Control plane routing in photonic networks

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A thesis submitted to University College London for the degree of Doctor in Engineering (Eng.D).

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August 2011

Declaration

I, Robert John Friskney, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed: Date:

Abstract

The work described in the thesis investigates the features of control plane functionality for routing wavelength paths to serve a set of sub-wavelength demands. The work takes account of routing problems only found in physical network layers, notably analogue transmission impairments.

Much work exists on routing connections for dynamic Wavelength-Routed Optical Networks (WRON) and to demonstrate their advantages over static photonic networks. However, the question of how agile the WRON should be has not been addressed quantitatively. A categorization of switching speeds is extended, and compared with the reasons for requiring network agility. The increase of effective network capacity achieved with increased agility is quantified through new simulations. It is demonstrated that this benefit only occurs within a certain window of network fill; achievement of significant gain from a more-agile network may be prevented by the operator's chosen tolerable blocking probability.

The Wavelength Path Sharing (WPS) scheme uses semi-static wavelengths to form unidirectional photonic shared buses, reducing the need for photonic agility. Making WPS more practical, novel improved routing algorithms are proposed and evaluated for both execution time and performance, offering significant benefit in speed at modest cost in efficiency.

Photonic viability is the question of whether a path that the control plane can configure will work with an acceptable bit error rate (BER) despite the physical transmission impairments encountered. It is shown that, although there is no single approach that is simple, quick to execute and generally applicable at this time, under stated conditions approximations may be made to achieve a general solution that will be fast enough to enable some applications of agility.

The presented algorithms, analysis of optimal network agility and viability assessment approaches can be applied in the analysis and design of future photonic control planes and network architectures.

Acknowledgements

I am grateful to my supervisor, Professor Polina Bayvel, for her guidance throughout this work. I would also like to thank the other academics, administrators and students at UCL Electronic Engineering who have helped me get to this point, and my proofreaders: Sarah Lilly, Peter Darton and Ruth Friskney.

I also acknowledge the significant improvement to the clarity of the thesis due to the suggestions made by my examiners, Professor Andy Valdar of UCL and Dr. Hans-Jorg Thiele of Nokia-Siemens.

I acknowledge the kind help and support I have received towards this course of study from my colleagues past and present at Nortel and Ciena. Notable among these are my colleagues at the Kao-Hockham laboratories at Nortel Harlow who launched me into the field of photonics. Sadly, that group was disbanded in the collapse of Nortel.

Acknowledgements of help on particular topics are given in the relevant sections.

I gratefully acknowledge support from both the Engineering and Physical Sciences Research Council (EPSRC) and my employers during the course of this thesis, Nortel and Ciena. This thesis is not written on behalf of my employers and no part of it should be taken as any form of statement or utterance by them.

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k	The number of alternative optimal or near-optimal paths to be considered in a k-shortest path algorithm.
l	Average length of the optical path.
p	A wavelength-path (usually a member of P).
t_s	An operator's acceptable worst-case wavelength-path setup time (Chapter 3).
w	A particular wavelength (in the sense, reciprocal frequency).
A_n	Network agility (see Chapter 3 for definition).
A_p	Path agility (see Chapter 3 for definition).
A_s	Switch agility (see Chapter 3 for definition).
$D(x,y)$	Sub-wavelength demand from node x to node y.
D_x	Optical signal distortion at measurement point x (Chapter 4).
N	Number of nodes.
$N\lambda$ *(A-WRON)*	Minimum number of wavelengths that would be required to serve the demands by an A-WRON according to the Baroni lower bound.
$N\lambda$ *(M-ILP)*	Minimum number of wavelengths that would be required to serve the demands by WPS, calculated according to Myers's ILP (Chapter 2).
$N\lambda$ *(LRF)*	Minimum number of wavelengths that would be required to serve the demands by WPS, calculated according to the Longest-Route First heuristic proposed in Chapter 2.

L	Number of links.
P	The set of all wavelength-paths.
$P(B)$	Blocking probability (given conditions stated near the usage).
W	The set of all wavelengths. w is usually a member. Wavelength as in reciprocal frequency, not wavelength-path.
α	The normalised number of bi-directional links with respect to a fully-connected mesh topology (as defined in Appendix B).
$\beta_{(s,d)}$	Arrival rate for wavelength demands from node s to node d.
δ_{pw}	A function that indicates whether wavelength-path p travels over wavelength w (1) or not (0). See equation 2-2.
ε	Permissible (small) variation away from optimum path lengths in the Myers ILP assessed in Chapter 2.
λ_x	Wavelength-path x.
$\mu_{(s,d)}$	Departure rate for wavelength demands from node s to node d.
Δ	The mean nodal degree of a graph.

List of abbreviations

Terms introduced in this thesis are in italics. Other terms are names or common terms within the industry. A brief explanation is given for key general terms.

AMS-IX	The Amsterdam Internet Exchange. See http://www.ams-ix.net/.
ASE	Amplified Spontaneous Emission. See section 4.1.1.
ASTN	Automatic Switched Transport Network: See ITU-T standard G.8080 and related documents from http://www.itu.int/rec/T-REC-G/en. One version of ASTN uses a GMPLS control plane.
AUR-E	Adaptive Unconstrained Routing – Exhaustive [wavelength consideration]. See AUR-F.
AUR-F	Adaptive Unconstrained Routing – Fixed [sequence of wavelength consideration]. An algorithm for simultaneous routing and wavelength allocation discussed and extended for WPS in Chapter 2.
A-WRONs	*Agile Wavelength Routed Optical Networks: A term defined in this thesis, in section 1.7.3.*
BER	Bit Error Rate.
DCM	Dispersion Compensation Module: A unit used to partially or wholly ‘undo’ the chromatic dispersion effects of a length of transmission fibre.
DGD	Differential Group Delay.
DP-QPSK	Dual-Polarization Quadrature Phase-Shift Keying. The modulation format for the Ciena 40/100G transmission system described in Appendix A.
DSP	Digital Signal Processing or Digital Signal Processor.

DWDM	Dense Wavelength Division Multiplexing: A form of WDM with tightly-packed channels (see ITU-T G.694.1). As opposed to Coarse WDM (see ITU-T G.694.2) which has wider channel spacing/fewer channels.
eDCO	Electronic Dynamically-Compensating Optics. A Ciena term. See Appendix A.
EDFA	Erbium-Doped Fibre Amplifier.
EON	European Optical Network. One of the test networks used for analysis in Chapters 2 and 3. See Appendix B.
FEC	Forward Error Correction.
FF	First-Fit: A well-known simple heuristic for wavelength allocation for a set of routes. Described in Chapter 2.
FWM	Four-Wave Mixing. See section 4.1.1.
GMPLS	Generalized Multi-Protocol Label Switching: A control plane for SONET, OTN, DWDM and other technologies. A family of standards developed within the IETF's Common Control and Measurement Plane (CCAMP) working group. http://datatracker.ietf.org/wg/ccamp/.
IETF	Internet Engineering Task Force: See http://www.ietf.org/.
ILP	Integer Linear Programming. A mathematical method for finding an optimal solution to a class of problems.
IMDD	Intensity Modulation with Direct Detection. As opposed to phase-modulated or QAM and coherent reception. In this thesis, always assumed to be OOK.
ISIS-TE	Intermediate System to Intermediate System extensions for Traffic Engineering. A data-distribution protocol used within GMPLS and ASTN as an alternative to OSPF-TE. See IETF RFCs 5305 and 5307.

ITU-T International Telecommunication Union – Telecommunication standardization sector. See http://www.itu.int/.

IW *Infrastructure Wavelengths: See definition in Chapter 3. As opposed to wavelength-on-demand.*

LRF *Longest-Route First: A heuristic algorithm for wavelength routing for WPS, proposed in Chapter 2.*

MEMS Micro Electro Mechanical Systems.

M-ILP Myers-Integer Linear Program. The ILP formulation due to Myers for wavelength allocation in WPS. Described in Chapter 2.

MINTS Minnesota Internet Traffic Studies: A website collecting data on internet traffic throughput around the world, http://www.dtc.umn.edu/mints/

MPLS MultiProtocol Label Switching. See IETF RFC 3031.

NSFNet National Science Foundation Network. One of the test networks used for analysis in Chapters 2 and 3. See Appendix B.

NRZ Non-Return-to-Zero line code.

OBS Optical Burst Switching: See section 1.7.2.

OCS Optical Circuit Switching. Discussed within section 1.7.3.

ODU Optical channel Data Unit: See ITU-T G.709. e.g. ODU2 is payload of approximately 10Gbps payload.

OEO Optical-Electrical-Optical: The process of performing an operation (e.g. switching, or regeneration) such that it requires conversion of the optical signal into electronic form (e.g. such that it can go through an electronic switch) and back again. An all-optical operation does not require the two conversions. See discussion in section 1.3.

(O)OFDM	(Optical) Orthogonal Frequency Division Multiplexing.
OOK	On-Off Keyed: The simplest and most common form of intensity modulation.
OPS	Optical Packet Switching: See section 1.7.1.
OSA	Optical Spectrum Analyser.
OSNR	Optical Signal-to-Noise-Ratio. See section 4.2.4.1.
OSPF-TE	Open Shortest Path First with Traffic Engineering extensions. See IETF RFC 3630. A data-distribution protocol used within GMPLS and ASTN as an alternative to ISIS-TE.
OTDM	Optical Time-Division Multiplexing
OVE	Optical Viability Engine. See section 4.1.
PBB-TE	Provider Backbone Bridge – Traffic Engineering. IEEE 802.1Qay.
PCE	Path Computation Element. See IETF RFC4655, http://datatracker.ietf.org/doc/rfc4655/.
PDL	Polarization-Dependent Loss.
PMD	Polarization Mode Dispersion.
PON	Passive Optical Network.
POP	Point of Presence. A telecommunication demarcation point or interface point between two or more companies or entities.
QAM	Quadrature Amplitude Modulation.
QoS	Quality of Service.

QPSK	Quadrature Phase-Shift Keying. Mostly used in the form of dual-polarization QPSK (DP-QPSK). See Appendix A.
RCN	Randomly-Connected Network. The RCNs used in Chapters 2 and 3 are illustrated in Appendix B.
ROADM	Reconfigurable Optical Add-Drop Multiplexer.
SDH	Synchronous Digital Hierarchy. See e.g. ITU-T G.707. The ITU-T equivalent to SONET.
SONET	Synchronous Optical NETworking. See e.g. Telcordia (formerly known as Bellcore) standard GR-253-CORE. The American equivalent to SDH.
SPM	Self-Phase Modulation. See section 4.1.1.
WA-ILP	*Wavelength Allocation Integer Linear Program. An ILP formulation proposed in Chapter 2 of this thesis for allocating a specific wavelength to each of a set of paths.*
WDM	The process of injecting multiple channels onto a fibre, separated by the wavelength of their light. See DWDM.
WPS	Wavelength Path Sharing. The subject of Chapter 2.
WROBS	Wavelength-Routed Optical Burst Switching. See section 1.7.2.
WRON	Wavelength-Routed Optical Networks. See section 1.3 for an introduction.
WSS	Wavelength-Selective Switch. References are provided in Chapter 2.
XFP	10 Gigabit Small Form Factor Pluggable. Small Form Factor Committee INF-8077i. ftp://ftp.seagate.com/sff/INF-8077.PDF.
XPM	Cross-Phase Modulation. See section 4.1.1.
XpolM	Cross-Polarization Modulation. See section 4.1.1.

Chapter 1 Introduction

1.1 Outline of problem space

The problem space described in this thesis is how to meet data-transport traffic demands in telecoms optical-fibre network cores. The core is an administratively-defined boundary. There is usually access networking around it, which is outside of the scope of this thesis. The access networking could comprise some or all of routers, Ethernet switches, TDM switches, or any other form of aggregation layer, the effect of which is then represented as the point-to-point demands placed upon the core nodes.

A key part of addressing those demands is the connection routing process that happens as part of the network planning/design process or some form of automated provisioning system e.g. Generalized Multi-Protocol Label Switching (GMPLS)/Automatic switch-transport network (ASTN). [GMPLS] [ASTN]

Demands are considered in terms of streams of packets whose destinations may vary from packet to packet. On-demand circuit-switched connections are covered as a trivial form of packet stream, where the destination remains the same for all of the packets in the stream.

Throughout the thesis it is assumed that there is a finite set of nodes N in the core, and that the bandwidth demand from node x to node y can be expressed as D_{xy} where $D_{xy} \geqq 0$, $x \in N; y \in N$ and $D_{xx}=0$. The latter is because it is assumed that the access equipment transports any local demand without reference to the core network, for simplicity. Then all the demands that the network needs to serve are contained with the matrix of the D_{xy} values.

Resilience/protection/behaviour-on-fault arrangements are not considered in this thesis, to simplify the analysis. A study on this area in collaboration with the author may be found in [Dong 03] and [Dong 06], with the resultant scheme patented as [Friskney 02e] and [Friskney 03a].

1.2 Why dense wavelength division multiplexing (DWDM)?

Worldwide demand for communications bandwidth has been growing fast for some years and continues to do so. For example [Swanson 08] says IP traffic grew 48 percent to 4,949 petabytes/month during 2007, forecasting 62 percent for 2008. [Cisco 11] forecasts 32 percent annual growth from 2010 to 2015 and predicts 80.5 exabytes/month in 2015. [Deloitte 07] reports 7.4%/month growth at the Amsterdam Internet Exchange (AMS-IX which takes 20% of Europe's traffic), equivalent to an annual compounded rate of 236%. The [MINTS] website at the time of writing provides a survey of recorded traffic data from 76 POPs (points of presence), showing a traffic-weighted average annual growth rate of 80% for 2008 – the MINTS reports lag the current date by several years, but are worthy of note for using real and detailed data from a comprehensive set of the Internet's largest peering points. The MINTS site-by-site breakdown shows significant variation between sites (from an 81% annual drop, to a 1200% annual growth for data collected for periods as short as a year to 2007) which explains the variation in numbers between these different sources – there's no one place to measure, each POP experiences different traffic growth, and not all POPs will supply data. However, all of this data suggests that that overall growth is positive, sustained (over all years studied), and significant.

Instead of trying to carry such huge amounts of traffic between a single high-speed transmitter/receiver pair (examples below), or using many fibres, dense wavelength division multiplexing (DWDM) has become common (as discussed in [Falcao 02] and e.g. [Sivarajan 04] describes the DWDM networks of nine companies in India including the two largest carriers), where multiple separate transmitter/receiver pairs can be multiplexed onto the same fibre operating at different wavelengths.

Coarse Wavelength Division Multiplexing (CWDM, see ITU-T standard G.694.2 for details of a standardised version) also exists but is out of scope of this thesis as it's not normally used in core networks or with photonic routing.

Super-fast single-channel lab systems can achieve spectacular throughputs in the lab. For example:

- [Richter 11] arranged 256 copies of a 40Gbps 16-QAM signal using 128-way optical time-division multiplexing (OTDM) and dual-polarization multiplexing to achieve 10.2Tbps.
- [Hillerkuss 11] took 650 copies of a 40Gbps 16-QAM signal using 325-way optical orthogonal frequency-division multiplexing (OOFDM) and dual-polarization multiplexing to achieve 26Tbps.

However, these single-channel systems are not yet ready for commercial consideration. It is not appropriate to criticise these papers for impracticality because the target of the work in these examples was to explore high bitrate propagation and optical inverse fast Fourier transforms respectively. However, to achieve the stated throughputs they would require 256 or 650 (respectively) separate 40Gbps modulators, which would be extremely expensive.

The fastest modern commercial systems are based on DWDM and run at 10-100Gbps per wavelength, with 100Gbps/wavelength just having been first commercially deployed at the time of writing (see Appendix A). 40Gbps Ethernet standardisation was completed in mid 2010 in [IEEE 802.3ba].

An example state-of-the-art commercial DWDM system is described in Appendix A, capable of up to 88 wavelengths of 100Gbps over 1000km, or 88 wavelengths of 40Gbps over 2000km of fibre, achieving a total of 8.8Tbps/fibre in the former case.

1.3 Wavelength-routed optical networks (WRONs)

The previous section discussed DWDM for a point-to-point link. At the end of such a link, all of the wavelengths may be converted into an electronic signal (i.e. received). Alternatively, some or all of them may be optically routed into a further DWDM link to reach their ultimate destination. This optical routing could be carried out by something as simple as a demultiplexer/patch panel combination, or an automated photonic switch. Thus, a network can be formed, steering traffic in units of a wavelength. Such a network is referred to as a wavelength-routed optical network (WRON e.g. in the comprehensive early treatment by [Baroni 98]), because the path taken by traffic is dependent upon the wavelength at which it is injected.

If wavelengths can be directly switched through a node to their destination in the optical domain, then they do not have to go through an optical-electronic-optical (OEO) conversion sequence – i.e. received, switched, re-transmitted. The primary reason for using WRONs is that photonic switching is cheaper than electronic switching, as well as reducing space consumed by switching equipment, heat, power etc.

A further advantage of WRONs versus OEO switches is modulation transparency – under the right conditions[1] the optical components (optical amplifiers, muxes etc.) do not require a particular bit-rate or modulation format of the signal to be used. This has the advantage that, as demands grow, paths may be selectively upgraded to newer, faster transmitters/receivers without needing to replace any intermediate components along the path. This further means that low-cost transmitters/receivers can be used for metro-scale

[1] A line system will be able to support only a certain range of modulation formats. Some example factors that would prevent the use of a new one:

- Any wavelength muxes/demuxes must allow an adequate channel signal bandwidth for the new format.
- The chosen route must have a suitable dispersion map or the transceivers must have electronic dispersion compensation as newer systems do, such as the one described in Appendix A.
- Any monitoring equipment must not rely on a property of the modulation that may not be shared.

This transparency has been demonstrated in practice recently with the Ciena 40G transmission system which due to quadrature phase-shift keying (QPSK) and polarization multiplexing and resultant 10GBaud operation [http://www.nortel.com/corporate/investor/events/120307/men_40g_optical_teach_in.pdf] was able to be deployed on line systems designed for its NRZ OOK (i.e. non-QPSK, non-polarization-diverse) 10G predecessor. In Appendix A, this line system is further described and also shown to support 100G wavelengths.

wavelengths, multiplexed with high-performance long-haul transmitters/receivers. Appendix A describes a commercial use of this.

Practically, to add new wavelength-paths, or move existing ones, it will be necessary to configure all of the intermediate photonic switching elements, and/or ensure the transmitter is using the chosen frequency. The time taken to achieve this can vary from hours/days/weeks (for a technician to physically visit all of the sites, and wire up patch panels as needed, and physically install fixed-wavelength transmitters) to nanoseconds (e.g. lithium-niobate modulators). The time taken to establish a new wavelength path and factors that influence this, other than switch technology, are discussed in Chapter 3.

In the literature, the term wavelength-routed is sometimes, equivalently, written as λ-routed or lambda-routed.

1.4 The coherent revolution

During the course of this work, optical transmission has experienced a revolution in the form of coherent reception. An example coherent line system with numbers for the below parameters is described in Appendix A, but in brief, coherent reception has the consequences that:

- The receiver is able to detect signal phase (in addition to the amplitude that OOK uses), allowing the transmitter to use phase modulation and also enabling electronic mitigation of impairments though post-receiver digital signal processing (DSP).
    - Allowing more bits/Hz without increasing the baud rate and thus impairments.
    - Enabling electronic polarization mode dispersion (PMD) compensation.
- The receiver is frequency-selective (according to the tuning of its local oscillator laser) and so does not need to have a per-wavelength filter in front of it.
    - Increasing flexibility and lowering the cost of deploying it in an agile wavelength system. See the colourless filters section of Appendix A.

Thus, coherent reception enables higher bit-rates to have more tolerance for impairments while still improving network agility. Pre-coherent systems are usually on-off keyed (OOK).

Coherent systems with electronic dispersion compensation (Appendix A includes the specification of the Ciena 40/100G system as ±50,000ps/nm chromatic dispersion tolerance) effectively eliminate the need for dispersion compensation modules (DCMs). Corning SMF-28e is chosen for this section as a representative example because Corning, the world's largest fibre manufacturer, describes this fibre in [SMF-28e] as their "standard single mode fiber" and "the world's most widely demanded full-spectrum fiber". I calculate from the SMF-28e data-sheet that it achieves a dispersion of 16.2ps/(nm.km) for λ=1550nm (Corning's C-band reference wavelength). Therefore, the Ciena system could tolerate the dispersion from just over 3,000km of uncompensated SMF-28e fibre, which is 50% greater than its claimed un-regenerated reach of 2,000km, which is to say that dispersion becomes irrelevant in normal circumstances, in which I include all newly-laid fibre, and thus all new networks. Older networks have dispersion compensation installed already, and so excess chromatic dispersion will not prevent deployment of phase-modulated wavelengths.

PMD tolerance is now considered. Taking the common example of Corning SMF-28e again, its specified PMD is 0.20ps/√km. Therefore, the 25ps PMD tolerance specified in Appendix A allows for the PMD from up to 15,625km of SMF-28e – far beyond this line system's specified reach. Therefore PMD can now be ignored for new networks. Whether this assumption can be applied to existing networks is considered in the next few paragraphs.

My industrial experience includes several commercial service providers in North America some of whose older fibres have much higher PMD than the above specification for SMF-28e. [Breuer 03] provides similar evidence for the network of Deutsche Telekom. [Breuer 03] is an exceptional paper in that it provides public domain PMD information for an existing commercial network. Breuer collected PMD measurements of all 10,000 fibre segments in the network – which have installation dates of 1985 (nearly 10 years before PMD appeared on manufacturer fibre specification sheets) to 2001. Fibre is expensive to install or re-lay in the ground and therefore it will continue to be re-used rather than replaced if there is any way it can be. Therefore, while this paper could be considered out of date, it is likely that the fibre he describes is still present, and that Deutsche Telekom still want to use it.

Breuer's data is reviewed in this paragraph for the improved number of Deutsche Telekom links that a coherent system can address versus an older OOK system. Breuer found a mean PMD of 0.17ps/√km (near to the SMF-28e worst-case value above) but an exceptionally poor maximum of 4.79ps/√km. Breuer also showed that 40% of links are unsuitable for OOK 40Gbps usage by the criterion cited, that the maximum differential group delay (DGD) should be lower than 1/10 of the bit duration for a typical path length of 600km. It will be observed that by this criterion, the target for a 10Gbps wavelength is 10ps, less than half the tolerance of the Ciena 40Gbps system, but comparable to the 15ps specification of the 10G OOK Non-Return-To-Zero (NRZ) reference system illustrated in Appendix A. For that path length, the Ciena system's total 25ps tolerance translates to a tolerance of just over 1ps/√km. The raw data used in [Breuer 03] is not supplied in that paper to allow for an exact calculation, but this would be in excess of the 10Gbps 89% of installed fibres. The 2.5Gbps (40ps target) 98.5% of installed fibre is not quite comparable because that pertained to 1000km paths. By inspection of Breuer's graph, I estimate that the Ciena system would address over 96% of Deutsche Telekom's installed fibre plant. This is an enormous improvement versus 60% for a hypothetical OOK 40Gbps system. In fact this is a gross underestimate of the benefit of the coherent system, as the paper also shows that the PMD in one span is almost uncorrelated with that likely to be found in an adjacent span, so a path may be considered a random mix of performance. However the paper also teaches that PMD must still be considered when assessing older networks, as some paths will be impassable (e.g. if that link of 4.79ps/√km is >25km).

For the reasons stated (practical immunity to chromatic dispersion and, in most fibres, PMD, ability to increase bitrate significantly without incurring additional penalties over OOK systems), coherent is expected to be the chosen technology for most long-haul systems going forward. This is illustrated through it having been chosen by OIF as the basis for its 100G standard [OIF-FD-100G-DWDM]. In smaller metro systems the decreased capacity and reach requirements may mean that cost continues to drive the deployment of OOK.

The work in this thesis is applicable to both OOK and coherent systems except where the differences are discussed. This is because the question of finding an optimal set of wavelength-paths (discussed in Chapters 2 and 3) is not specific to what is being sent along them except in terms of bitrate and the binary question of whether a path is viable or not (which is discussed in Chapter 4).

1.5 Definitions used throughout this thesis

The following definitions relating to wavelength-routed optical networks are used throughout the rest of this thesis.

1.5.1 Wavelength-link

Wavelength-link: a wavelength for the span of one network physical link, i.e. the unit of capacity for allocation in a wavelength-switched photonic network. This is a term introduced by this thesis.

1.5.2 Wavelength-path

Wavelength-path: A specific sequence of wavelength-links (a route) running from the optical transmitter of a particular light frequency to its associated optical receiver. The light is not electronically switched/processed between the transmitter and receiver. The same concept is described as a “lightpath” elsewhere, such as [Baroni 98]. However, in more recent work such as [Malenstein 09], that term has been generalised to include regenerated paths, so this thesis uses its own term to specifically refer to a purely photonic path.

1.5.3 Wavelength continuity constraint

By the definition of a wavelength-path above, it does not get regenerated (no OEO conversion) at any intermediate point. As optical wavelength conversion is not commercial at this time (e.g. as noted in [Zalesky 09]), the wavelength-path will retain the same frequency on every link it traverses. Therefore, it does not just consume an interchangeable unit of capacity on each link, but a specific frequency that other wavelength-paths are then precluded from using. Therefore blocking may occur for a route when there is free capacity on every link, but where there is no single frequency that is free on all links. Studies such as the author's collaboration in [Lao 04] quantify the benefit of adding wavelength converters.

This is the **wavelength continuity constraint –** that a wavelength-path must use the same frequency along all of the links in its path. This is a term commonly used in the literature and the industry.

Wavelength allocation should be considered when wavelength-path routing algorithms are being compared, because blocking will increase the number of wavelengths that are required for any given solution.

An equivalent problem existed in early TDM switches that were space-switches only, i.e. which could move traffic between ports, but were incapable of moving traffic between different timeslots due to a lack of ability to buffer. Electronic space-time switches (capable of switching between both port and timeslot) were rapidly introduced to address this problem. For example, [Majumder 05] provides a particularly detailed discussion of this problem. In a photonic network, the equivalent of timeslot interchange would be wavelength conversion.

1.5.4 Black-box channel model for a wavelength-path and discussion of visible Quality of Service (QoS)

A higher network layer will use a wavelength-path as a black-box 'bit-pipe' - a channel into which an electronic serial bit-stream can be injected, that will emit that bit-stream in another location. More formally, this is a black-box channel model, shown pictorially in Figure 1-1.

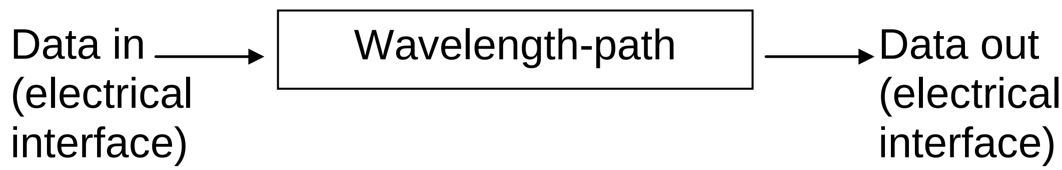

Figure 1-1 Black-box channel model of a wavelength-path

The reason for using such a model is that the higher layer is not affected by the choice of modulation format, forward error correction (FEC) etc. except in how it influences the performance perceived from such a black box – the quality of service (QoS) experienced by the client. It is for this reason, to take the most significant technology change of recent years as an example, that the change from on-off keyed (OOK) to phase-modulated/coherent-reception systems can occur without change to the clients (such as the SONET or Ethernet switching layers).

