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DESIGN AND PERFORMANCE ANALYSIS OF PURE AND HYBRID WDM OPTICAL NETWORKS

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ABSTRACT

In optical networking, information-bearing electrical signals are transported by up-converting the signals into the optical domain and then transmitting them over high-capacity low-loss optical fiber links. Furthermore, optical switching nodes with a large throughput can be used to alleviate the contention for fibers, route the optical signals and avoid failed fiber links. This guarantees a robust always-on service for entities transporting their signals via the optical network. Based on those merits, optical networking technologies are now being increasingly adapted in most operational medium and long range networks. Of the existing technologies, wavelength-division multiplexing (WDM) transmission is ubiquitous due to its ability to multiply the capacity of the installed fiber base and to enhance the flexibility of provisioning of the fiber capacity by utilizing the wavelength degree of freedom in an intelligent optical layer.

This thesis focuses on flexibility improvement techniques that enable dynamic provision of bandwidth available in optical networks within acceptable cost bounds. The aforementioned nodes for optical connection provisioning are studied in detail. From the study, novel node architectures are proposed with improved scalability for handling more connections and reduced signal impairment for increased transmission range. The thesis proposes techniques for incorporating dependability enhancement during initial node design stage and the gradual node scaling after deployment by optimizing the allocation of redundant modules. Analytical comparison based on example dependability-enhanced nodes indicate significant improvements compared to corresponding nodes without redundancy.

Hybrid WDM networks utilize an extra optical degree of freedom in addition to signal wavelength. The virtues of hybrid WDM as an optical layer grooming method are investigated. To that end, the thesis pays particular attention to hybrid OCDM (optical code-division multiplexing)/WDM transmission. The connection acceptance improvement due to OCDM/WDM transmission is analysed and the possible limitations of various light-path schemes are noted. The potential application of hybrid WDM for radio-over-fiber systems is explored for an urban-wide hierarchical metropolitan network. In that case, the more complex hybrid WDM scheme showed significant improvement in utilization of optical resources compared to conventional WDM implementation. Semi-hybrid WDM is proposed as a compromise solution between pure and hybrid WDM implementations. Furthermore, a 60 GHz radio-over-fiber OCDM/WDM system is proposed and guidelines are presented for possible performance improvement.

Keywords: Optical networking, Optical layer, Wavelength-division multiplexing, Optical cross-connects, Optical add-drop multiplexers, Transmission performance, Hybrid WDM, Optical code-division multiplexing, Radio-over-fiber

PREFACE

The work in this thesis was carried out at the Communications Laboratory of the Helsinki University of Technology (HUT). I take this opportunity to express my sincere gratitude to my supervisor Professor Sven-Gustav Häggman, as well as previous supervisors: the late Professor Seppo J. Halme and A. Professor Raymond Rugemalira, for providing me with the opportunity to do this work. Moreover, their continuous guidance, valuable comments, proofreading of the thesis and numerous stimulating discussions is immensely appreciated. The administrative and support staff of the Communications Laboratory also in one way or another made the path even smoother, for that I am thankful.

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To my sisters, brothers, friends and the Tanzanian community in Finland, I thank you warmly for providing me with a home away from home. The comfort I derived from that kept me in the right frame of mind as I embarked on this challenging voyage.

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Last but not least, I thank my parents for providing me with the proper means and encouragement for me to wade through the wide and deep academic pond. For that I shall be eternally grateful and hope that they may share in whatever joy or success that may come my way.

Espoo, June 10, 2004

Edward Mutafungwa

This thesis is dedicated to the memories of Robert Mutafungwa and Seppo J. Halme.

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LIST OF FIGURES

LIST OF PUBLICATIONS

The thesis is comprised of a detailed introduction and an appendix with the following publications henceforth referred to as [P1], [P2], ..., [P8].

[P1]. **E. Mutafungwa**, "Circulating loop simulations for transmission performance comparison of various node architectures," *Journal of Optics A: Pure and Applied Optics*, Vol. 3, no. 4, pp. 255–261, Jul. 2001.

[P2]. **E. Mutafungwa**, "Optical hop number limits imposed by various 2×2 cross-connect node designs," *Optics Express*, Vol. 9, No. 8, pp. 400–410, Oct. 2001.

[P3]. **E. Mutafungwa**, "An improved all-fiber cross-connect node for future optical transport networks," *Optical Fiber Technology Journal*, vol. 7, no. 3, pp. 236–253, Jul. 2001.

[P4]. **E. Mutafungwa** and K. Kazaura, "A modified optical add-drop multiplexer with improved transmission performance," Presented at *The 7th Asia-Pacific Conference on Communications, APCC 01*, Tokyo, Japan, 17–20 Sep. 2001 and published in IEICE Transactions on Communications Vol. E84-B, No. 11, Appendix pp. 546-549, Nov. 2001.

[P5]. **E. Mutafungwa**, "GORA: An algorithm for designing optical cross-connect nodes with improved dependability," *Computer Communications*, Vol. 25, No. 16, pp. 1454-1464, Oct. 2002.

[P6]. **E. Mutafungwa** and S. J. Halme, "Analysis of the blocking performance of hybrid OCDM-WDM transport networks," *Microwave and Optical Technology Letters*, Vol. 25, No. 16, pp. 1454–1464, Oct. 2002.

[P7]. **E. Mutafungwa**, S. J. Halme, K. Kazaura, M. Matsumoto and T. Wakahara, "Strategies for resource provisioning in optical networks supporting broadband wireless access networks," *Journal of Optical Networking*, Vol. 2, No. 3, pp. 55–68, Mar. 2003.

[P8]. **E. Mutafungwa**, S. J. Halme, K. Kazaura, M. Matsumoto and T. Wakahara, "Millimeter wave over fiber systems using hybrid OCDM/WDM Transmission," *International Journal of Infrared and Millimeter Waves*, Vol. 24, No. 7, pp. 1113–1126, Jul. 2003.

LIST OF ACRONYMS

AN	Access Node
ANSI	American National Standards Institute
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BWAN	Broadband Wireless Access Networks
CC	Code Converter
CCP	Control-layer Control Plane
CVWP	Code Virtual-Wavelength Path
CWDM	Coarse WDM
CWP	Code Wavelength Path
DGD	Differentical Group Delay
DN	Distribution Node
DWDM	Dense WDM
EDFA	Erbium-Doped Fiber Amplifier
ETSI	European Telecommunications Standards Institute
FAP	Fixed Access Point
FBG	Fiber Bragg Grating
FCAPS	Fault, Configuration, Accounting, Performance and Security
FEC	Forward Error Correction
FFP	Fiber Fabry-Perot
FSC	Fiber-Switch Capable
FTIR	Frustrated Total Internal Reflection
GA	Genetic Algorithm
GMPLS	Generalized Multiprotocol Label Switching
GORA	Genetic Optimum Redundancy Allocation
GVD	Group Velocity Dispersion
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
ITU	International Telecommunication Union
ITU-T	ITU Telecommunication Standardization Sector
LAN	Local Area Network
LSC	Lambda Switch Capable

LSP	Label Switched Path
L2SC	Layer-2 Switch Capable
MAN	Metropolitan Area Network
MEMS	Micro Electro-Mechanical Systems
MMW	Millimeter-Wave
MZI	Mach-Zehnder Interferometer
NDF	Nonzero Dispersion-Shifted Fiber
NNI	Network-Network Interface
NP	Nondeterministic Polynomial
NPV	Net Present Value
NRZ	Non-Return to Zero
OADM	Optical Add-Drop Multiplexer
OC	Optical Circulator
OCDM	Optical Code-Division Multiplexing
OCh	Optical Channel
OCP	Optical-layer Control Plane
OCSP	Optical Carrier Service Provider
ODU	Optical Data Unit
OEO	Optical-Electrical-Optical
OIF	Optical Internetworking Forum
OMS	Optical Multiplex Section
OMUI	Optical Multiuser Interference
OOC	Optical Orthogonal Codes
OOK	On-Off Keying
OOO	Optical-Electrical-Optical
OSNR	Optical Signal-to-Noise Ratio
OTDM	Optical Time-Division Multiplexing
OTM	Optical Transport Module
OTN	Optical Transport Network
OTS	Optical Transmission Section
OTU	Optical Transport Unit
OXN	Optical Cross-Connect Node
PBG	Polymer Bragg Grating
PDH	Plesiochronous Digital Hierarchy
PIC	Photonic Integrated Circuit
PMD	Polarization Mode Dispersion

PP	Power Penalty
PSC	Packet Switch Capable
PXN	Photonic Cross-Connect Node
QoS	Quality-of-Service
RAP	Radio Access Point
RCA	Routing and Channel Assignment
RF	Radio Frequency
RFC	Request for Comments
SAN	Storage Area Network
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SMF	Standard Singlemode Fiber
SONET	Synchronous Optical Network
SPRing	Shared-Protection Ring
STM	Synchronous Transport Module
STS	Synchronous Transport Signal
TDM	Time Division Multiplexing
TSC	TDM Switch Capable
UNI	User-Network Interface
VCWP	Virtual-Code Wavelength Path
VCVWP	Virtual-Code Virtual-Wavelength Path
VWP	Virtual-Wavelength Path
WC	Wavelength Converter
WDM	Wavelength-Division Multiplexing
WP	Wavelength Path
WSC	Waveband Switch Capable
1R	Regeneration without Retiming or Reshaping
2R	Regeneration with Reshaping
3R	Regeneration with Retiming and Reshaping

LIST OF SYMBOLS

S_v	Set of nodes in a network
v_i	ith member of S_v
V	Number of network nodes
S_ℓ	Set of links incident on a node
ℓ_i	ith member of S_ℓ
D	Number of incoming/outgoing links on a node
S_f	Set of fiber links in a network
f_i	ith member of S_f
F	Number fibers in a single cable link
S_ω	Waveband set
ω_i	ith member of S_ω
W	Number of wavebands in a single fiber
S_λ	Wavelength set
λ_i	ith member of S_λ
N	Number of distinct wavelengths in a single fiber
Λ	Maximum number of channels on a single fiber
Δf_s	Interchannel frequency spacing
$\Delta\lambda_s$	Interchannel wavelength spacing
S_x	xDM channel set
x_i	ith member of xDM channel set
ρ	Bragg grating reflectivity
Ψ	Total revenues attributed to a particular node
C_{Tot}	Costs attributed to a particular node
δ_t	Discount factor over period t
S_c	Code set
c_i	ith member of code set
$c_n^{(j)}$	nth chip of code c_j
B	Bit Rate
L_c	Length of code (processing gain)
w	Code weight
T_c	Chip duration
$\psi^{(j,k)}$	Cross-correlation between codes c_j and c_k
P_b	Bit error probability
ϵ	Pulse spreading to bit duration ratio

Δf	Spectral Width
D_{GVD}	GVD Coefficient
$\langle \Delta\tau \rangle$	Time-average DGD
D_{PMD}	PMD Coefficient
$PP_{\mathrm{dB,PMD}}$	Power penalty due to GVD
$PP_{\mathrm{dB,PMD}}$	Power penalty due to PMD
α	Pulse form factor
γ	Power splitting ratio between two polarization states
P_B	Blocking probability
ρ_{h_j}	Offered load on the jth hop
ϱ	Reflectivity
$H_{\max}$	Maximum number of hops
G	Granularity

1. INTRODUCTION

1.1 Motivation

Optical-based communications networks employing optical fiber links (waveguides) possess significant advantages over other transmission media such as air and copper wires. [1–3]. These include, a virtually inexhaustible fiber capacity and relatively lower levels of signal impairment. Furthermore, signal transmission at different wavelengths (that is, optical frequencies located within the 185-385 THz range) for *wavelength-division multiplexing* (WDM) has improved utilization of existing fiber plant and enhanced network flexibility [3–9]. Moreover, major breakthroughs in optical device technologies (e.g., optical amplifiers [10]) and mass deployment of fiber in the late 1990s has moved fiber closer to users and has lowered the optical transmission cost per information bit.

The wavelength-based flexibility of WDM and high capacity of fibers has inspired the development intelligent optical networking [2, 5, 11]. The "intelligence" here refers to the capabilities for arbitrary topology discovery, computation of routes, automated bandwidth provisioning and restoration from network failure [12]. Therefore, intelligent optical networks are able to provide a dynamic, flexible, expedited, streamlined and reliable information transport service for legacy networks. Moreover, such optical networking techniques are generally considered to be an attractive option for all tiers of the communication network hierarchies. However, several challenging obstacles have to be overcome before the vision of intelligent optical networking becomes a reality. The obstacles include, among others, the need for cost-effective designs (e.g., for switching/routing [2, 5], signal quality maintenance [13] etc.), effective symbiosis with legacy networks [12] and efficient optical resource management [11].

The objectives of this thesis—based upon the aforementioned obstacles—are three-fold. First, the impact of various reconfigurable optical nodes on overall network transmission performance is analyzed. These nodes are the most essential building block for intelligent optical networks. The second objective is the exploitation of the knowledge of transmission performance of various nodes to propose novel node architectures and design techniques. Finally, the third objective is the study and development of complimentary optical multiplexing stages as a means of scaling and streamlining optical layer bandwidth resources.

1.2 Main Research Contribution

The primary research contributions presented in this thesis are in the general areas of optical switching and bandwidth resource utilization. Using a simulation setup devised and tested in [P1], an extensive study and performance comparison of previous optical switching node proposals was carried out in [P2]. Based on the observations of [P2] novel all-fiber all-optical nodes for mesh and ring topology optical networks are proposed in [P3] and [P4] respectively. These nodes demonstrate enable longer coverage without electronic regeneration by reducing impairment effects on the WDM signals they handle. Furthermore, the all-fiber nodes can be implemented with a relatively lower number of component modules compared to other nodes of similar dimensions. By considering the large traffic streams handled in the optical layer, a dependability design concept is proposed in [P5] for general optimized discrete optical node design with maximum robustness for given cost constraints. Moreover, the dependability-based technique enables the evaluation of efficient upgrade options for node scaling.

The potential of hybrid WDM is analyzed as an optical layer grooming technique for improving optical resource utilization. Focus is placed on hybrid OCDM (optical code-division multiplexing)/WDM transmission networks. An analysis of the blocking of connection requests in hybrid OCDM/WDM networks is carried out in [P6]. The analysis considers the 4 new possible lightpath schemes created by the hybrid OCDM/WDM. A lightpath scheme which enables code and wavelength routing with wavelength conversion is identified as providing the right balance between cost and resource utilization efficiencies. Application of hybrid WDM in optical networks handling heterogenous fixed and wireless traffic is proposed and guidelines for optimum implementations are presented in [P7]. Three WDM schemes (pure, semi-hybrid and hybrid WDM) are considered and analyzed for a heterogenous traffic metropolitan access network. Furthermore, a radio-over-fiber system using hybrid OCDM/WDM transmission is proposed in [P8].

