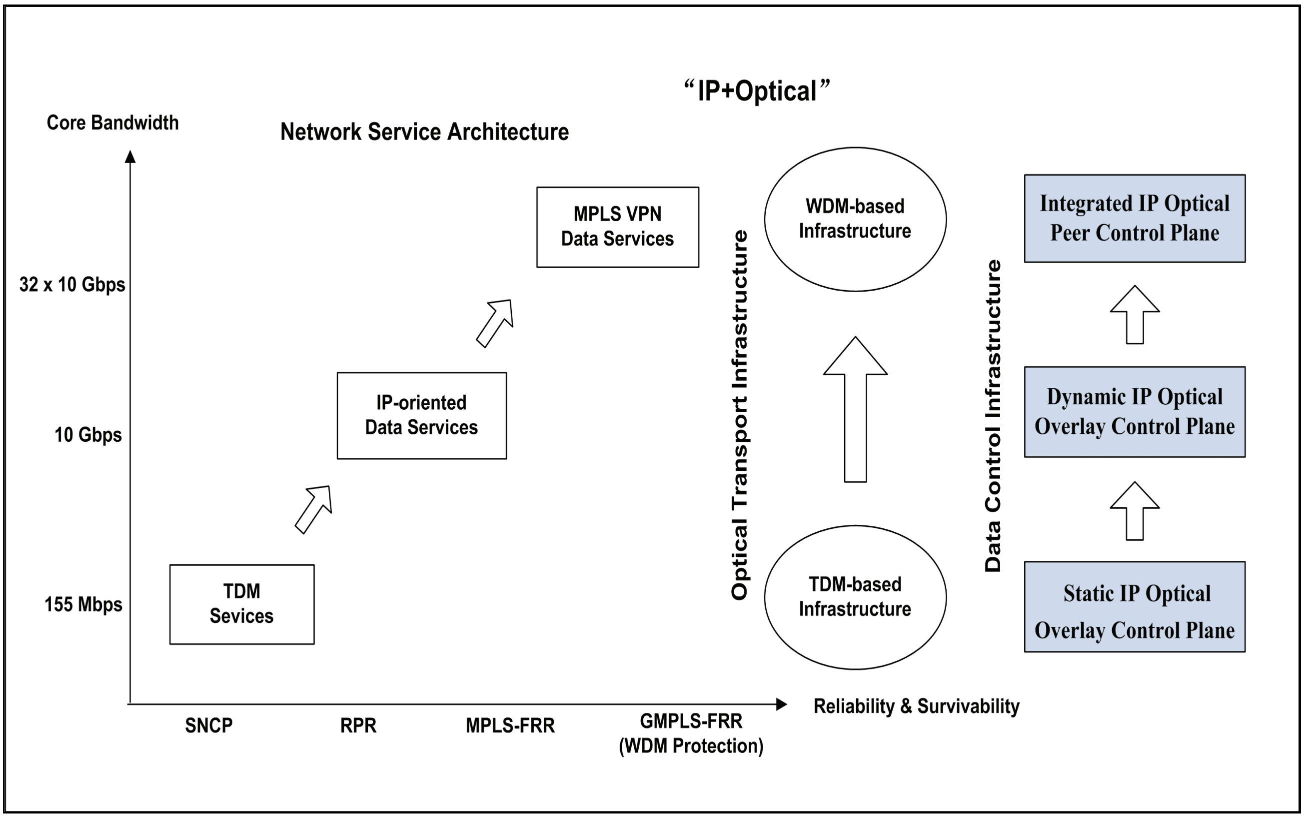

Figure 6.12: A Roadmap of the Development Trends of ShPTnet

6.9 Conclusion

This chapter provided a comprehensive case of a large ongoing OTN system upgrade project of the next generation ShPTnet. It provided an in-depth study on the engineering implementation processes, including the technical requirements analysis, overall system constructions and future development layout of the next generation ShPTnet. This revolutionary optical transport infrastructure is expected to ensure future SMEPC in their fully networked business environment with unprecedented efficiency, flexibility and reliability. Thus, the project demonstrates the latest trends in the optical transport service of metro and regional power system communications. This project can also to be considered a state of the art ICT implementation in power system communication and management field for other areas of China and even the entire Asia Pacific region.

This chapter also illustrates the development trends of OTN for large enterprises and organisations, especially on the infrastructure optimisation and resource utilisation of their legacy optical networks. The observation result, which is a network development roadmap, shows that the evolutionary progress of future business oriented OTN infrastructure will primarily suit the proposed infrastructural framework theoretically and commercially. As the above chapter five already provided a detailed analysis on the framework from the network protection standpoint, this chapter presented a systematic evaluation on the framework from the network efficiency standpoint. Thus, the outcomes of these two chapters, which would be considered as two crucial validations of the framework, are summarised in the conclusion of this research.