Some key black box/QoS parameters for a wavelength-path are latency, jitter, protection switching time (and outage probability), availability and post-forward error correction (FEC) bit error rate (BER). The latter (BER) is required for the concept of optical viability introduced in section 1.5.6 and the subject of Chapter 4 and so is further discussed in the next section.

1.5.5 Acceptable bit error rate (BER)

Acceptable bit error rate (BER): A black box bit error rate that a service provider has decided is acceptable for a particular service type (application). The previous section describes the black-box model, and its other measurable quality of service parameters.

As examples, industry BER requirements for the most commonly-used line protocols are:

- 10^{-12} for SONET with bit-rate >= OC192 [GR-253-Core] Older systems were designed to a target of 10^{-9} [Goralski 00]
- 10^{-12} for 1000Base-X, 10GBase-X and 10Gbase-R Ethernet [IEEE 802.3-2005]. Other optical Ethernet variants within the standard with slower bitrates have less-demanding requirements, of 10^{-10} or 10^{-9}.

The above target BERs are measured at the client level and so would be measured after forward error correction (FEC) had been performed. Sometimes acceptable BER for a given FEC implementation is specified pre-FEC. This is because pre-FEC BER can be measured much more quickly than post-FEC BER, as quantified in Chapter 4.

1.5.6 Optical viability

Optical viability: a property of a wavelength-route such that if it is provisioned then a BER will be achieved at the receiver that is acceptable for the purpose to which this wavelength-route will be put (see the previous section for example acceptable BER values). Optical viability is a term used in some parts of the industry.

Along a wavelength-path, by definition the signal is not electronically regenerated at intermediate switching points. Therefore, there will be some paths resulting in sufficient signal impairment that an acceptable BER will not be achieved. Causes of impairment are discussed in Chapter 4. To briefly summarise that introduction, there is not just a fixed number of kilometres that the signal can travel before BER drops below the acceptable threshold - some impairments such as dispersion can be reversed, and have an optimal value, so it is possible for a longer, better-compensated route to be viable where a sub-section of that route which is exceptionally poorly or over-compensated is not viable.

Chapter 4 also discusses past work in which network engineering approaches are used where viability does not have to be considered at the time of setting up a wavelength, because any wavelength allowed by network policy is guaranteed to be viable. However, this simply means that the concept of viability has been shifted to the stage of network planning, or setting network engineering rules. Therefore, it is asserted that for all photonic networks, a choice must be made of engineering approach to ensure that optical viability is achieved for in-service wavelengths. Chapter 4 discusses some possible approaches to this problem.

1.5.7 Agility

Switch, wavelength-path and network agility are formally defined in Chapter 3, which also shows how they are related, and what factors contribute to them.

As an informal summary, in this thesis, agility is measured in terms of the time taken to provision new wavelengths, measured to the point where that wavelength is ready to transmit user data with acceptable BER.

Greater agility (the ability to set up new wavelengths faster) translates to the ability to re-deploy network resources (wavelength links) more rapidly, to better serve changing traffic demands. This relationship is formally discussed in Chapter 3.

1.5.8 Bandwidth stranding

Bandwidth stranding: the situation where bandwidth is allocated to a connection but not fully used by that connection. That bandwidth is then unavailable for other users (e.g. where a connection X is full and a new demand has arrived making it desirable to expand X) on the same links and so hastens blocking of requests for more bandwidth.

For example, if a 40Gbps wavelength is allocated to serve a 2.5Gbps traffic demand from A to Z and there are no other demands between the same source and destination then 37.5Gbps of bandwidth is stranded until more demand arrives – or the 2.5Gbps demand terminates and this wavelength can be torn down. This bandwidth granularity mismatch of small demands and comparatively big wavelengths is getting worse with the rise of commercial 100G per wavelength systems such as that shown in Appendix A.

The low efficiency of bandwidth usage resulting from bandwidth stranding may be addressed by using a multiplexing client layer.

Traditionally electronic time-division multiplexing (TDM) layers such as SONET/SDH have been used to address this wavelength/demand gap.

Connection-oriented packet/frame technologies without fixed/pre-allocated sizes using technologies such as MPLS or IEEE 802.1Qay/PBB-TE (first described in [Friskney 04]) are becoming more popular as an alternative to TDM layers.

All-optical alternatives to address the wavelength/demand gap are reviewed in section 1.7.

Bandwidth stranding is a problem of any technology with connections with fixed sizes, or where the connection size may be changed less quickly than the demand size changes. The latter scenario is the subject of Chapter 3.

Bandwidth stranding is a common term in network planning.

1.6 Network planes diagram

In this section is Figure 1-2, a generic model of the functions within the network explored within this thesis. It is provided such that later sections in this chapter can be given in the context of a particular area of this diagram.

The top plane shows a client layer that is connected together via the photonic switching plane. There will be a quantity of traffic (which may be zero) to be moved between any pair of its nodes at any time. Some traffic will be broadcast/multicast. The subject matter of this thesis is the photonic layer, so the nature of the client layer is out of scope of this thesis except with respect to these traffic demands. As discussed in section 1.5.8, to avoid bandwidth stranding the client layer will usually be some sort of electronic switching/multiplexing layer, but photonic techniques to bridge the demand/wavelength size gap are discussed in section 1.7.

The next plane down is the opto-electronic conversion plane, where the photonic realm is entered. The equipment at this layer may be whole circuit packs such as the long-haul transponders described in Appendix A, or commodity chewing-gum-packet-sized units such as DWDM XFPs (ten gigabit small-form-factor pluggable modules). A number of key transmission attributes discussed at length in Chapter 4 are implemented in this plane, such as:

- Transmitter choices (the modulation format, forward error correction (FEC), the transmission wavelength)
- Receiver compensation for some of the signal impairments caused by the photonic switching plane such as chromatic dispersion – all of which are discussed at length in Chapter 4.

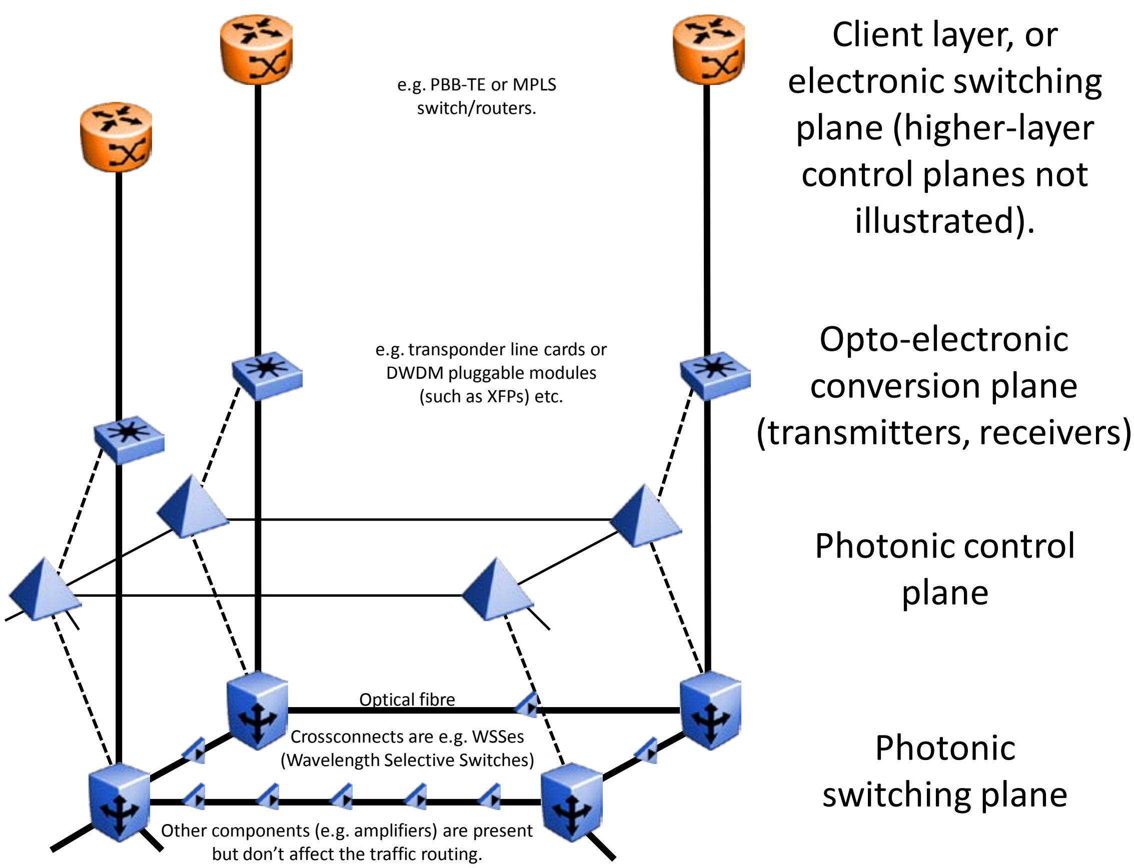

Figure 1-2 The network planes considered in this thesis

The next plane down for user data (which does not pass into the control plane) is the photonic switching plane. This directs the optical signals emitted by the opto-electronic plane's transmitters to their corresponding receivers via fibre and switching elements such as wavelength-selective switches (WSSes). For the purposes of Chapters 2 and 3 this signal-routing function is the primary area of interest. There can be many other components within the photonic switching plane to help improve the quality of the signal ultimately received, such as optical amplifiers. Chapter 4 discusses at length the impact of fibre transmission and optical components upon signal quality, and how to determine whether the received signal will achieve an acceptable BER as defined in section 1.5.5.

To the side of the diagram between the opto-electronic conversion and photonic switching planes, forming a parallel layer, is the photonic control plane. Client data does not flow to this layer, which is why it is illustrated to the side of the data-path. Its key functions discussed throughout this thesis are to set the photonic switching plane to implement its route decisions for a wavelength-path, and to configure the transmitter's wavelength such that it is not being used along the path of that wavelength-path. Chapter 4 also discusses value that may be derived from adjusting other transmitter parameters such as modulation format. See section 1.8 for further discussion of the usage of control planes within this thesis. The control plane will need communication paths to signal to the hardware it is controlling, and if it is distributed, within its own nodes. The latency of these communication paths is a significant issue discussed in Chapter 3.

Higher layers have control planes, but these are outside of the photonic scope of this thesis. Design of a multi-layer control plane including the photonic layer would need to include all of the factors discussed in this thesis. However, the routing algorithms would need to be enhanced to be multi-layer. This is an item in Chapter 5's further work section.

Power balancing (not illustrated) is the function of adjusting network component settings such that all wavelength-paths are received at a power level that achieves an acceptable BER (if this is possible). Power balancing is sometimes considered part of the function of a photonic control plane. However, because it is an independent process from the routing and wavelength allocation that is the primary subject of this thesis, it is not further considered – it is assumed that it will happen automatically in the background. This assumption reflects the behaviour of the Ciena system described in Appendix A.

1.7 Bridging the gap between wavelength and demand sizes

A problem with WRONs (see section 1.3) is that the total demand from the access layer will probably not correspond to an integer number of wavelengths. This section reviews the most common approaches in the literature for addressing this mismatch in the photonic domain (optical packet switching/optical burst switching), and why they are not usable at this time. Then the approaches discussed in the remainder of the thesis are described: a generalised view of the present mode of operation (named here as A-WRONs, agile WRONs), as well as introducing a less well-known alternative approach (wavelength path sharing).

1.7.1 Optical packet switching (OPS)

An optical packet switching node inspects a header on each packet that is received and from this determines on which port to send it to the next node, in similar fashion to an IP router or Ethernet switch (described in [Boudriga 08]). Thus, the packet makes its way hop-by-hop to its destination. However, the packet has travelled optically all the way from source to destination because all intermediate components process the data as light rather than electrons, thus the disadvantages of OEO conversion are not incurred.

Therefore, the efficiency of IP-style statistical multiplexing can be achieved while eliminating the expense/power/heat of any electronic switching from the network core, except for the lesser expense/power/heat of electronic packet header inspection and routing.

However, because the packets do not arrive according to a pre-coordinated schedule, there will sometimes be contention for an output port. To avoid packet loss, buffering must be available. Unfortunately the only known methods of optical buffering are not very practical (reviewed in [Zhou 03][Bawab 02][Burmeister 08]): e.g. fibre delay lines

(FDLs) are physically bulky as discussed in [Boudriga 08] and [Mack 08] and as per the example[2]; micro-ring resonators allow loops to be embedded on a semiconductor die as per [Ding 08], although this does not reduce the need for the sheer volume of storage. Photonic crystals solve the underlying problem by slowing down the light (e.g. as per the preliminary work in [Baba 07], however, as [Burmeister 08] demonstrates convincingly, slow-light devices currently suffer from dispersion, bandwidth and loss issues that prevent them achieving useful amounts of buffering. Burmeister concludes that recirculating silica or silicon delay lines (which can be integrated onto a silicon wafer) are a convenient and practical solution. However, taking the benchmark from the previous footnote of 100ms, using Burmeister's density figure of 0.1ns/cm, this would require a cumulative total of 10,000km of delay line. Even his CRS-ideal slow-light technology achieving 30ns/cm would require approximately 33km of delay line – still quite impractical.

Further, to achieve comparable efficiency of link fill to electronic switches, OPS requires full wavelength conversion – the ability to wavelength-convert all of the packets simultaneously arriving on all of their ports at all wavelengths to a different wavelength than the one they arrived on – to avoid conflicts where the same wavelength from two

[2] To give an example of the impracticality of the physical bulk of the fibre delay line required to replace the electronic buffering in a modern Ethernet switch: the Cisco 7600 ES+ series of line cards claims 100ms buffering/direction per port [Cisco7600ES+]. Taking an example of Corning SMF-28e optical fibre, 100ms requires a length of $\frac{t \times c}{N}$ (where t = 100ms, c = speed of light, N = refractive index at 1550nm , which is approx 1.47 [Corning SMF-28e]) approx 20400km , which assuming a single layer of fibre on the recommended 50mm-diameter spool and an average of the specified 245um coated fibre diameter would require a spool 31.8km high, which would be infeasibly physically large, without even considering other issues such as the transmission loss and signal degradation of such a lot of fibre. A practical implementation would probably need multiple short loops to allow data to be tapped off after less than the full delay where there was a slot free on the output transmission fibre, but the sum of the lengths of the short loops would have to at least equal the length calculated above – sending the data around a shorter loop multiple times would work in the style of a recirculating loop (such as described in Fig 2 of [Boudriga 08]), but would require additional loops for data subsequently received.

different ports needs to end up on the same egress port [Mohamadzadeh 06]. As yet, these have not become cheaper than electronic options (as noted in [Zalesky 09]), although research progresses with e.g. [Raz 09], [Marconi 09].

Therefore, until a breakthrough in the areas of buffering and wavelength conversion occurs, optical packet switching is generally accepted to be non-commercial, and thus not further discussed.

1.7.2 Optical burst switching (OBS)

[Qiao 99] introduced optical burst switching as an evolution of optical packet switching (for more recent reviews, see e.g. [Zalesky 09], [Hernandez 09], [Yoo 06]). The difference is most clear in the 'tell and wait' case, where transmission of a packet is delayed for a while to allow the header time to be processed by intermediate switching nodes. This delay means that further packets to the same destination may have arrived before the first can be transmitted, such that a stream of packets may be transmitted together as a burst. One aspect of further work has been on burst release strategies: when to deliberately delay the signalling of a burst to increase its size and thereby gain efficiency, e.g. [Zalesky 08].

Figure 1-3 shows a generic diagram of optical burst switching, where a photonic-switched core ('Optical layer') is terminated by electronic routers (i.e. with electronic buffering capability) which aggregate up packet flows into bursts across the photonic core.

[Qiao 99] discussed the use of fibre delay lines. Some more recent papers share this idea such as [Boudriga 08]. For the reasons discussed in the OPS section, this thesis will ignore this aspect of Qiao's proposal as *currently* impractical and use the now commonly-held definition of OBS as including no optical buffering as per [Weichenberg 06], [Weichenberg 07] and [Zalesky 08].

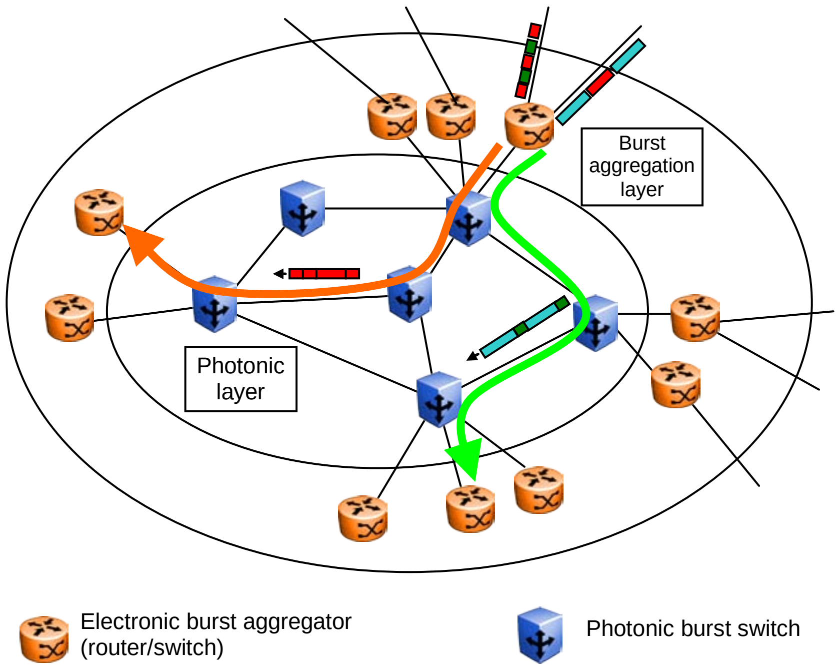

Figure 1-3 Generic optical burst switching (OBS) network diagram, after [Duser 02]

Because core congestion is inevitable where the burst is transmitted without knowledge that there is capacity for it to traverse the network (as Qiao proposed), and this leads to burst loss, inefficient routing (via deflection routing) or a need for buffering, an alternative scheme has been proposed where a signalled acknowledgement that bandwidth is available is required before a transmitter will send a burst. In essence, a short-lived connection is established for the burst. This scheme was proposed as Wavelength Routed Optical Burst Switching (WROBS) in [Duser 02] or Optical Flow Switching in [Weichenberg 06]. This thesis will refer to it as WROBS.

As a WROBS scheme must buffer up any traffic that arrives between the decision that a burst should be sent and the time that the burst is authorised, WROBS bursts are longer than unacknowledged bursts (tens of kilobytes [Duser 02]) for the same burst-sending strategy. To justify the signalling overhead of setting up a tell-and-wait burst, it is usual for the burst-sending strategy to wait from the arrival of the first packet of a burst for as long as its latency budget will allow, to maximise the opportunity for more packets to arrive that can join that burst.

More recent work has covered Quality of Service (QoS) in OBS. E.g. reserved sub-wavelength bandwidth connections over an OBS network reviewed in e.g. [Hernandez 09], as is the possibility of sharing such links with best effort traffic; [Boudriga 08] discusses using buffering to achieve sophisticated QoS like Ethernet or IP; while [Das 08] shows convincingly that adjusting the average burst size according to the congestion level will increase throughput.

To minimise dropping (or buffering) on congestion for tell-and-go, [Qiao 99] proposed using deflection routing – the idea of sending the burst out of an alternative port where there might be available capacity to get it to its destination. That is to say, the burst is deliberately sent the 'wrong' way as the only alternative is dropping it.

As with OPS, reasonable efficiency is only achieved in tell-and-go type schemes if full wavelength conversion is available. For the reasons discussed in the OPS section, this will be regarded as impractical until a breakthrough is made in the field and disregarded for the purposes of this thesis.

Suitability of these approaches is split by network size and target traffic QoS. Acknowledged bursts have the advantage that the data will not be lost in transit and so provide predictable performance characteristics, as opposed to unacknowledged bursts which may require retransmission of the user data. However, unacknowledged burst systems do not need to wait for a round-trip delay before transmitting, offering lower minimum/expected latency and being able to work networks three times as large for a given tolerable latency (because this must be divided between the signalling round-trip and the transmission time in WROBS).

Therefore, lacking buffering/wavelength conversion as per OPS, OBS is not an option for the general case of large national networks. [Duser 02] calculates that if an edge delay constraint of 10ms (very generous when low latency is now a key differentiator in the industry) is acceptable then a network diameter of 1500km may be achieved – inadequate for US and other larger continental networks. Further, fast switching components are required for large-scale networks/networks at high utilisation – for small-scale OBS networks many wavelength routes can be pre-set with the chosen transmitter wavelength selecting which one will get its traffic to its destination, but this strands capacity and thus is not scalable.

1.7.3 Agile wavelength-routed optical networks (A-WRONs)

In this thesis, **agile wavelength-routed optical networks (A-WRONs)** are defined as being WRONs, where wavelengths are re-arranged/added according to a planning cycle (which may be triggered by a link fill threshold being exceeded) rather than immediately in reaction to a particular packet arrival. Spare capacity is provisioned with a goal that new requests for bandwidth received until the next opportunity to add wavelengths will not be blocked due to capacity exhaustion.

With longer planning cycle frequencies (hours/days), A-WRONs correspond to the state of the commercial art (see Appendix A) of ROADM (reconfigurable optical add-drop multiplexer)-based line systems, although a human is usually involved in interpreting demands and considering network re-engineering.

Replace that human with an automated function, and in the limit of extremely fast planning cycles this becomes very similar to WROBS, but critically it is still different in that OBS is trying to serve a packet that has just arrived, whereas A-WRON is trying to serve the unknown packets that are about to arrive.

As the planning cycle becomes faster (more agile), less spare capacity bandwidth is required, so theoretically the network should operate more efficiently. Assessing the actual achievable value of this agility is the subject of Chapter 3, which also more thoroughly defines A-WRONs.

The same concept is described as Optical Circuit Switching (OCS) by [Zalesky 09], however his analysis is limited to an extremely fast (millisecond ‘planning interval’) version. Further Zalesky’s connections are bidirectional, for no apparent reason except convention in connection setup. This thesis assumes unidirectional wavelength-paths, as an upper bound of efficiency (as bidirectional connections are just a special case of unidirectional connections). This assumption is not fully realistic as many applications require approximately symmetric latency, which may be achieved by a routing constraint to this effect, but is usually and more simply addressed by routing bidirectional wavelengths.

1.7.4 Wavelength path sharing (WPS)

A-WRONs provide a dedicated wavelength for each wavelength demand. They will therefore suffer from bandwidth stranding. WPS (proposed in [Myers 01] addresses this by allowing a network with slow wavelength-switching times (unlike OBS/OPS) to still achieve sub-wavelength granularity at the optical layer.

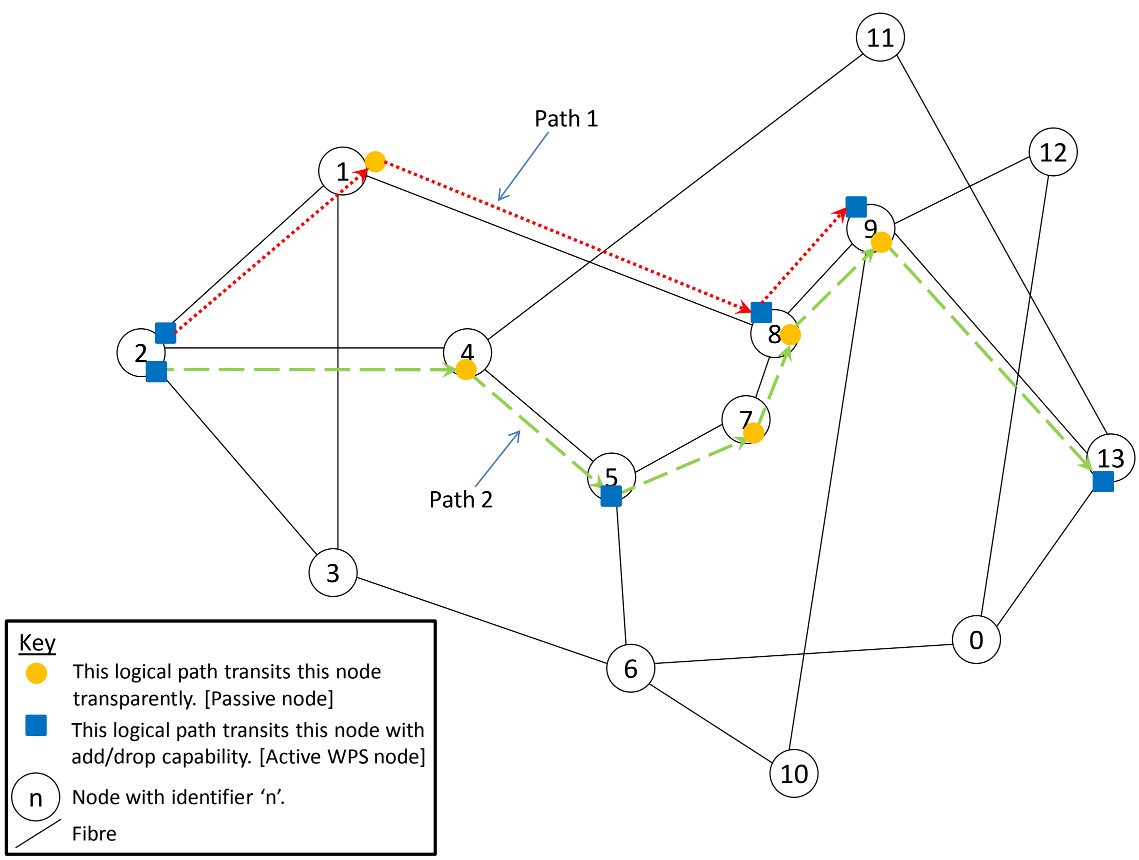

Figure 1-4 Basic principles of WPS illustrated on the NSFNet (see Appendix B)

It does this by allowing multiple demands to share a single wavelength without requiring the photonic switch matrix to cross-connect at the speed of demand variation.

Figure 1-4 shows the principle of WPS, where a wavelength-path (Path 1) is established along a route 2-1-8-9. This path can serve demands between any of the nodes that are active along the path - 2, 8 and 9. Node 1 is acting as a conventional WRON switched node.

Similarly, path 2 is a wavelength-path along the route 2-4-5-7-8-9-13. Nodes 2, 5 and 13 are active, with 4, 7, 8 and 9 being passive. This second path is shown to make the point that a node may be active for one path, but passive in another – nodes 8 and 9 in this figure. A passive node requires less equipment and introduces less optical impairment into the path.