1.3 Organization of the Thesis

The primary goals of the thesis have been summarized in Section 1.2. The rest of the thesis is organized as follows. In Chapter 2, the prevailing trends in optical networking are described in detail. Section 2.1 maps out the immediate evolution paths for optical networking. Particular attention is paid to the optical layer implementation and signaling standards in Sections 2.1, optical node operation in Section 2.2 and resource allocation in Sections 2.3/4. Chapter 3 outlines the research framework by providing a background of the main research subtopics, namely, transmission performance analysis (Section 3.1), optical node design (Section 3.2) and hybrid WDM (Section 3.3). In Chapter 4, a compendium and clarifications are presented for each of the Publications [P1]-[P8] (the actual publications appear in Appendix A). Finally, Chapter 5 provides concluding remarks and speculates on future research topics.

2. TRENDS IN OPTICAL NETWORKING

The evolution of the information communication technologies has always been driven by the changes in the quantity and type of information to be communicated between any two (or more) distinct locations or users. In the previous decade, the make-up of the information—previously dominated by vocal information—has been transformed into a potpourri of audio/voice, alphanumeric and pictorial information. This is attributed to the fact that, in a period that has come to be known as the "information age", the use information communication technologies permeate virtually all societal pursuits (e.g., academic, political, entertainment, business etc.).

It is therefore paramount that communication networks are reliable, affordable, flexible, scalable and possess substantial information carrying capacity, so as to meet the increasingly high user expectation of the communication services. Furthermore, the promise of increased revenue streams and the deregulation of the communications market has attracted new entrants keen on competing against the incumbent network operators for service provision. Therefore, this competitive and dynamic communications market demands strategic selection of the most optimum networking solutions for increased user satisfaction and operator success [14].

Among the identified solutions are technologies for facilitating and handling optical information signals [1–3]. The network-wide proliferation of those optical communication technologies paves the way for intelligent optical networking [2, 3, 5, 6]. As a prelude to the in-depth description of the underlying research work of this thesis, here follows a brief overview of the evolution towards optical networking and possible implementation options

2.1 Evolution Towards Optical Networking

Legacy networks and other entities that use facilities provided by optical networks are collectively known as clients. In the majority of existing implementations, clients only use optics exclusively for fiber transmission and provision of wavelength capacity increments. Therefore, the signaling (routines for connection setup/deletion), signal switching and routing is performed by client layer networks.

The synchronous digital hierarchy (SDH or SONET [synchronous optical network] in North America) is the most ubiquitous of existing clients and employs WDM for fiber reuse [15]. This time division multiplexing (TDM) transmission standard is the successor of the plesiochronous digital hierarchy (PDH) [16], and like its predecessor, it is tailor-made for circuit-switched voice applications. The next-generation SDH/SONET is now being updated for data traffic by adding the necessary line-rate flexibility (using virtualconcatenation [17] and the link capacity adjustment scheme [18]) and protocol transparency (generic framing procedure [19]) features.

The architecture of the optical transport networks (OTN) is being standardized by the ITU (International Telecommunication Union) Telecommunication Standardization Sector (ITU-T) Study Group 15. These OTN specifications (ITU-T G.872) [20] are evolved from the SDH/SONET standards. However, unlike the latter, the OTN accounts for and exploits the multiwavelength nature of WDM systems. Higher line rates are reached in SDH or SONET by time-interleaving STM-1 (synchronous transport module) or STS (Synchronous Transport Signal) basic frames respectively. By contrast, higher rates achieved in the OTN's optical transport module (OTM) by bundling wavelengths together.

An alternative view of optical networking is inspired by transformation of the service landscape which has seen the increased dominance of Internet Protocol (IP) traffic [21]. To that end, the adoption of optical IP networking promises optimal handling of IP traffic by using flexible network topologies [22–25], efficient routing mechanisms [22, 24, 26] and the likelihood of optical statistical multiplexing gain [27, 28]. Possible implementations include the direct transport of IP packets directly over WDM networks [22–24, 29] or via data-centric standards such as Ethernet [30]. These implementations overcome the rigidity of connection-oriented networking standards (e.g., first-generation SDH/SONET, ATM [asynchronous transfer mode] etc.) [23]. Moreover, excess overhead and duplication of functions associated with multiple client layers (e.g., IP over ATM over SDH/SONET architectures) is avoided [22].

2.1.1 The Optical Layer

The general vision of the next generation intelligent optical networks is of a system capable of providing an optical-domain-based, format-independent grooming, routing, signaling and management of signals with distinct center frequencies (wavelengths) [2]. The key to these intelligent optical networks is the introduction of a conceptual *optical layer* which plays the role of a server layer for the client layers found immediately above it. A schematic of the physical inter-connections between the optical networks and its various clients is depicted in Figure 2.1. The primary function of the optical network is the provisioning of fiber capacity for the client networks. For instance, in Figure 2.1, IP traffic between IP routers labeled A and B can transferred over the optical connection indicated by a dashed line.

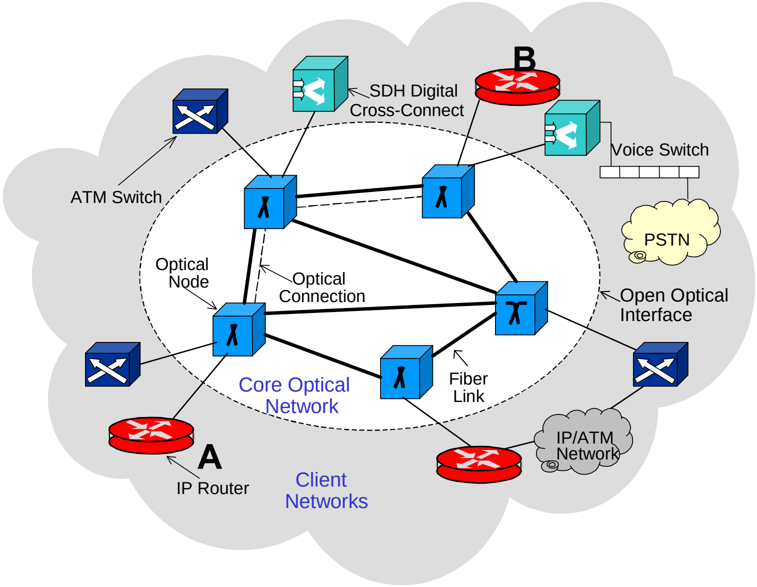


Fig. 2.1. The possible interconnection between an optical network and various client networks. As an example, an optical connection is provided for two communicating IP routers **A** and **B**.

Further benefits that can be expected from such an implementation is improved flexibility due to the wavelength reconfigurability capabilities of the optical network. This provides client networks with facilities for delivery of bandwidth-on-demand, bandwidth brokerage, service differentiation, alleviation of network congestion and the non-disruptive wavelength scaling of network capacity. Moreover, wavelength-level management is also possible for monitoring the quality-of-service (QoS) integrity of existing connections and the rapid service restoration in the event of any network failure. Unfortunately, some of the necessary optical layer enabling technologies (e.g., optical switches, optical 3R regenerators, wavelength converters etc.) are yet to mature (qualify for field deployment) and the cost of most components remains relatively high [31]. However, the cost constraints obstacles should be relaxed with the continued developed of photonic integrated circuits and automated manufacturing for volume production.

2.1.2 Signaling Standardization Efforts

The interworking between the optical and client layers is a crucial step towards intelligent optical networking [12]. Standards that provide guidelines for the interworking between the layers are being defined by bodies such as ITU-T, the Internet Engineering Task Force (IETF), American National Standards Institute (ANSI), European Telecommunications Standards Institute (ETSI), Institute of Electrical and Electronics Engineers (IEEE) and the Optical Internetworking Forum (OIF) [32]. Specifically, these standards define the synergy between optical-layer control plane (OCP) and client-layer control plane (CCP). The control plane is a complex distributed software component that provides functionalities of signaling and routing necessary for network intelligence. The aforementioned synergy seeks to facilitate the amalgamation of the intelligence residing in the optical and client layers. This represents a paradigm shift from legacy operator-assisted or centrally managed service provisioning via the management plane [33]. A traditional management plane entrusted with FCAPS (fault, configuration, accounting, performance and security) management functions is rather complex, error-prone and leads to long connection setup times. Therefore, the introduction of a distributed control automates and expedites the provisioning of optical layer connections by enabling auto-discovery of network resources, routing and assisting the management plane in fault and performance management.

The developed standards can be classified into two primary interconnection models: the peer-to-peer and overlay models. For the peer-to-peer model, an optical-aware CCP the is capable of setting up (and tearing-down) optical layers connections via a user-network interface (UNI) that mirrors the OCP's network-network interface (NNI) [12]. The most prominent standard based on the peer-to-peer model is the generalized multiprotocol label switching (GMPLS) proposed by the Network Working Group of the IETF [34]. By contrast, the overlay model only uses the OCP to manage optical layer connection control. This implies that the optical connection requests placed by the CCP are relayed to the OCP through the latter's UNI. Overlay models standards include ITU-T G.8080 which defines the OCP for optical networks [35] and its associated standards: G.8070 for control functions, G.7713 for connection management and G.709 for optical NNI. Complementary standardization is being done by the OIF to specify the Optical UNI 1.0 with work on UNI 2.0 and NNI is underway [36]. The augmented (dynamic overlay) and overlay+ models are enhanced versions of the overlay model [2, Chapt. 9].

2.2 Optical Node Operation

The key to the idea of intelligent optical networking and its eventual success is the development of reconfigurable optical nodes [2,5]. By reconfiguring the switches or routers within optical nodes in response to a connection request, it is possible to dynamically setup or take down a wavelength path or *lightpath* between any optical line terminals. Furthermore, the nodes have add and drop ports which provide a gateway for passing traffic from and to the client layer networks. This overall inherent flexibility of optical nodes enables a network operator to manage bandwidth efficiently, accommodate network growth and improve network restoration via the optical layer. Moreover, it offers a cost-effective way of handling pass-through or express traffic—which is the largest fraction of total traffic—by reducing the required number of client layer network devices.

An optical network typically constitutes V optical nodes (as shown in Figure 2.1) denoted by a node set $S_v = \{v_1, v_2, ..., v_V\}$. The physical link between these nodes are cable ducts , whereby each node could have up to D incoming/outgoing links represented by a link set $S_\ell = \{\ell_1, \ell_2, ..., \ell_D\}$. In practice, each cable link is deployed as loose-tube or tight-tube cable each with a bundle of up to F fibers denoted by a fiber set $S_f = \{f_1, f_2, ..., f_F\}$. Furthermore, each fiber is capable of carrying up to N wavelengths belonging to the wavelength set $S_\lambda = \{\lambda_1, \lambda_2, ..., \lambda_N\}$. In some cases, wavelengths are grouped together into W separate wavebands according to a waveband set $S_\omega = \{\omega_1, \omega_2, ..., \omega_W\}$ where $\omega_i \subset S_\lambda$, $1 < |\omega_i| < N$ and $\sum_{i=1}^{W} |\omega_i| = N$. The term *channel* in WDM networks usually refers to the wavelength used in setting up an end-to-end circuit for a particular connection. Hence, the maximum number of channels that could be accommodated on each individual fiber Λ is equivalent to the maximum wavelength number, $\Lambda = N$. A channel nomenclature system is introduced here whereby each channel is represented by a 4-tuple, $(\ell \in S_\ell, f \in S_f, \omega \in S_\omega, \lambda \in S_\lambda)$. So for instance, $(\ell_2, f_1, \omega_3, \lambda_7)$ refers to the seventh wavelength in the third waveband of the first fiber on the second link.

Switching is the primary function of optical nodes and is used for mapping any input channel $(\ell_{\text{in}}, f_{\text{in}}, \omega_{\text{in}}, \lambda_{\text{in}})$ on an incoming link to an output channel $(\ell_{\text{out}}, f_{\text{out}}, \omega_{\text{out}}, \lambda_{\text{out}})$ on an outgoing link(s). Generally an optical node is capable of performing switching at different hierarchical levels (see Figure 2.2) [37]. At the fiber level, an aggregate WDM signal is switched (e.g., for protection switching [2, 11]) from one incoming fiber to another outgoing fiber (that is, a channel mapping where $f_{\text{in}} \neq f_{\text{out}}$). For the waveband switching level, signals with connections with channels belonging to a common waveband are switched together if they share the same outgoing fiber [38–40]. The wavelength switching level handles each wavelength channel individually and forms for the basis of wavelength-routed networks which have been widely studied [11]. An exception is made for pass-through traffic, whereby no switching is carried out by the node because the input and out channels exactly similar. This hierarchical arrangement is necessary to reduce the node complexity (number and/or dimensions of internal component modules)by eliminating the need for a node to always switch each wavelength channel individually [40].

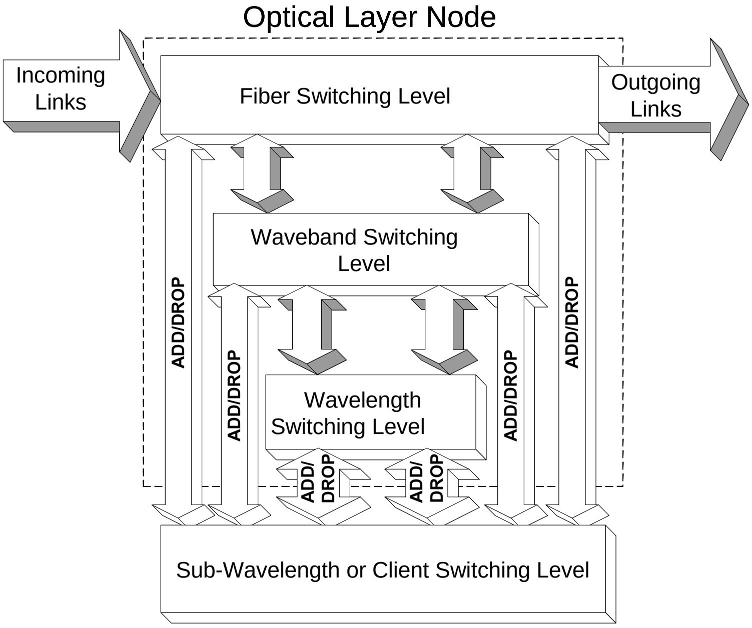


Fig. 2.2. A general optical node and its main switching levels.

Each of the higher switching levels has ports for adding/dropping signals from/to the sub-wavelength switching level (See Figure 2.2). The sub-wavelength switching level is intended for signals with a line rate lower than a single wavelength channel rate (e.g., STM-1/STS-3 [155.52 Mb/s] level SDH/SONET signal on a 2.5 Gb/s wavelength channel). At present, sub-wavelength switching or routing is performed exclusively in the electrical domain using client layer devices such as STM-1 SDH digital cross-connects, IP routers and ATM switches. Implementations of optical domain sub-wavelength switching based on optical packet switching are yet to mature for field deployment [27, 41–44]. To that end, optical burst switching, a compromise between the feasibility of wavelength switching and flexibility of packet switching, is being studied as an optimum solution for handling bursty self-similar traffic in the optical layer [45, 46]. The establishment of lightpaths is described in IETF (GMPLS) and ITU-T (OTN) standards as label switched path (LSP) and optical channel trail setup respectively. The standardized interfaces earmarked for various optical node switching levels are summarized in Table 2.1.