Chapter 7: Conclusion

7.1 Principal Conclusion

7.1.1 Major Contributions

There are three major contributions of this research. Firstly, a framework demonstrating the future development orientations of the OTN infrastructure was developed and explained. The framework illustrates that the future OTN infrastructure will emphasise the convergence of IP-oriented data services and optical transport foundations. It shows the data control plane of future OTN systems will gradually migrate from the initial overlayed IP Optical static model to the ultimate integrated IP Optical peer model. In the meanwhile, the framework also indicates that next generation OTN systems will focus on enhancing network reliability and efficiency, which are two significant dimensions of the framework evaluated. Secondly, this research provides a systematic analysis on the development of protection technologies in metro core optical networks, along with a field test of OTN network fast recovery from a real ISP lab. This test provides a statistical analysis on the performance of the OTN protection by utilising the emerging MPLS-TE FRR network recovery technology. In addition, it can be considered by other optical service providers as a practical experiment in evaluating the framework from the network survivability aspect. Thirdly, this thesis gives a representative case study of a large OTN engineering project of SMEPC. It produces an evolutional roadmap demonstrating the infrastructural development of this ongoing project. The roadmap can be also utilised by other large enterprises in optimising their existing OTN network service architecture. Moreover, it provides crucial observational evidence for validating the framework from the angle of OTN network efficiency.

7.1.2 Minor Contributions

There are also a number of minor contributions of this thesis. First, this research provides an exhaustive referencing and historical overview on the topic of the OTN infrastructure. It also presents a systematic comparison between the legacy, current and future OTN network protection technologies. Second, various OTN infrastructure design and implementation diagrams and topologies are provided as visual guides for network planners. Third, as the case study was conducted based on a large electric power company, it gives some inspiration for other power suppliers or related industries on designing and implementing their specific next generation telecommunication system by utilising the latest OTN technologies.

7.2 Major Implications

This research aims to provide a clear vision of the evolutionary process of the OTN infrastructure. The potential readers are expected to be network planners, especially for network managers and CTOs from large enterprises and service providers. The proposed framework will assist them to access the latest trends within the development of the OTN infrastructure, including related industry standards, advanced technologies and market directions. Thus, the framework will ensure those readers have a guide to build the next generation optical backbones to suit their increasing and complex networked business demand. This research focuses mostly on the metro OTN system due to the rapid increase of the metro optical networking market in recent years. The operation model of delivering data services across a metro optical ring structure is recognised as a most effective solution with sufficient reliability. Therefore, the potential target market of the framework will be middle to large cities or regions with dense populations and business environments. As most metropolises have a centralized demand market of various network services, it is reasonable to believe that the high efficient **IP over Optical** OTN service architecture will be firstly deployed in these areas.

7.3 Links to Earlier Findings

There are several links between this research and related OTN industry standards.

Firstly, the ITU-T recommendation G.871 and G.872 defined the initial fundamentals of OTN, including various technical specifications of optical transport components and optical transport technologies. However, this research focuses on optimising the existing and future OTN infrastructure, by demonstrating the development trends in network service architecture, system reliability and efficiency. Secondly, as MPLS-TE FRR (RFC4090) approved by IETF in mid-2005, this research provides a crucial field test on this innovative network protection technology by using commercial equipments. In addition, there is also a detailed technical comparison between the test results of MPLS-TE FRR with other emerging OTN protection technologies such as the RPR (IEEE 802.17). On the other hand, there are also some connections between this thesis and former research. Some previous researchers focused on improving the infrastructure of related optical data communication system, such as Optical Grid Computing Networks (Simeonidou, Nejabati & O'Mahony, 2004) and Optical Storage Networks (DeCusatis, 2005). However, the proposed OTN infrastructural framework of this study can be considered as a common solution in enhancing their achievements. Moreover, the case study, which is a successful example of the next generation OTN project in power system communications, will also assist them in designing and implementing their specialised OTN-based communication systems.

7.4 Recommendations

7.4.1 CWDM or DWDM?

As one of the main themes of this research surrounded DWDM, it should be stated again that this technology is still overpriced due to the present immature photoelectric manufacturing techniques. There are some pivotal technical difficulties needed to be solved urgently. For example, the current backbone line rate are typically running at OC-192/STM-64 (10 Gbps) or OC-768/STM-256 (40 Gbps) level which require much higher optical operating power than ever before. Under this circumstance, the optical signal-to-noise ratio (OSNR) will drop dramatically and some particular physical impairments such as optical attenuation, dispersion and fibre nonlinearities will become more visible. Moreover, higher operating power will also lead to overlap between different wavelength channels because of the temperature flapping during signal transmission. In most long-haul DWDM systems, the latest laser monitoring and cooling systems have to be applied which result in even more expensive productive costs.