Chapter 2 introduces WPS in more depth and proposes a number of enhancements.

1.8 Photonic control planes, routing and path computation elements (PCEs)

Each of the previous sub-sections (A-WRONs and WPS) has assumed the ability to set up and tear down wavelength-paths along (near-)optimal routes. How optimal those routes are determines the efficiency of the network – how much traffic it can carry before money must be spent on addition of capacity. To put that another way, for a network operator, the routing efficiency determines how much revenue-earning traffic they can support with their principal capital asset, the network. Thus, effective routing is a key factor in their continued commercial survival, and therefore extremely important.

In the context of this thesis, the “Photonic control plane” is defined as a software entity:

- Of which a user can request connectivity;
- That can create and delete wavelength-paths by commanding nodes to set up sections of that path (such as nodal cross-connections) in response to traffic demands that may be sub-wavelength.

This is very similar to a non-photonic control plane, except that this entity is serving its demands with wavelength paths. Implicit within that are photonic-specific constraints such as wavelength continuity and viability as discussed elsewhere in this chapter.

This definition includes technologies commonly described as control planes such as the ASTN/ASON [ASTN] architecture and [GMPLS] protocols/architecture. However, it deliberately also includes management systems that directly control nodes for the purpose of path setup. This inclusion is made because the routing function is the same for both cases, so this thesis does not make a distinction. Some example differences – not relevant to this thesis – are that:

- Signalled control planes usually: reside on the controlled equipment; form a highly-distributed computing environment (usually one instance per node); react to network events such as faults (in addition to *external* stimuli such as new connection requests that management systems also react to); may provide some form of restoration/protection on failure.
- Management systems usually: reside on a server rather than the controlled equipment; form a highly-centralised computing environment (the basic configuration being one or a resilient pair of servers); only provision the network when directed by external stimuli (like new connection requests); may provision (but not directly provide) protection mechanisms in the network.

There are exceptions to each of the differences listed – for example, the Nortel LH1600 OPC card was a management system that ran on an HP workstation that was physically housed in a card that sat in an optical transmission shelf and managed the local sub-network.

However, the control/management plane distinction provided above does not cover all possibilities as it is legitimate, and within e.g. the [GMPLS] standard, for a higher-level entity (e.g. a management system or OSS) to fully-specify (every port, every node) all routes explicitly, meaning that the actual control plane would be offering no intelligence to the question of where traffic is placed.

Therefore, define:

"Control plane routing": the algorithms that determine which wavelength-paths should be establish to serve a given set of wavelength-sized and sub-wavelength demands, and which wavelength-links each wavelength-path should be routed over.

Then, if a higher-level OSS is indeed doing all of the routing calculations, it is considered part of the control plane routing.

This is a broader definition than classic routing and wavelength allocation (RWA – e.g. used in [Raza 08], [Duser 02]) as the input of control plane routing is not a set of wavelength demands, but a set of sub-wavelength demands. Further, as will be seen later, a key parameter investigated is how fast the wavelengths are re-arranged to suit the sub-wavelength demands.

The concept of 'outsourcing' the routing function from control planes to a separate entity was introduced in [RFC4655] as a Path Computation Element (PCE). This is a more limited definition than the one in this chapter because it assumes there is a GMPLS control plane in existence to receive the original connection request, rather than allowing that to be a management system. Further, the stated purpose of the Internet Engineering Task Force's (IETF's) PCE work is to define a *mechanism* to allow the separation of the PCE – deemed a hard problem that may need to be handled differently for each operator/domain – from the standard signalling. The IETF PCE Working Group does not actually attempt to solve the routing problem. PCE is sometime informally used with a more general definition similar to "control plane routing", but the term "PCE" has a specific and well-defined meaning in the IETF and so the separate term "control plane routing" is defined for use in this thesis for the general case.

In summary, the control plane usage within this thesis is compatible with but does not assume GMPLS or ASTN. This thesis is focussed exclusively on the routing question and is not concerned about any other aspect of control planes, for example the choice of method of signalling information between nodes.

1.9 Research question and current open issues

This thesis addresses the research question of how the control plane routing should address changing traffic demands.

To investigate this, the following significant issues must be addressed:

1. WPS must be evaluated as an alternative to fast switching in A-WRONs. The integer linear programming (ILP)-based routing algorithm given with its original proposal in [Myers 01] must be **evaluated for speed of execution**, and thus practicality for on-line use. A faster **alternative routing algorithm must be proposed**, and **evaluated for optimality against the ILP and theoretical lower bounds**.
2. The **value of agility** in A-WRONs must be assessed. First, a **formal definition of agility** must be provided. Many switching technologies are available to offer different network agilities, however **the benefit to the network operator of faster switching/greater agility must be evaluated** in terms of the greater network efficiency that the control plane can achieve.
3. **Network engineering approaches such that the control plane routing can deliver optically viable wavelength-paths** must be reviewed, the most optimal approach **proposed and evaluated** for practical applicability. This must be done for both traditional (on-off keyed) and newer modulation formats/detection techniques.

1.10 Thesis structure

In order to address these issues, the remainder of this thesis is structured as follows:

In **Chapter 2**, WPS is presented in detail. The Integer Linear Programming (ILP) formulation given by Myers to find routes, while providing optimal results, is shown to be unacceptably slow for online execution, so a new heuristic algorithm is provided. Performance of the two is then compared. A new ILP formulation for allocation of specific wavelengths, obeying the wavelength continuity constraint, is provided. The best-known heuristic for WRONs, AUR-E is adapted for WPS and compared with the Myers ILP.

In **Chapter 3**, the value of network agility is evaluated. Firstly, a formal definition of agility is provided for switches, wavelength-paths and networks, with the relationship between these and other factors that may contribute to them. The literature on switching speeds is reviewed to extract the range of switching speeds currently available. Then, new simulations are performed that evaluate the practical benefit achieved by reconfiguring the network at different intervals, in terms of delaying the time at which an upgrade must be performed, i.e. new investment must be applied to the network.

In **Chapter 4**, optical viability is reviewed. Causes of non-viability are discussed. Use of viability in a control plane context is described. Network engineering approaches that avoid the need to actively calculate viability for each new wavelength are reviewed. Techniques to incorporate optical viability into routing algorithms are reviewed. Error analysis is used to show that open-loop calculation based on previously-measured link characteristics, when using the best commercially available measurement equipment, is no better than performing predictions based on equipment specifications. The differences in impairment calculations for phase-modulated coherent systems are considered, and adaptation of the specify-and-predict approach to coherent viability calculation is described.

In **Chapter 5** conclusions and ideas for further work are presented.

1.11 Contribution of this work

The novel contributions of this thesis are the following:

i) An **alternative hardware configuration** for WPS that delivers savings in OE/EO conversions (the amount varying with acceptable blocking probability and traffic load), where the one originally proposed in [Myers 01] did not.

ii) A **heuristic algorithm for routing WPS logical connections** to achieve execution time savings relative to Myers' ILP, at some cost in efficiency of the result. This was published in [Friskney 03].

iii) An **ILP formulation for optimal wavelength allocation**. This was included in [Friskney 03].

iv) A **heuristic algorithm for simultaneous routing and wavelength allocation** for WPS, derived from AUR-F and AUR-E, reducing the efficiency cost relative to Myers' ILP.

v) A **definition of network agility.**

vi) A **categorisation of switch times** by application type.

vii) **Simulations** to quantify the effects in terms of network bandwidth efficiency of increased network agility on an infrastructure wavelengths system.

viii) A **comparison of methods of optical viability calculation**. A shorter version was co-published as [Peeters 04]. The author collaborated on a related technique, co-filed and granted as US patent [Peeters 03], which is not otherwise discussed in this thesis.

ix) **Error analysis for a measure-and-predict optical viability**. Published in [Friskney 02].

x) The proposal of the **adaptive use of phase/amplitude modulation** to achieve optimal spectral efficiency for a given set of bitrates and reach requirements. Granted as US patent [Friskney 02c].

1.12 Publications arising in the course of the research described in this thesis

[Dong 03] S. Dong, C. Phillips, **R. Friskney,** "Differentiated-Resilience Provisioning in Wavelength-Routed Optical Networks". International Teletraffic Congress (31st August-5th September 2003) 2003, Berlin, Vol. 5A-B, pp921-930.

[Friskney 02] **R. Friskney,** K. Warbrick, S. Poliakoff, R. Heath, "Link-based photonic path performance prediction and control". Proc. European Conference on Optical Communications (ECOC) 2002 (6th-12th September 2002), Copenhagen, Vol. 3, pp1-2. Paper 7.4.3.

[Friskney 03] **R. Friskney,** "Path allocation for wavelength path sharing". Proc. London Communications Symposium (LCS) 2003 (8th-9th September 2003).

[Peeters 04] B. Peeters, D. Forbes, **R. Friskney,** J. Shields, "Optimal routing in hybrid networks by decoupling the route calculation from the assessment of optical route viability". European Conference on Networks & Optical Communications (NOC) 2004 (29th June-1st July 2004), Eindhoven.

[Lao 04] R.N. Lao, **R. Friskney,** R.I.Killey, "Effect of Sparse Wavelength-Conversion on Network Tolerance to Inaccuracy in Traffic Load Forecasts". European Conference on Optical Communication (ECOC) 2004 (September 2004), Stockholm.

[Lao 04-2] R.N. Lao, **R. Friskney,** R.I.Killey, "Investigation of the tolerance of wavelength-routed optical networks to inaccuracy in traffic load forecasts". Optical Fiber Communication Conference (OFC) 2005 (6th-11th March 2005), Vol. 4. Paper: OThS4.

[Lao 05] R. N. Lao, **R. Friskney**, R. I. Killey, "Investigation of the tolerance of wavelength-routed optical networks to inaccuracy in traffic load forecasts". Journal of Optical Networking, Vol. 4, Issue 3 (3rd March 2005), pp144-156. http://www.osa-jon.org/abstract.cfm?URI=JON-4-3-144

[Dong 06] S. Dong, C. Phillips, **R. Friskney,** "Differentiated-Resilience Provisioning for the Wavelength-Routed Optical Network". Journal of Lightwave Technology, Vol. 24, Issue 2 (February 2006), pp667-673.

1.12.1 Patents pending and granted

The following patents which I contributed to were filed by Nortel. They were subjected to an internal peer review before doing so to determine whether it is worth the considerable cost in attorney fees etc. to have them professionally drafted and filed, and in which countries it was deemed strategic to do so. Grant occurs only after an extensive multi-year government examination, with iterative legal and technical argument and re-drafting, which is why grant occurs many years after filing. Note: The title submitted is often changed by the attorneys in each country and therefore the one listed here may not correspond to official records, hence reference numbers are provided where known.

[Fisher 02] D. Fisher, N. Bragg, **R. Friskney,** "Concatenated Transmission of Synchronous Data". US filing 10/054,188, filed June 2002. Granted 22nd April 2008 as US patent 7,362,777.

[Friskney 02a] **R.Friskney,** R. Heath, K. Cordina, "Transient Location for Optical Networks". US filing 10/109,199, filed March 2002.

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Chapter 2 Wavelength path sharing (WPS)

In the previous chapter, it was shown that agile wavelength routed optical networks are important, and the design challenges for these were discussed – notably in serving sub-wavelength demands photonically to achieve advantages such as eliminating the cost of optical-to-electrical (OE) and electrical-to-optical (EO) conversions. In addition, an approach (wavelength path sharing) was introduced for serving such demands without using the comparatively fast switching speeds of OPS/OBS (ns/ms, as discussed in Chapter 1) but while still achieving sub-wavelength granularity.

In this chapter, wavelength path sharing and its advantages as introduced by [Myers 01] are further described. The shortcomings of this approach are then described, in terms of the hardware configuration proposed by Myers not delivering savings in OE/EO conversions relative to a fully-electronic switch. An alternative hardware configuration is proposed that addresses this shortcoming.

Myers provided an integer linear programming formulation for finding wavelength-path routes for WPS. This is referred to as M-ILP within this chapter. However, as an ILP with bounded variables is NP-hard, this will scale poorly in execution time. Indeed, Myers had to use a restricted formulation to get results on his limited test networks. Therefore a novel heuristic is proposed for WPS control plane routing – the longest-route first (LRF) algorithm. The performance of this alternative is then evaluated for comparison with Myers's wavelength count results.

A new wavelength allocation ILP formulation (WA-ILP) is then introduced. WA-ILP is then used in order to re-evaluate the LRF heuristic, under the wavelength-continuity constraint, versus the M-ILP formulation.

Finally, a further novel heuristic (AUR-F), this time performing *simultaneous* routing and wavelength allocation, is also provided (as an extension to an A-WRON version) and evaluated.

2.1 Wavelength path sharing (WPS) principles and advantages

Wavelength path sharing (WPS) is the subject of this chapter. Therefore, this section provides an outline of WPS as originally defined in [Myers 01]. The next section describes and compares similar schemes in the literature.

The principle of wavelength path sharing is illustrated in Figure 2-1. In [Baroni 98]'s usage of WRONs, defined as "A-WRONs" in Chapter 1, a wavelength-path (which Baroni refers to as a lightpath) is allocated from a source to a destination node via zero or more intermediate nodes. Critically, the intermediate nodes cannot receive, or add/remove traffic to/from the wavelength-path.

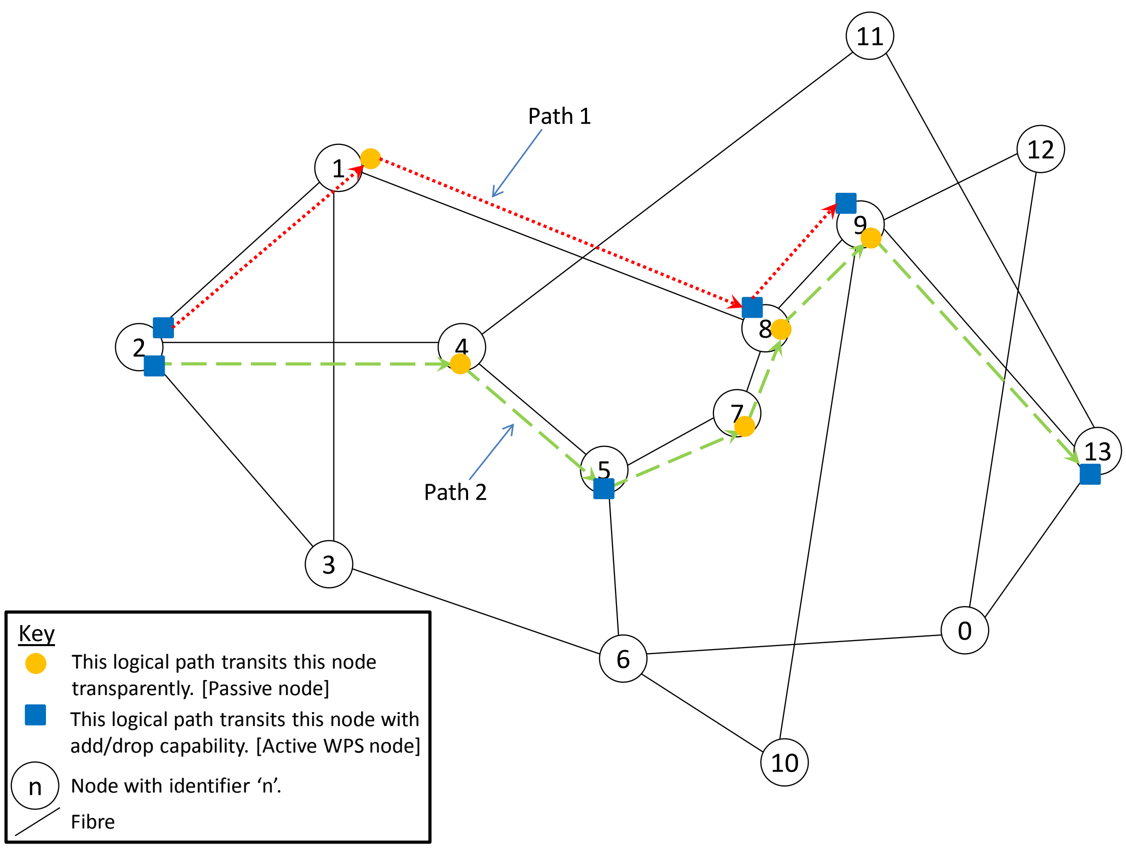

Figure 2-1 Basic principles of WPS. Two example paths overlaid on the NSFNet (see Appendix B) topology. Reproduced from Chapter 1.

By comparison, in WPS, some or all of the intermediate nodes may be 'active', defined as the ability to receive/intercept the traffic or inject their own. Thus, provisioned wavelength routes may be time-sliced to service demands to/from active intermediate nodes.

Figure 2-1 illustrates a 'physical' wavelength path set up along the route 2-1-8-9 ('Path 1', dotted line) – just as could be set up in an A-WRON. However, nodes 2, 8 and 9 are 'active' and so have different behaviour from nodes in A-WRONs. They can, per-packet or per-burst, be instructed by the control plane to do any or all of:

- Allow the packet/burst through unaffected
- Receive the packet/burst
- Block the packet/burst and optionally transmit their own packet/burst

Node 2 does not have anywhere to receive from on this logical path, so it may just transmit, or not transmit, as instructed by the control plane.

Therefore, any one of the following demand groups can be all served *simultaneously*:

- 2-9 , or
- 2-8 and 8-9

We, therefore, **define**:
- A **physical path** as the complete sequence of nodes, active or not, traversed by the wavelength channel (or lightpath). In this example, that is 2-1-8-9.

- A **logical path** as the complete sequence of active nodes (in which the originating and terminating node are included). In this example, that is 2-8-9.

The diagram shows a path 2. The physical path is 2-4-5-7-8-9-13. The logical path is 2-5-13. Demands served are therefore 2-5, 5-13 and 2-13. This path is included to show that the passive nodes for one path may be active nodes for another path as shown for nodes 8 and 9. This saves equipment at such nodes.

Figure 2-2 is a diagram similar to that provided by Myers to show the hardware for performing WPS. It consists firstly of components to achieve A-WRON functionality, in that incoming DWDM traffic is demultiplexed to individual wavelengths which are then directed, by a routing matrix (photonic switch), to their destination.

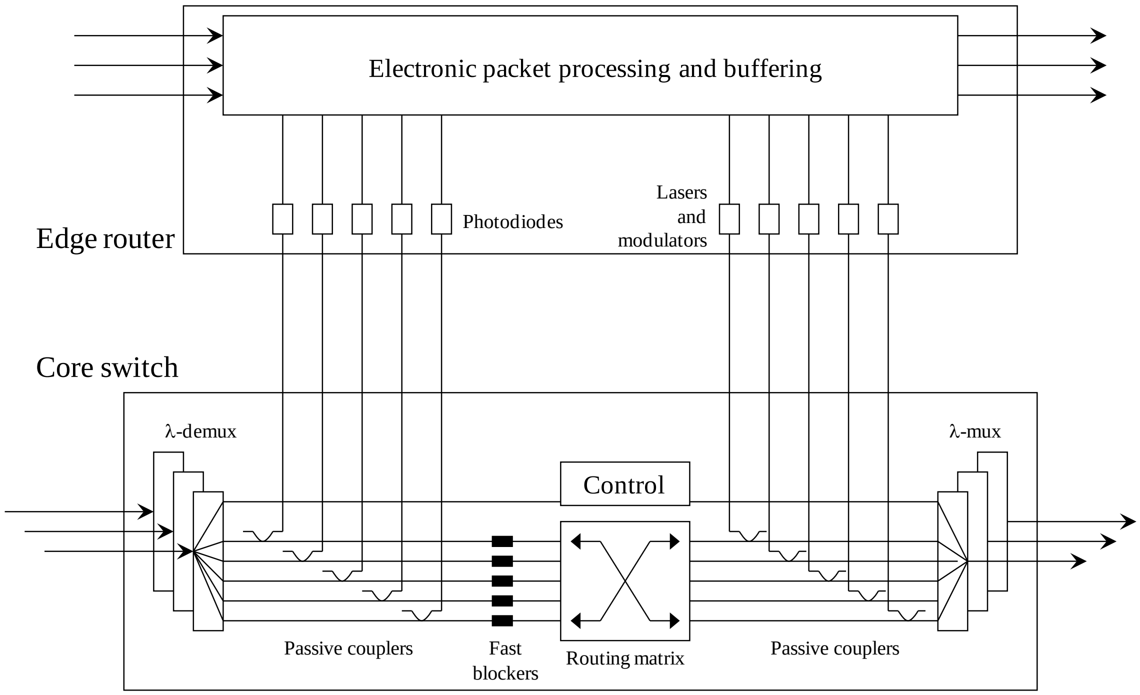

Figure 2-2 Hardware in an 'active' WPS node required to allow selected passing traffic, steered through the photonic routing matrix, to be received/inserted/passed through.

WPS adds to standard WRON hardware passive splitters (terminated by optical receivers) before the routing matrix and couplers (terminated by optical transmitters) after the routing matrix, such that traffic may be received/inserted (respectively) from/into the flow of traffic along a wavelength-path. Furthermore, modulators are added to act as fast wavelength blockers when traffic is being inserted (or if traffic is being received and there is no need to also send it on to a receiver elsewhere, i.e. such that the traffic needs to be dropped). Modulators are used because the block must be inserted/removed fast enough to allow one packet to be received locally and blocked, then the next packet to be transparently passed through.

Therefore at this node, a particular incoming wavelength-path, at a particular instant, may be:

- Transparently passed through to the next node, as in an A-WRON intermediate node.
- Received, and also allowed to pass through to the next node (for multicast/broadcast applications)
- Received and blocked. That is to say, dropped.

If the wavelength-path is blocked (i.e. not being transmitted on upstream) at this node, the part of the wavelength-path downstream of this node may optionally be used for additional traffic from this or a later node – spatial sharing.

2.1.1 Motivation for using wavelength path sharing (WPS)

[Myers 01] analysed the efficiency achievable for different logical path lengths. In particular, Myers proved analytically that under uniform demand a 3-node logical path allows 100% efficiency in using every segment of its physical path. Longer logical paths have a lower efficiency: $\frac{4}{N+1}$ for N odd, $\frac{4(N-1)}{N^2}$ for N even, where N is the number of nodes, with efficiency measured as the bandwidth utilisation of the least-utilised link, normalised to a link capacity of 1, with $N \geq 3$. Therefore consideration is limited to a 3-node logical path within the rest of this chapter. With this limitation, Myers analytically proved a theoretical lower bound where WPS would use half of the wavelengths required by an A-WRON, as judged by the Baroni theoretical lower bound. This result was for a uniform traffic matrix, with half of one wavelength per demand.

This is a significant saving in the number of wavelengths required to serve a set of demands, and is a further reason for considering WPS.

2.1.2 Alternatives to WPS in the literature

In this section, similar techniques to WPS in the literature are reviewed to show why WPS has been considered in this work and also as an introduction to the concepts involved because their routing algorithms are referenced later.

A similar scheme to WPS was later proposed in [Chlamtac 03] called Light-trails[1] and developed in subsequent papers, a sample of which is referenced in this section. This proposed an identical hardware configuration to that of Myers. It is similarly motivated in that it uses existing mature components for wavelength switching rather than requiring more advanced technology e.g. switches capable of optical burst switching/optical packet switching. However, the (unidirectional) light-trails in this work were different from Myers's in the areas of topology, trail-sharing, collision management and support for passive transit nodes, as illustrated in the tables below.

Approach name	**Key papers**
Light-Trails	Originally introduced in [Chlamtac 03]. Developed in [Gumaste 04], [Gumaste 06], [Gumaste 08].
Light-Mesh – not further considered as access networking is outside of the scope of this thesis.	A later extension ([Gumaste 05], [Gumaste 08a], [Gumaste 09]) of Light-Trails. Addresses highly-constrained passive optical network (PON)-replacement access networks.
Light-Frames	An extension of Light-Trails introduced in [Gumaste 03a], named in [Gumaste 06a] and then extended in e.g. [Ayad 08].
Wavelength Path Sharing (WPS)	The subject of this chapter. Introduced in section 2.1.

Table 2-1 List of wavelength-path sharing techniques considered, with key papers.

[1] I gratefully acknowledge a very helpful conversation with Christopher Pluntke of the UCL Optical Networks Group during which he suggested the similarity of Light Trails to WPS.

Approach name	**Light-Trails**	**Light-Frames**	**Wavelength Path Sharing (WPS)**
Applicable topologies.	2-fibre rings or unbranching lines – no routing flexibility and so no photonic cross-connect except for the wavelength blocker.	No restrictions - arbitrary mesh	No restrictions - arbitrary mesh
Growth and shrinking of lightpaths	Light trails may automatically grow and shrink along the pre-defined constrained topologies.	No support - routing decisions would be needed to extend the trail at branching points.	No support.
Trail-sharing	Wavelength blockers at active nodes are used solely to separate semi-permanent (meaning not moved per-packet) light-trails, not between frames. As a consequence, downstream nodes are starved of transmission opportunities by *any* upstream transmitter sending traffic. Trail-sharing could be added to this scheme.	As Light-Trails	One trail can *simultaneously* be used by two or more frames at once, separated by a modulator used as an optical blocker. This increases the traffic that may be served.
What happens when more than one transmitter at once has	Ethernet collisions result in invalid frames which have to be re-sent, at a cost of additional bandwidth and frame latency variation. The re-send mechanism requires nodes to cache any received-from-upstream	As per Light-Trails, plus [Gumaste 06a] requires nodes to have a total map of the network's	Pre-arranged slots. No collisions.

data to send?	frames while sending downstream, then later re-send the upstream frames if a collision was detected. See the row below on the impact this has on OEO requirements and transparency.	topology to determine whether to retransmit on a collision or not because the packet may have also taken an alternative path – much more complex than standard Ethernet.	
Scope to reduce OEO equipment, bitrate and format transparency	To enable resending on collisions, all receivers along the path must be capable of all bitrates/formats that might be used upstream of them. Then, why not remove the photonic bypass path altogether and act as a 2-node electronic switch at all times at every node? While this would increase latency of through-traffic due to the additional processing, it would entirely eliminate the wasted bandwidth of Ethernet collisions, remove the need for the related guard times for collision detection, and also increase optical reach as the signal would be wholly regenerated.	As Light-Trails	Only the originating transmitter and terminating receiver are used by any given burst. I.e. WPS is completely transparent to the capabilities of other devices on the bus.

Support for passive transit nodes (WRON-type nodes that don't participate in per-packet switching)	No, but could be enhanced. Chlamtac et al. acknowledge that this causes inefficiency in that this causes the centre of the light trail to become a 'hot-spot' versus the links at the ends. Including superfluous switching introduces unnecessary optical impairment. It is possible that the desire for more transmitters on the bus, and hence more scope for opportunistic use of bandwidth, reflects the strong preference of statistical multiplexing versus Myers's slotted system.	No, but could be enhanced. See previous column for further notes.	Fully supported. Myers recommended using 3-node 'trails' to achieve 100% utilisation efficiency, which requires passive transit nodes if any reasonable reach is to be achieved.
Broadcast and multicast suitability	Larger number of nodes on a trail makes this more effective than a 3-node WPS logical path.	As with Light-Trails.	3-node logical paths slightly more efficient than A-WRON.