2.3 Optical Resource Management

The most important and exhaustible resource in wavelength-routed WDM optical networks is wavelength channels. Typically, when a connection request is made, the wave-

Switching Level	**IETF (GMPLS) Interfaces**	**ITU-T (OTN) Layers**
Fiber	Fiber-Switch Capable (FSC)	Optical Multiplex Section (OMS) Optical Transmission Section (OTS)
Waveband	Waveband Switch Capable (WSC) Lambda Switch Capable (LSC)	Optical Multiplex Section (OMS) Optical Channel (OCh)
Wavelength	Lambda Switch Capable (LSC)	Optical Channel (OCh)
Sub-wavelength	Packet Switch Capable 1-4 (PSC1-4) Layer-2 Switch Capable (L2SC) TDM Switch Capable (TSC)	Optical Data Unit (ODU) Optical Transport Unit (OTU)

Table 2.1. The Standardized interfaces and layers for various optical node switching levels.

length list is scanned for free (un-allocated) wavelength channels. In the likely event that no channels are free, then the request is rejected and the connection blocked [11]. The adverse consequences of blocking include loss of revenue, reduced competitiveness and user service dissatisfaction. Using the current feasible state-of-the-art optical technologies guarantees less than $\Lambda = 200$ wavelength channels. By contrast, client layer standards, such as ATM, could have thousands of route identifiers albeit at a lower granularity.

Various measures could be taken to alleviate the shortage of wavelength channels in the optical layer. The number of free wavelengths is usually maximized by increasing efficiency of wavelength reuse using carefully designed algorithms for routing and channel assignment (RCA) as part of optical layer traffic engineering [47]. A possible objective would be the maximization of established connections for given a wavelength number. The connection blocking can be further reduced by increasing the number of channels. New channels can be accommodated by broadening the current 1530-1565 nm (C-band) transmission window limit of erbium-doped fiber amplifiers (EDFA) [48, 49]. Window broadening can be enabled by amplification outside the C-band [10, 50–53] and/or the use of fibers with reduced water-peak (1400 nm) attenuation [54]. Alternatively, the inter-channel frequency spacing Δf_s could be narrowed so as to accommodate new wavelengths in the band gaps between two existing adjacent wavelength channels. The lowest channel spacing for dense WDM (DWDM) currently standardized by the ITU-T G.694.1 wavelength grid is $\Delta f_s = 12.5$ GHz (0.1 nm) [55].

However, the aforementioned solutions increase optical transmission costs per bit, may requires technologies that are yet to mature and reduces system tolerance to frequency drifts (maximum allowable frequency drift of $\pm\Delta f_s/5$ specified by ITU-T). This has seen increased emphasis on coarse WDM (CWDM) [56] which has 16 channels ($\Delta f_s = 2500$ GHz [20 nm]) specified by ITU-T G.694.2 [57]. Unfortunately, CWDM lacks the scalability of DWDM and its implementation is currently limited to un-amplified systems with a maximum range of 80 km.

2.4 Hybrid WDM

Hybrid WDM is another method that could be used to alleviate wavelength channel exhaust and further enhance network flexibility. In hybrid WDM transmission, an optical signal's extra degrees of freedom x (where x is e.g. time, polarization, signature code, sub-carrier frequency etc.)—in addition to signal wavelength—to reference a channel [11]. Up to M distinct signals belonging to a set $S_x = \{x_1, x_2, \cdots, x_M\}$ could be multiplexed by x-division multiplexing (xDM) using the x degree of freedom.

The term hybrid WDM, within the context of this thesis, refers to the general technique where xDM is performed before WDM prior to being launched on to an outgoing fiber (that is, xDM/WDM transmission). This form of hybrid WDM is distinct from other hybrid optical layer concepts that share the same term, such as, hybrid analog/digital signal format transmission [58], hybrid wavelength/sub-wavelength routing [59] or hybrid CWDM/DWDM transmission [60]. A channel in hybrid WDM systems is indexed by a 5-tuple, $(\ell \in S_\ell, f \in S_f, \omega \in S_\omega, \lambda \in S_\lambda, x \in S_x)$. Furthermore, the maximum number of channels that could be accommodated on each individual fiber is now $\Lambda = N \cdot M$ since each wavelength is re-used M times in the x degree of freedom. Therefore hybrid WDM offers the possibility of scaling channels counts within the optical-amplifier-boosted C-band window whilst maintaining feasible spacing ($\Delta f_s \geq 100$ GHz [0.8 nm]).

Hybrid WDM also adds some grooming properties to a network. The concept of grooming in communication networks is described by Barr and Patterson as "*...the optimization of capacity utilization in transport systems by means of cross-connections or conversions between different transport systems or layers within the same system*" [61]. A commonly tackled grooming problem in WDM-based networks is the grooming (packaging) of lower granularity (line rate) sub-wavelength client layer traffic into wavelength channels [62–64]. Grooming has the advantage of minimizing complexity and required number of client layer devices. Since the granularity of the individual components of WDM and xDM/WDM aggregates are similar, then hybrid WDM could be considered to be a optical layer grooming method. The grooming capability of hybrid WDM has the potential to improve wavelength utilization efficiency, relax routing constraints and reduce the complexity of WDM infrastructure.

3. RESEARCH FRAMEWORK

This chapter presents the necessary background and provides a framework for the research presented in publications [P1]-[P8] summarized in Chapter 4. The three main subtopics of the framework and their related publications are: transmission performance analysis [P1], [P2], optical node design [P3]-[P5] and hybrid WDM techniques [P6]-[P8].

3.1 Optical Transmission Performance

The ITU-T E.800 standards expound on the inter-relationship between the network performance and the QoS offered by the network [65]. This relationship forms a direct link between the performance of optical nodes and the binding service level agreement (SLA) between the customers and the optical carrier service provider (OCSP).

Optical networks are engineered to guarantee that the transmission performance meets the agreed specifications [2]. When a WDM signal is impaired it results in erroneous reception of the transmitted signal. This reduced transmission performance is usually represented by the deterioration of received signal's bit error-rate (BER). WDM signals traversing long range (> 500 km) optical networks (e.g., [66, 67]) are mainly impaired by the non-ideal characteristics of fiber waveguides (e.g., polarization mode dispersion [68], four-wave mixing [69] etc.) and accumulative noise of long optical amplifier chains [48]. Transmission performance of nodes is also an important aspect of network performance with significant implications for all-optical network coverage as demonstrated in thesis [P1]-[P4]. Since the diameter of medium range (metropolitan or access) networks is relatively shorter compared to long range networks, then the average inter-nodal fiber link distances are also much shorter [37]. Hence the influence of optical node-induced signal impairments in medium range networks is more significant compared to fiber or optical amplifier related impairments.

In practice, these node-induced WDM signal impairments such as crosstalk interference [70, 71] and dispersion [72] are attributed to the imperfection of various component modules (e.g., leaky switches [70], misaligned WDM filters [73] etc.) that constitute the node. Moreover, the severeness of signal impairment tends to increase proportionally with the distinct channel number, optical node dimensions (number of input/output fiber ports) or the number of intermediate nodes traversed [74–77]. Since lightpaths are typically composed of more than a single physical fiber span, then these impairments place a limit on the overall network coverage and/or capacity [78], [P1]-[P4]. In practice, the quality of the WDM signal could be preserved by deploying electronic regenerators (that is, client network transponders) at each wavelength port of an optical node [79]. However, for this "opaque networking" scheme, optical-electrical-optical (OEO) conversion is required in each transponder as depicted in Figure 3.3a. These OEO conversions increase investment costs, floor space (footprint) and power requirements. Moreover, the transponders are locked to a fixed line rate and tend to be more expensive with increasing line rate (becomes very difficult beyond 10 Gb/s).

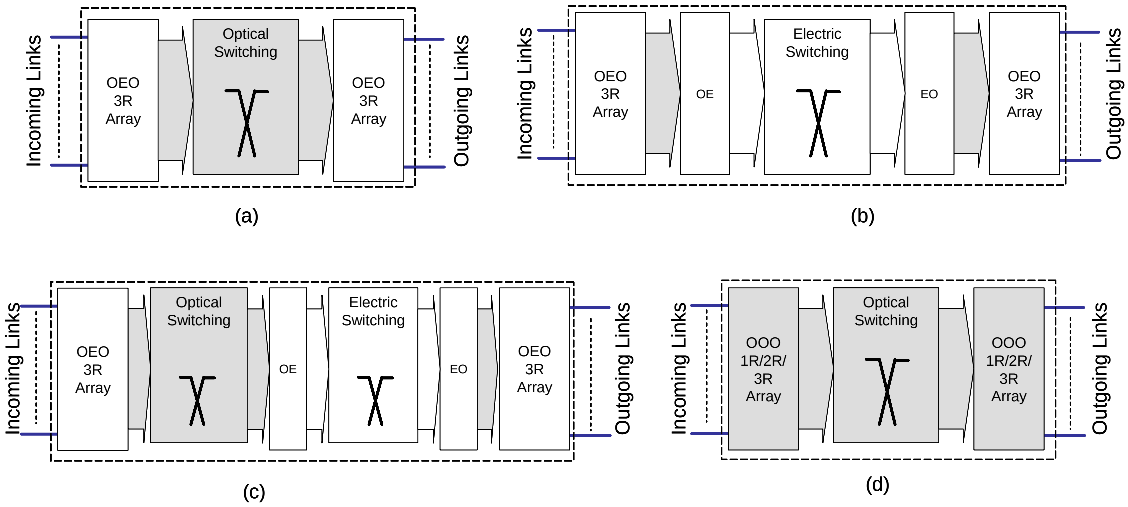


Fig. 3.3. An optical node employing (a) OEO 3R regenerators and optical switches (b) OEO 3R regenerators and electrical switches [OE-optical to electrical converter, EO-electrical to optical converter] (c) hybrid optical and electrical switching (d) strictly OOO 1R, 2R or 3R regenerators and optical switches. The blocks handling signals in optical domain are shaded.

The cost and flexibility disadvantage of transponders has increased the demand for all-optical 2R/3R regenerators that only involve optical-optical-optical (OOO) conversions [13, 80]. The same argument is used when choosing nodes that employ OOO switching instead of OEO switching device modules [81]. The complexity of these alternative OXN implementations are further illustrated in Figure 3.3b-d, with the all optical OXN Figure 3.3d being the least complex. However, most OOO regenerator designs are yet to mature for field deployment [13]. Therefore, compromise network designs (translucent networks)—whereby transponders are deployed strategically in nodes on network/sub-network edges—are seen as the optimum solution for medium range networks [82]. This means that the transparent optical networking is limited within all-optical islands interconnected using purely OOO nodes. For successful intelligent optical networking, the diameters of all-optical islands should be maximized by using optical nodes which induce minimal impairment, such as those proposed in [P3] and [P4]. It is therefore essential to analyze the impact of various node designs on the network's transmission performance. This task is tackled in this thesis in [P1] and [P2].

The wide range of proposed node architectures [83–85] means the experimental setups (such as [86]) for transmission performance analysis of all the proposals is too costly. However, the complex mathematical modeling—such as that required for transmission performance analysis—can now be tackled cost-effectively using the significant computational power at the disposal of design engineers [87–89]. The improvement in computing power has seen the increased use of computing tools that simulate (imitate) full optical network physical layer operations [90–94]. For this thesis, the VPItransmissionMaker simulation package formerly known as Photonic Transmission Design Suite [93]), is the designated simulation tool.

3.2 Optical Node Design

Optical nodes enable an OCSP to utilize efficiently and cost-effectively the capacity of the existing dormant fiber plant [95]. However, optical nodes contribute the most towards overall network cost and performance of both short and medium range optical networks. Therefore, the design of optical nodes is one of the most important aspects of overall optical network design [2] and this thesis tackles this issue effectively.

3.2.1 Deployment Considerations

The deployment and evolution of optical nodes is dictated by factors such as topology, signaling, service type, client networks and optical layer technologies [96]. The simplest optical node is the optical add-drop multiplexer (OADM) and is used to provide connectivity in WDM ring topologies [85,97]. However, in order to realize the full potential of intelligent optical networking that is, lower operating cost, high flexibility, efficient capacity utilization and robustness, optical mesh network designs become necessary [2, 8, 96, 98]. Unlink WDM rings, optical mesh topologies employ the relatively more complex optical cross-connect nodes (OXN) [83,84,99]. Optical nodes are usually characterized by the number of input/output fiber ports ($D \cdot F$) in the nodes. Since most nodes are symmetrical in design, then $D \cdot F \times D \cdot F$ is usually referred to as the dimensions of an optical node. A majority of the research on the design and performance of WDM nodes and networks has only considered single-fiber links where $F = 1$ and hence $D \times D$ is the node dimensions. Although research on multi-fiber link networks is now gaining some interest (e.g., [100,101]), this thesis will only focus single-fiber link networks.

The main distinction between the OXNs and OADMs is that, an optical node is an OADM if it has a 1×1 dimension, otherwise it is an OXN. A 2×2 OXN is the fundamental OXN, since it is the most basic OXN architecture and can be used to construct larger OXNs (see for instance Figure 3.4) [102]. Furthermore, the role of 2×2 OXNs is not limited to mesh networks as they could be used for interconnecting single-fiber WDM rings as shown in Figure 3.5a [103]. Moreover, 2×2 OXNs can be used as OADMs since most practical WDM rings are more likely to be implemented in resilient 2- or 4-fiber shared-protection ring (SPRing) configurations as shown in Figures 3.5c and 3.5d [2, 104]. Paradoxically, it is also possible to construct 2×2 OXNs from OADMs (see Figure 3.5b) [105].