Consequently, a new recommendation named G.695 'Optical Interfaces for Coarse Wavelength Division Multiplexing (CWDM) Applications' has been introduced and approved by the ITU-T in last year. CWDM is intended to find a balance between performance and economics at this phase. It defines three operational spectrum windows that can be flexibly utilised to multiplex signal under maximum 16 wavelengths per fibre. DWDM system usually use wavelength spacing level at 0.1nm to 1nm, contrastively, CWDM broadens this with a much wider wavelength gird at 20nm. Thus, a 30%-50% cheaper (Fibres.org, 2005: 2) WDM-based solution with simpler system architecture is achieved. Although CWDM is an emerging technology, it tends to be popular in the optical transport market, adopted by medium scale enterprises and ISPs who require large network bandwidth (save fibre resources) while are sensitive to the capital investment.

7.4.2 GMPLS or ASON?

In this paper, the main outcome is inspired by RFC3717 'IP over Optical Networks: A Framework'. Unassailably, IP is recognised as the dominator standard represents future development trends of the whole internetworking and telecommunication industries. For satisfying future transport foundational requirements, how the OTN infrastructure adapts and interoperates with upper IP data control plane, is the major goal of GMPLS developed in the IETF. However, another emerging recommendation named Automatically Switched Optical Network (ASON) architecture was proposed by the ITU-T (2001d). This architecture is recently becoming a new attraction in the OTN market, especially for the metro optical data transport field (Alcatel, 2005: 6).

By contrast with GMPLS, ASON emphasises more on the detail issues of the OTN implementation and deployment aspects, including the adaptation process of the OTN infrastructure with traditional telecoms elements such as ATM and SONET/SDH systems.

As described in previous chapters, the basic conception of GMPLS is to merge all network elements (from IP to TDM to WDM) onto a common control environment, which is the simplified peer mode control plane. Comparing with this progressive approach, the methodology of ITU seems more conservative. Basically, ASON concerns on the infrastructure migration tasks from legacy TDM-based network onto WDM-based OTN within an overlay mode control plane. It is an explicit architecture defines a suit of top-down requirements, rather than control protocols, for all individual subsystems in the OTN infrastructure. The OIF, interestingly, plays an impartial role (see Figure 7.1) in the competition of the OTN data control plane.

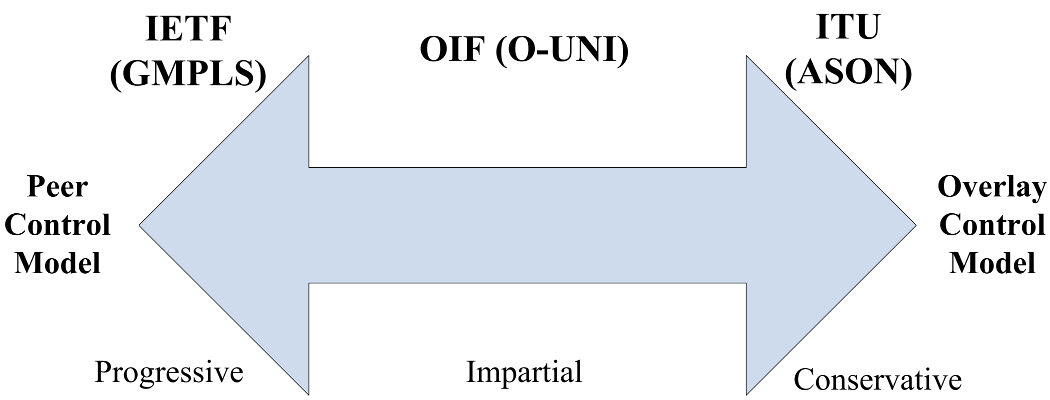

Figure 7.1: The Major Role (Achievements) of each OTN Standards Organisation

Due to the composition of the OIF are mainly equipment vendors, the primary mission of them focuses on improving optical transport technologies. However, after the acknowledgement from the market of O-UNI 1.0, which is based on ASON requirements with adoption of GMPLS protocols, the OIF will keep on working with its second version (Nic, 2002: 8). This factor possibly illumine IETF and ITU to start collaborating with each other, for accelerating the process on building an intelligent

OTN, in terms of fast network implementation and service provision with automatic wavelength routing and restoration. Therefore, an OTN solution called ASON/GMPLS architecture has emerged. Very positive to this is that a series of worldwide ASON/GMPLS field interoperability testings were conducted by the OIF recently (Foisel, 2004), which means that practical deployment is imminent.