Table 2-2 Comparison of wavelength path-sharing techniques

2.1.2.1 More detail on Light Frames

"Light-frames" (from e.g. [Gumaste 06a]) is now described, because it is the expansion of light-trails to full mesh networks and so is the nearest equivalent to WPS. Light-frames introduced the concepts of 'strings' (the light-trails themselves) and 'threads' (point-to-point connections between nodes in different strings). Interconnection between strings and threads may be all-optical, but the per-wavelength interconnection includes a blocker such that the linkage may be made OEO to break optical cycles or otherwise. This allows quite generalised directional acyclic tree bus structures, in that there may be merge/join points between the light-trail-style topologically linear buses. Similar to the need for long strings, no argument is offered for why this is useful. Indeed the early [Gumaste 03a] dismisses the option as too complex. However, it offers the option to use OEO bridging between strings and trails where an OOO merge point is not desirable for any reason (such as the excessive packet collisions it might cause if it were put between two busy lines). By comparison, WPS (the subject of this chapter) does not consider photonic interconnection between its ‘strings’ and thus assumes that demands will be handled photonically from their ultimate source within the photonic network to their ultimate destination within the photonic network, thus maximising the benefit from OOO switching.

In conclusion, while Light-Frames are not the same as WPS for the reasons described, there seems no reason why the listed shortcomings of the former could not be addressed (by using the per-node modulators to allow sharing of the path; to change the control system so there were no collisions and hence no need for the re-send mechanism; to allow in-active transit nodes) and thus make Light-Frames a generalisation of WPS.

Considering each of these limitations separately:

- Uniform traffic: It is possible to contrive traffic patterns where longer WPS paths achieve 100% bandwidth efficiency. For example, this could be achieved by the following pseudo code (considering normalised bandwidth units):
    1. Start with a null demand matrix, i.e. $D(x, y) = 0 \qquad \forall x, \forall y$ where *D(x, y)* is the demand from node *x* to node *y*.
    2. For each path A-B-C-D amongst a given arbitrary set of 4-node logical paths:
        - For each *demand* in {(A, B), (B, C), (C, D)}:
            - *D(demand)* ← *D(demand) + 1*
            - That is to say, take the simplest example of only having demands between immediate neighbours on the logical path.

  Paths longer than 3 nodes suffer from ‘hotspots’ – that is to say, there are more potential demands going across the central link(s) ({(A,C), (A,D), (B,C), (B,D)} in the above example) than across each of the outermost two links ({(A,B), (A,C), (A,D)} for the first link of the above example). Therefore, the demands going across the core links must average out to be smaller than those going across the edge links (1/4 vs. 1/3 in this example) in order to achieve 100% bandwidth utilisation (still assuming that only one logical path serves each demand).

Such contrived or very specific cases do not fit the scope of this chapter, which is to consider the general case, and so this possibility is not further considered.

- Multiple logical paths: If the same demand could be split across more than one logical path, this could help to serve particularly large peak demands that did not fit within one logical path's bandwidth, or to compensate for the uneven bandwidth provided by logical paths with more than 3 nodes, as per the uniform traffic point. These are valid cases declared out of scope of this chapter for reasons of complexity. This is because, in addition to the simple WPS case, it would add for each logical path the parameter of the fraction of each demand it was serving. This is without loss of generality because a larger demand that could be split across two logical paths may be modelled as two smaller demands.

Routing algorithms devised in connection with the light-trails-based work are reviewed later.

The remainder of this chapter will focus purely on 3-node WPS paths as the problem which needs to be solved, as only this configuration can achieve 100% bandwidth efficiency, as per the Myers analytical derivation. This derivation is under the particular conditions of uniform traffic and no more than one logical path servicing each demand.

Two problems with WPS (the hardware design proposed does not achieve the goals of photonic networking, and the M-ILP routing algorithm provided by Myers is an ILP and hence scales poorly) are now described and solutions proposed.

2.2 Discussion of WPS nodal hardware

2.2.1 Discussion of Myers's hardware proposal and identification of problems

The nodal implementation illustrated in Figure 2-1 requires that a receiver and transmitter for each wavelength exist at each active intermediate node. In other words, the benefits of photonic networking that involve elimination of optical-electrical-optical conversion are not achieved, because dedicated OE and EO hardware is required anyway.

One benefit of photonic networking is still attained, that of wavelength bitrate/format transparency.

Wavelength bitrate/format transparency would allow, for example, nodes A-D to communicate using more-expensive transmitter/receivers (perhaps with higher speed or longer reach) while B and C could be equipped with much cheaper transmitters/receivers (perhaps of lower speed or shorter reach).

The commercial case study in Appendix A shows where real-world advantage has been taken of this kind of bitrate/format transparency in a non-WPS case, allowing terminal transmitters/receivers to be selectively upgraded from 10Gbps to 40Gbps to 100Gbps without having to replace intermediate nodes' equipment.

However, in WPS as defined above, all transmitters/receiver pairs along a wavelength-path must share a common modulation format, as during *some* of the timeslots they will be communicating with each other. Therefore, photonic transparency cannot be used unless multi-rate transmitters/receivers are used. For cost reasons, multi-rate transceivers are unlikely to be used in the bandwidth-hungry network core, even though multi-rate modems are conceptually well-understood, as it is not cost-effective to pay for a 40Gbps-capable transmitter and then only run it at 10Gbps, due to the significant amount of line-card hardware that has to be dimensioned to its highest bit-rate (FEC processing/backplane comms/client port count etc.). Network edges (where wavelength capacity is not so critical, rates are lower and so the cost impact of multi-rate cards is less prohibitive) are outside the scope of this thesis.

Therefore, for the cost reasons outlined above, the property of photonic transparency is not usable by WPS as defined here. While it would be possible to construct a modified form of WPS where mixed but fixed-rate transmitter/receiver pairs are used in one wavelength-path and can only communicate with other transceivers of the same rate, and it would be possible to operate such a network, this option is disregarded for simplicity – the analysis presented here would present a best case in terms of bandwidth efficiency such a network, but only for the case where all demand positioning happened to align with the placement of different transmitter sizes, which is unlikely in practice.

2.2.2 New proposed nodal hardware layout for supporting WPS

As discussed in the previous section when considering which benefits of photonic networking WPS offers, WPS does not allow the user to benefit from photonic transparency and Myers's proposed hardware configuration does not reduce the number of OE/EO conversions in the network versus a fully electronically switched network. This section describes an alternative nodal hardware layout which overcomes the second problem – it shows how WPS can reduce the number of OE/EO conversions, and the monetary/heat/space/power costs associated with them.

In order to achieve this, the transmitters/receivers must be wavelength-tunable (a commercially realistic assumption, see Appendix A) and an additional aggregation photonic switching layer must be placed between the WPS splitters and the receivers as illustrated in Figure 2-3. This shows that it is possible to exploit the sub-100% duty cycle of the receivers/transmitters in order to share them between the passive splitters/couplers.

The example in the figure shows five wavelengths being aggregated down to require only three transmitters/receivers – rather than one per wavelength. Such a reduction introduces a new point of blocking. However, in many practical cases, there will already have been at least one potential blocking point in Myers's configuration should the electronic switching matrix be dimensioned to suit anything less than peak load in terms of dropped/added traffic.

Assuming that an active node cross-connects multiple fibres, each of which has its own pool of transmitters/receivers, the pool could be shared between all such fibres dynamically, for further statistical multiplexing gains. Characterising these gains is beyond the scope of this chapter, as it requires choices in terms of acceptable switch blocking probability which is a subjective matter of policy.

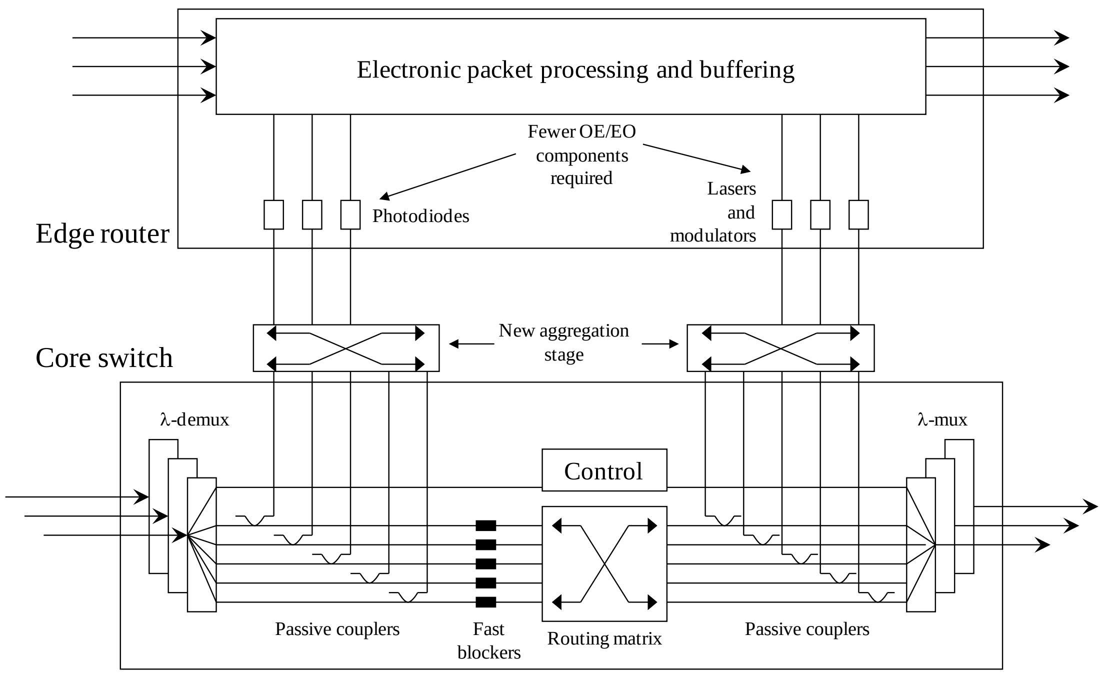

Figure 2-3 Illustration of a WPS active node hardware configuration proposed in this thesis using intermediate aggregation stage to save OE/EO conversions

Alternatively, a wavelength-selective switch (WSS) (see [Takahashi 08] and [Ma 08] for a discussion of what a WSS is) can be used instead, shown in Figure 2-4. This effectively combines the functions of the demux/mux/passive-taps/power-balancing-attenuators/routing-matrices and aggregating-MEMS layer all into one device.

The configuration proposed in this section does require that the transmitters, receivers and aggregating components (such as the new routing matrix in the first figure) be capable of switching at a speed adequate to change between adjacent local and remote bursts (i.e. be OBS capable). There is precedent for this, e.g. in the 25ps switching period achievable with the Liquid-Crystal-on-Silicon WSS shown in [Roelens 08] and 400ns total of a commercial laser analysed in [Anandarajah 08]. For comparison, whilst there are no standards for OBS itself, 10Gbps Ethernet [802.3-2005] is specified as having a standard inter-frame gap of 9.6ns. Thus, while further developments in speed may be needed, there is reasonable expectation that this can be achieved. e.g. [Cai08] quotes 1.6us for the laser described therein, but convincingly states that, theoretically, switching can be achieved at the level of nanoseconds, as the limiting factors were in the experimental conditions (current pulse source and optical detector) rather than the laser itself.

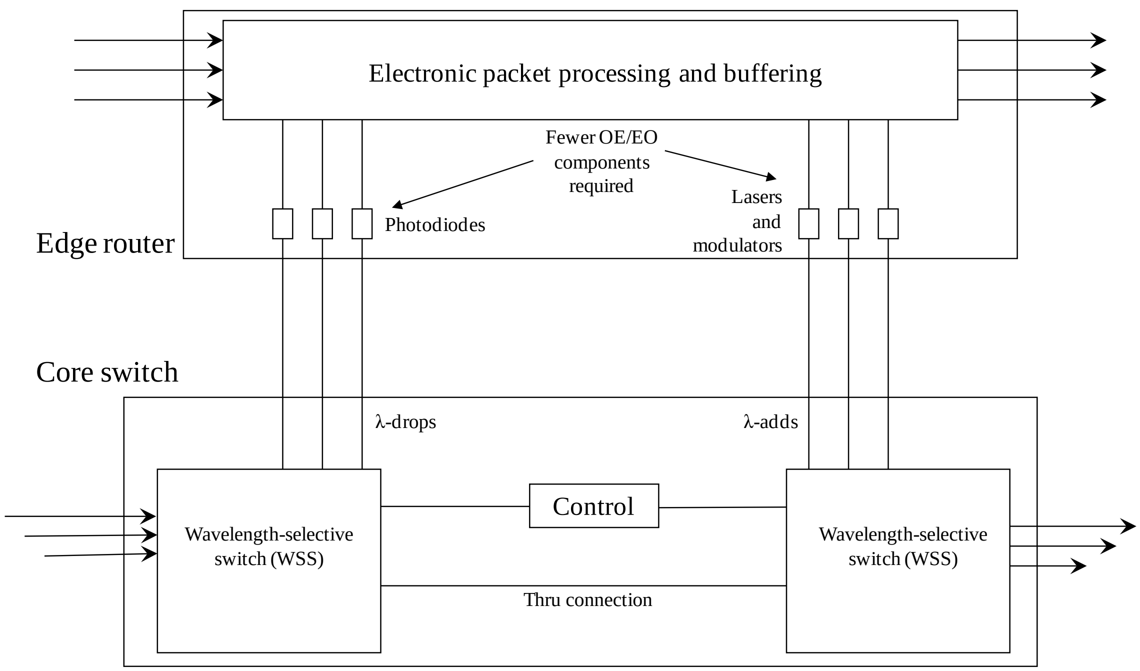

Figure 2-4 Illustration of alternative proposal in this thesis for WPS active node using wavelength selective switches to save OE/EO components

It will be observed that if the photonic switching elements are capable of switching fast enough to aggregate wavelengths to receivers/transmitters on a per-packet basis, this hardware configuration would be capable of doing OPS/OBS directly. However, network operators may choose to do WPS anyway, for some of the reasons previously discussed in Chapter 1 for not using OPS/OBS, e.g. lack of buffering, lack of wavelength conversion, latency requirements and network size that preclude the round-trip signalling of WROBS.

The remainder of this chapter does not make any assumptions regarding the particular hardware configuration used to implement WPS.

2.3 Routing algorithm proposal

2.3.1 Why is a new routing algorithm needed?

Much has been written on how to route and allocate wavelengths to serve demand patterns with A-WRONs (e.g. [Baroni 98], [Zapata-Beghelli 08], [Belgacem 08]). However, this task is different when considering WPS networks. Referring back to Figure 2-1: a physical path (2-1-8-9) is chosen not to support a demand directly, but to support one of several possible logical paths (2-8-9 in this example), any of which will simultaneously satisfy several demands; in the example given, the demand set is {(2, 8), (2, 9), (8, 9)}. The objective is to ensure that every demand in the traffic matrix is satisfied, and to do so using a minimum of resources. I.e. not wastefully serving some demands multiple times or with more bandwidth than is required. For example, if, in addition to Figure 2-1, the same network also contained logical path 7-8-9 then the demand 8-9 is wastefully/unnecessarily served by both logical paths. Therefore, WPS routes groups of demands, and part of the routing operation, unlike A-WRON, is to choose an optimal *set* of demand-groups to route.

In his proposal Myers assessed potential network utilisation gains of WPS by transforming the wavelength-path placement problem into an integer linear programming problem and using standard optimisation software to gain an answer.

While ILP approaches often achieve extremely good results due to optimising an exact formulation of the problem, they are notorious for their long execution time (because, with bounded variables, as used in this case, they are NP-hard). However, in this particular case, the execution time scaled up in size so rapidly that [Myers 01] had to use a restricted formulation of the problem in order to obtain results in what he described as a "reasonable period". As the results below (section 2.3.6) show, even this restricted formulation could fail to complete within several days for large networks (43 or 46 nodes failed to complete within four days, where networks up to 21 nodes completed in less than twenty seconds). Therefore, to achieve a result in a reasonable time span for more general (i.e. larger) network sizes, a more scalable heuristic is required.

[Zapata-Beghelli 08] reviewed routing and wavelength assignment (RWA) algorithms used in existing A-WRONs, concluding that the Adaptive Unconstrained Routing with Exhaustive wavelength consideration (AUR-E) (first proposed in [Mokhtar 98]) is the best heuristic for routing a network in terms of reducing blocking probability. AUR-E is very computationally intensive due to separately running the Dijkstra shortest path algorithm for each wavelength supported in the network. However, it is still an improvement relative to an integer linear programming (ILP) approach and incurring the NP-hard scaling that brings (such as [Belgacem 08], although he has a technique for reducing the scaling problem, by breaking the problem down into chunks and ILP-solving each chunk separately). This is the intuitively expected answer for two reasons: a) an adaptive algorithm should perform better than a static algorithm (as the former has more information – current network state – to work on); and b) an algorithm performing simultaneous routing and wavelength allocation has the opportunity to consider the joint optimum between these two axes, where separate routing and wavelength allocation phases as per Zapata-Beghelli's alternative algorithms can only provide the combination of optimum routing allocation with the separately-optimal wavelength allocation on those routes. The simulation results later in this section seem to back up Zapata-Beghelli's conclusions as will be seen in section 2.4.5.

None of the existing RWA algorithms, which were designed for WRONs, deal with the problem of WPS routes explicitly or serving multiple demands as used in WPS. The nearest equivalent work to WPS is light-frames and therefore is it appropriate to review the routing algorithms proposed in that area for suitability.

2.3.2 Review of Light-Frames routing algorithms

This section reviews key papers in Light-Frames work in terms of the routing algorithms proposed and also discusses why they are not suitable for finding the best wavelength-paths in the scenario described in this chapter.

The Light-Trails (e.g. [Chlamtac 03]) and Light-Mesh (e.g. [Ayad 08]) work describes constrained topologies (rings or pre-planned paths) and so there are no routing decisions to be made, merely decisions on where each Trail should be allowed to start/end (with a semi-permanent block before/after). These assume that those constrained technologies already exist and so do not provide routing algorithms to determine where they should be placed.

The Light-Frames concept (e.g. [Gumaste 06a]) works on arbitrary meshes and as such it routes paths similar to those required for WPS.

[Gumaste 06a] offered an ILP formulation for routing strings and threads. However, its minimisation objective is for the number of strings, threads and OEO nodes (an OEO node is just an OOO node with wavelength blocking activated, so incurring no additional cost), rather than any direct measure of network resource usage, and so it cannot be relied upon to produce optimal results. Similarly, [Ayad 08] provides an ILP which minimises trails rather than wavelengths. Without a fixed trail length there is no way of directly calculating wavelength-link usage from trail count. Indeed [Fang 04] notes that different solutions are required to optimise wavelength-links instead of number of trails. As the existence of more trails does not in itself cost more money, except in the number of wavelengths it consumes, this seems the wrong optimisation; it makes more sense that wavelength-links should be optimised directly. It would be possible to argue that using more trails requires more transceivers/per-wavelength optics. However, this argument is inapplicable to the Gumaste proposal because the light-trails proposal possessed switching nodes on all available wavelengths (to allow the light-trail lengths/routes to be dynamic). Thus, the light-trails hardware cost is actually related to the number of wavelengths that may be used, rather than the number of trails used.

Therefore, as per the previous section, an algorithm is required that finds optimal logical paths that serves multiple demands (as occurs in WPS) and, as per this section, this must be done such that optimality is assessed in terms of wavelength-links, being a more direct and simple measure of network capacity consumed than those which have been reviewed in this section.

Proposal and references	**Topology considered**	**Minimisation objective**
Light-Trails (e.g. [Chlamtac 03])	Constrained (rings, or pre-planned)	N/A
Light-Mesh (e.g. [Ayad 08])		
Light-Frames ([Gumaste 06a])	Arbitrary mesh	Count of strings, threads and OEO nodes.
Light-Frames ([Ayad 08])	Arbitrary mesh	Trail-count
This Chapter (LRF, AUR-F)	Arbitrary mesh	Network capacity consumed (Wavelength-links)

Table 2-3 Summary of properties of routing algorithms discussed in this section

2.3.3 New heuristic routing algorithm 1 – longest-route first (LRF)

2.3.3.1 Pseudo-code

The objective is to produce an algorithm that executes faster than the M-ILP formulation but produces comparable results in terms of minimizing the number of wavelength-links consumed to serve all demands. This novel heuristic algorithm, "Longest-Route First" (LRF), outputs a list of logical paths (with supporting physical paths) that, for a given target network topology, fully satisfy all traffic demands.

The algorithm builds on the Light-trails proposals such as [Gumaste 06]'s “Longest pair heaviest-load assignment”, generalised to cope with a mesh topology (instead of a simple ring), to accommodate passive transit WPS nodes, and enhanced with the analysis (of the non-WPS case) done by [Zapata-Beghelli 06]. This algorithm shows that k-shortest-path first-fit achieved near-optimal results at a much reduced computational cost versus the best heuristic solution of an adaptive routing algorithm such as AUR-E [Mokhtar 97].

The algorithm produces logical paths of length limited to 3 nodes (as previously discussed in this chapter, this is the limit at which 100% usage of the network may be achieved with uniform traffic).

Within the following pseudo-code, demands are denoted by the ordered tuple *(s, d)*, denoting a unidirectional demand from node *s* to node *d*. Establishing a WPS logical path *(a, b, c)* serves the demands *(a, b)*, *(b, c)* and *(a, c)*. Notation in square brackets denotes computational complexity of the step, with the net effect discussed in the next section.

Pseudo-code for the LRF algorithm is:

1. Calculate the *k*-shortest paths between all pairs of nodes. [*Demands.O(n log n)*]
    a. For each pair of nodes, sort the *k*-shortest paths such that they are in order of increasing length (defined as number of hops in the implementation for generality, but could also be done by link weight or geographical distance). [*Demands.O(n log n)*]
    b. As steps 1 and 1.a are traffic invariant, they may be done offline.
2. Sort the unidirectional traffic demands in order of decreasing distance. Define this ordering as demand $(s_A, d_A) < (s_B, d_B)$ if the shortest path between the nodes (s_A, d_A) is shorter than the shortest path between the nodes (s_B, d_B). [*O(n log n)*]
3. For each un-served traffic demand *(s, d)* in the list, in order (as sorted in the previous step):
    a. For each path identified in the previous step of length greater than 2 nodes, find the central node of the path and designate this as both *q* and *r*. If the centre of the path falls between two nodes, designate one node *q* and the other *r*.
        i. Test if *r* is such that the demands *(s, r)* and *(r, d)* have not yet already been met. If that is the case, establish the WPS logical path *(s, r, d)* and go back to step 3 to consider the next demand *(s, d)*. If only one of those demands has not been met, set *b*= *r* and continue to step ii.

ii. Test if *q* is such that the demands *(s, q)* and *(q, d)* have not yet already been met. If that is the case, establish the WPS logical path *(s, q, d)* and go back to step 3 to consider the next demand. If only one of those demands has not been met, set *b*=*r* and continue to step iii.

iii. Move *r* one hop along the path towards *d*. Move *q* one hop along the path towards *s*. Go to step i.

iv. Once both ends have been reached go back to step a, and then consider the next path in the list.

v. Once all paths have been considered, if a match has not already been found as per steps i or ii, if a partial match node (*b*) has been found then establish a WPS logical path *(s, b, d).* If no such partial match was found, establish a sub-length WPS logical path of *(s, d)*.

b. Go back to step 3 and consider the next demand *(s, d)* in the list.

Step 3 will terminate when all demands have been served.

It is assumed that the network is fully connected, i.e. that no *(s, d)* exist such that there is no possible path from *s* to *d*. This assumption is without loss of generality, as any demands between the partitions of a disconnected network are not directly serviceable and so must be dealt with by a means other than WPS.

Note: Where wavelength allocation is also considered, as described in section 2.4 onwards, an additional heuristic (AUR-F) doing simultaneous routing and wavelength allocation is proposed in section 2.4.3.

2.3.3.2 Algorithm execution complexity

The computational complexity of the action in each step is marked next to it. However, there are multiple parts to step 3, so the net total complexity of this must be calculated, as follows:

- Assume there are n^2 demands as is the worst case, achieved by e.g. a uniform traffic demand.
- The k-shortest paths of step 1 must therefore be executed n^2 times, resulting in a complexity of $O(n^3 \log n)$.
- Step 1.a likewise has complexity $O(n^3 \log n)$.
- There are at worst, n^2 iterations of step 3.
- The k iterations of step a (due to the k shortest paths) may be disregarded for scaling analysis, being a constant.
- As a result, steps i-v just iterate along the length of a path l, $O(l)$.
- Therefore, step 3 costs $O(n^2.l)$.

Each iteration of step 3 may address up to three separate demands, but this just introduces another constant factor which should be ignored for worst-case complexity analysis.

Therefore step 1 dominates the complexity, so the LRF algorithm achieves a complexity of $O(n^3 \log n)$.

However, if step 1 and 1.a may be executed in advance, then the processing for each demand as it arrives is much reduced such that only steps 3.a.i-3.a.v need be executed.

Therefore, in normal usage, the complexity of the LRF algorithm is $O(n^2.l)$, where l is the average length of the optical path.

2.3.4 Objective of the simulation

The objective of the simulation is to compare the performance of the LRF algorithm with the M-ILP formulation. In this section, performance is measured in terms of the number of wavelengths consumed ($N\lambda$ in the results below) for consistency and comparison with

Myers's results. An alternative approach of considering performance in terms of continuous wavelengths is described and pursued in section 2.4 onwards, to which this first simulation is an approximation.

As a benchmark, the A-WRON lower bound of wavelengths required for the same network is found, as derived in [Baroni 98].

2.3.5 Simulation conditions/assumptions

A uniform traffic model is assumed, for comparability with Myers's results, with an average of 0.5 wavelengths per (*source*, *destination*) node pair, and no traffic starting and terminating at the same node (as the access layer will directly switch that traffic). The traffic model is static throughout this chapter: changing traffic is discussed in the next chapter. As per Myers, these are the best-case conditions for 3-node WPS paths – where they should achieve 50% cost-savings versus A-WRONs.

The networks simulated are the standard analysis networks taken from [Zapata-Beghelli 06] shown in Appendix B (as are the other simulations performed in this thesis). The choice of these topologies, and their characteristics, are described there.

Demands are routed unprotected, as per the assumption stated in Chapter 1. This is also to remain consistent with Myers in order to allow the results to be compared.

2.3.6 Results of simulations

With $\varepsilon = 1$ or 2, the M-ILP [Myers 01] failed to run to completion within a few days, it was necessary to limit ε at 0. This will have affected the results for the worse, as it constrains the M-ILP to only considering shortest paths. Myers also had to use $\varepsilon = 0$ for some of his runs where $\varepsilon = 1$ failed to terminate 'in a reasonable time'. The difficulty of getting these results is a practical demonstration of the unsuitability of an ILP approach to practical usage on larger networks due to execution time.