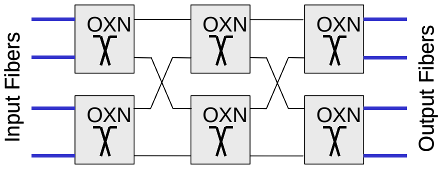
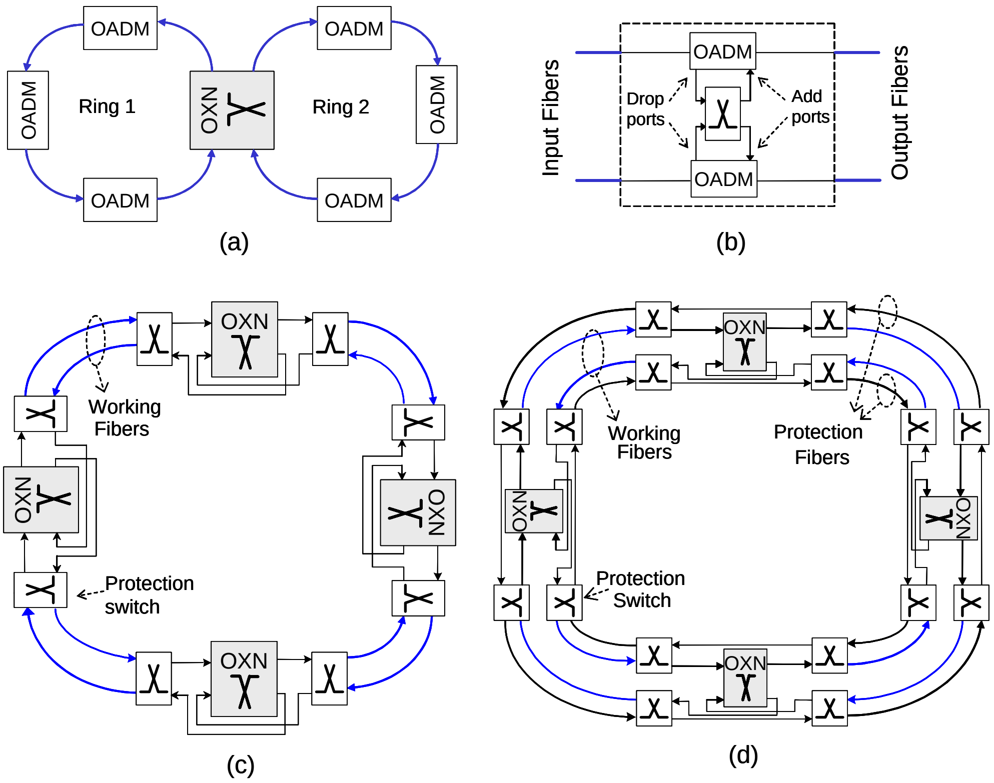


Fig. 3.4. A 4×4 OXN implemented by connecting 6 2×2 OXNs in a three-stage Clos network arrangement.



(a) (b) (c) (d)

Fig. 3.5. Examples of (a) Inter-connection of 2 single-fiber rings using a 2 × 2 OXN (b) implentation of a 2 × 2 OXN using 2 OADMs (c) 2-fiber WDM SPRing constructed using 2 × 2 OXNs and (d) 4-fiber WDM SPRing constructed using 2 × 2 OXNs.

3.2.2 Node Dependability

Another important network performance component investigated in this thesis is dependability [P5], which refers to availability performance and its influencing factors, such as reliability, maintainability, and maintenance support [65]. Optical nodes are composed of various components modules for executing functions such as demultiplexing, switching, multiplexing and amplification [83]. In practice, each of these modules are designed as line cards which are plugged into slots of a shelf. If possible, some of the slots are usually left vacant for any future node scaling requirements. Multiple shelves are then in turn grouped together and placed on a rack. Each optical node constitutes one or more racks of equipment depending on the node's complexity.

Since these optical nodes handle large amounts of traffic, then their availability is significant to an OCSP's revenue stream. For instance, a demultiplexer failure in a fully utilized 2×2 OXN of a 4 WDM × 10 Gb/s system could disrupt 40 Gb/s of incoming traffic.

Therefore, to avoid such possible loss of revenue, redundant line cards are placed in vacant slots and are immediately called into service when one of the active line cards fails. Previous reliability analysis of various OXN architectures have highlighted the need for redundancy in almost all of the OXNs analyzed [106]. Dependable node designs proposed in this thesis [P5] enable an OCSP to strike a compromise between the service availability requirements stipulated in a SLA and the investment costs (affordable redundancy) required to maintain that availability.

3.3 Hybrid OCDM/WDM

Several alternative multiplexing methods other than WDM have been briefly compared in [P7]. Among those multiplexing methods considered, optical code-division multiplexing (OCDM) has been gaining some significant research interest [107–110]. The OCDM method now rivals optical TDM (OTDM) as a viable alternative, due to its relative ease of implementation. In an OCDM system, multiple connections share a fiber simultaneously by using distinct pseudo-random sequences, also known as signature codes. Recent developments have seen the research emphasis of OCDM expand from low-rate (≤ 155 Mb/s) short range networks (≤ 10 km e.g., LAN, first mile etc.) to include high-capacity (≥ 2.5 Gb/s) medium-range (10—200 km e.g., MAN, SAN etc.) code/wavelength routed networks [108, 109, 111]. OCDM is easy to deploy (plug-and-play) in legacy WDM systems with minimal disruptions to the existing setup and can be implemented using off-the-shelf optical technologies [110].. Moreover, OCDM improves security [110] and enables asynchronous operation unlike TDM-based systems [108]. Furthermore, OCDM is inherently flexible making it independent of bit rate, signal format and network topology.

This thesis focuses on OCDM overlays over the legacy WDM layer (that is, hybrid OCDM/WDM). With hybrid OCDM/WDM transmission, a network's capacity scalability is improved by enabling the scaling of the number of usable channels in two dimensions: code and wavelength [112, 113], [P6]. Therefore, up to M different signature codes from the code set $S_c = \{c_1, c_2, ..., c_M\}$ can by reused each member of S_λ on the same fiber link (see Figure 3.6a). The order of the $M = |S_c|$ is usually referred to as the cardinality of a code set. An increase in maximum channel count from $\Lambda = N$ to $\Lambda = M \cdot N$ is expected when WDM is upgraded to OCDM/WDM transmission, thus decreasing the likelihood of a connection being blocked.

3.3.1 Unipolar OCDM Systems and Dispersion Limitations

A wide range of OCDM implementations have been proposed and are chronicled by Karafolas *et al* in [107]. Direct-spreading (or direct-sequence) spread spectrum is widely considered to be the most suitable method for enabling the commercial deployment of OCDM systems [11,108,110]. In 1D amplitude (unipolar) encoded direct-spreading OCDM, each "1" data bit is transmitted as a pseudo-random stream of narrower pulses or chips which correspond to a particular signature code. The amplitude level of the chips takes on values of 0 or 1 (see Figure 3.6a), with orthogonal codes being distinguished by the temporal location of nonzero chips in the code.

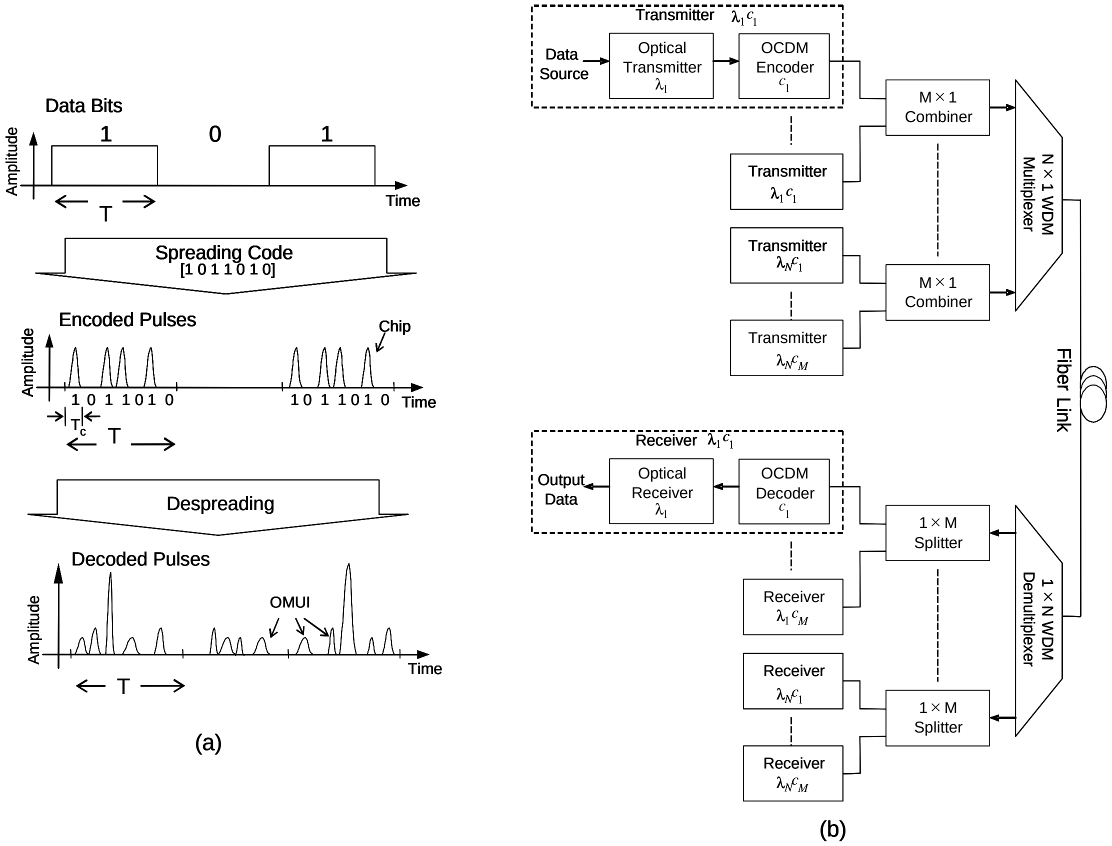


Fig. 3.6. (a) An M OCDM × N WDM system diagram. (b) Example of 1D unipolar amplitude encoded 101 data bit stream.

Consider a data signal stream produced by a transmitter j in an on-off keying (OOK) system and represented by a binary sequence $a_l^{(j)} \in \{0,1\}$ with a bit duration T. For the commonly used non-return to zero (NRZ) modulation, $T = 1/B$ where B is the bit rate. Prior to transmission over fiber, this signal stream is imprinted with a signature code $c_j = \left\{c_n^{(j)} | n = 0,1,2,\ldots,L_c - 1\right\}$, where $c_n^{(j)}$ is the nth chip of the jth code, L_c is the code length (number of chips) and $c_n^{(j)} = c_{n+L_c}^{(j)}$. The encoded stream $y^{(j)}(t)$ is formulated as

[11]

$$y^{(j)}(t) = \sum_{l} \sum_{n=0}^{L_c-1} a_l^{(j)} c_n^{(j)} r\left(t - nT_c - lT\right) \tag{1}$$

where $T_c \leq T/L_c$ is the duration of each chip and $r(\cdot)$ is a unit-amplitude rectangular pulse. Ignoring receiver noise, the corresponding kth decoded signal stream at the receiver is

$$d_k^{(j)}(t) = \sum_{l} a_l^{(j)} \psi^{(j,k)}\left[t - (l+1)T\right], \qquad \forall k \tag{2}$$

where

$$\psi^{(j,k)}(t) = \sum_{n=0}^{L_c-1} \sum_{p} c_p^{(j)} c_{p+n}^{(k)} r\left(t - nT_c\right). \tag{3}$$

In practical systems [107]

$$\psi_0^{(k,k)} = w \tag{4}$$

$$\psi_n^{(j,k)} > 0, \qquad \forall n \text{ when } j \neq k \tag{5}$$

$$\psi_n^{(k,k)} > 0, \qquad n \neq 0 \tag{6}$$

where $\psi_n^{(j,k)} = \sum_p c_p^{(j)} c_{p+n}^{(k)}$ and w is the code weight (total non-zero chips). From above, (4) represents the desired autocorrelation peak obtained when a user transmits a "1" bit. The OMUI is represented by (5) and (6) which is the nonzero crosscorrelation and time-shifted autocorrelation respectively. An upper limit is placed on the performance of OCDM systems when OMUI levels become comparable to the autocorrelation peaks. Optical orthogonal codes (OOCs) are a typical class of signature codes that are optimized to minimize OMUI in OCDM-based systems [114]. The commonly recommended constraint is $\psi_n^{(j,k\neq j)} = \psi_{n\neq 0}^{(k,k)} = 1$, which bounds the cardinality of OOCs by [114]

$$M = \left\lfloor \frac{L_c - 1}{w\left(w-1\right)} \right\rfloor \tag{7}$$

where $\lfloor y \rfloor$ denotes the integer part of y. An example of a hybrid OCDM/WDM system is depicted in Figure 3.6b.

Assuming an equal probability of transmitting "0" and "1" bits, the OCDM system bit error probability P_b when n codes are in use is given by $P_b\left(w,n\right) = 0.5 \cdot \left(P_{b0} + P_{b1}\right)$ where P_{b0} and P_{b1} are the error probabilities when "0" and "1" bits are transmitted respectively. Since it is usually assumed that majority of errors occur in the latter case due to OMUI exceeding the receiver threshold then $P_b\left(w,n\right) \simeq P_{b0}/2$ whereby [114]

$$P_{b0} = \sum_{j=w}^{n-1} \binom{n-1}{j} \left(p'\right)^{j} \left(1-p'\right)^{n-1-j} \tag{8}$$

and $p' = w/2L_c$ is the probability of overlapping "1" chip pulses (note: more accurate but computationally demanding techniques for evaluating P_b are available [115]).

It is clear from (8) that, for a given P_b constraint, any increase in code cardinality requires longer OOCs. Unfortunately, for a given fiber link distance L there is an upper limit on chip-rate distance product $(L \cdot L_c \cdot B)$ due to fiber dispersion which causes the temporal spreading of chip pulses [109]. The dispersion is attributed to GVD and the Maxwellian distributed PMD mechanisms which occur due to the differing group velocities of a signal's wavelength components and polarizations respectively [2].

Using expressions for dispersion limitations of OOK-NRZ systems [2], the respective OCDM distance limits of the two mechanisms can expressed as

$$L < \epsilon / \left(\Delta\lambda \cdot L_c \cdot B \cdot D_{\mathrm{GVD}}\right) \tag{9}$$

$$L < \left(\langle \Delta\tau \rangle / D_{\mathrm{PMD}}\right)^2 \tag{10}$$

where ϵ is the pulse spreading to bit period ratio (e.g., ITU G.957 specifies $\epsilon = 0.491$ for a power penalty $PP_{\mathrm{dB,GVD}} = 2$ dB), $\Delta\lambda$ is the spectral linewidth, D_{GVD} the GVD coefficient, D_{PMD} the PMD coefficient and $\langle \Delta\tau \rangle$ is the time-averaged differential group delay two principle polarization states. The power penalty attributed to PMD is exponentially distributed and is related to $\langle \Delta\tau \rangle$ by [2, 116]

$$PP_{\mathrm{dB,PMD}} = a \cdot \left(\langle \Delta\tau \rangle \cdot L_c \cdot B\right)^2 \cdot b \cdot (1-b), \tag{11}$$

where $a \in [12, 25]$ is the pulse form factor and $b \in [0, 1]$ is the power splitting ratio between the two polarization states.

As an example, Figure 3.7 depicts a received autocorrelation peaks (that is, decoded pulses) after traversing $B = 2.5$ Gb/s links using ITU G.652 standard singlemode fibers (SMF, $D_{\mathrm{GVD}} = 16.0$ ps/nm-km; $D_{\mathrm{PMD}} = 0.2$ ps/$\sqrt{\mathrm{km}}$) and ITU G.655 nonzero-dispersion fibers (NDF, $D_{\mathrm{GVD}} = 3.0$ ps/nm-km; $D_{\mathrm{PMD}} = 0.1$ ps/$\sqrt{\mathrm{km}}$) of length $L = 10$ and 50 km. The length of the codes is set at $L_c = 13$ and 25 corresponding to a code cardinality of $M = 2$ and 4 respectively for $w = 3$. The autocorrelation peaks of after NDF links are more clearer due to the lower dispersion than that encountered in SMF links. Moreover, when L_c or L is increased, the autocorrelation peaks become distorted and indistinguishable from OMUI. Therefore, GVD and/or PMD compensation will be necessary (especially for SMF links) if OCDM is to be utilized in metropolitan or backbone networks [109].