7.4.3 Future Research

As described in chapter one, the framework developed in this study is expected to be utilised as a guideline for network planners from large enterprises and ISPs in building their carrier level optical-based business data communication infrastructure. This research emphasises on data transport performance rather than cost within a reasonable capital investment. This is the reason why this thesis mainly centres on DWDM optical transport technology, which satisfies infrastructural level business data communication requirements with great scalability and flexibility. However, with the continuous development of the OTN, CWDM is becoming a more cost-effective solution in optical data communication, especially for medium size enterprises and ISPs who require abundant network bandwidth with a lower cost. As a consequence, one of the future research intensions will focus on CWDM technology and its market. In particular, there is a need for more case studies to be conducted from different industry environments to evaluate the practical performance of CWDM technology in building the future OTN systems. Furthermore, future research will consider more commercial issues, such as the optimisation of total cost and the migration process of legacy systems

In addition, due to the fact that the latest ASON architecture is still immature and needs to be further approved, the main outcome of this research is developed based on the RFC3717, which is recognised as an effective model in OTN implementation till now. Nevertheless, as the big success of O-UNI 1.0, it is reasonable to accept that the future OTN infrastructural development in terms of the data control plane aspect will accentuate the interoperation of ASON and GMPLS. As this research provided a large scale MPLS-based network protection test, it is highly recommended to extend the representative test bed to the GMPLS-based environment. Moreover, since this research evaluated the proposed framework from network reliability and efficiency, however, a more comprehensive analysis from other aspects such as network management should be conducted in the future.

7.5 Conclusion

This research presents a legible landscape of the development trends on current and future OTN infrastructure, along with a systematic evaluation from two representative dimensions. As this work has used a great deal of references from standard bodies, one could argue that depending on which organisation you belong to, it can determine the accurate directions of future OTN development. Different bodies are known for their own unique standardising approaches. For example, the IETF can be considered progressive and the ITU conservative. If these bodies do not collaborate in the future, the progress of OTN infrastructure will be stifled. However, with the best effort of those impartial parties, it is reasonable to believe that a more great deal can be achieved.

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Acronyms

ADSL	Asymmetrical Digital Subscriber Loop
AMR	Automatic Metering Reading
ANSI	American National Standards Institute
ASIC	Application-Specific Integrated Circuit
ASON	Automatically Switched Optical Network
ATM	Asynchronous Transfer Mode
BLSR	Bidirectional Line-Switched Ring
CR-LDP	Constraint-Routing Label Distribution Protocol
CWDM	Coarse Wavelength Division Multiplexing
DSS	Decision Support System
DWDM	Dense Wavelength Division Multiplexing
DPT	Dynamic Packet Transport
EMS	Energy/Element Management System
ERP	Enterprise Resource Planning
ESCON	Enterprise Systems Connection
FC	Fibre Channel
FDM	Frequency Division Multiplexing
FDDI	Fibre Distribution Digital Interface
FSC	Fibre Switch Capable
FTTB	Fibre to the Building
FTTC	Fibre to the Curb
FTTCab	Fibre to the Cabinet
FTTH	Fibre to the Home
GBE	Gigabit Ethernet
GFP	Generic Framing Procedure
GMPLS	Generalized Multiprotocol label Switching
GUI	Graphic User Interface
IEEE	Institute of Electrical and Electronics Engineering

IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
IP	Internet Protocol
iSCSI	Small Computer System Interface over Internet Protocol
ISIS	Intermediate System to Intermediate System protocol
ISP	Internet Service Provider
ITU	International Telecommunication Union
LAN	Local Area Network
LCAS	Link Capacity Adjustment Scheme
LCT	Local Craft Terminal
LDP	Label Distribution Protocol
LSC	Lambda Switch Capable
LSP	Lable-switched Path
LSR	Lable-switched Router
MAC	Media Access Control
MAN	Metropolitan Area Network
MIS	Management Information System
MPLS	Multiprotocol Label Switching
MPLmS (MPλS)	Multiprotocol Lambda Switching
MS-SPRing	Multiplex Section Shared Protection Ring
MSPP	Multiservice Provisioning Platform
MSSP	Multiservice Switching Platform
MSTP	Multiservice Transport Platform
NFS	Network File System
NNI	Network Node Interface
OA	Optical amplifier
OADM	Optical add/drop multiplexer
OIF	Optical Internetworking Forum
OSPF	Open shortest path first

OVPN	Optical Virtual Private Network
OXC	Optical cross-connect
PHB	Per-Hop Behaviours
PMOS	Power Market Operation System
POS	Packet over SONET/SDH
PSC	Packet Switch Capable
QoS	Quality of Service
RPR	Resilient Packet Ring
RSVP	Resource Reservation Protocol
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SCNP	Subnetwork Connection Protection
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SONET	Synchronous Optical Network
SPC	Stored Program Controlled
SRP	Spatial Reuse Protocol
TDM	Time Division Multiplexing
TE	Traffic Engineering
UNI	User Network interface
UPSR	Unidirectional Path Switched Ring
VCAT	Virtual Concatenation
VCI	Virtual Circuit Identification
VPI	Virtual Path Identification
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WR	Wavelength Router