Simulations were run, for each network, using the following parameters:

N	Number of nodes
L	Number of links
α	The normalized number of bi-directional links with respect to a fully-connected mesh topology (as defined in Appendix B).
Δ	The mean nodal degree in the graph
$N\lambda$ *(A-WRON)*	Minimum number of wavelengths that would be required to serve the demands by an A-WRON according to the Baroni lower bound.
$N\lambda$ *(M-ILP)*	Minimum number of wavelengths that would be required to serve the demands by WPS, calculated according to Myers's ILP (M-ILP)
$N\lambda$ *(LRF)*	Minimum number of wavelengths that would be required to serve the demands by WPS, calculated according to the LRF algorithm proposed in this chapter.

Table 2-4 Key parameters used in this chapter. This information is a subset of the List of symbols at the front of the thesis.

Network parameters					Benchmark	Existing ILP		Proposed heuristic	
Network	N	L	α (2d.p.)	Δ (2d.p.)	Non-WPS benchmark $N\lambda$ *(A-WRON)*	$N\lambda$ *(M-ILP)*	$N\lambda$ *(M-ILP)* / Benchmark %	$N\lambda$ *(LRF)*	$N\lambda$ *(LRF)* / Benchmark %
Tor3	9	18	0.5	4	3	2	66.67%	4	133.33%
Eurocore	11	25	0.45	4.55	4	3	75.00%	5	125.00%
NSFnet	14	20	0.22	2.86	13	8	61.54%	10	76.92%
EON	20	39	0.21	3.9	18	9	50.00%	15	83.33%
UKNet	21	39	0.19	3.71	19	11	57.89%	14	73.68%
ArpaNet	20	31	0.16	3.1	33	17	51.52%	22	66.67%

Table 2-5 Comparison of LRF with M-ILP and A-WRON

The LRF also used ε to indicate the maximum permitted deviation from the shortest path. The optimal value of ε varied per network, so the algorithm discussed henceforth is where the LRF is executed with $\varepsilon = 0$ then $\varepsilon = 1$ then $\varepsilon = 2$ in sequence and the best result chosen. A maximum value of $\varepsilon = 2$ was chosen, as higher values do not appear to give any significant improvement.

The results of the LRF heuristic relative to M-ILP, compared to the calculated Baroni lower bound are provided in Table 2-5.

With the USNet (46 nodes/76 links) and Eurolarge (43 nodes/90 links) network scenarios, M-ILP failed to run to completion after approximately four days of execution time (each), reinforcing the need for a new heuristic, e.g. LRF, for networks of practical size.

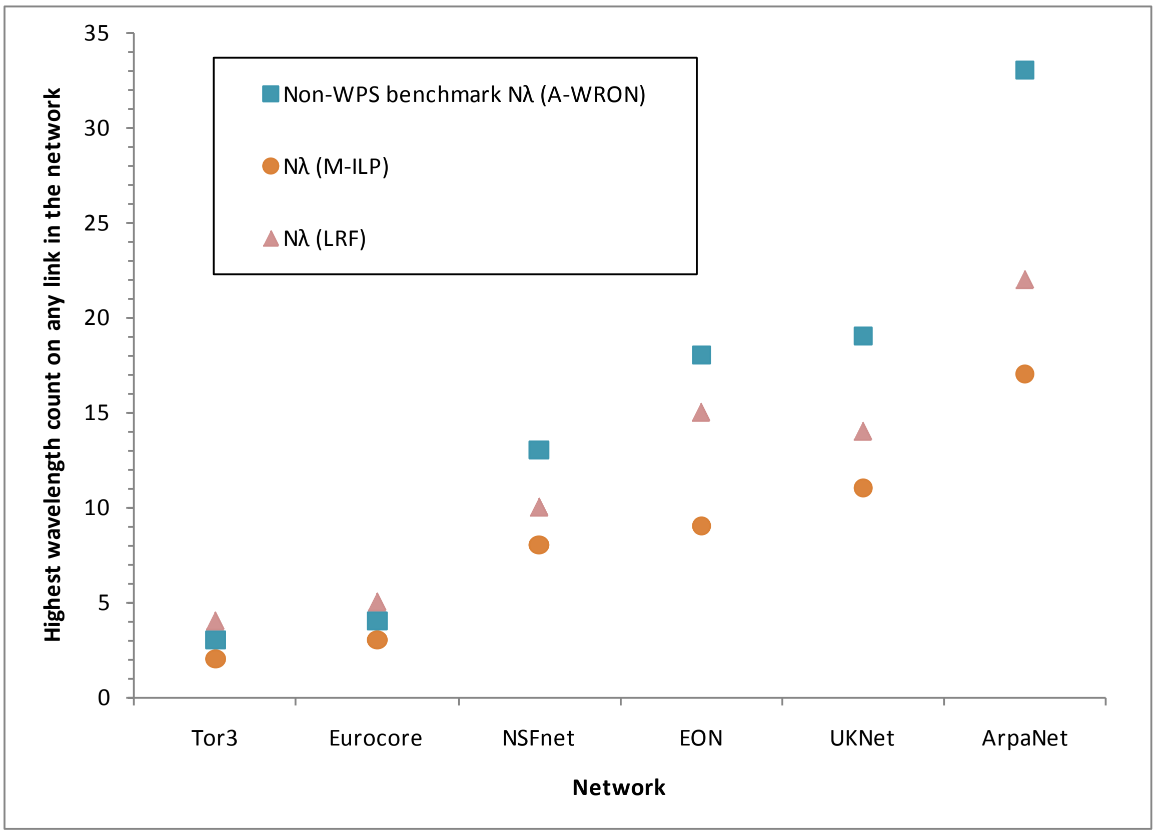

Figure 2-5 The performance of the LRF heuristic algorithm versus Myers's ILP (M-ILP) and the Baroni lower bound in terms of the number of wavelengths consumed.

[Myers 01] proves (by trivial analytical derivation) that the theoretical minimum achievable number of wavelengths required, relative to an A-WRON, is 50%.

The results from the table are shown in graphical form in Figure 2-5. The network graphs are ordered in terms of increasing Nλ (A-WRON), which for these graphs is the same as decreasing alpha. This is an arbitrary sorting.

The reason for using a heuristic algorithm was to decrease the processing time required. Table 2-6 shows the measured time in achieving the results above for each method over each graph. Note that a non-trivial amount of time is spent formulating the M-ILP before it can be fed to the solver, because the problem formulation requires all possible logical and physical paths to be enumerated. For clarity, these times have been displayed separately.

These results were produced using an (otherwise unloaded) Intel T2050 1.6GHz running Windows XP Media Center SP3 with 1.5Gb of RAM, averaged over three runs. Execution times did not vary significantly over the three runs.

Network data					A-WRON execution time (seconds) (2d.p.) [for interest only]	Existing ILP		Proposed algorithm (LRF) execution time (seconds) (2d.p.)	Proposed (LRF) vs. Existing (M-ILP) (total time) % (2d.p.)
Network	N	L	α (2d.p.)	Δ (2d.p.)		M-ILP prep time (seconds) (2d.p.)	M-ILP execution time (seconds, 2d.p.)		
Tor3	9	18	0.5	4	0.05	0.01	0.01	0.05	310.87%
Eurocore	11	25	0.45	4.55	0.24	0.02	0.03	0.1	221.99%
NSFnet	14	20	0.22	2.86	0.32	0.03	0.03	0.12	193.55%
EON	20	39	0.21	3.9	5.55	0.12	2.63	0.52	18.79%
UKNet	21	39	0.19	3.71	11.22	0.13	1.88	0.55	27.47%
ArpaNet	20	31	0.16	3.1	3.43	0.1	1.53	0.39	23.64%

Table 2-6 Execution time of the different algorithms considered over standard analysis networks

2.3.7 Analysis and discussion of simulation results

M-ILP only achieved the Myers theoretical exact lower bound (on performance of 50% with 3-node paths) with the EON network, but not with other networks. Nonetheless, both M-ILP and LRF achieve an improvement over the non-WPS A-WRON value, showing that WPS is providing benefit.

As would be expected, LRF provided less optimal results than the M-ILP formulation benchmark (an average of approximately 50% more wavelengths). However it is significant that, for the larger networks where efficiency is more important, the LRF heuristic is still bettering (by 17-33%) the A-WRON *theoretical* lower bound (as well as running to completion within a reasonable time period, even on networks where M-ILP did not). Using A-WRON, this theoretical bound is not always achievable in practice, or with a practical algorithm, making the improvement demonstrated here more significant.

For general use, both algorithms (M-ILP and LRF) should be modified such that they never achieve a worse result than A-WRON, as there is no advantage to WPS except in terms of saved wavelengths. A simple way of doing this would be to run a (reasonably optimal) A-WRON routing algorithm at the same time and use whichever result produced the lower wavelength count.

Both of these routing algorithms (M-ILP and LRF) always use a 3-node logical path if one is physically possible, ignoring more efficient 2-node options, resulting in sub-optimal results in some situations. This is justified as, when consuming the same number of links, 3-node paths are preferable over 2-node paths because they serve 3 demands rather than 1. However, one 3-node path consuming x links is clearly less efficient than three 2-node paths averaging $< x/3$ links each. A more-optimal WPS placement would have the A-WRON lower-bound wavelength-count as its upper bound: A-WRON point-to-point wavelengths can be considered 2-node logical paths and thus a sub-part of the optimization-space that the WPS route-placer is considering.

The heuristic can be judged as a success in that, where an ILP performs poorly (if at all, in the case of larger networks), LRF is able to show significant (>20%) value for WPS while saving a significant (70-80%) proportion of the execution time. This advantage in execution time would increase with larger networks to the point where the LRF would get results where the ILP did not complete within reasonable time.

With smaller networks (where execution time is less of an issue), LRF did take longer to execute but this is believed to be due to a lack of optimisation in the start-up of the heuristic execution. It is expected that further work could eliminate this anomaly.

It should be noted that, in most of these cases, M-ILP does not achieve its theoretical 50%, which may be due to the limited value of $\varepsilon=0$ (required for reasonable execution time as discussed in section 2.3.6). Increasing ε is likely to improve the M-ILP's results at a cost of increase execution time.

The purpose of the LRF algorithm and these simulations was to provide and prove a faster and more scalable alternative to M-ILP, which both calculate routing. However, routing without wavelength allocation does not fully account for wavelength-links consumed. The next section describes why this is the case, proposes an additional new routing algorithm with wavelength allocation (AUR-F) and compares its bandwidth efficiency to those already seen in the simulations discussed so far in this chapter.

2.4 The effect of wavelength allocation and why it is important to consider wavelength continuity and unique wavelengths

In the previous section, two routing algorithms (M-ILP and LRF) are compared for performance in terms simply of the maximum number of wavelength-links required on any link. The choice of simulation conditions allows comparison with Myers's results.

However, as WPS does not include wavelength conversion, it must in practice use one frequency of light along the whole route of each wavelength-path (the wavelength continuity constraint, as defined in Chapter 1). Because of the possibility of blocking (a particular wavelength already being taken on a link when provisioning a new wavelength-path) this will usually increase the number of wavelengths actually consumed across the whole network.

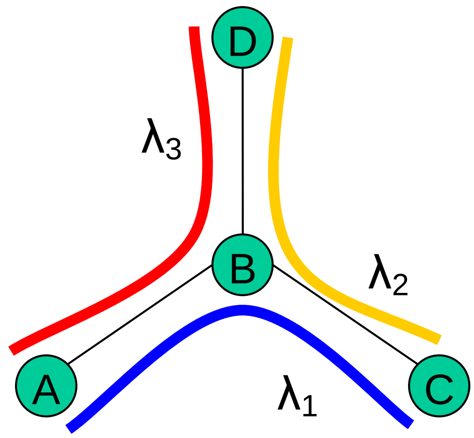

Figure 2-6 Illustrating wavelength blocking - why more continuous wavelengths may be required than are actually present on any given link.

To illustrate the difference between counting simple wavelengths (referred to by Myers as 'congestion') versus continuous (unique) wavelengths, consider the trivial example of wavelength blocking given in Figure 2-6. This shows a four-node network {A, B, C, D} interconnected with three single bidirectional fibre-pairs, with bidirectional demands of (A-C), (A-D) and (C-D). Within such a scenario, *three* different (unique) light-frequencies are required to accommodate the demands, even though no single link has more than *two* wavelength services on it.

Note: In this example, a uniform set of demands would not experience the problem. That is to say, if demands {A-B, B-C, B-D} were added then no wavelengths need to be stranded.

This chapter concentrates on the problem of how to route a known set of demands most efficiently. Incremental and changing demands, which lead to sub-optimal wavelength allocation (and thus wavelength blocking is a bigger problem), are discussed in the following chapter.

It is important to evaluate the number of continuous unique wavelengths (light frequencies) rather than simply the number of occupied wavelengths because it is the exhaustion of the former which causes blocking, and thus for money spent on capacity upgrades.

For example, the Ciena line system described in Appendix A is sold as supporting 88 wavelengths on the C-band. If this equipment had 60 wavelengths in use, but a new demand could not be placed on this fibre due to wavelength blocking, then the operator would be faced with the choice of deploying an additional fibre or L-band amplifier upgrades (both incurring capital expenditure). Alternatively, a less-preferable route with available capacity could be used, accelerating capacity blocking elsewhere in the network.

Therefore, the two routing algorithms (M-ILP and LRF) are now compared again using the performance measure of continuous wavelengths, based on the following assumptions:

2.4.1.1 Assumption: No wavelength conversion

Full wavelength conversion (at all nodes in the network, all incoming wavelengths may be translated to a different frequency before egress) eliminates the possibility of wavelength blocking, and the relevance of this section, but adds cost. For example, [Pedro 09] discusses the current technical immaturity of all-optical wavelength conversion, leading to the need for expensive electro-optical (O-E-O) wavelength conversion. The option of full wavelength conversion (meaning that the output of every switch may convert wavelengths, which if this is done electro-optically means full OEO at every switch and so no photonic pass-through at all) is therefore not compatible with the objective of this thesis to investigate fully-photonic networking.

The effect of partial wavelength conversion (where wavelength converters are deployed selectively to ease congestion) depends on how the converters are placed through the network. e.g. [De 07] compares several approaches and presents strong simulator-based evidence for an 8-15% improvement for their own proposal. Therefore, for simplicity and generality, partial conversion is declared out of scope.

2.4.1.2 Assumption: No parallel fibres required

For the same total capacity, *n* parallel fibres between the same pair of nodes decreases wavelength blocking because each light-frequency can be sent *n* times before blocking occurs. [Baroni 98] section 3.8 shows this analytically.

No parallel fibres are assumed for simplicity of interpreting the results and generality – not introducing the granularity arrangements of a particular system.

In my industrial experience, this also best represents today's deployed networks. This is because larger demands (those more than a significant fraction, say 10% of the size of the wavelength) will be allocated dedicated wavelengths or fibres. Thus, the agile network is only serving smaller demands.

Thus, and also after considering leasing-out and glass-through connections, it is reasonable to assume that many fibres may be lit in a duct without any particular sub-wavelength network (such as the WPS network considered here) having more than one fibre to a particular destination.

2.4.1.3 Assumption: Wavelength exhaustion has not been reached for any fibre

As with the no-parallel-fibres assumption (above), this is to retain generality by avoiding introducing the granularity chosen by any particular line system; instead keeping it a simple linear utility function, the count of continuous wavelengths.

This would be realistic for existing single-fibre-pair networks wanting to delay the expense of lighting/adding parallel fibres. It is a loose upper-bound for multi-fibre networks which will be less prone to blocking as discussed above. Networks with a few parallel fibres added in hot-spots will perform noticeably better than discussed here as the hot-spots are where wavelength blocking is most likely to occur. This is discussed in [Baroni 98] section 3.8.

2.4.1.4 Assumption: Consistent line systems on all links

The objective of this simulation is to minimise the maximum number of continuous wavelengths used by any link.

This would be an inappropriate metric if the network consisted of a mix of links of dissimilar wavelength capability (e.g. some supporting 44 wavelengths and some supporting 88). However, as per the previous assumptions, this would require building in a particular granularity model which would decrease the generality of the results and so this factor is disregarded.

This assumption is justified in terms of modern line-systems, such as the Ciena system described in Appendix A, that do not have any fixed-frequency components (once a fibre span has amplifiers it can carry any supported C-band wavelength). However, older systems with fixed demultiplexing filters may support/require progressive upgrades in order to add further bands/groups of e.g. 4 or 8 wavelengths, so deferring the expense of the additional group filters would be beneficial versus the results shown here.
Again, introducing such system-specific details would lose generality of the results derived later.

2.4.2 New wavelength allocation ILP formulation (WA-ILP)

This section describes a new ILP formulation (WA-ILP) that allocates specific continuous wavelengths to a given set of routes, on a given single-fibre-per-link network. This ILP formulation provides optimal wavelength allocation in terms of the number of wavelength-links consumed. This optimal allocation is required to provide a lower bound of wavelength usage to compare against the algorithms proposed in later sections. WA-ILP is not itself considered to be practical for online use because, as with all ILPs, it is an

NP-hard algorithm, i.e. it will scale exponentially in terms of execution time with increased network size.

For example, the first-fit (FF) wavelength allocation (as described in e.g. [Zhu 09]) algorithm is simple and commonly used, for example in [Almeida 08]. Its execution time is extremely good, O(*W*) where *W* is the number of wavelengths, making it suitable for online usage. However, it is a heuristic whose results are not necessarily optimal, as shown later in this chapter.

The WA-ILP formulation has been derived from the [Baroni 98] formulation for the number of wavelengths required for A-WRONs (his equation 3-9 onwards) by eliminating the route-choice elements. WA-ILP is expressed as follows:

P is the given set of wavelength routes.

u_ω is a boolean flag to indicate whether wavelength ω is used anywhere in the network.

W is the number of unique wavelengths available.

$$u_\omega = \{0,1\} \qquad \forall \omega \in 1...W \tag{2-1}$$

$$\delta_{p\omega} = \begin{cases} 1 & \text{If path p travels over wavelength } \omega \\ 0 & \text{Otherwise} \end{cases} \tag{2-2}$$

Any particular wavelength can only be used once on each link.

J is the complete set of links.

I(x) is 1 if *x* is true and 0 if *x* is false.

$$\sum_{p \in P} \delta_{p\omega} I(j \in p) \leq 1 \qquad \forall j \in J \quad \forall \omega \in 1 \ldots W \tag{2-3}$$

Each path must be assigned a wavelength.

$$\sum_{\omega \in W} \delta_{p\omega} \geq 1 \qquad \forall p \in P \tag{2-4}$$

u_ω must be set if any path uses the wavelength ω:

$$\sum_{p \in P} \delta_{p\omega} \leq u_\omega \qquad \forall \omega \tag{2-5}$$

And the overall purpose of the optimisation is to perform wavelength allocation whilst minimising the total number of wavelengths used in the network:

Objective:

$$\min N_\lambda = \sum_{\omega \in W} u_\omega \tag{2-6}$$

W must be set to a number of wavelengths large enough to allow a feasible solution, and thus for the ILP to terminate successfully. Values of W larger than strictly necessary to allow a solution result in a longer execution time but do not affect the resulting count.

2.4.3 New heuristic routing algorithm 2 – Adaptive unconstrained routing with fixed wavelength sequence allocation (AUR-F)

The LRF and M-ILP routing algorithms previously discussed have required a separate second phase of wavelength allocation. Separating these phases has been shown [Mokhtar 98] to reduce efficiency of the routes produced. A novel algorithm is presented in this section, extending Mokhtar's work to apply to WPS, to choose the route and wavelength simultaneously. It will be shown that this algorithm achieves substantially greater efficiency (approximately 50% wavelength saving) versus LRF with a subsequent wavelength allocation phase.

The proposed algorithm is based on the Adaptive Unconstrained Routing with Exhaustive wavelength allocation (AUR-E) as proposed in [Mokhtar 98]. This was found to be the most efficient (as measured in terms of blocking probability) A-WRON RWA algorithm in Mokhtar's paper and, in a broader comparison, more recently [Zapata-Beghelli 06]. Defining the terms used in this name:

- Adaptive means that the route the algorithm chooses will depend on current network usage. This is as opposed to Fixed routing which is traffic unaware and thus solely dependent on the static network topology.
- Unconstrained is as opposed to Alternate routing. In Alternate routing, multiple routes are calculated from the static network topology, and then those for which there is inadequate free capacity are eliminated to leave zero or more choices. Unconstrained routing is not limited to a set of routes and so will always find a route if one exists for which there is capacity on the network.
- Exhaustive wavelength allocation means that the demand is routed on all wavelengths and the shortest path chosen.

As the Exhaustive wavelength allocation variant of this algorithm executes by considering every possible wavelength, it assumes that demands are being applied to a particular finite set of wavelengths. However, the objective problem statement of this chapter while closely related to that is slightly different – the minimisation of the number of wavelengths required to support a given set of demands. Therefore, the Fixed wavelength allocation sequence variant is used instead (AUR-F) as being suitable for an unconstrained number of wavelengths. [Mokhtar 98] showed that this produced nearly the same results as AUR-E (he did not provide particular numbers, but his graphs make a strong case), while being substantially lower in execution complexity (between 36% and 58% in the examples provided). This execution time advantage increases with the number of wavelengths available as AUR-F can visit fewer where AUR-E must visit all of them but decreases with rising blocking probability as where the network fill is higher, AUR-F will block on earlier wavelengths and so have to visit more in total).

2.4.3.1 Pseudo-code

The AUR-E algorithm outputs a list of logical paths - with supporting physical paths allocated to a particular wavelength - that fully satisfies all traffic demands on a given network topology. The objective is to produce an algorithm that executes faster than M-ILP combined with WA-ILP while producing comparable results.

Demands are denoted by the ordered tuple *(s, d)*, denoting a unidirectional demand from node *s* to node *d*. Establishing a WPS logical path *(a, b, c)* serves the demands *(a, b)*, *(b, c)* and *(a, c)*. *w* denotes a wavelength from the set of wavelengths *W*.

It will be observed that this algorithm is very similar to LRF (Section 2.3.3), the critical difference being the sequential wavelength allocation in steps 3a, 3c and 3d. Further, only considering shortest paths is equivalent to setting ε to zero. However, as AUR-F accepts the first path for which there is free capacity, and the path calculation is performed on available capacity, paths with $\varepsilon > 0$ would never be considered. Therefore, this constraint does not affect the results.

Pseudo-code for the algorithm is: [Notation in square brackets denotes computational complexity of the step, with the net effect discussed in the next section]

1. Calculate the shortest path between each node. As this is traffic invariant, it may be done offline. [$O(n \log n)$]
2. Sort the unidirectional traffic demands in decreasing order, where ordering is defined as demand $(s_A, d_A) < (s_B, d_B)$ if the shortest path between the nodes (s_A, d_A) is shorter than the shortest path between the nodes (s_B, d_B). [$O(n \log n)$]
3. For each un-served traffic demand *(s, d)* in the list, in order:
    a. $w \leftarrow 0$
    b. Calculate all shortest paths *(s, d)* based on current available capacity for wavelength *w*. [$O(n \log n)$]
    c. Execute step 3a of the LRF heuristic previously described in section 2.3.3.1

i. If a path has been found go back to step 3 of this algorithm to try the next demand. [*O(ln n)* – the only loop is over the length of a path, times the number of paths found in the previous step]

d. As a satisfactory path has not yet been found: $w \leftarrow w + 1$

e. Go to a and consider the next demand in the list.

Step 3 will terminate when all demands have been served.

As with LRF, it is assumed that the network is fully connected. I.e. that no *(s, d)* exist such that there is no path from *s* to *d*. As before, this is assumed without loss of generality as any demands between the partitions of a disconnected network are not serviceable and so must be dealt with by another means than WPS.

2.4.3.2 First-fit (FF) algorithm execution complexity

As mentioned, neither M-ILP nor LRF perform wavelength allocation (they just route traffic) and hence both require a second algorithm to perform wavelength allocation. AUR-F does wavelength allocation simultaneously with finding routes. Therefore, it is not appropriate to compare AUR-F's execution time to either M-ILP or LRF directly: the additional cost of the wavelength allocation step should be considered.

The FF (first-fit, referenced in section 2.4.2) algorithm has a complexity of O(*[W].[P].l*) where:

- *[W]* is the number of wavelengths supported by the line system (a constant factor) to be iterated over;
- *[P]* is the number of paths to be wavelength-allocated, assumed to be O(n^2) here – the worst case of a full mesh of demands (divided by the constant factor of three demands served by each WPS logical path).
- *l* is the average path length as, for each iteration over a wavelength for a path, the algorithm must check whether a particular link is used. If a simple sparse matrix is used with indices of <*wavelength*, *start node*, *end node*> each lookup is of constant time. More storage-efficient techniques would (probably) be preferable,

however, as a sparse matrix would require exactly $[W].n^2$ elements. l can be approximated to $log\ n$.

Therefore, the net complexity of using FF as the wavelength allocation stage after either M-ILP or LRF is $O(n^2\ log\ n)$. However, as this is done in sequence after the routing algorithm, not within any kind of iteration, it can be ignored as this is of smaller order than the routing algorithm itself.

2.4.3.3 AUR-F execution complexity

The additional loop over wavelengths of step 3a, 3d, 3e mean that AUR-F has higher complexity than the LRF algorithm. However it does eliminate the need for the wavelength allocation step.

As will be seen in this derivation, the largest-scaling step is step 3; steps 1 and 2 are negligible by comparison. The same worst-case assumption can be made as is made in section 2.3.3.2, namely that the worst-case number of demands is n^2, giving this number of iterations of step 3. The worst case number of iterations around steps 3a/3d/3e is $[W]$, which is a constant factor for any particular network and so can be disregarded. Step 3b includes the $O(n\ log\ n)$ shortest path calculation, which dominates the other steps. Therefore, the net complexity is $O(n^2.[W].n\ log\ n) = O(n^3\ log\ n)$.

Therefore, AUR-F scales just as well as LRF with network size, meaning comparison between them can be solely on bandwidth efficiency.

While the first few steps can be pre-calculated as with LRF. Because AUR-F is adaptive (performs its routing calculation based on current network usage), its key routing stage (3.b) is within the per-demand loop, therefore pre-calculation can reduce the absolute time, but not the scaling. With pre-calculation, complexity is therefore still $O(n^3\ log\ n)$.

2.4.4 Conditions for wavelength-aware simulations

Having described a set of algorithms (M-ILP, LRF and AUR-F), wavelength allocation approaches (WA-ILP and FF), and network assumptions, the bandwidth efficiency of each algorithm is now compared by simulation to determine the most efficient algorithms and also to illustrate the difference between this and the non-wavelength-continuous case studied before in section 2.3.6.

The same networks and traffic demands as the previous (non-continuous wavelength) simulations were used.

For WA-ILP, *W* was set to the output count from the FF algorithm (briefly described in section 2.4.2) – a known feasible solution and thus meeting the "large enough" requirement, as well as being available from a previous stage of the simulation. It is also a practical real-world source because FF executes in negligible time compared to the WA-ILP solution.