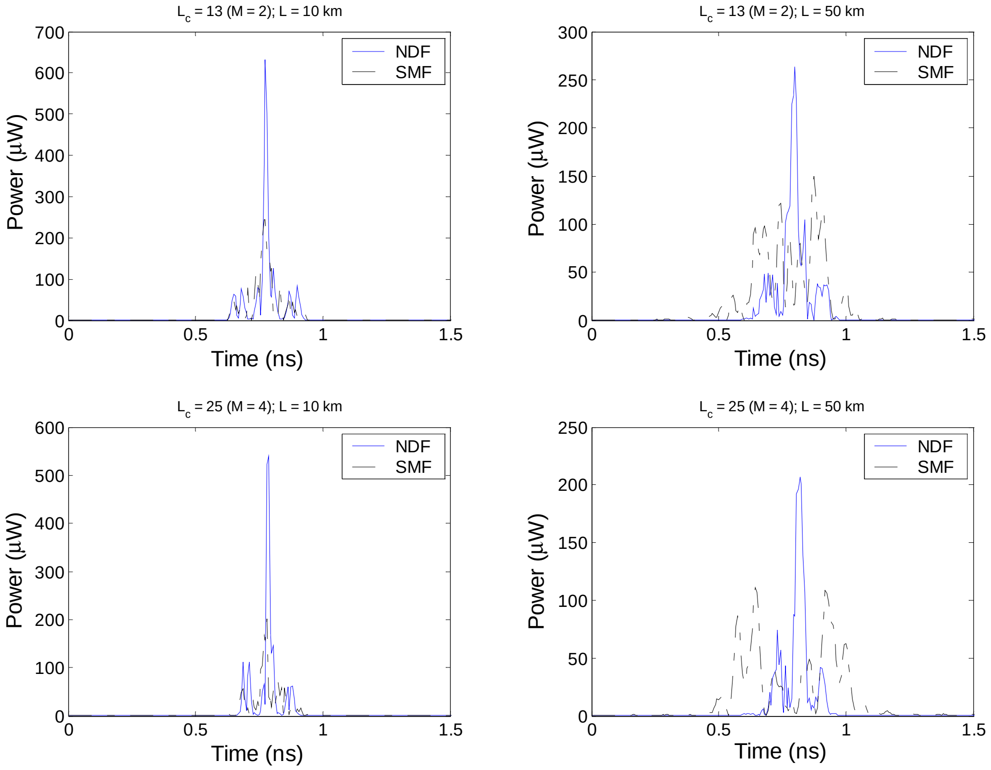


Fig. 3.7. The received autocorrelation peaks when $L_c = 13$ or 25 and $L = 10$ or 50 km for SMF and NDF links.

The dispersion penalties could also be reduced by lengthening the chip pulse duration by using relatively shorter length phase encoding [107, 108] or 2D/3D wavelength-time codes [112, 117, 118]. Furthermore, required code lengths for given cardinality could be reduced by relaxing the cross-correlation constraints through the use of error-correction coding [119–125] and improved decoder or receiver designs [111, 126, 127]. Unfortunately, the feasibility of these solutions is hindered by the lack of mature technologies (e.g., optical hard-limiters), the need for phase-control, the speed versus cost limitations of receiver electronic integrated circuitry and the need for expensive devices (e.g., multiwavelength transmitters). Moreover, OCDM systems using wavelength-time codes are more severely affected by the fiber dispersion slope and could cause inband crosstalk when hybridized with existing WDM systems.

3.3.2 Hybrid OCDM/WDM Lightpath Schemes

An optical hop is defined as the physical link span traversed between two adjacent optical nodes. In WDM-based networks, a lightpath is termed as a wavelength path (WP) if it uses the same wavelength on each of its optical hops and a *wavelength continuity* constraint (input to output channel mapping, iff $\lambda_{\text{in}} = \lambda_{\text{out}}$) is placed on the RCA algorithm [47]. In order to relax this constraint and reduce the number of required wavelengths, each port of a node could be upgraded with a wavelength converter (WC) [128,129] that enables the lightpath to occupy any free member of wavelength set S_λ (mapping also possible if $\lambda_{\text{in}} \neq \lambda_{\text{out}}$) on each subsequent optical hop [47]. The lightpath is now known as a virtual-wavelength path (VWP). The differences between the two lightpath schemes is illustrated using a three hop lightpath for a system with $N = 3$ and $M = 2$ (see top half of Figure 3.8). For illustrative simplicity, the channel for the WDM case in Figure 3.8 is referenced by only $\lambda \in S_\lambda$, and usable channels for each hop are indicated in square brackets.

In OCDM/WDM networks, connections are also assigned signature codes $c \in S_c$ in addition to wavelengths. Therefore, using previously defined nomenclature an input and output channels can now be represented $(\ell_{\text{in}}, f_{\text{in}}, \omega_{\text{in}}, \lambda_{\text{in}}, c_{\text{in}})$ by $(\ell_{\text{out}}, f_{\text{out}}, \omega_{\text{out}}, \lambda_{\text{out}}, c_{\text{out}})$ respectively. Again for illustrative simplicity, a channel for OCDM/WDM networks is just referenced by a 2-tuple, $(\lambda \in S_\lambda, c \in S_c)$ in Figure 3.8. Now, if a lightpath has a distinct code *and* wavelength over all its hops, it is known as a code wavelength path (CWP). As a result, both the *code continuity* (mapping, iff $c_{\text{in}} = c_{\text{out}}$) and wavelength continuity constraints are placed on the RCA algorithm. If only WC upgrades of the optical nodes are carried out, the wavelength continuity constraint is eliminated and the lightpath is a code virtual-wavelength path (CVWP). Alternatively, code converter (CC) [130–132] upgrades remove the code continuity constraint (mapping also possible if $c_{\text{in}} \neq c_{\text{out}}$) and therefore a CWP is transformed into a virtual-code wavelength path (VCWP). Furthermore, if nodes are equipped with both WCs and CCs, all the aforementioned continuity constraints are eliminated and the lightpath becomes a virtual-code virtual-wavelength path (VCVWP). Several proposals have been made for all-optical dual code-wavelength converters. These include, experimental demonstrations for dual converters based on nonlinearity in semiconductor amplifiers [133] and super-continuum picosecond pulse sources [113]. These dual converters have the potential to offer large savings in node upgrade costs and are easier to control compared to discrete WC and CC used together.

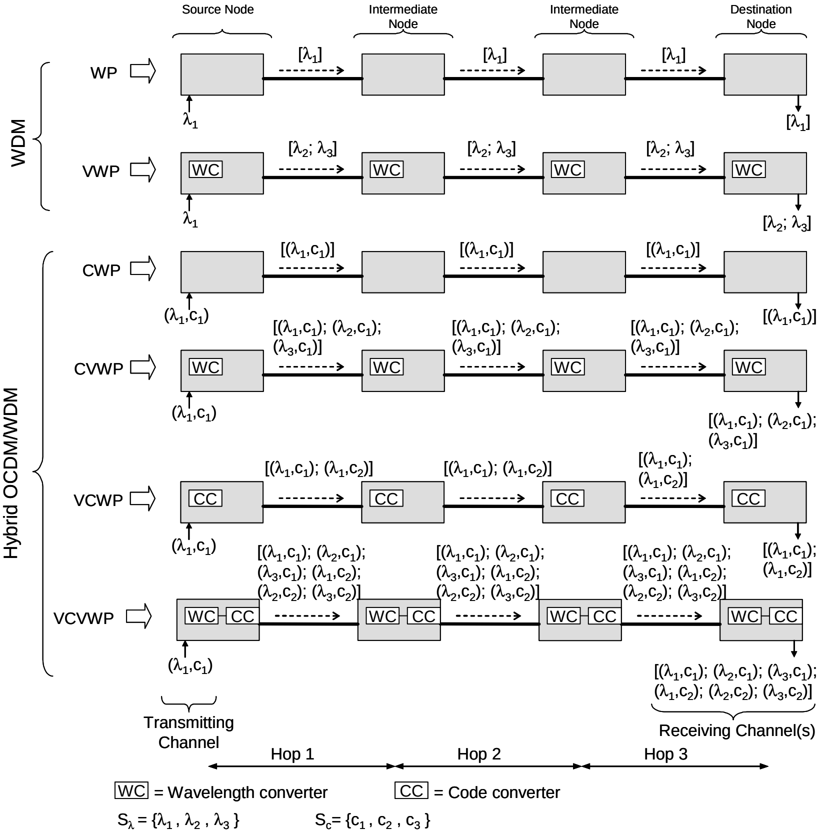


Fig. 3.8. Implementation of a 3 optical hop lightpath for wavelength path (WP), virtual-wavelength path (VWP), code wavelength path (CWP), code virtual-wavelength path (CVWP), virtual-code wavelength path (VCWP) and virtual-code virtual-wavelength path (VCVWP) schemes for a system with $N = 3$ and $M = 3$. Code converters (CC) and wavelength converters (WC) are used to resolve contention for outgoing fiber links.

In order to take full advantage of the additional flexibility of OCDM/WDM lightpath (CWP, CVWP, VCWP, VCVWP) schemes, it is essential to engineer optical nodes for both code and wavelength switching. A possible node architecture for hybrid OCDM/WDM networks is devised here and illustrated in Figure 3.9. The input ports at the upper part of the node are reserved for OCDM/WDM lightpaths and lower input ports are for legacy WDM (WP, VWP) lightpath schemes. Furthermore, it is possible switch connections between OCDM/WDM and WDM networks. The main node components are WDM and OCDM switching blocks for switching signals according to their wavelength and code respectively. However, proposals for OCDM switching fabrics [134,135] have been relatively few compared to WDM. The interest has mainly been on using OCDM codes as labels and the code correlation peaks to control states of label switched routers used to setup label switched paths [132, 136].

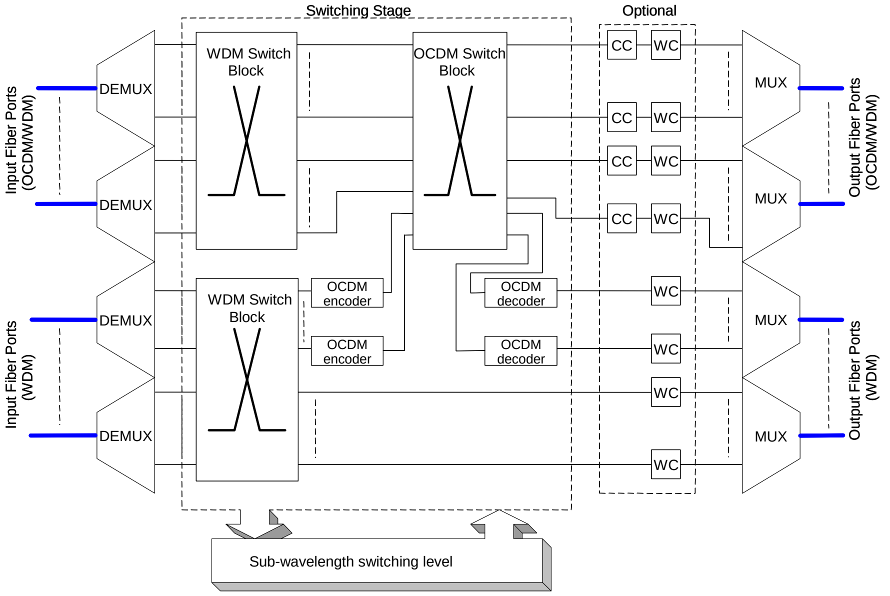


Fig. 3.9. A wavelength level OXN designed for fully reconfigurable OCDM/WDM systems.

3.3.3 Blocking Performance Analysis

Consider a hybrid OCDM/WDM network with a node set S_v and link set S_l. Each member of S_l represents a single fiber capable of simultaneously accommodating up to $\Lambda = M \cdot N$ channels (Recall that N and M equals the maximum number of wavelengths and codes respectively). If $V = |S_v|$, a total of $V \cdot (V-1)/2$ routes exist in the network when traffic in the opposite direction is carried on a separate fiber. When a connection request arrives, a lightpath is setup over the ith route denoted by $r_i = \left\{h_1, h_2, \ldots, h_{|r_i|}\right\}$ where h_j is the jth hop of the route, $r_i \subset S_l$ and $|r_i| \in [1, V-1]$ is the number of optical hops in the route.

Analytical models of the network blocking probability for various WDM and OCDM/WDM lightpath schemes (see Figure 3.8) are presented here based on the following traffic assumptions:

- network traffic distribution is symmetrical between any node pair and is uniformly distributed throughout the network;

- connections requests arrive according to a Poisson process and the call holding time is exponentially distributed;
- static shortest path routing and random wavelength/code assignment are used throughout;
- the occupancy of different links and channels is statistically independent;
- there are no attempts to re-request a connection if it is initially blocked;
- only one fiber is deployed per link; and
- all wavelength and code converters (if used) are fully tunable and are deployed in each network node.

The overall network blocking probability P_B is evaluated as an ensemble average of the blocking probability experienced over all the different network routes. Let $Y^{(n)}$ and $X_{\Lambda}^{(h_x)}$ in a Λ channel system be random variables indicating the number of free channels on an n hop route and xth hop of the route respectively. The network blocking probability is obtained from

$$P_B = \sum_{i=1}^{V \cdot (V-1)/2} P\left(Y_{\Lambda}^{(|r_i|)} = 0\right) P\left(r_i\right) \tag{12}$$

where $P\left(r_i\right)$ is the probability that the connection over route r_i is active.

A fixed channel lightpath is defined here as a lightpath which uses the same wavelength/code from source to destination (WP, CWP). On the other hand, an interchangeable channel lightpaths may utilize different wavelengths and codes on different hops of a route (VWP, VCVWP). The VCWP and CVWP schemes are partially fixed channel lightpaths whereby a lightpath uses either the same wavelength or code from source to destination.