As will be seen from the results, a more aggressive choice of *W* may have been both possible and beneficial in decreasing execution time. However, as the choice of *W* does not affect the count of wavelengths produced (which was the objective), this effect was not further investigated.

2.4.5 Simulation results and discussion

The results shown in this section compare a count of unique wavelengths used in the network (not just the maximum count of wavelengths used across all links separately – see section 2.4 for an explanation of this distinction) for all of the algorithms discussed thus far in the chapter. Specifically, results are compared for:

- The routing algorithms used in the previous simulations (the LRF heuristic and M-ILP)
- The WA-ILP and FF heuristic wavelength allocation algorithms as applied to both routing algorithms.

- The AUR-F combined routing and wavelength allocation algorithm from section 2.4.3.

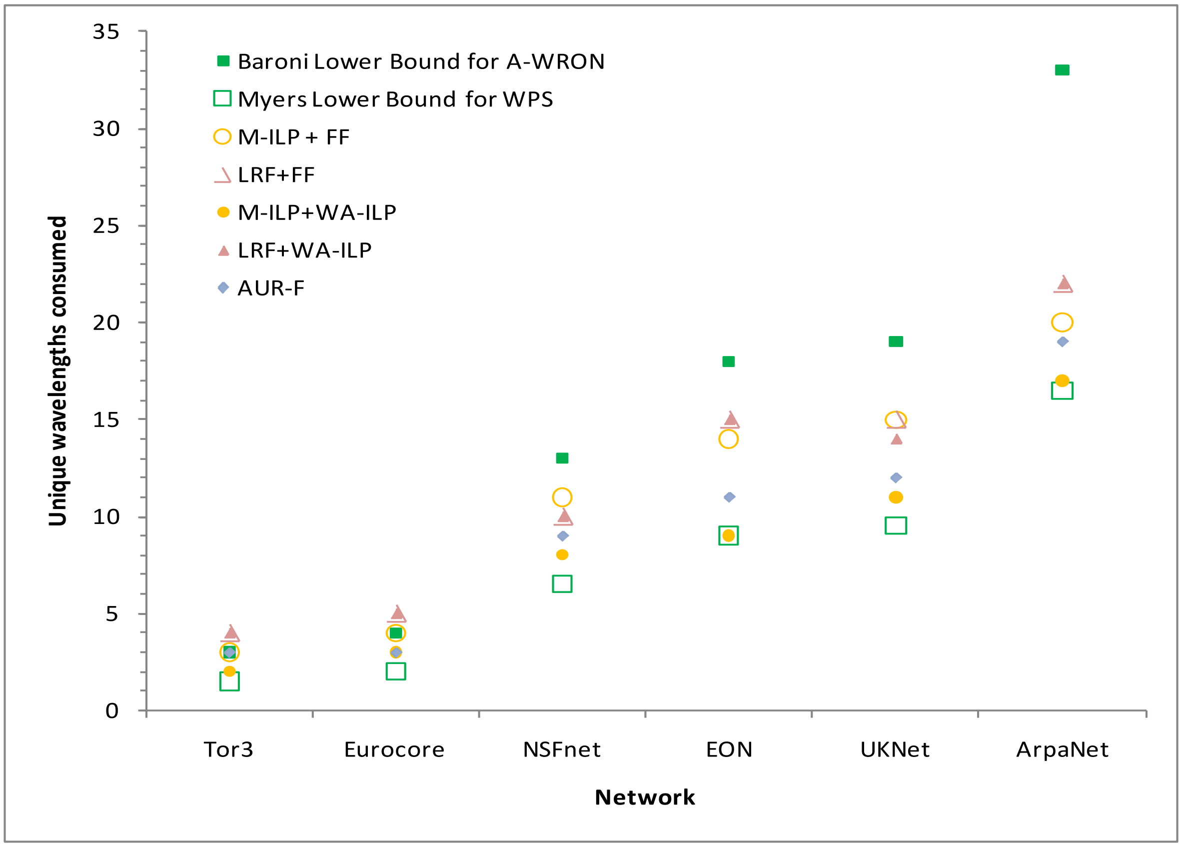

Figure 2-7 Results from simulation/ILP results comparing different wavelength allocation approaches for different network architectures as listed in Appendix B

Both the [Baroni 98] lower bound for A-WRON wavelength usage and the [Myers 01] lower bound for WPS wavelength usage are also provided as a reference. This is because Myers is a strict theoretical lower bound on what efficiency is achievable, and Baroni is the theoretical lower bound of A-WRON and as such, the point at which WPS ceases to have an unquestionable advantage in wavelength usage over A-WRON, so can be considered an upper bound.

Networks are ordered by $N\lambda$ (A-WRON) which for these graphs is also decreasing alpha. Note: It is hard to see the results for LRF+FF in the graph because they are the same as for LRF+WA-ILP, except for a difference of one for UKNet.

Network	Baroni Lower Bound for A-WRON	Myers Lower Bound for WPS	M-ILP + FF	LRF+FF	M-ILP+WA-ILP	LRF+WA-ILP	AUR-F
Tor3	3	1.5	3	4	2	4	3
Eurocore	4	2	4	5	3	5	3
NSFnet	13	6.5	11	10	8	10	9
EON	18	9	14	15	9	15	11
UKNet	19	9.5	15	15	11	14	12
ArpaNet	33	16.5	20	22	17	22	19

Table 2-7 Bandwidth efficiency comparison of simulations considering allocation of unique wavelengths. Myers lower bound should be rounded up to the nearest integer for comparisons, as a non-integer value is not achievable in a real system.

Comparing FF to WA-ILP: Judging from the simulations results shown in Table 2-7, FF is an excellent choice of wavelength allocation algorithm to use in association with LRF if WA-ILP proves unacceptably slow (as networks increase in size) because FF achieves very similar results (just one more wavelength consumed over all of the test networks used, averaging to a ‘cost’ in bandwidth efficiency of 1% for using this much more scalable heuristic).

However, when using M-ILP, the penalty for using FF instead of WA-ILP is higher; averaging around 38%. If the user is using an ILP for routing then they are presumably less concerned about execution time than a user executing a heuristic algorithm, so given these results, it would seem more sensible to also use an ILP wavelength allocation algorithm.

Notably, for these uniform all-to-all traffic patterns and WA-ILP, the number of unique wavelengths required is the same as the count of wavelengths required calculated in the previous section – WA-ILP has achieved the perfect lower bound result in these cases.

It should be noted that the first fit algorithm behaves (relatively) better (approx 37%) with the routes produced by LRF versus the routes calculated by M-ILP. This may affect many of the conclusions, e.g. [Almeida 07] [Almeida 08], drawn in the literature from running tests with first-fit and no other validation.

2.4.6 M-ILP versus LRF versus AUR-F comparison

The routing algorithms included in Table 2-7) are compared in this section. The FF results are ignored because the WA-ILP can be taken as providing optimal wavelength allocation.

LRF+WA-ILP is able to offer an approximately 25% saving versus the Baroni lower bound for the larger networks, delivering a significant fraction of the benefit of WPS as benchmarked by M-ILP+WA-ILP.

M-ILP+WA-ILP offers a 25-50% gain over the A-WRON, clearly demonstrating the potential for WPS to save wavelengths, and achieves the Myers lower bound for WPS in half the cases (as fractional wavelength counts must be rounded up to integers in practice). However, being NP-hard, it does not necessarily complete within a reasonable time.

AUR-F offers a significant improvement over LRF+WA-ILP (averaging 22% of its wavelengths) and critically, is always at least as good as the A-WRON Baroni lower bound. It does not quite reach the performance of M-ILP+WA-ILP on average, but the difference is quite small (M-ILP+WA-ILP averages 14% fewer wavelengths).

Again I note that the Baroni lower bound is theoretical and so the actual gains of WPS versus practical A-WRON systems will be larger. In particular, the Baroni lower bound assumes full wavelength conversion which the other methods do not.

2.4.7 Simulations using randomly-connected networks

The simulations were repeated using a sequence of 38 Randomly-Connected Networks (RCNs) plus NSFNet to determine how the algorithms' (in Table 2-7 above) performance changes according to different networks with the same size. Diagrams of a representative sample of these RCNs are shown in Appendix B.

The RCNs were selected to have a fixed 14 nodes – the same as NSFNet – for comparability with this most-studied of analysis networks. RCNs were generated from a nominal alpha of 0.15 to 0.35 at nominal increments of 0.005, giving 38 graphs (excluding endpoints). Exact values of α achieved were not precisely equal to these values, as the actual values were quantised according to the integer numbers of links that could be assigned on the network (the granularity of 0.005 was approximately twice that achievable, giving the advantage of 2-3 RCNs for each α value). This range of α was chosen because it covered the space of realistic delta connectivity values shown by the analysis networks (in fact going from approx 2.14 to approx 4.71).

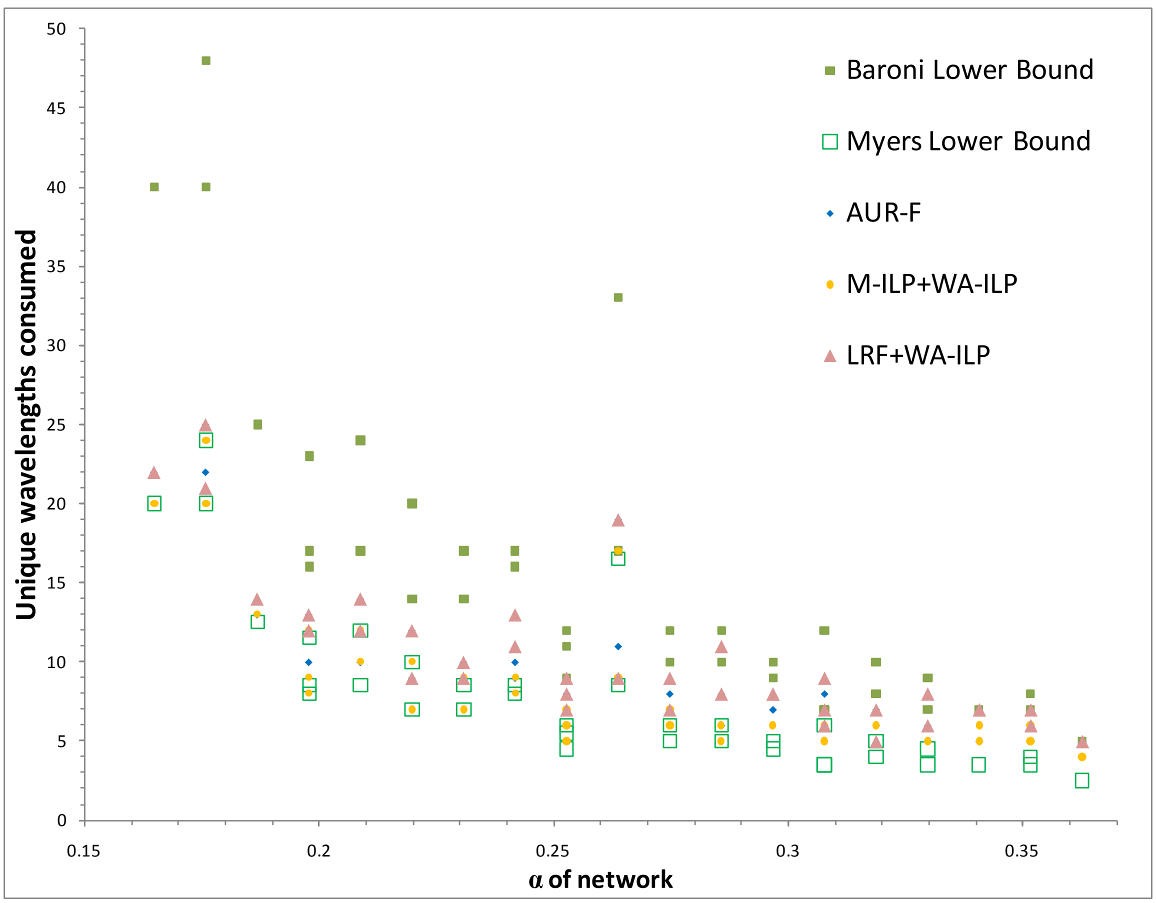

Figure 2-8 The proposed heuristics (LRF and AUR-F) compared against the Myers ILP (M-ILP) and theoretical lower bounds (Baroni for A-WRON, Myers for WPS).

Tor3 and EuroCore have higher alpha values only because they have fewer nodes. For reference, NSFNet has α = 0.22 as per Table 2-6.

Echoing the results from the standard analysis networks of Table 2-6, AUR-F performs extremely well – very close to or equal to M-ILP + WA-ILP approach (M-ILP averaging 12% lower on this data-set), far better than the simple LRF + WA-ILP approach (AUR-F averaging 50% of the unique wavelengths consumed as LRF).

While it might appear that the gap narrows with higher alpha, this is only in absolute terms: The gap is fairly constant in relative terms allowing for the quantisation error of requiring few wavelengths on a richly connected topology (comparing the bottom 10 alpha values to the top 10 alpha values gives a cost versus ILP of 11% falling to 3% and a mean gain versus LRF of 4% rising to 14%).

On three of the graphs, LRF + WA-ILP outperformed AUR-F slightly (by one or two wavelengths), so a better approach would be to run both algorithms in parallel and take the least costly result.

2.5 Chapter summary

This chapter described a particular example of agile photonic networks achieving sub-wavelength granularity – wavelength path sharing (WPS) as introduced by [Myers 01]. An alternative hardware configuration was proposed.

To make WPS work, a routing algorithm is required. M-ILP was found to not scale to larger real-world networks. Therefore, a new heuristic, LRF, was proposed.
LRF was shown to provide inferior performance (approx 50% more wavelengths) relative to M-ILP in terms of wavelength consumption efficiency (as would be expected), but still providing a significant gain (approx 20% over the Baroni theoretical lower bound of A-WRONs’ wavelength usage) with faster execution time (approx 70%) with larger networks due to superior scaling.

Further simulations were executed looking at first-fit (FF) wavelength allocation in terms of minimising continuous wavelength requirements, as this is a more practical parameter for network dimensioning than an abstract count of wavelengths. Validating the simulations using a new wavelength-allocation ILP, WA-ILP, showed that FF noticeably favoured the routes found by LRF over those found by M-ILP (by approximately 35%). This shows that comparing routing algorithms by combining them with FF will give misleading results relative to an optimal (e.g. ILP) wavelength allocation, because the proportional 'cost' (sub-optimality in terms of wavelengths consumed) of FF may be systematically biased towards one algorithm, as was found here.

Using the WA-ILP (i.e. optimal wavelength allocation) results did not change the conclusion from the FF-based simulations. However, introducing a novel WPS routing algorithm based on AUR-F offered a scalable algorithm at a low cost in wavelength utilisation (averaging 12% across all topologies tested) relative to the M-ILP formulation, given the traffic and other assumptions used in this chapter.

Therefore, for larger networks where the execution time of M-ILP + WA-ILP for the optimal solution is prohibitive, AUR-F may be recommended as providing reasonably efficient results.

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Chapter 3 The value of agility

In the previous chapter, improved routing algorithms for static traffic in wavelength path sharing (WPS) were discussed and its claims for reduced wavelength usage relative to conventional A-WRONs confirmed. Efficient routing of static traffic is an important part of initial planning of a network, or where existing traffic can be re-arranged by the control plane. However, real networks must work with both growing and changing traffic, requiring reconfiguration of switches.

Photonic devices vary both in how fast they can switch – and in price. A key network design question is then: what added value does a more expensive faster switch provide? This chapter aims to answers that question.

To investigate the value of agility, first a formal definition of network agility is provided, with discussion of what factors contribute to it. Then a survey of switching technologies is given, together with the corresponding switching speeds. Finally, the impact of different network agility in terms of network efficiency achieved by control plane routing (measured as time before additional network capacity is required to serve demands) is evaluated by simulation. For generality, the particular control plane approach and complexities such as signalling latency are disregarded. This would be equivalent to assuming a centralized route-processor with instantaneous communication to all nodes, which becomes less reasonable for geographically larger networks with larger signal propagation delays.

The work described in this chapter has been carried out in the context of A-WRONs, providing more general applicability than the WPS focus of the previous chapter.

3.1 A formal definition of agility for switches, paths and systems

Optical path viability is covered in Chapter 4, however this chapter assumes that the control plane has chosen a path it knows to be viable (including any impairments via switches). The reason for making this assumption is for generality - to exclude the case where a path for user traffic is set up, found to be non-viable (e.g. the receiver forward error correction reports an unacceptable inadequate bit error rate), and thus to exclude the variation of time taken by the choice of retry algorithm. The impact of this assumption is dependent upon the path viability approach chosen as discussed in the next chapter. For example, if known-viable routes are the only ones considered by the routing algorithm then the situation will be exactly as described in this chapter barring faults. However, if path performance is predicted then there will be an error probability and, thus, a fraction of paths (quantifiable, as discussed in the next chapter) where the setup time targeted is not met due to the need for a retry – where results in this chapter would be in error.

3.1.1 Switch agility

Switch agility, A_s, is defined in this work, for a given switch node *s*, as the speed at which a new connection may be established through a switching node, such that

$$A_s = t_n - t_{cs} \tag{3-1}$$

t_{cs} is defined as the first time where the switch starts to change its configuration to establish the new connection.
t_n is defined as the first time at which a new signal, as part of the new connection, may pass 'acceptably' through this node

'Acceptably' is defined for the purposes of equation (3-1) and for the work described in this chapter as meaning that a signal can pass through the corresponding entity (such as switch/path/network) and that the signal performance has stabilised such that a new wavelength is experiencing something close to the expected long-term impairment for the end-to-end path rather than any transient effects.

That is to say, A_s is the fastest time that a new connection through a switch of a particular equipment type can be brought from no light to an acceptable operational condition, assuming it is already being injected to the switch such that the additional complications described and discussed in the next subsection (e.g. transmitter turn-up time, amplifier coupling) are not contributing to A_s. To measure this, make the switch under test be the last component before a receiver, and the path otherwise be pre-established. t_n would then be the time at which the receiver could achieve an acceptable BER as defined in Chapter 1. This definition assumes the wavelength-path is viable (i.e. will *ever* achieve an acceptable BER) and disregards the time taken by the receiver to lock onto the signal, so this test could only be achieved in a lab-type setup with external clock recovery and known polarization etc. states.

The trivial case where the new and old paths are identical is not part of this definition, as no switching action – no agility – is required in that case.

Example real-world values for A_s are discussed in section 3.2 below.

3.1.2 Path agility

Path *p* is defined for the purposes of the definitions in this chapter as the set of switches which that path goes through, i.e. $p = \{s_1, s_2, s_3, \ldots\}$

Then for that p, path agility $\boldsymbol{A_p}$ is defined similarly to the previous section as the speed at which a particular new path can be set up 'acceptably' such that:

$$A_p = t_{np} - t_{cp} \qquad \textbf{(3-2)}$$

where:
t_{cp} is defined as the first time at which the switches start to change their configuration to establish the new path.
t_{np} is defined as the first time at which a signal as part of the new path may pass 'acceptably'.

As will be seen in section 3.2 below, A_s is primarily determined by the switching technology chosen.

How A_s relates to A_p is also influenced by additional parameters such as: whether the multiple switches in a path are changed sequentially or in parallel; how much control-signal propagation delay there is in signalling changes to specific switches. In this chapter, these factors are disregarded because it is assumed, for simplicity, that a central control point sets all switches in parallel, starting simultaneously, with zero propagation delay (as stated in the introduction to this chapter) – i.e. disregarding different approaches that a practical distributed control plane would require. This simplifying assumption is required because the objective of this thesis is to investigate and quantify the need for photonic network agility, so control plane algorithm and implementation choices are out of this scope. Using these assumptions therefore means that A_p is a lower bound on the performance of these out-of-scope factors. Should it be desirable to investigate such control-plane delays, they can be incorporated as a fixed increment to A_p, without affecting the non-technology-specific elements of the subsequent discussion in this chapter.

A_p also accounts for additional factors unrelated to A_s, such as network policy on how fast transmitter power may be increased, without impairing existing wavelengths by causing transients in optical amplifiers carrying both new and old wavelengths, for example, as discussed in e.g. [Murakami 08] and [Friskney 02a]. Since the aim of the work is to focus on the value of switch agility, these factors are disregarded. This also will cause the results in this chapter to give an optimistic view of the value of agility. This assumption is reasonable within metro-scale networks with few amplifiers to reduce system margin with transients. It is an assumption that OPS and OBS systems also have to make. For example, [Murakami 08] achieved complete suppression of the transient caused by repeatedly adding/removing 29 channels out of 30 in his 6-EDFA 300km transmitter-receiver test configuration, where switching speed was >= 0.5ms. Further work would be required to see what impact it has in long-haul networks with longer chains of amplifiers which would thus cause more wavelength-coupling/transient behaviour. 300km is a metropolitan-area networking scale, rather than the multi-thousand-kilometres long-haul systems required to reach across e.g. the US [CIA09]

Given the mentioned simplifying assumptions, A_p becomes:

$$A_p = \max(A_s) \quad \forall s \in p \tag{3-3}$$

And if all switches in the network are of the same type, as could be dictated by network policy, then:

$$A_p = A_s \tag{3-4}$$

For a greenfield (new-build) network, that all switches are of the same type is a very likely case. The only unrealistic assumption here is in disregarding control plane signalling propagation time, which is discussed earlier in this section, and in the next section.

3.1.3 Network agility

The definitions of A_s and A_p given in the previous two sections were given in terms of specific nodes (switch types) and paths (sequences of nodes and terminal equipment) – of which there would be many in a network. However, it is simpler to compare technologies if this can be reduced to a single value for the network. In this work, the agility of a network A_n is defined as:

$$A_n = \max(A_p) \quad \forall p \in P \tag{3-5}$$

where P is the set of potential paths, as selected by the operator. An example of why this might not be the full set of possible paths is that if A_p is related to path length then it may be necessary to bound the longest paths that will be configured, in order to bound A_n.

The simplifying assumptions discussed in the previous two sections mean that equation (3-4) is valid for all paths, therefore for the remainder of this chapter:

$$A_n = A_s \tag{3-6}$$

That is to say, the thesis objective of determining the required network agility may be translated to the much simpler objective of determining the required switch agility – within these assumptions.

The purpose of this chapter is to compare the impact of switching technologies rather than the time taken by routing algorithms, and so the time taken to calculate new paths is assumed to be zero.

As a brief aside on the potential speed of control planes, [Cugini 05] demonstrates experimentally a 5ms outage when doing a network restoration to a pre-calculated path – very fast by comparison to the other methods he illustrates such as a polling-based technique taking up to 40ms even to notice a failure, resulting in outages of 80-1080ms. His results are unrepresentative in that they do not consider the speed-of-light delay to signalling that would occur in a real system where nodes were not adjacent to each other in a lab. This limits the potential speed of such restoration schemes in networks containing significant lengths of fibre such as the US. Between the coasts of Oregon and Maine (the most distant of the contiguous states) is approximately 4300km (measured from [Times 03]) which at a speed-of-light in fibre of 2.998×10^{8}m/s / 1.4682 (Corning's SMF-28e+ refractive index at 1550nm) gives a round trip time of approximately 42ms. The speed of light sets a strict lower bound at which protection or rerouting could happen symmetrically regardless of network agility. This means that the aforementioned assumption of zero control plane signalling latency becomes less reasonable as the network becomes geographically larger or switching times faster – when signalling propagation times (42ms as derived above seeming a likely upper bound) approach or exceed switching times.

3.2 Review of agility of photonic switching elements

The aim of this section is to illustrate some values of A_s for currently available technology and practical options for photonic switching elements, and introduce a new categorisation approach for these based on switch speed.

[Ma 03] provides a comprehensive review of different switching technologies, including in terms of switching speed defined in similar fashion to A_s. An example of an exception would be [Pan 08] where prior knowledge of a new configuration is used to partially set up the switch, prior to disrupting the old configuration, to minimise the time where no valid data is being passed.

[Ma 03] offers a categorisation of multi-millisecond-order (useful for protection switching of circuits), nanosecond-order (useful for packet-switching applications) and picosecond-order (for bit-level OTDM). It is proposed in this thesis that additional useful categories are 0.1-10 seconds (useful for automatic traffic restoration, but not capable of imperceptible protection) and a fifth category with switching times in excess of 10 seconds, useful for (re-)configuration, but not restoration. The reason for the choice of threshold of 10s is that this is the criterion of the US Federal Communication Commission (FCC)'s Automated Reporting Management Information System (ARMIS) for an outage that is likely to be noticed by a human (as opposed to machine) user [Tellabs 09]. Ma has not noted these two additional application areas, both of which show other forms of value from agility and therefore parts of the scope of this chapter.

At the end of this section, a selection of technologies is grouped according to this scheme.

This section uses two example switching approaches – robot patch panels and manual intervention – and derives A_s values for them. These are the slowest switching approaches considered within the comparison table. Therefore, they are often dismissed or not considered e.g. by Ma. However they provide two (extreme) examples of the configuration speed-category proposed in the previous section.

'**Manual intervention**' was the only option until photonic switching became viable and the lowest capital expenditure to install – it would be expected to be no additional capital cost assuming a fibre patch panel is installed anyway. Therefore, manual intervention is the benchmark against which all other options must be considered. It is also included to describe the upper bound in latency.

3.2.1.1 Robot patch panels

Fibre patch panels with robot arms [Mizukami 04][Mizukami 05] achieve the objective of being able to reconfigure a node accurately without a human physically visiting the site for each connection, at a much lower cost and usually lower optical loss (<1dB – just connector loss) than ‘real’ switches such as WSS. If speed is not an important consideration then additional patch-panels may be added over time to what one arm can adjust, offering the advantages of effectively limitless scalability, in-service upgrade and decreasing cost-per-port (as the cost of the arm is amortised across an increasing number of ports).

Two reasons for robot patch panel switching speed being much slower (approximately 1 minute per connection change [Mizukami 05]) are the need to physically move the robot arm around, and that there are only a limited number of arms, often one, for the patch panel, so the arm may be busy with another connection as a new demand arrives.

A_s(one connection) = 60 seconds [Mizukami 05]

A_s(all connections on 200x200 cross-connect used in [Mizukami 05])

= 200 x A_s(one connection) = 200 minutes.

3.2.1.2 Manual intervention - Installation, re-routing and operations or some such – ‘People in vans’

Technicians following instructions to re-patch connections from computer-generated job-sheets (potentially generated by an automated routing system) may be considered as a wavelength switching system.

As with robot patch panels, there will be a limit to how many connections a person can modify at a time. Unlike other methods here, this option has a non-negligible error rate, and collateral damage rate (interruption to non-related existing connections due to confusion/mislabelling etc.).

Scheduling and physical travel to site will mean that latency will be measured in hours and days (see below) in the general case. However, some large sites will have staff physically situated in them.

Review of the literature did not find yield any results on characterisation of normal operational practices of this type. Therefore, below is a derivation of an agility value from some simple assumptions, to give an example.

Consider a national network in the continental United States land-mass 9,161,923 sq. km. [CIA 09].