For fixed channel lightpaths, the probability of $P\left(Y^{(|r_i|)} = 0\right)$ can be evaluated recursively by [137]

$$P\left(Y_{\Lambda}^{(|r_i|)}=k\right)=\sum_{x=0}^{\Lambda}\sum_{y=0}^{\Lambda}P\left(\Lambda-k|\Lambda-x,\Lambda-y\right)\cdot \\ P\left(Y_{\Lambda}^{(|r_i|-1)}=x\right)P\left(X_{\Lambda}^{(h_j)}=y\right) \qquad (13)$$

whereby $\Lambda = N \cdot 1$ for WP schemes, $\Lambda = N \cdot M$ for CWP and the conditional probability $P\left(\kappa|a,b\right)$ is evaluated by

$$P\left(\kappa|a,b\right)=\begin{cases}\frac{\binom{a}{\kappa}\binom{\Lambda-b}{b-\kappa}}{\binom{\Lambda}{b}} & \text{if } \max\left(0,a+b-\Lambda\right)\leq\kappa\leq\min\left(a,b\right)\\ 0 & \text{otherwise}\end{cases} \qquad (14)$$

Furthermore, using the traffic's statistical assumptions made above, the jth hop occupancy probability $P\left(X_{\Lambda}^{(h_j)}=y\right)$ in (13) can be computed by the truncated Poisson distribution

$$P\left(X_{\Lambda}^{(h_j)}=k\right)=\left(\sum_{m=0}^{\Lambda}\frac{\rho_{h_j}^{m}}{m!}\right)^{-1}\frac{\rho_{h_j}^{k}}{k!} \qquad (15)$$

where ρ_{h_j} is the offered load on the jth hop.

For interchangeable channel lightpaths, $P\left(Y_{\Lambda}^{(|r_i|)}=0\right)$ in (12) is obtained directly from

$$P\left(Y_{\Lambda}^{(|r_i|)}=0\right)=1-\prod_{j=1}^{|r_i|}\left(1-P\left(X_{\Lambda}^{(h_j)}=\Lambda\right)\right) \qquad (16)$$

where $\Lambda = N\cdot 1$ and $\Lambda = N\cdot M$ for VWP and VCVWP lightpath schemes respectively.

In the case of partially fixed channel lightpath schemes, $P\left(Y_{\Lambda}^{(|r_i|)}=0\right)$ could be obtained using the recursive expression (13). However, the variable Λ and term $P\left(X_{\Lambda}^{\left(h_{|r_i|}\right)}=y\right)$ are replaced by Λ_{nc} and $P\left(Q_{\Lambda_{nc},\Lambda_c}^{(h_j)}=y\right)$ respectively. The variable Λ_c and Λ_{nc} are the orders of the set of convertible and non-convertible channel entities (code or wavelength), while $Q_{\Lambda_{nc},\Lambda_c}^{(h_j)}$ is a random variable indicating the number of free non-convertible entities on the jth hop. Using expressions previously derived by Yates *et al* for hybrid TDM/WDM networks, $P\left(Q_{\Lambda_{nc},\Lambda_c}^{(h_j)}=y\right)$, is given by [138]

$$P\left(Q_{\Lambda_{nc},\Lambda_c}^{(h_j)}=y\right)=\sum_{n=0}^{\Lambda_{nc}\cdot\Lambda_c}P\left(Q_{\Lambda_{nc},\Lambda_c}^{(h_j)}=y|n\right)\cdot P\left(X_{\Lambda}^{(h_j)}=k\right) \qquad (17)$$

The conditional probability $P\left(Q^{(h_j)}_{\Lambda_{nc},\Lambda_c} = y|n\right)$ is evaluated recursively

$$P\left(Q^{(h_j)}_{\Lambda_{nc},\Lambda_c} = y|n\right) = \begin{cases} \frac{\binom{\Lambda_{nc}}{y}\cdot\sum_{i=0}^{\min(\Lambda_c-1,n-y\cdot\Lambda_c)}\binom{\Lambda_c}{i}\chi([\Lambda_{nc}-y-1]|[n-y\cdot\Lambda_c-i])}{\binom{\Lambda_{nc}\cdot\Lambda_c}{n}} & \text{if } 0 \leq n-y\cdot\Lambda_c < \Lambda_c \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

beginning from $\chi\left(1|\left[n-y\cdot\Lambda\right]\right) = \binom{\Lambda_c}{n-y\cdot\Lambda_c}$.

When the CVWP scheme is used, wavelength is the convertible entity, therefore $\Lambda_c = N$ and $\Lambda_{nc} = M$. The exact opposite is true for the VCWP scheme. Moreover, in both CVWP and VCWP schemes, $\Lambda = \Lambda_{nc} \cdot \Lambda_c$.

3.3.4 Hybrid WDM for Heterogenous Networks

A potential future application of hybrid WDM is the transportation of heterogenous wireline and wireless traffic over common fiber infrastructure. Wireless networks avoid the limitations of high cabling costs, can be installed rapidly and enable user mobility [139]. Broadband wireless access networks (BWAN) are proving to be attractive in de-regulated access network environments. In particular, the millimeter-wave (MMW) band located at the oxygen absorption band (60 GHz), presents opportunities for wireless data rates of over 100 Mb/s [140]. To that end, there has been suggestions for using the MMW band for the next generation of wireless networks [141].

Optical networks have been identified as the suitable candidate for the implementation of BWAN's backhaul networks that inter-connect the central station, MMW base stations and/or MMW antennas [142]. Implementation of WDM-based optical backhaul utilizes multiple wavelength channels for scaling (on an as-needed basis) to increase number of cells or traffic, simplifying infrastructure sharing and leasing capacity for additional revenue streams. Furthermore, the more reliable fiber-optic transmission extends the range between antennas and base stations. Moreover, it is possible to adopt state-of-the-art optical technologies for radio physical layer functions such as beamforming, antenna remoting and so forth [143]. Hybrid WDM promises even further capacity scalability necessary for deployment of more base stations and antennas as investigated in this thesis [P7].

4. SUMMARY OF PUBLICATIONS

The publications [P1]-[P8] can be classified into three main subtopics according to the research framework of Chapter 3. The transmission performance analysis introduced in Section 3.1 is presented in [P1] and [P2]. Based on the results presented in [P2], modified OXN and OADM designs are presented in [P3] and [P4]. Furthermore, a general technique for reducing the complexity of reliable optical nodes is presented in [P5]. Finally, hybrid WDM techniques are presented in [P6]-[P8].

4.1 Publication [P1]

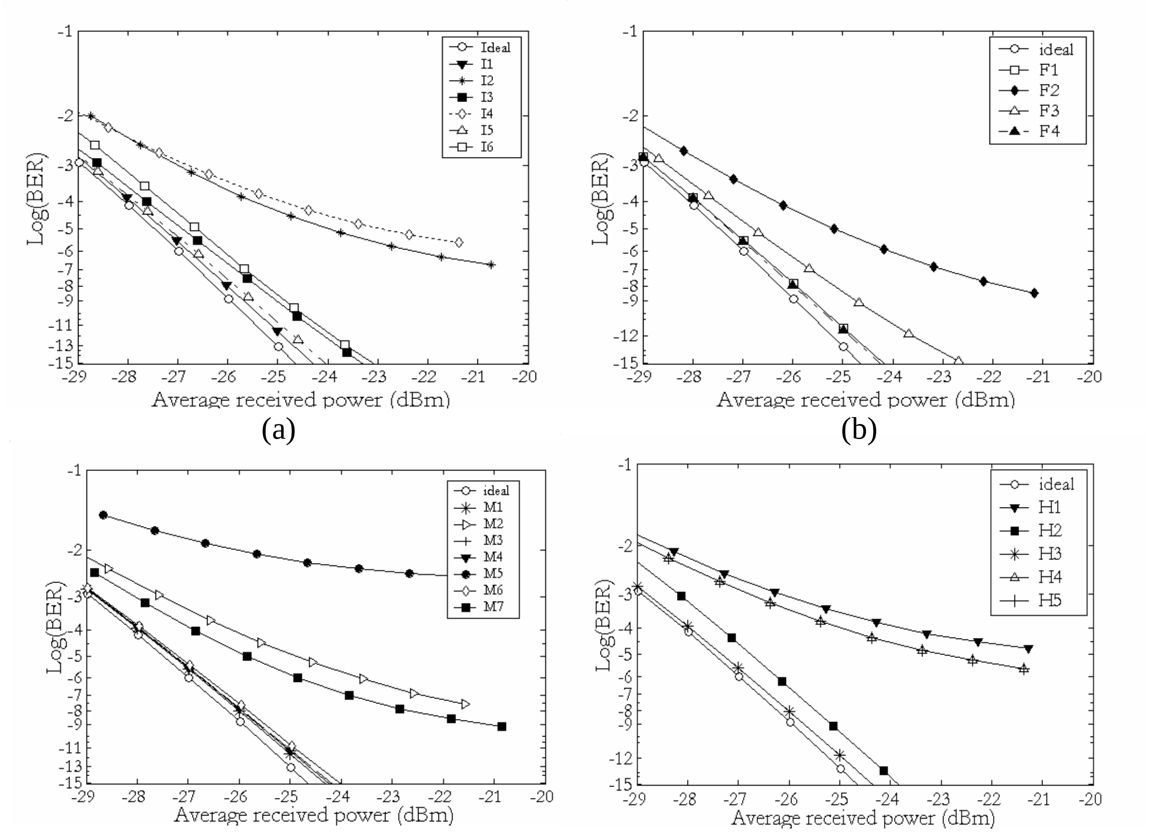
A simulation setup for analyzing the impact of optical nodes on transmission performance is proposed in [P1]. Using a circulating-loop arrangement, the received signal quality is evaluated after every node and the limit on number of traversable nodes is determined for a given BER/Q-factor criterion. This limit is the maximum number of optical hops $H_{\max}$ achievable for a given system. Only 2×2 all-optical OXNs (also known as photonic cross-connect nodes, PXN) are considered in the analysis because it is the most basic OXN architecture and its importance for various implementations as described in Section 3.2.1. Therefore, the $H_{\max}$ for a 2×2 OXN can be viewed as the upper-limit on optical hops for a particular OXN.

For all the simulations, the worst case condition is assumed, whereby the OXNs only use the wavelength switching level. This means that the OXNs are more complex [40] and hence have greater sources of impairment [75]. Furthermore, the number of wavelengths channels is 4 and each optical hop was 30 km long. Simulation comparisons where carried out for a few selected OXNs. For some OXN designs, it was noted that a 20 dB improvement in individual switch crosstalk isolation increased $H_{\max}$ by up to 8 hops. This translates into a significant increase in the diameter of transparent all-optical islands.

4.2 Publication [P2]

The simulation setup proposed in [P1] is applied to a wider range of nodes in [P2]. As in [P1], only 2×2 OXNs based on OOO wavelength level switching is considered for a 4 channel WDM system. A OXN classification according to the OXN's constituent modules (in particular, the wavelength level switches) is proposed. The four main categories and corresponding OXNs simulated in [P2] are (a) integrated-Optic OXNs implemented using photonic integrated circuits (PICs) [144–149] (b) all-fiber OXNs utilizing components made from specialty fibers [150–153] (c) microoptic OXNs constituting stand-alone or combined components that relay an optical beam by collimating, reflecting, shaping or diffracting the beam [154–160] (*d*) hybrid OXNs made of a combination of component technologies from the previous three categories [153, 161–164].

The simulation results indicate that microoptic and all-fiber OXNs provide the best transmission performance and hence maximizes $H_{\max}$. Alternative simulation results (using same setup and parameters of [P2]) are illustrated in Figure 4.10, whereby the BER is plotted against the average received power. As a follow-up to [P2] it has been suggested that forward error correction (FEC) may increase $H_{\max}$ by up to 5 hops [165].



(a) (b)

(c) (d)

Fig. 4.10. Simulated BER versus received power curves after 7 OXNs. The nodes considered are ideal nodes and (a) integrated nodes I1, I2, I3, I4, I5, I6 from [144–149] respectively (b) all-fiber nodes F1, F2, F3, F4 [150–153] respectively (c) microoptic nodes M1, M2, M3, M4, M5, M6, M7 from[154–160] respectively and (d) the hybrid nodes H1, H2, H3, H4, H5 from [153, 161–164] respectively.

4.3 Publication [P3]

All-fiber implementations of an OXN have very low coupling losses, sufficient polarization independence, large crosstalk isolation and operate on wide bandwidths. Furthermore, their transmission performance in [P2] has been observed to be comparable to other OXN designs. Moreover, the inexpensive fabrication and packaging procedures of fiber device modules allows volume production of these all-fiber OXNs. A comprehensive review of the all-fiber device modules is carried out and an all-fiber OOO switching OXN is proposed in [P3].

The proposed node has a configuration similar to the all-fiber node of whereby tunable fiber Bragg grating (FBG) filters are used for wavelength demultiplexing and switching [152]. The main modifications described in [P3] and illustrated in Figure 4.11 are:

(i) An extra double-stage fiber Fabry-Perot (FFP) filtering stage with high-selectivity [166] is added so as to suppress the sidelobes of the FBGs [167].

(ii) The silica-based FBGs are replaced with plastic or polymer Bragg gratings (PBGs) which can be tuned over a relatively wider wavelength range (over 80 nm [168]) due to the latter's lower Young's modulus (measure of stiffness or elasticity) [169]. This enables the future exploitation of guard bands for tighter wavelength channel spacing and allows the node to function in systems (e.g., CWDM) operating within and beyond the C-band.

(iii) The node is configured to reuse common component modules for both wavelength and waveband level switching. This is unlike most hierarchical OXN designs which have a separate tier of components reserved exclusively for wavelength and waveband switching [40].

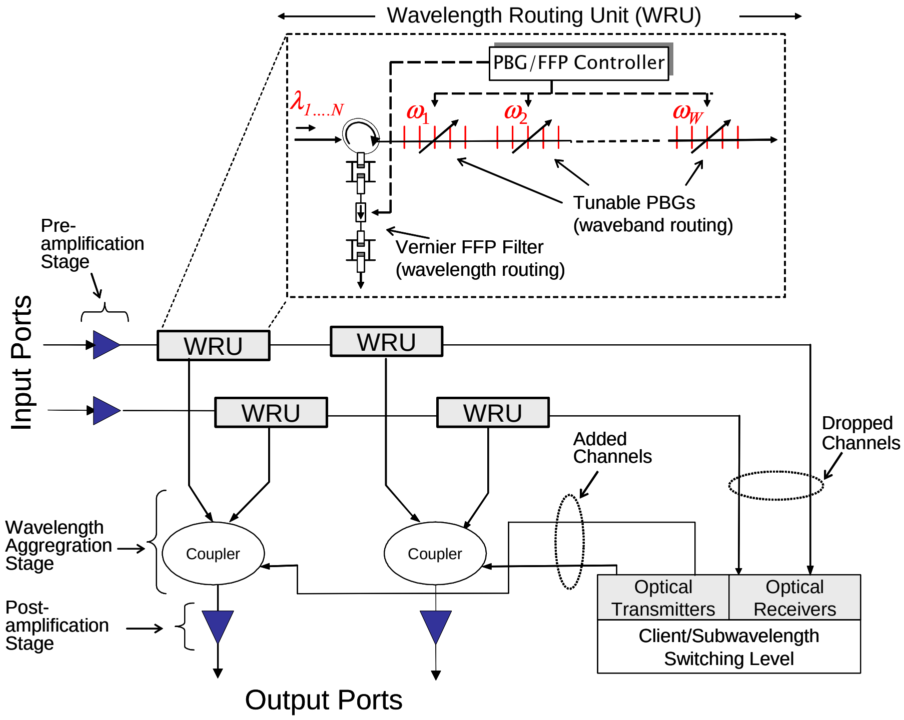


Fig. 4.11. A 2×2 all-fiber OXN architecture based on the modifications proposed in [P3].