Assuming the land is divided evenly into 50 uniform circular territories (area: approx. 183,000 sq. km, radius: approx 242km) in the centre of which is a maintenance depot at which staff are ready to immediately leave to make a cross-connection (i.e. ignoring scheduling, which is necessary to get a general answer as scheduling varies company-to-company, but the assumption is not realistic except for where the company is deliberately paying to maintain a high level of staff readiness at all depots for most-rapid response to problems).

Assuming nodes are uniformly distributed across the circle, the average distance they will then have to travel is *2.radius/3* i.e. approx 161km. Adjust this to compensate for road distance being larger than direct distance by a factor of 1.20 (the combined United States figure from [Ballou 02], other countries ranged from 1.12 to 2.10, with for example the United Kingdom factor being 1.40) gives approx 194km. Assuming an average driving speed of 40km/h, this gives approximately 5 hours average driving time.

Assume that a well-trained human with a clear work-order, adequate spare patch cords and a well-labelled patch-panel can move a connection in 1 minute.

In addition, assume that, for consistency with the robot patch-panel switch speed, the patch panel input x output port count is 200x200. This similarly gives 200 minutes to reconfigure the entire patch panel.

This gives the value of A_s as approx 490 minutes.

Experience within Nortel indicates that this value could be achieved if an operator chose to deploy sufficient manpower to have resources (people) available and waiting to be dispatched at any moment, or for a particularly critical case, but that in normal operation today job-scheduling would mean that a few days is a more likely average value, assuming all equipment was already installed. However, this is on the basis of an operator who uses photonic reconfiguration just for new configuration and fault repairs, rather than periodic capacity optimisation as discussed in this chapter. If the operator were to find they had a business case for the latter approach then this would be on the basis of a level of staffing to achieve a chosen average/worst-case response time.

As will be seen later in this chapter, it is not necessary to arrive at a precise value for the manual intervention option, having established that it is by far the least agile option and provided a rough order of magnitude value, for comparison.

Historically, the manual approach has been the only approach used, in all parts of the network. The stated scope of this thesis is the core network where manual patching is still a common technique, but ROADMs (reconfigurable optical add-drop multiplexers, allowing greater agility than manual changes) are increasingly being installed opportunistically when doing other upgrades, or for new installations.

3.2.2 Example technologies, grouped by category

The consequences of higher or lower agility are discussed in the second half of this chapter. To provide context to that, this section illustrates the range of switch speeds currently available. It also illustrates the speed-categorisation by application suitability proposed in section 3.2. These are the three categories outlined by Ma, reproduced here because it usefully brings together a substantial amount of information into one place. Example A_s values are given in each case.

Category	Technology	Technology variant and A_s
Configuration-capable $A_s > 10s$	People in vans	A_s=1-490+ minutes [approx, see above]
	Robot patch panels	A_s=1-200 minutes [see above]
Restoration-capable $A_s > 100ms$	Thermo-optical switch using coated microsphere resonators	A_s≈100ms
Protection-capable $A_s > 200\mu s$	Free-space mirror/gap-closing MEMS	A_s=7ms
	Deformable mirror MEMS	A_s<1ms
	Thermo-optical: silica-based MZI interferometric switch	A_s<4.9ms
	Electro-optic: nematic liquid crystal	A_s≈1ms
	… many more options, see [Ma 03]	
OPS-capable	MEMS waveguide MOEMS	A_s=32-200ns
	Electro-optic: Lithium Niobate	A_s=5ns
	SOA-based switch	A_s=200ps
	Electroholographic switch	A_s<10ns
	…many more options, see [Ma 03]	

Table 3-1 Comparison of optical switching technologies to agility requirements of applications

As the bit period of a 10GBaud on-off-keyed (OOK) signal is 100ps and none of the technology Ma lists manage to achieve a shorter switching interval than this, there are no entries for the OTDM category.

A_s values given come from [Ma 03] unless otherwise stated.

The discussion in section 3.1.3 regarding signalling propagation latency is pertinent to this table. For the US with its worst-case round-trip signalling latency of 42ms there is decreasing value in agility in the ‘protection capable’ (A_s<100ms) or faster classes for the purposes of reconfiguration efficiency discussed in this chapter because signalling propagation time would become significant or start to dominate. The value of these would be for other applications that do not suffer from signalling latency such as pre-planned protection with symmetric fault detection or OPS. However, for the Netherlands (worst-case round trip time 3ms), slightly faster agile switching technologies would have value within A-WRONs.

3.3 Ways in which network agility provides value

Towards the objective of finding a way to quantify the value provided by agility, this section categorises the ways in which this value is provided.

The following categorisation is required. Define:

- **Wavelength-on-demand** as the scenario where a wavelength may (but not always will, perhaps because there is already sufficient capacity) be deployed in direct response to a demand for a new wavelength or sub-wavelength connection arriving, to serve that demand. Wavelength-on-demand is a well-known concept in the industry and literature.
- **Infrastructure wavelengths (IW)** as the scenario where wavelengths are never deployed directly to serve a newly-arrived connection demand. However, the wavelengths are moved around as part of a periodic traffic optimisation to relieve hotspots in a higher multiplexing layer. To the best of the author's knowledge, the IW concept has not been defined before, but it is simply the converse of the well-known wavelength-on-demand idea.

The network operator will require that new demands are served with a certain maximum or average delay for a particular type of service. This may be contractual, but if not then it will be in terms of their expectations. Define t_s as the acceptable provisioning latency of a new demand.

The subordinate sections to this one describe the values that agility provides, but in summary they are:

Value 1: Automation of a manual process. As has already been discussed, automation per se at any speed provides benefits such as reduced misconnection rate and reduction of staff costs. However, these benefits do not change with how agile the automation is and so detailing or quantifying values solely from automation is out of scope of this work, except to note they exist

Value 2: If $A_n \leq t_s$, the network can provision wavelengths-on-demand. See section 3.3.1.

Value 3: With wavelength-on-demand, smaller A_n, new application types – new t_s values – are enabled, giving the carrier an increased addressable market if there is any effective demand for the new types. The nature of such new markets is substantially a marketing/commercial question and so out of scope of this thesis.

Value 4: In an IW network, a smaller A_n allows spare wavelength bandwidth to more accurately track demands, resulting in lower blocking probability. See section 3.3.2. Quantifying this is the subject of the remainder of the chapter.

A particular conclusion is that apart from in meeting the thresholds discussed in values 2 and 3, there is no value in greater agility except value 4.

3.3.1 Wavelengths on demand

As per value 2: If $A_n \leq t_s$, the network can provision wavelengths-on-demand.

This means the network operator can now do some or all of:

- offer services photonically (i.e. at lower cost than electronically-switched services as discussed in Chapter 1).
- provide bandwidth to a higher switching layer as it needs it. This avoids blocking due to inadequate bandwidth in the photonic layer interconnecting the higher switching layer.

For the discussion in section 0, it is assumed that no prior knowledge of demands is present, although a statistical expectation may be maintained. This is for simplicity and because it is rarely the case that a large proportion of demands are known. If they were, this would effectively make wavelengths on demand possible with very slow switching speeds, provided the foreknowledge exceeded A_n - t_s where $A_n > t_s$.

Following on from value 2:

Potential value: As $t_s - A_n$ increases, wavelengths-on-demand can be provisioned faster (e.g. as faster switching technologies are found).

It is significant that this potential value does not allow the operator to do anything new, just the same operations as value 2 but faster. Therefore, it is proposed that there is little value in A_n being substantially less than t_s. If faster switching gives more costly switches, as it often does, this provides a significant design parameter for the target switches. That is to say, faster is not always better – although it is never worse, all other attributes (notably cost) being equal.

However, t_s is dependent upon the application(s) you are trying to serve. Or conversely, as A_n becomes small enough, it will pass the next application threshold and enable a new type of service. Some non-exhaustive examples of application thresholds are provided in section 3.2.

An example of such an application threshold from my industrial experience of photonic networks at the time of writing: a number of carriers in the Americas, Europe and Asia are requesting photonic mesh restoration to replace existing electronic-switched protection schemes (some example requests are for 2s, 5s or 10 second restoration). Current end-user service level agreements in terms of outage times must be maintained, so there is a simple pass/fail criterion: if we cannot meet this protection speed application threshold, our solution simply cannot be considered for this purpose. 50ms photonic protection is also being requested by a smaller number of carriers.

Currently, fast restoration is requested far more than fast automated provisioning – because the 10G/40G/100G optical transponders supported by agile line-systems are extremely expensive and so only physically installed when required for a new service, whereas a restoration action uses no new equipment – it just moves the traffic to some pre-existing spare bandwidth. Colourless networking and electronic dispersion compensation have made photonic network much more attractive to service providers because they open up many more route possibilities (see Appendix A for more details of these technologies in Ciena's portfolio today):

- Colourless transponders and filters (multiplexers/demultiplexers) mean that transponders may be installed and then the optimal wavelength at the time of service activation used.
    - As opposed to having to pre-order and plan components of a particular wavelength months in advance, and thus getting a less-optimal wavelength and route choice.
    - And allowing the wavelength-service to be re-planned onto a different route/wavelength remotely, i.e. without an expensive site-visit.
- Electronic dynamically-compensating optics (eDCO) means that the wavelength path routing algorithm can disregard chromatic dispersion as a constraint because the tolerance of the system exceeds anything likely to be found in a practical system. [±50,000 ps/nm – example in Appendix A] With non-eDCO systems, a path had to be found that fitted within the narrower tolerance of a conventional receiver [For comparison Ciena's older 10G NRZ example in Appendix A achieved ±500ps/nm]

Constraints still exist (e.g. accumulated noise). This is the subject of Chapter 4.

These application threshold examples illustrate value 3: That t_s is particular to a set of target applications, so improved A_n may enable new application sets and thus new revenue.

3.3.2 Infrastructure wavelengths (IW)

Where wavelengths are not provisioned on demand, this does not necessarily imply that $A_n > t_s$ – using IW may be the operator's choice.

In an IW system, A_n can be considered as the delay between identifying a need to rearrange wavelengths, and being able to satisfy that need. Therefore, at any given time t_0, sufficient spare wavelength capacity needs to be active to support all traffic that arrives until time $t + A_n$ – and these wavelengths must have been requested at time $t_0\text{-}A_n$ according to a prediction of the demands $2.A_n$ later (at absolute minimum – if one switch cycle starts as soon as the last has finished). Unless traffic demands are perfectly predictable, this implies a non-zero blocking probability, *P(B)*. Blocking probability is of concern to carriers as a blocked request for additional capacity is lost or delayed revenue.

Quantifying the impact of changing A_n upon *P(B)* is the objective of the remaining section of this chapter.

Qualitatively, value 4 will be clear, that smaller A_n allows spare wavelength bandwidth to more accurately track demands, resulting in lower blocking probability.

As an alternative approach, the author collaborated in a study of the effect of inaccuracy in traffic forecasts on routing algorithms in [Lao 04], [Lao 04-2] and [Lao 05].

3.4 Quantifying the effect of increased agility on an infrastructure wavelengths system via simulation

The previous section raised the question of how changing A_n will affect the blocking probability of an infrastructure wavelengths (IW)-based system. This section answers that question by first defining in more detail how an IW system would work, and defining a specific one for analysis.

Simulations are then performed with the objective of comparing blocking probability at different A_n values.

3.4.1 The infrastructure wavelengths model for analysis

The defining feature of an IW network is the way in which wavelength-paths are reconfigured to match demands. The algorithm to determine when and where wavelength-paths will be placed/re-placed will be referred to as an IW algorithm in the remainder of this chapter. Define the following two categories of IW algorithms:

- **Traffic-stable**: where in-service wavelengths/traffic will not be part of any infrastructure rearrangement.
- **Traffic re-arranging**: where in-service traffic may be moved onto a different route in order to achieve a more efficient arrangement of the traffic

In equivalent situations in real networks, traffic re-arranging algorithms are usually avoided because this involves disrupting services, which eats into the down-time allowed under the service level agreement (SLA) in the operator's contract and may result in dissatisfied customers.

However, the objective of this work is to show the maximum potential benefit from agility, so the traffic-rearranging approach will be taken to provide an upper bound of performance for the traffic-stable approach. This makes the simulations memoryless – i.e. one time-cycle is not affected by the sub-optimal decisions of a previous one – until the first blocking starts to occur, at which point there is the subtle memory effect of which calls are on the network, and which are not.

From my industrial experience: A well-established major national carrier in the Americas recently issued requirements for a traffic re-arranging SONET network. They believed that they could achieve significant capacity gains by re-optimising routes and wavelengths every 3-6 months due to the high level of traffic growth and churn they were experiencing.

It is assumed that the higher-level switching layer will not support intermediate hops – i.e. the switching layer is just present to pack sub-wavelength A-Z demands onto a wavelength going from the same A to the same Z. This is quite unrealistic but not impossible, again to find the upper bound of benefit from agility. The impact of this is that calls will be blocked that would not have been if they could be routed via some intermediate node. This is discussed further in Chapter 5's further work section.

For simplicity in interpreting results, the wavelength layer will reallocate at regular intervals t_w, rather than individual wavelengths rerouting at uncoordinated times. For a traffic re-arranging IW algorithm that is quite realistic as a re-optimisation would commonly be a whole-network calculation. Also, the re-optimisation would be triggered by a block occurring, not just by a regular time-period. A traffic-stable IW algorithm, being less traffic disruptive, is better able to respond immediately when a block happens.

It must be the case that $A_n << t_w$ such that some traffic can flow in between switching actions.

3.4.2 Simulation conditions

The simulations described below were executed on NSFNet (diagram in Appendix B). This network was chosen to facilitate comparison with the literature as it is a very commonly-used analysis network (amongst the many papers using it, the most relevant examples are the work being built on in this and the previous chapter from [Baroni 98], [Myers 01] and [Zapata-Beghelli 08]). It was also used in Chapter 2. Later the simulations are also executed on some of the randomly-connected networks (RCNs) from Chapter 2 to verify that there's nothing atypical about the behaviour on NSFNet.

As described in section 3.1 above, the network agility A_n may be represented by switch speed A_s with the assumptions described there, e.g. the operator uses the same switch technology throughout the network. The scope of this chapter is circuit-switched wavelengths, therefore, the class of OPS or OBS-capable switch speeds (defined in section 3.2) are disregarded. Thus, switching speeds from 'protection-capable' up to the manual intervention (defined in section 3.2.1.2) option are considered. It is assumed that no switching technologies slower than manual intervention would be considered. This is not necessarily true – automation has cost and accuracy benefits even if very slow.

However, no slower mechanisms are proposed in the literature at this time as per the comparisons referenced in section 3.2.2.

The simulation was implemented as a discrete event simulator, where the events were traffic arrivals, departures, and wavelength re-allocation. When each event executed, it generated a new event of the same kind and added it to the queue at a time according to the traffic model (arrivals/departures, as per previous section) or a fixed offset (wavelength re-allocation). Time was taken to be continuous and floating point to avoid quantising the Poisson distribution into a Bernoulli distribution. The discrete event approach allows any intervals without events to be skipped.

3.4.3 Traffic model

The traffic model used in the course of this work is based on principles of:

- A steady (non-growing/non-shrinking) traffic load. This is not very realistic, but helps to get good statistical confidence on *P(B)*.
- Churning traffic so that hotspots appear and disappear, to test the traffic handling on the network and to reflect real-world behaviour of traffic moving around.
- The traffic load should be causing exhaustion in some areas of the network so that there is a purpose for the wavelength reallocation, but not to exhaust all areas (total saturation).

Wavelengths were normalised to a dimensionless size of 1. Traffic demands are of uniform size of 1/20 of a wavelength, to make it easier to interpret and generalise from the results. This size is chosen arbitrarily to provide some sub-wavelength granularity without requiring very large quantities of demands to fill the wavelengths. This order of magnitude is chosen to reflect a common disparity between two orders of multiplexing, e.g. the number of Optical channel Data Unit 1 (ODU1 - 2.5Gbps) circuit demands addressable by a 40Gbps wavelength (16).

The network was assumed to be initially dimensioned in terms of wavelengths by taking a uniform demand matrix $\beta_{(s,\,d)}$ (i.e. where $\beta_{(x,y)} = \begin{cases} 1 : x \neq y \\ 0 : x = y \end{cases}$), shortest-path routing wavelengths and adding 20% headroom, arbitrarily.

A Poisson calls arrival process was used for each source-destination pair *(s, d)* with an average arrival rate of $\beta_{(s,\,d)}$. Hold time was taken to be exponentially distributed with mean $1/\mu_{(s,\,d)}$. For a stable traffic load, $\mu_{(s,\,d)} = \beta_{(s,\,d)}$, although this means that an initial traffic load equal to the starting non-uniform traffic matrix had to be applied. This was done by allowing a load-up time at the start of the simulation, but using the normal arrivals/departures process.

Ethernet and other packet traffic has been shown from analysis of extensive data to be self-similar [Leland 94] with more recent data confirming that application changes have not altered this conclusion [Gupta 09], making the choice of the Poisson distribution and its event-independence unrepresentative due to the long-range dependence shown in real traffic. However, the scope of this work considers only connection requests for which no such criticism of the Poisson model has been made. This also provides comparability with prior work in the literature (to pick some examples used elsewhere in the thesis, [Almeida 08], [Bagula 07]).

The simulation runs in abstract time from 0 to 1000 simulator ‘ticks’ which can be scaled to fit any switching speed of interest. The traffic arrivals/departures occur in continuous floating point time and so may be scaled freely.

For example, exploring the range of reconfiguration intervals from 1 to 1024 ‘ticks’ is equivalent to going from the 100ms of thermo-optic switches down to close to the 35.3us of ferroelectric liquid crystal.

Different load levels were achieved by varying the call holding time and measuring the resulting average occupancy of a link.

A link capacity of 22 wavelengths was used because this was the upper limit that gave an acceptable run-time (stretching into several days per run). The results can be scaled up to the 40 wavelengths representative of an older network such as NSFnet, or the 88 wavelengths of new systems such as described in Appendix A.

Exploration of networks with more nodes would be possible by further constraining the link capacity and/or by increasing the degree of mesh connectivity (α). However, the objective was to explore behaviour on the common analysis networks given.

3.4.4 Traffic re-optimisation phase

During the periodic traffic re-optimisations, the following algorithm was executed (AUR-F modified as per previous chapter):

1) Sort demands *D* to be longest-first, measured by the simple shortest path.
2) For each demand, *d* a member of *D*:
    a. For each possible wavelength, *w*:
        i. Find the *k*-shortest paths that could serve *d*
        ii. If there are such, use the shortest to serve *d* and move on to the next demand (which may be another connection to serve *d*).
        iii. Next *w*
    b. Next *d*

This serves the traffic currently present for each A-Z demand.

However, the spare traffic capacity within the wavelengths will need to serve any additional traffic that arrives between the time of one traffic re-optimisation and the next. Therefore, spare bandwidth should be allocated. That is to say, where equipment is present in excess of that calculated to be required until the next re-optimisation period, it should be provisioned anyway such that there are spare wavelengths ready to transport unanticipated demands instead of allowing them to be blocked.

The following algorithm was used for this:

1) Take *D*, sorted in order of the 'neediest' demand – the one which has least free traffic slots at present.
2) For each demand *d*, a member of *D*:
    a. Attempt to route d, running through each wavelength in turn.
    b. Next *d*
3) If there were any wavelengths allocated in the last iteration, go to 1 until it is not possible to add a wavelength to any demand.

Note: It is not clear that fully-allocating wavelengths in this fashion is realistic, as it assumes that there is an infinity of transceivers and subtending routers etc. to make use of them.

An alternative approach would have been to consider simply the longest path as per the first phase, or the demands with most traffic to serve – assuming that expansion is proportional to the current load.

3.4.5 Simulation steps

Normal operation:

Traffic (model described in the previous section) demands were applied to the chosen network sequentially as they arrived. If a demand cannot be served, this adds to the count of blocked connections, used to calculate the blocking probability as a fraction of the offered demands that were blocked. When their holding time expires, calls are immediately removed. As multi-hop routing at the higher layer has been excluded, the only routing decision is the choice of which wavelength-path to use towards the destination. A most-full-first algorithm was be used, to maximise the free wavelengths.

In parallel with the process of demands arriving/departing is the infrastructure wavelengths optimisation process. This operates every time period t_w. At the end of each such period, the network is re-optimised – i.e. wavelength-paths are routed afresh and traffic re-packed onto them.

Routing and wavelength allocation was performed according to the AUR-F algorithm as this gave good efficiency in the previous chapter, with acceptable execution time.

Start-up phase:
Due to the memoryless nature of total re-optimisation, there need not be a start-up phase where the network loads up with traffic. Instead, the simulation started with a full load of traffic present and an immediate re-optimisation phase to serve it.

Termination condition:
Each simulation run terminated when 1000 new connection requests had been offered to each demand.

The blocking probability calculated over the whole run was recorded.

Each simulation run used a given network and value of t_w, so that the whole set of both of these were iterated over

3.4.6 Simulation validation

The results from trivial networks of 2 and 3 links were hand-validated and found to be accurate.

The wavelength reallocation interval was taken to "0 and infinity" – equivalent to 1 (every tick) and 1024 (never) in the abstract time-space of the simulation discrete event simulator. These were found to fit with the trends shown by the other points, as expected.

Load was decreased to very low levels, and no blocking occurred at all, as expected.
Load was increased until exceptionally high blocking resulted (up to 32%) as would be

expected. That is to say, the simulations were executed until they achieved a level of blocking far higher than any network could commercially operate at.

3.4.7 Discussion of detailed results: blocking probability plotted against reconfiguration interval

This section discusses the simulation results of blocking probability *P(B)* against the wavelength reconfiguration interval.

Graphs showing these detailed results are in Appendix C. The next section re-formats this data into a summary graph.

No blocking at all was seen at average loads of 1 and 6 slots/demand (recalling that there are 20 slots per wavelength), so these cases are not illustrated, as being trivial.

To avoid unrepresentative simulation runs, the simulations were repeated eleven times. This value was chosen as it corresponded to one week of simulation time.
Practical simulations were stopped as soon as 10% blocking probability was reached – as being commercially unrealistic. However, for curiosity, a single simulation run at 22, 25 and 32 wavelengths (an arbitrary choice of values) was performed to explore how blocking probability further evolved and to validate the simulations. These correspond to Figure C-7, Figure C-8 and Figure C-9 respectively. As will be seen, 22 wavelengths/link corresponds to a commercially unacceptable P(B)=7.5-10% across the whole range of reconfiguration intervals and the others rise further to P(B) over 33% for 32 wavelengths/link.

Looking at the graphs referenced in this section, each for a fixed level of load: Each exhibits a trend to a lower blocking probability with higher agility, as would be expected. For 12 slots/demand it goes from a negligible 0.3% to 0%. For 22 slots/demand from 10% to 7.4%. For 25 slots from 14% to 13%. For 32 slots from 33% to 32%. This is in line with the second set of graphs: The curve of P(B) against agility is seen to flatten out where agility can provide no or little benefit (very low or high network fills) – where the t=1 value is non-zero starting (imperceptibly on these graphs) at 16 slots/demand and rising thereafter.

3.4.8 Results: Blocking probability versus load

As a summary of the detailed results shown in Appendix C, in this section the results are graphed to illustrate how the blocking probability varies with load.

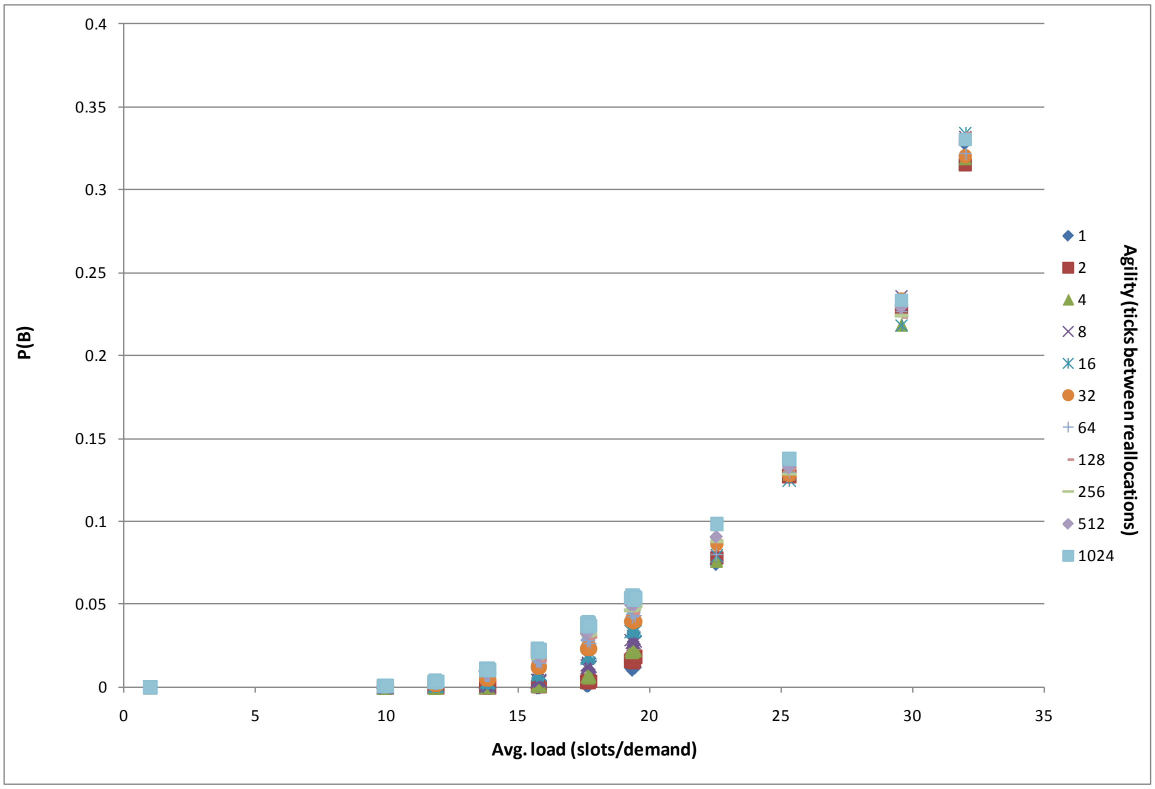

Figure 3-1 Blocking probability against load

Looking at Figure 3-1, it is no surprise that the blocking probability rises with average load. At negligible load (up to approximately 10 slots/demand) the blocking probability is zero for all configurations (there is no scope for blocking). It is interesting that, as soon as blocking starts to occur, the different reconfiguration intervals spread out in performance (going to a maximum difference of 5% versus 1% at average load of approximately 19), then reconverge as the blocking probability gets very high (33% to 32%) – where the network is near-full and reallocation is of no assistance. That is to say, faster reallocation provides significant benefit only within a particular load window.