The improved all-fiber OXN's transmission performance was compared to that of all-fiber OXN's with no modifications, using the simulation setup suggested in [P1]. The transmission performance is quantified by the simulated optical signal-to-noise ratio (OSNR) variation with cascaded OXNs (unregenerated hop numbers) as shown in Figure 4.12. It was observed that unmodified OXNs have significantly reduced OSNR when N is increased. By contrast, the change in OSNR of modified OXNs less exaggerated for modified OXNs, thus enabling the cascading of a larger number of OXNs. Some of the recommended modifications in [P3] have been further exploited by third parties for alternative all-fiber OXN design proposals [170].

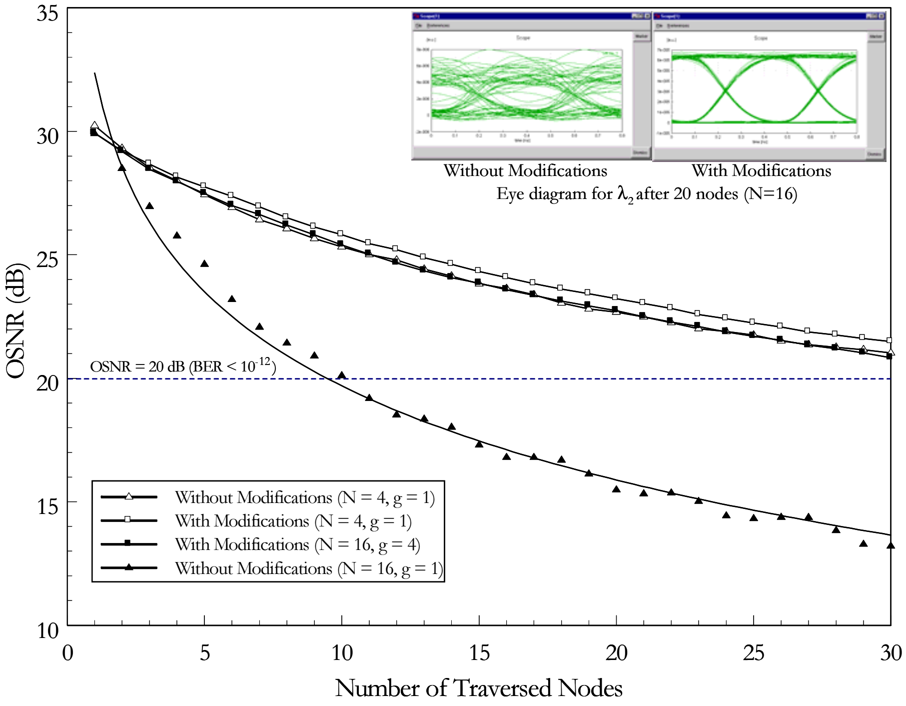


Fig. 4.12. Received optical SNR (OSNR) for signal at λ_2 versus traversed nodes with(out) modifications for an N wavelength system (g is number of wavelengths in a waveband).The eye diagrams after 20 nodes, are shown inset.

Recent developments indicate that FBGs could be tuned over a 90 nm by using combined tensile and axial strain tuning [171]. PBGs employing the same method should be tunable over twice their usual limit (> 160 nm), since as mention above, plastic fibers possess higher elasticity than silica fibers. Furthermore, axial strain tunable FBGs with a tuning speed of 21 nm/ms have been reported [172]. Since PBGs require relatively shorter piezoelectric actuator displacement, then they could be tuned even more rapidly. This ensures that PBG-based OXNs have sub-milliseconds switching speeds (sufficient for optical circuit or burst switching) when operating in C/L-bands. Moreover, improvements in the PBG fabrication process has seen reflectivity improve from $\varrho = 90\%$ reflectivity (6 dB crosstalk rejection) used in [P3] to $\varrho = 99.8\%$ (28 dB crosstalk rejection) [173]. This reduction in crosstalk power penalties should enable the construction of large PBG-based all-fiber OXNs or further improve transmission performance.

4.4 Publication [P4]

The OXN modifications proposed in [P3] are adapted to design an all-fiber PBG-based OADM in [P4] as shown in Figure 4.13a. This OADM is suitable for single-fiber WDM ring or linear/bus topologies (see Figure 4.13). As was the case for all-fiber OXNs in [P3], the modified all-fiber OADM has better transmission performance, improved modularity and is more flexible compared to conventional FBG-based OADM designs.

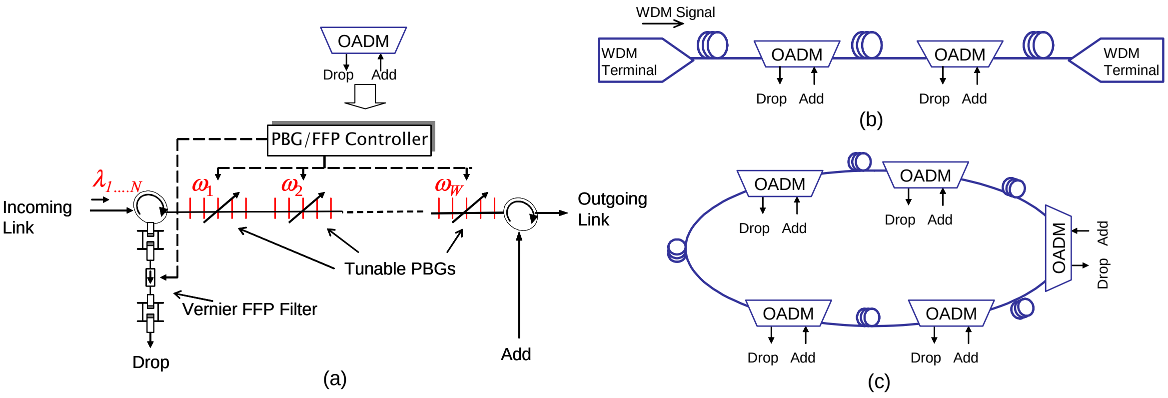


Fig. 4.13. (a) The main components of the proposed all-fiber OADM and the use of OADMs in (b) point-to-point links and (c) single fiber rings.

4.5 Publication [P5]

In [P5], an algorithm for design of dependable nodes is proposed. The algorithm evaluates the optimum allocation of redundant modules in OXN that strikes a balance between availability and node cost. This objective is achieved by maximizing the net present value (NPV) of cashflows attributed to the OXN. The problem is formulated as maximize $F = \left.\frac{\Psi(t)-C_{Tot}(t)}{(1+\delta_t)^t}\right|_{t=T}$ subject to limits on the number of redundant modules for a given OXN sub-system where δ_t is discount factor for calculating present values of costs incurred in period t, Ψ is the revenue and C_{Tot} is the total costs respectively. The problem of optimum redundancy allocation is computationally difficult (NP-hard) [174]. Problems described as NP-hard, can be solved using genetic algorithms (GA)—a class of evolutionary-based adaptive and stochastic optimization algorithms [175]. A GA is employed a genetic optimum redundancy allocation (GORA) algorithm to solve the OXN redundant module allocation in [P4].

An example of a wavelength level OXN with no redundancy is shown in Figure 4.14a. Three redundancy schemes are analyzed; global duplicate redundancy, local standby redundancy and k-out-of-n:G parallel redundancy. These redundancy schemes illustrated in Figures 4.14b, 4.14c and 4.14d respectively.

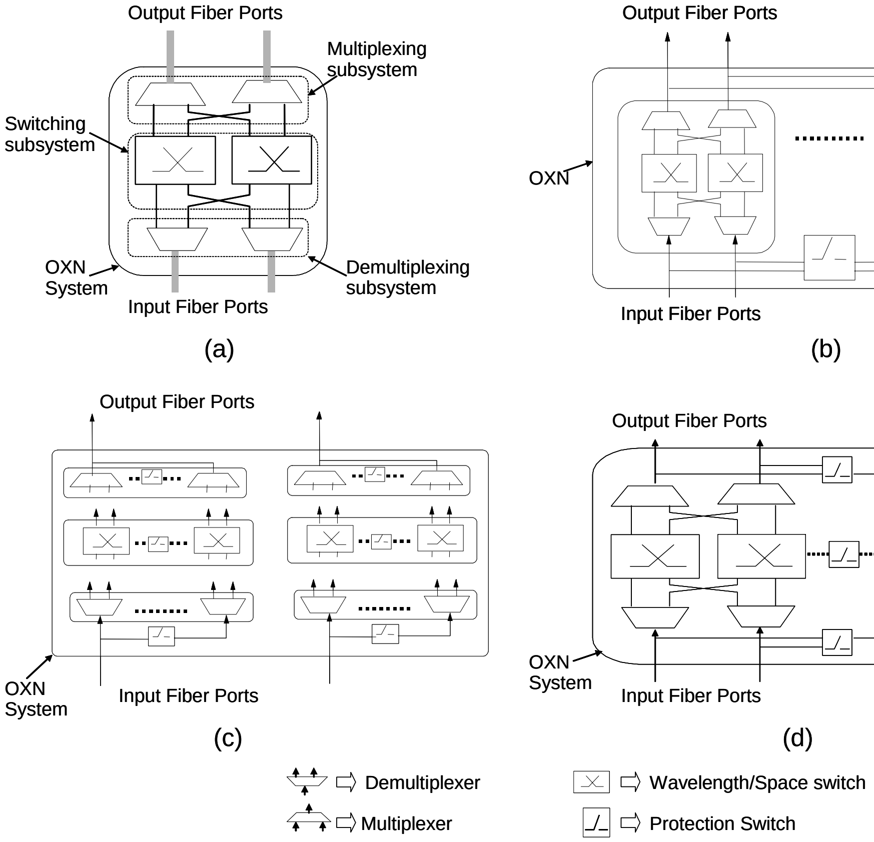


Fig. 4.14. An example of a wavelength switching level 2 × 2 OXN with (a) without redundancy (b) global duplicate redundancy (c) local standby redundancy and (d) k-out-of-n:G redundancy.

The proposed GORA algorithm is used to allocate local standby and k-out-of-n:G on four example 2 × 2 OXNs. The global duplicate redundancy does not employ the GORA algorithm since redundancy is provided by simply duplicating an entire OXN. Corresponding OXN architectures with no redundancy are used as the benchmarks and the percentage change in NPV using the three redundancy schemes is compared in Figure 4.15. For the majority of the cases analyzed, the GORA-based k-out-of-n:G redundancy scheme provides the largest increase in NPV. Furthermore, the relationship between wavelength channel number and NPV improvement observed to be dependent on OXN architectures. Therefore, the GORA algorithm be used as part of a optical network planning process by providing an effective way to further improve the interaction among crucial network management processes such as planning, maintenance and impact analysis of new OXN technologies. This should simplify the management of increasingly complex optical networks, the determination of appropriate management strategies as well as expediting project and business cases.

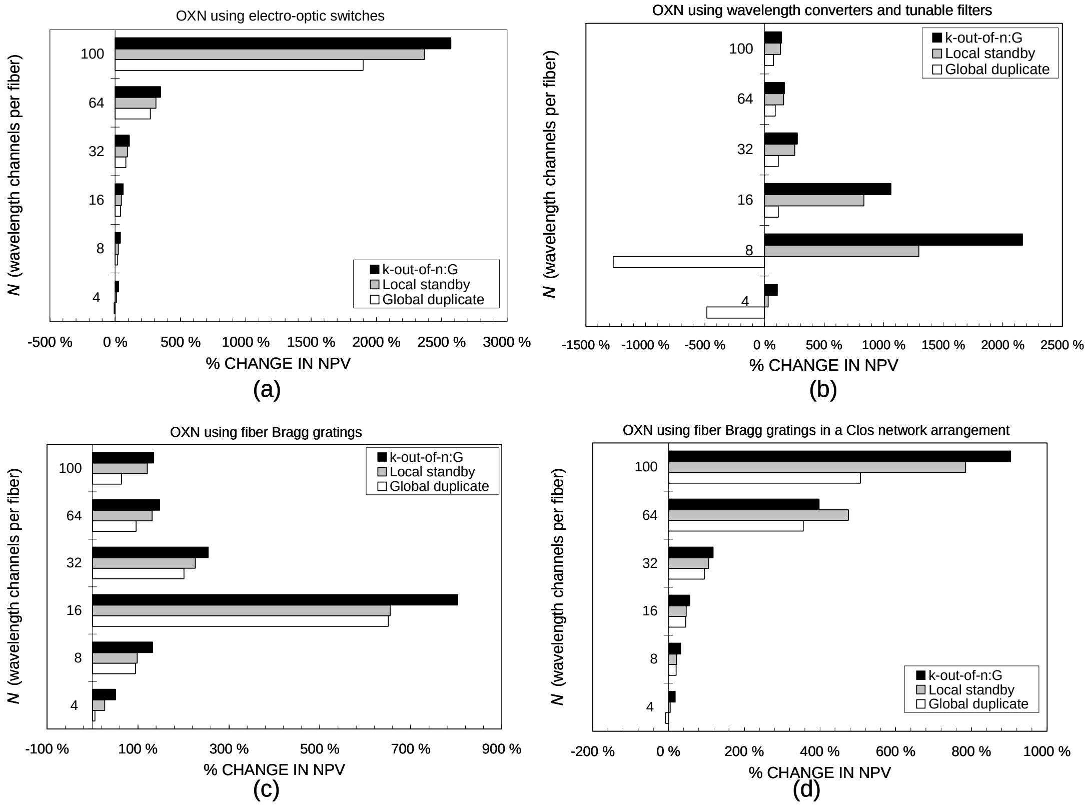


Fig. 4.15. The change in OXN NPV from OXNs with no redundancy versus wavelengths per fiber for OXNs based on (a) electro-optic switches [83], (b) wavelength converters and tunable filters [83], (c) fiber Bragg gratings [152] and (d) fiber Bragg gratings in 3-stage Clos network arrangement [153].

4.6 Publication [P6]

The publication [P6] analyzes the RCA problem for OCDM/WDM networks. The analysis takes into account the additional set of lightpath schemes (CWP, VCWP, CVWP &

VCVWP) described in Section 3.3. The blocking analysis of different lightpaths is carried out on an example regional network. For the sake of comparison, WP/VWP lightpath schemes are also considered with the possibility of client layer grooming capabilities for line rates of up to 40 Gb/s. A fixed shortest-path routing scheme with constraints on $H_{\max}$ is used. For channel assignment, a prefix-based first-fit assignment routine is employed whereby, the free channel with the lowest wavelength prefix is assigned first [that is, (λ_i, c_j) assigned before (λ_m, c_n) if $i < m$]. If free channels have the same wavelength prefix then least code prefix is selected [(λ_i, c_j) assigned before $(\lambda_{m=i}, c_n)$ if $j < n$].

The blocking performance of different schemes for 3000 trials analyzed in [P6] is compared here using cumulative distribution plots of Figure 4.16. The blocking performance of WP schemes could be improved by increasing granularity G (from 2.5 Gb/s up to 40 Gb/s) and upgrading to VWP schemes (see Figure 4.16a). However, OCDM/WDM lightpath schemes offer even better without the need to increase wavelength number or granularity (see Figure 4.16b). The improvements are most visible when the wavelength continuity constraint is relaxed by wavelength conversion (CVWP/VCVWP schemes) because in practice $N \gg M$ (due to OMUI and dispersion limitations outlined in Section 3). Therefore, the number of wavelength converters is almost always larger than code constraint relievers (code converters). The VCWP scheme only shows modest improvement for the same reason. The VCVWP scheme provided the best blocking performance due to higher possibility of resolving wavelength and code contentions on every hop. However, cost considerations and device maturity (for fully tunable WCs and CCs) currently limit the feasibility of the VCVWP scheme. Since, the CVWP scheme exhibits the best performance in terms of converter requirements and blocking performance, then it offers a more viable option.

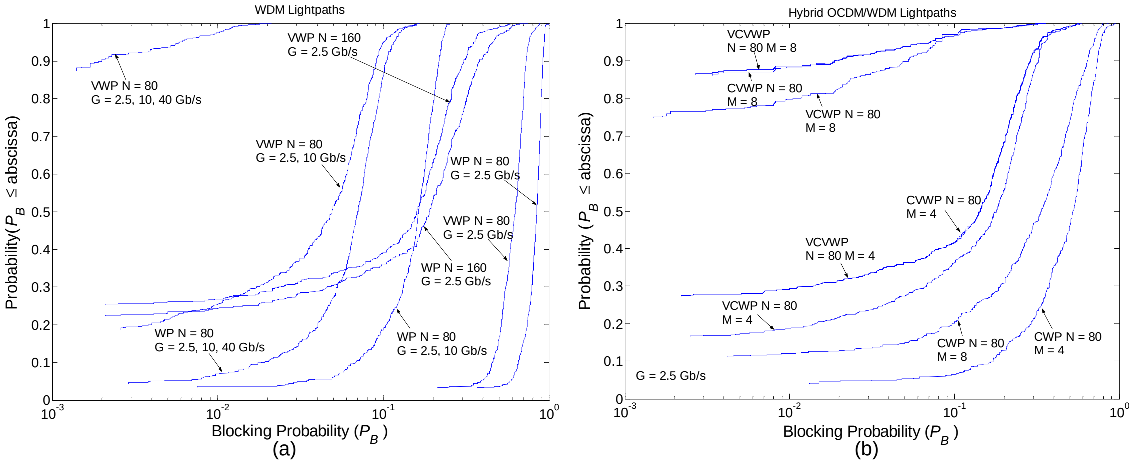


Fig. 4.16. Cumulative distribution of the blocking probability of (a) WDM lightpaths with different wavelength numbers [N = 80 or 160] granularities [G = 2.5, 10 or 40 Gb/s] (b)OCDM/WDM lightpaths with different code cardinalities [M = 4 or 8], N = 80 and G = 2.5 Gb/s.

4.7 Publication [P7]

The wireless caused by the proliferation of optical-backhaul networks for BWAN will put a significant strain on the resources (that is, wavelengths) when sharing existing WDM-based access and metropolitan network infrastructure bearing fixed network traffic. In [P7], techniques for reducing the demand for distinct wavelength channels using hybrid WDM (xDM/WDM) are investigated. Furthermore, a comprehensive review of possible xDM is techniques is carried out.

The following three optical layer multiplexing scenarios are considered (see Figure 4.17 for graphical representation):

(a) *Pure WDM*: whereby individual wavelengths assigned are for each wireless and fixed network connection request.

(b) *Semi-hybrid WDM*: multiple wireless connections on a common fiber link are x-division-multiplexed before sharing a single wavelength channel.

(c) *Hybrid WDM*: multiple wireless and fixed connections on a common fiber link are x-division-multiplexed together before sharing a single wavelength channel.

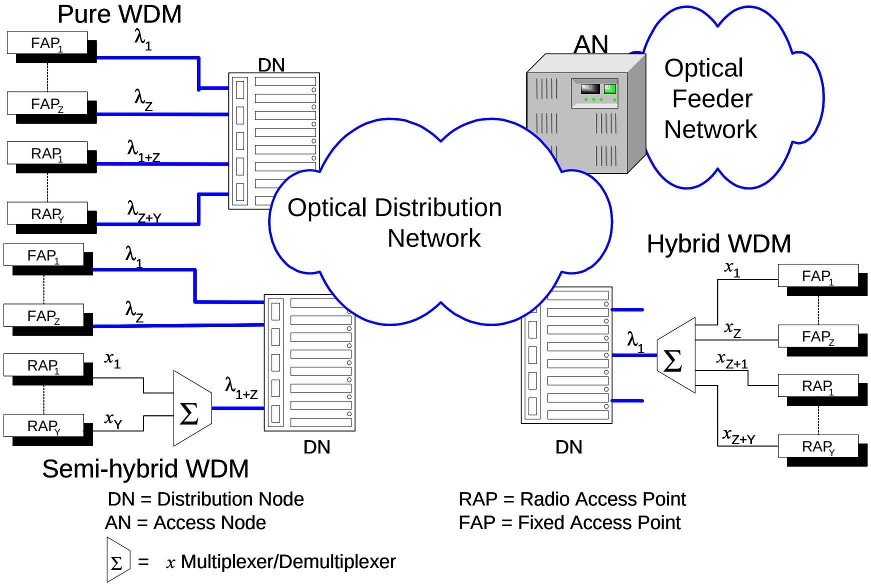


Fig. 4.17. The three (pure, semi-hybrid, hybrid) WDM schemes compared in the study of the heterogeneous networks. The optical line terminal for the wireless and fixed connections are the radio access point (RAP) and fixed access point (FAP) respectively. Each distribution node (DN) supports a maximum of Z and Y FAPs and RAPs respectively. The number of wavelengths required above for the pure, semi-hybrid and hybrid WDM schemes is $Z+Y$,$1+Z$ and 1 respectively.

Analysis is based on a hierarchical network modeled after [37], whereby the three main tiers are the feeder, distribution and customer networks (see Figure 4.17) . The feeder and distribution networks are assumed to be optical, with the latter being a 4-fiber SPRing. The number of required wavelengths is evaluated using the maximum load dimensioning models over a large number of randomly generated topologies.

From the analysis, the minimum wavelength requirements (represented by third quartile of the wavelength requirement distributions) for an example metropolitan access network using using pure, semi-hybrid and hybrid WDM schemes are listed in Table 4.2. Hybrid WDM requires the least number of distinct wavelength channels as shown in the table. However, the combined management of fixed and wireless connections is a nontrivial engineering task. Pure WDM is more straightforward to implement, but requires over

	Pure WDM	Semi-hybrid WDM		Hybrid WDM	
	–	$M = 4$	$M = 16$	$M = 4$	$M = 16$
With WC	87	63	61	29	21
Without WC	44	35	32	15	11

Table 4.2. The statistical minimum required wavelength channels for an example heterogenous metropolitan access network using pure, semi-hybrid and hybrid WDM schemes. Here M is the number maximum number of xDM channels

twice the number of wavelengths as hybrid WDM. Semi-hybrid WDM is considered to be a compromise solution of the aforementioned schemes. It was further noted that strategic deployment of a limited number of WCs has a profound impact on wavelength numbers for all schemes. However, the obstacles for OOO WC maturity [129] have to be overcome to make the solution feasible.

4.8 Publication [P8]

A hybrid OCDM/WDM 60 GHz MMW-over-fiber system is proposed in [P8]. Bipolar (0 and π) phase encoding is utilized for the OCDM multiplexing stage. Optical heterodyning is used to eliminate RF signal fading [176] at the base station due to the fiber-dispersion-induced phase-mismatching.

Simulations are performed for a hybrid 2 OCDM × 4 WDM × 155 Mb/s system, whereby each code is 7 chips long and the wavelengths are spaced by 100 GHz. Using the same specifications, 2 OCDM (pure OCDM), 2 WDM (pure WDM), and 8 WDM (pure WDM)—all with 155 Mb/s line rates—are simulated for comparison. For BER $< 10^{-12}$, the difference in performance between 2 OCDM and 2 WDM systems is negligible. However, the difference is more significant between 8 WDM and 2 OCDM × 4 WDM, due to the latter's BER floors induced by OMUI and WDM crosstalk. Techniques that could improve the BER of the OCDM/WDM system over by 4 orders of magnitude are identified and compared based on their relative merits.

4.9 Author's Contribution To Published Work

The author's contribution has been paramount for Publications [P1]-[P8]. The author of thesis is solely responsible for the ideas, writing, overviews, analysis, propositions, simulations and conclusions presented in all the listed Publications [P1]-[P8].

External assistance for the authoring is acknowledged in terms of supervision by the second author of Publications [P6]-[P8]. Furthermore, the second author in Publication [P4] assisted in the writing and document formatting for submission. Finally, the third to fifth authors of Publications [P7] and [P8] are credited for contributing expert advice on MMW-band systems and BWANs.

5. CONCLUSIONS

In this section, the main results of the presented work are summarized and critically analyzed. An overview of the future research topics building on this work is also presented.

5.1 Summary of the Work

This dissertation, analyzes the transmission performance of a wide range of OXNs. It unveils, the dependency between an OXN's transmission performance and its architecture. Based on the observation of the transmission performance analysis, a novel all-fiber OXN is proposed. Compared to other OXN architectures, all-fiber OXNs have relatively lower loss, lower crosstalk penalties and wider bandwidths. The all-fiber OXNs proposed here demonstrate even more improved scalability, transmission performance and flexibility advantages compared to previous all-fiber OXN proposals. Similar methodologies are used to propose a corresponding all-fiber OADM. Furthermore, an algorithm for designing more dependable optical nodes is given. The proposed algorithm (GORA) uses a genetic algorithm to perform optimum allocation of redundancy of a node's constituent component modules. This algorithm strikes a balance between a node's availability and cost.

Hybrid WDM is a grooming action that involves overlaying an optical xDM scheme over legacy WDM so as to improve the reuse of wavelength channels. Special emphasis is placed on OCDM/WDM transmission and its associated lightpath schemes (CWP, CVWP, VCWP and VCVWP). The improved agility due to the use of code switches and/or converters is noted in the analysis of connection blocking for different lightpath schemes. An application of hybrid WDM for 60 GHz MMW-over-fiber systems is proposed. Further blocking analysis based on an example hierarchical metropolitan access network confirmed the merits of semi-hybrid and hybrid WDM for the application. Finally, a novel MMW-over-fiber system using hybrid OCDM/WDM transmission is proposed and its transmission performance is analyzed.

In summary, the work presented in this dissertation further contributes to the understanding and design of both pure and hybrid WDM networks. The results present an additional argument for performance and cost optimized design of all-optical optical nodes. Furthermore, the work stresses the need hybrid WDM implementations using xDM/WDM transmission so as to perform optical layer grooming and avoid wavelength exhaust.

5.2 Critical Analysis of Results

Several critical comments may be made highlight limitations of research results and proposals made in Publications [P1]-[P8].

A physical layer simulator was used effectively for the relative comparison of various design options in [P1]-[P4] and [P8]. However, the absolute accuracy of the results obtained using the simulator is limited by the approximations required to improve the computation efficiency of the underlying models of the simulator. Furthermore, devices not available in the module library of the simulator are approximated by costume coding, combining or modifying the parameters of existing modules.

The all-fiber OXN and OADM of [P3] and [P4] respectively, have a scalability that is suitable for metropolitan core, metropolitan-edge and access networks. This is because nodes required for those networks have a low input/output port count due to smaller fiber bundles and reduced wavelength techniques such as CWDM. By contrast, nodes deployed in regional, national or continental backbone networks have larger dimensions (32×32 and above) due to larger channel aggregates and fiber counts. Those nodes may be better implemented using complex but highly scalable technologies such as 3D MEMS (micro electromechanical systems) [177].

Dependability-based node design method proposed using GORA in [P5] assumed nodes with a scalable number of discrete modules. However, in some cases integrated node designs (such as [178]) are a preferred alternative to discrete nodes. Since fully integrated nodes lack that modular property, then global duplicate redundancy is the only viable redundancy scheme. This reduces the need for optimum redundancy allocation techniques such as GORA.

The dispersion penalties incurred in hybrid OCDM/WDM transmission are only considered in [P6] for line rates of up to 2.5 Gb/s. The line rate scaling to 10 Gb/s (and inevitably 40 Gb/s) will tighten the distance limits even further. Such penalties precludes the use of the installed (mainly ITU G.652) fiber-base or necessitates the use of complex dispersion managements (e.g., [111]). Those costly measures may weaken the business case for the implementation of OCDM/WDM in regional and metropolitan core networks.

Publications [P7], [P8] only address the optical layer challenges of implementing hybrid WDM networks for handling heterogenous traffic. However, equally formidable challenges exist in the integration of databases, operations and services of wireline and wireless customers. These interworking challenges have polarized industry opinion between separating and integrating wireline and wireless networks [179]. However, that debate can be reduced by having OCSPs providing optical capacity separately to independent fixed and wireless service providers.

5.3 Future work

In [P3] and [P4] all-fiber node designs where proposed for OXNs and OADMs. The designs relied on the use of widely-tunable polymer grating devices. A new class of fiber known as the microstructured or holey fibers offer more tailorable properties compared to conventional silica fibers [180]. Therefore, it is possible to engineer more diverse and compact fiber devices using holey fiber technologies [181]. Moreover, holey fiber technology is not confined to silica fiber devices as polymer holey fibers are also being investigated [182]. Further research on these holey fiber devices should produce even more agile, compact, robust and feature-rich optical node designs.

The dependability-based node design presented here has only considered wavelength-level OXNs. Further work could be performed to design dependable hierarchical OXNs (that is, of Figure 2.2). This should offer means of quantifying the advantage of hierarchical nodes over non-hierarchical (only wavelength-level) nodes.

The transmission performance analysis of [P2] was restricted to nodes for WP lightpath schemes. Similar analysis is essential for CWP, CVWP, VCWP and VCVWP lightpath schemes described in [P6] using a variant of the node of Figure 3.9. The analysis in [P6], assumed that wavelength and/or code converters are available at all nodes and are fully tunable. However, further analysis is necessary for the practical case whereby the conversion will be sparse and have a limited tuning range due to cost and technical constraints.

The work in the thesis has concentrated only on two-stage hybrid WDM (xDM/WDM). However, this work could be extended and reproduced for multi-stage hybrid WDM (e.g., xDM/yDM/WDM where x and y are two distinct signal attributes) techniques which promise to offer even more efficient optical layer grooming. Moreover, a clear set of criteria needs to be defined for the performance comparison between client layer and hybrid WDM-based optical layer grooming methods.

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