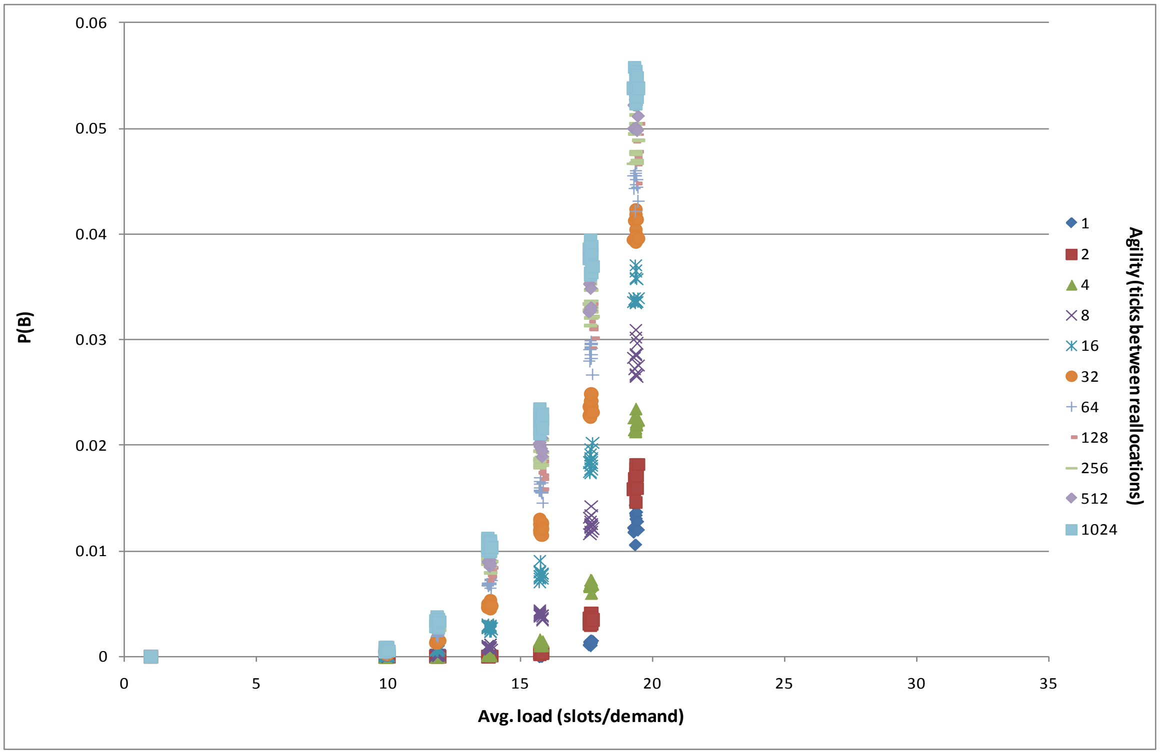

Figure 3-2 Blocking probability against load – focusing on the area of highest gain.

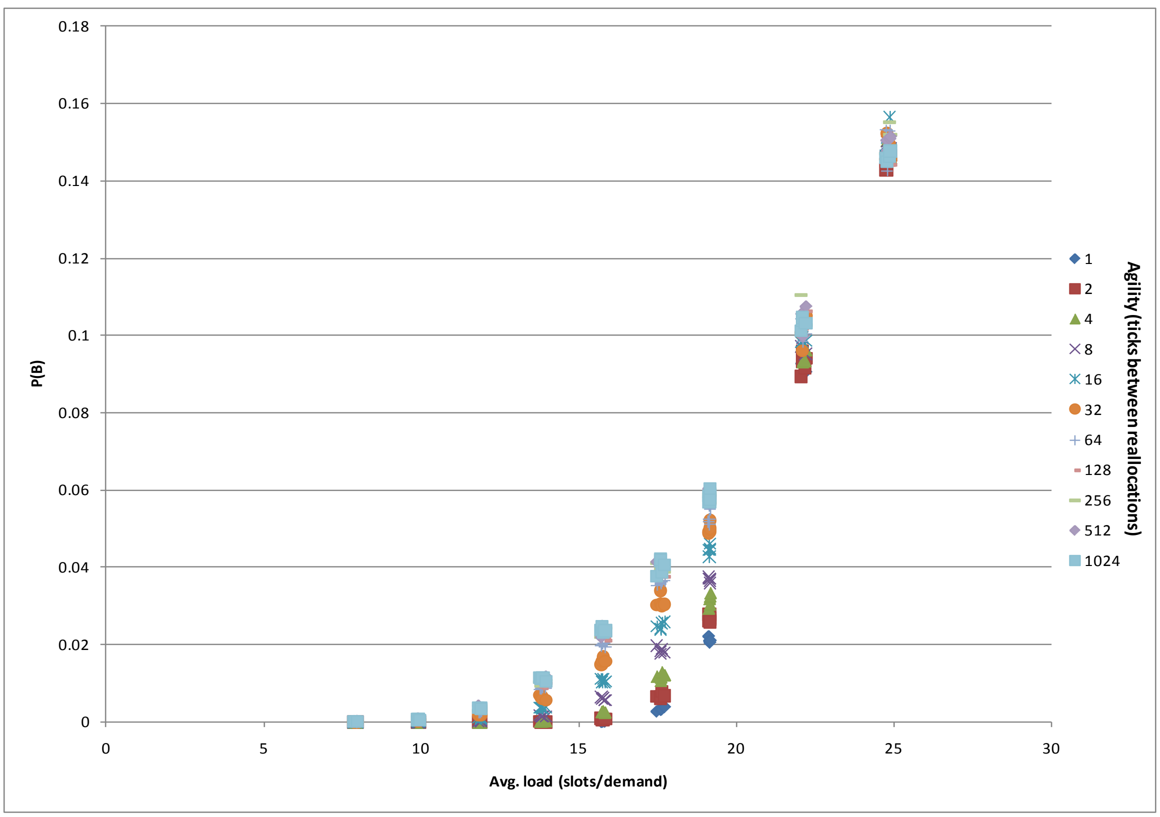

Figure 3-3 Re-running the simulations on an RCN from Chapter 2 with matching N/L/α to NSFNet (but different links) to illustrate there is nothing atypical about the previous results.

Figure 3-2 expands the y-axis of the results to show that the results are very clearly ordered by reconfiguration interval.

To illustrate the maximum benefit this can provide for a carrier with an example acceptable blocking probability threshold of 1%: The carrier can run their network at approximately 13 slots/demand with t=1024, or approximately 19 slots/demand with t=1. To put that differently, greater agility has effectively expanded the capacity of their network by 46%.

To verify that there is nothing exceptional about NSFnet, the same simulations were re-run using one of the Randomly Connected Networks from Chapter 2 (diagrams in Appendix B) with the same number of nodes (14) and links (20) and thus α value as NSFnet, but with the links arranged differently. After the experience of NSFnet, the maximum load was capped when P(B) exceeded 10% for all reallocation times, because that appeared to be a clearly unrealistic operating regime. The results are shown in Figure 3-3. Unsurprisingly, the results are very similar.

3.4.9 Chapter summary

In this chapter a formal definition of network agility was given and it was shown how some representative assumptions could make this equivalent to switch agility. The range of switch agility values in modern technologies was compared and a categorisation by function – configuration/restoration/protection/OBS/OPS, noting that human provisioning does appear on this scale – provided.

Then, simulations were performed to determine the network benefit that can be achieved from increased agility. It was observed that the benefit achieved depended significantly upon the network load – too low (negligible amounts of blocking) and there was nothing to improve on; too high and the network achieved inoperable amounts of blocking. Within the optimal window of load, an improvement of 46% usable network capacity could be achieved against a maximum acceptable blocking probability of 1% at the cost of a one thousand-fold increase in network agility – the equivalent of moving into the next technology category faster. This is a significant and worthwhile efficiency improvement.

However, the likelihood is that the operator's network will be installed with considerably more capacity than is required – below the load-level at which agility provides non-negligible advantage – and therefore spend a significant proportion of its lifetime not making use of the agility. Further, with geographically large networks the signalling latency may come to dominate connection setup time (e.g. the round-trip-time of 43ms across the continental US derived in section 3.1.3) such that switch speeds much faster than the signalling latency have negligible value.

The operator, when deciding what network agility they require, must therefore choose a blocking level that they deem acceptable. The maximum blocking level will determine whether will have their network at the right load-level to take advantage of more-frequent reallocations, or whether the need for reallocations will be rare enough that a slower and thus cheaper technology will suffice.

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Chapter 4 Path viability and its effect on photonic control planes

In the previous chapter, conditions were discussed under which greater photonic network agility could provide value to an operator in terms of new service types (requiring particular setup/restoration time bounds) or of network bandwidth efficiency – accommodating more traffic on the same network, or the same traffic with a smaller network. It was noted that it is possible to set up wavelength-paths in a photonic path that are not optically viable (i.e. that do not achieve an acceptable (according to operator policy) received Bit Error Rate[1]) and are thus not usable. It was assumed that it was possible to pre-determine whether a path was viable and thus there would never be the attempt made to set up a non-viable path. Because of this possibility of non-viability, *any* kind of photonic provisioning system/control plane will need to pre-determine the viability of a path before it is set up, or handle the case where a provisioned path proves to be non-viable by some technique.

The purpose of this chapter is to describe and compare these alternative approaches to viability calculation and to determine their implications on the use of photonic control planes.

Work published from 2002-2004 relating to 'traditional' IMDD (intensity-modulated direct detection) is described. Since then, phase-modulation/coherent reception and DSP technology has offered a dramatic step forward in bitrate and impairment tolerance. A section is provided discussing the implications of this on the earlier work.

First a formal definition of optical viability is provided for both the A-WRON and WPS cases discussed in this thesis, then alternative methods of pre-determining viability are reviewed, a new calculation of the error involved in prediction based on live impairment

[1] A formal definition of viability is given later in this chapter.

measurement is given for an IMDD system. Finally, the implications of the limitations discovered on usage of a photonic control plane are discussed.

4.1 Definition of optical viability and optical viability engine (OVE)

The ‘health’ of a wavelength-path is measured by the Bit Error Rate (BER). Each network operator will have a policy on the worst BER they will accept for a newly-provisioned wavelength-path. The target is commonly set in terms of the newly-provisioned BER - it is assumed equipment performance reduces over time.

BER is usually measured after all processing such as Forward Error Correction (FEC) has been applied, as this is the error rate that the service data is subject to. This target can then be common across all transmission media in terms of the requirements of the service application. Some operators set their viability targets in terms of the pre-FEC BER because lower error levels (that the FEC can remove from the service data) will be apparent. However, as the ultimate goal is to deliver service data end-to-end across the network with a particular BER, measuring viability pre-FEC would mean that different targets would be required according to the strength of the FEC used, so this is only appropriate within a set of similar transponders.

Definition: An optically viable path is one that meets or is better than (experiences less errors than) the operator’s target BER.

This definition (routes suitable “for path selection”) is shared with the IETF’s draft standards work in this area (see reference [Wson-impairments]). Common published standards for acceptable post-FEC BERs are given in Chapter 1. For transmission of >1Gbps, these provide a target of 1 error in 10^{12} bits received.

Direct measurement of BER would take a long time by machine standards – 10^{12} bits at 40Gbps takes 25 seconds. Methods for measuring the optical Q-factor include (after

[Mishra 10], for example) allowing the BER to be extrapolated by determining the edges of the optical eye.

For use in the comparison of routing techniques that follows, the further concept of Optical Viability Engine is required:

Definition: An Optical Viability Engine (OVE) is a software component that will indicate whether a given wavelength-path will be viable. [Peeters 04]

In standards (IETF) terms, optical viability (or "impairment validation" as the IETF calls it) is discussed in the reference [Wson-impairments] and commonly outsourced from the control plane to a "Path Computation Element" (PCE) functionality introduced in [RFC4655]. A photonic PCE is defined by the IETF as including the functionality of an OVE. Further discussion is in section 1.8.

4.1.1 Why may a wavelength-path be non-viable?

Unlike most other forms of data communications, the advantages of photonic networks (described in Chapter 1) come when no electronic processing at intermediate nodes is performed. Electronic processing gives '3R' (re-amplification, re-timing, re-shaping) regeneration implicitly, but only amplification is usually present in all-optical systems, so signal impairments accumulate at each hop. Thus, transitivity is lost – if A can reach B and B can reach C, then A may very well not be able to reach C if the longer path reduces the signal quality below a usable level. Some examples of impairments that accumulate (not necessarily additively) are noise and polarization mode dispersion (PMD),

Further complicating the problem, some parameters need to be within an optimal window rather than minimised, e.g. chromatic dispersion (for systems without electronic dispersion compensation, e.g. most existing installed systems). As an example, if A-B is non-viable due to excess positive dispersion and B-C is non-viable due to excess negative dispersion, on route A-B-C the dispersion may cancel out sufficiently to result in a viable path. An example of this would be where A-B was a long series of uncompensated fibre links and B-C was a short fibre link with a large dispersion compensation module.

Another form of non-viability is fundamental incompatibility – e.g. if link A-B was provided by vendor X, link B-C was provided by vendor Y and vendors X and Y used different wavelength grids, it might not be possible to route a wavelength via A-B-C regardless of the impairments on these links. Such fundamental incompatibility is declared out of scope of this chapter as it is not a common practical problem: photonic networks are usually designed to have line equipment only from a single vendor with regeneration before hand-off to another line system.

The impairments considered in this chapter are of two forms, **linear impairments** such as loss and dispersion and **non-linear** effects such as four-wave mixing (FWM), cross-phase modulation (XPM – the effects of which are described in depth in [Thiele 00]), cross-polarisation modulation (XpolM), self-phase modulation (SPM). Other fibre nonlinear impairments exist (e.g. stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS)) but these are negligible in current systems that compensate for them. A comprehensive treatment of all of these effects and noise sources such as amplified spontaneous emissions (ASE) can be found in [Agrawal 95] and [Agrawal 97].

The dispersion map is the sequence of fibre segments and network elements with chromatic dispersion effects, and the size and sign of dispersion of each segment/element. An example earlier in this section referenced the simple net sum of the positive and negative dispersion along a wavelength-path. However, the precise ordering of the elements within the map may increase or decrease other effects notably SPM and XPM as further discussed in [Thiele 00]. Other significant factors that likewise have an effect on the impairments that will be experienced are other channels' spacing, power and modulation format.

4.1.2 Control plane functions that require viability information, and the requirements this places upon the OVE

Any control plane function that involves provisioning a wavelength-path along a new or modified route will require a viability check: provisioning of new connections, modification of existing paths, protection or restoration around faults.

Below are listed how these set requirements on the system provisioning speed (i.e. network agility, the subject of the previous chapter), and thus indirectly on the operational speed of the OVE:

- Human-triggered provisioning needs ideally to complete within the span of human patience on a GUI – perhaps a few seconds.
- Machine-triggered provisioning, where an example would be a higher layer having gone past a congestion threshold, needs to dial up some extra bandwidth. This provides no particular time target, but the upper bound on connection setup speed will determine how late the upper layer can leave signalling for additional bandwidth and thus reducing the upper bound will result in greater higher-layer efficiency.
- Protection switching will require a bounded time. The well-known 50ms target (a common expectation codified in standards such as [GR-253-Core]) would be required for some paths. A US regulatory target described in the previous chapter is 10 seconds. 50ms is commonly delivered by using a pre-established backup path ([GR-253-Core] suggests this approach). If the photonic system is agile enough to calculate, validate and establish a wavelength-path within 50ms then pre-establishing the backup path may not be required – increasing network efficiency by not requiring more than half of the capacity of the network to lie permanently idle in the longer protection paths.

In addition to those control plane functions that use viability information, a control plane implies distributed intelligence, that path setup can be initiated from multiple points in the network – e.g. from any node. Section 4.2.4.1 describes later a method of extracting this information from the network and distributing it to all the nodes that will need it for their route computation. [Azodolmolky 09] provides more detail on a potential protocol infrastructure for distributing the information.

4.1.3 Opportunities for viability calculation optimisation in agile control planes versus static provisioned systems

Commonly today, wavelengths are provisioned such that they may be kept operating as on the same route and equipment for an estimated lifetime of 20 years, or a similarly lengthy period. This is associated with an unwillingness to disrupt a revenue-earning service once it is installed, and an existing slow, expensive and error-prone human-based re-routing process.

An agile photonic network with shorter wavelength lifespans has an advantage in terms of being able to ignore or reduce link budget margins for factors related to long lifespan (what [Azodolmolky 09] calls time-varying impairments). These factors are:

- Additional fibre loss later in life due to breakages fixed by splicing. The breakages are mainly caused by civil works activities accidentally digging through the fibres.
- Amplifiers[2] ageing and increasing their noise figure.
- Receivers ageing and becoming less sensitive.
- The ability to use current measured performance values (where present) versus component specifications. This option is discussed in much more detail in the measure-and-predict section later.

Examples of where at least some wavelength-paths may have predictably shorter lifespans are:

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[2] It is assumed that amplifiers are EDFA in this chapter, as that reflects the experimental work that was done. However, the work equally applies if they are Raman amplifiers additionally or instead of EDFAs because it is the net effect of a span that is being considered. This statement assumes that measurement points are not further impaired by the Raman pump light. For the specify-and-predict approach it assumes that the effect of the Raman pump is specified as well as for an EDFA which may not be true if the transmission fibre is not well characterised – e.g. the Raman is an upgrade on old poorly-specified fibre.

- Where a service is pre-booked for a stated finite duration, rather than the expectation that it will serve until cancelled. Currently this is not general practice and so is only seen for rare special events (e.g. the Olympics). However, it is not a significant restructuring of the customer/carrier relationship as prices would often be adjusted/renegotiated every few years anyway.
- Where a particular service type is defined to have a maximum lifetime. For example, if the ability to dial-up wavelengths were provided to users with large but short-term requirements (e.g. virtual machine migration between data centres, downloading of large experimental data-sets) then their contract could state that each path would automatically be terminated after 24 hours in the unlikely case its termination had not already been requested by the customer.
- Where the carrier expects to perform regular network defragmentation (re-optimisation) of their wavelength-routes. A major North American carrier currently has a policy of defragmenting their SONET network every 6 months due to the exceptional growth they are experiencing, so it may be assumed that as agile wavelength networks develop it may be seen with wavelength-paths too.
- Where a wavelength-path is provisioned temporarily as a restoration route and the operator has a policy of fixing the original route and reverting the traffic to it, so the expected requirement for the restoration path is just the worst-case repair time. This is common practice because the original path would have been chosen as part of an overall optimal path layout, or because it was the least-cost path available. Further/alternatively, the restoration path may have higher latency (e.g. due to more fibre-kilometres traversed) which the end-customer could detect and complain.

Reduced link budget margins mean that more wavelength-paths are viable without regeneration, notably longer wavelength paths. This will reduce the number of regenerators required to operate a network, and thus the network cost. Or conversely, for a fixed set of regenerators, allow more network traffic to be accommodated.

Control planes still need to leave some margins for factors such as PMD that can change faster than a wavelength is likely to persist. For example, a submarine fibre (perhaps the most stable environment a cable could be in) was found to change its PMD value by >0.25ps over 70% of 15s intervals during daytime in [Zhang 07]

Required operating margin and the different approaches to it are factors that are often not considered in the networking literature e.g. [Azodolmolky 09] describes the EU research network DICONET which is very similar to the agile WRONs described in this thesis. He states that his Q factor estimator predicts performance based on the currently-provisioned wavelengths before deciding whether to provision new wavelength X. However, if further wavelengths are added, these will result in greater impairment to X (e.g. via cross-phase/cross-polarisation modulation (XPM/XpolM) or four-wave mixing (FWM)). Other system changes may similarly result in increased impairment (e.g. power re-balancing due to wavelength adds/deletes elsewhere). If the operating margin of X is not adequate to allow for this increased impairment, it will then fail in operation before its design lifetime has expired. As mentioned, on a longer timescale, effects such as fibre breaks and re-splicing may similarly cause an operating wavelength to fail. Therefore, required margin (and its relationship to anticipated wavelength duration of being in-service) is a key factor in viability.

As this work does not assume any particular control plane approach, it is equally applicable to Grid-type control systems which dial up both IT and networking capacity as described, to pick a recent example among many, [Grosso 09]. This paper is chosen particularly because it uses the Nortel/Ciena photonic system used as an example throughout this thesis.

4.1.4 Viability and WPS

Wavelength path sharing is described in Chapter 2. In terms of viability, each transmitter-receiver pair must be separately considered, i.e. each demand service along a given logical path. The example in section 4.1.1 is directly translatable to WPS as it shows where in a viable path A-B-C, the sub-paths A-B and B-C may be non-viable.

However, in terms of determining whether a particular transmitter-receiver pair is viable, WPS is using precisely the same technology as A-WRON and so the viability calculation problem is the same – applied for each of the transmitter/receiver pairs within a planned logical path. Therefore this chapter discusses only the A-WRON case without loss of generality.

4.2 Comparison of control plane and provisioning approaches to viability calculation

This section reviews the different approaches that control planes/provisioning systems can take to calculating viability and compares them according to the criteria given next. It is a write-up of concepts co-published in [Peeters 04].

4.2.1 Criteria for comparing viability approaches

The following parameters are used to compare the different techniques:

- Speed of response of viability calculation. At the time of writing, the most accurate technique that Ciena has to predict performance is the split-step Fourier propagation simulation (a recent approach including a review of this area is provided in [He 10]), which takes over 24 hours to execute for a single wavelength route. This is not compatible with restoration targets of 10 seconds or 50 milliseconds as set out earlier in the chapter, but could be used for pre-planned activities.
- Accuracy of result - percentage of false positives/negatives. False positives may cause the need to tear-down and retry the connection, causing additional setup latency. False positives within the allocated margins for PMD etc. will cause unreliability – wavelength-paths that appear to be viable but sometimes (e.g. in adverse polarization conditions brought on by strong winds on fibres) fail unexpectedly. False negatives will reduce network efficiency by rejecting optimal paths. [Azodolmolky 09] considers this another form of blocking. An alternative approach would be to allow a retry.

- Constraints on network design. These and their impacts are discussed in the individual sections.
- Efficiency at minimizing OEO regeneration.

The methods in the next sections fit into three broad categories:

- Apply planning constraints such that viability calculations are not required for new paths.
- Run sophisticated viability calculations.
- “Try it and see”. Actually provision a path and measure performance at the receiver to determine whether it is viable.

4.2.2 Optical islands

The physical topology is divided up into ‘islands’. Between the islands all traffic is regenerated. Thus, each island is a separate photonic domain. The islands are engineered such that any ‘sensible’ (e.g. “up to 6 hops” or “within 2 hops of the shortest path”) photonic path is viable [Saleh 00].

Where there are natural boundaries already between small (all ‘reasonable’ paths viable) network domains, e.g. between photonics rings with dissimilar types of optical systems (e.g. different vendors), then the optical islands approach is the obvious choice.

The advantage of this method is that viability calculation is not required per-path and so causes no calculation delay. Further, any reasonable routing algorithm may be used, provided it is compatible with the planning rule used. This method is therefore commonly used (usually implicitly and without discussion) for systems like OPS/OBS, where there is no time for attempting a second path.

Where a domain has only partial reachability, but the operational simplicity of islands is desired, the domain may be transformable into an island by using longer reach/more expensive transponders.

The disadvantages of this method are that:

- Wavelengths travelling very short distances that happen to cross an island boundary will be regenerated when these paths would be viable without regeneration – i.e. unnecessary cost. This example is equivalent to an inaccurate viability prediction.
- It is a significant network design constraint to use only limited-size (determined by reachability) islands.

4.2.3 Network trial and error

The path is provisioned and the BER of that path is measured. If the BER is satisfactory and the system determines that the path will stay viable for its expected lifetime (see below), the path is accepted for traffic. If the path is not accepted, an alternative path may be tried – algorithms discussed below.

Even if the wavelength-path immediately achieves adequate BER, it does not mean it will continue to be viable. Time-varying impairments such as PMD [Savory 06] may later increase. Therefore, a margin above the target BER will be required, calculated from the known statistics of the impairments, the policy of the operator on acceptable risk, and the duration for which the path can be measured before a decision is required. The reader is referred back to section 4.1.1 which discusses how long a direct BER measurement may take, although a pre-FEC BER measurement would normally be used as this will get a more rapid result. Further, depending upon the acceptance policy of the operator, the path may need to dry run for longer periods to e.g. experience day/night changes in performance. A trade-off must be struck between network bandwidth efficiency (minimising margins) and setup speed (using larger margins to compensate for lack of knowledge of the statistics of variable impairments encountered rather than longer measurement periods).

This approach is very well-suited to a system where:

- routing is done via a least-cost path;
- the dominant impairment is simply additive (such as noise);

- the noise added by each link is proportional to its routing algorithm link cost;

or otherwise such that the least-cost path is also an approximation to the least-impaired path. Given this assumption, the first path tried is likely to succeed. In contrast, if the first few tries fail, it is unlikely that any path will succeed and the connection can sensibly be rejected.

Contrariwise, if the routing algorithm is unlikely to try the least-impaired path, then the system must budget for several failed attempts before one succeeds.

Because this approach makes use of actual measured end-to-end performance on the route to be used, it can make use of unexpectedly good performance (e.g. equipment outperforming its specifications) where the greater margins of other approaches may cause them to regenerate unnecessarily. It is the only method usable when photonic performance cannot be modelled effectively in advance.

It is unattractive where any of the following conditions hold:

- A large number of 'sensible' routes will be non-viable, causing it to be very cumbersome - trying lots of useless routes.
    - E.g. long-distance networks where at least one or two steps of regeneration will be required.
    - It would need to be combined with a simple regenerator-selection, which would then need its own viability calculation approach.
- Setting up paths can only be done slowly and carefully to avoid disruption of other wavelengths and/or has a cost of some sort – e.g. potentially requiring equipment to be deployed, requiring some manual intervention, risking interruption of service of other wavelengths.
- The margin for variability has to be high - e.g. the network is prone to large day/night performance variations, PMD, component ageing margin. Some of these may be removed by operating the path for a long period (e.g. a few weeks) and averaging the performance before a pass/fail report is given. Ageing margin may be adjusted if an expected hold-time is known for the path. Such multi-week

measurement periods may not be compatible with the targets of the operator for agility/time to revenue. They are also not compatible with needing to try several routes to find a suitable one.

- Regenerators are likely to be required along the path and the routing algorithm must determine where they are to be used – in the most naïve implementation this algorithm would have to try every possible unregenerated route before trying every possible one-regenerator route, then every possible two-regenerator route and so on. Heuristic enhancements would be possible e.g. after two failed un-regenerated path attempts, add the regenerator topologically nearest to the shortest paths.
- Already-operating wavelengths have such a small margin that each provisioning act carries a non-negligible risk of disrupting service.

In terms of the parameters for evaluation:

- Speed of viability "calculation" in this case is the sum of the number of failed path setups plus the measurement times required.
- Accuracy of result: A trade-off with measurement time, as discussed above.
- Constraint of network design: No constraints.
- Efficiency in minimizing OEO regeneration: This simplest version does not address the problem at all. It will use an unregenerated path where it can be viable.

4.2.4 Measure-and-predict

During the operation of the network, each of its links are characterised in terms of impairments by direct measurement - a possible implementation is provided below. Then, when a new route request is received, a viability prediction is made on the basis of this information. Example equations for doing this are given in section 4.3

Definition: A probe wavelength-path is one not used for end-user data, and is solely established to enable characterisation of the segments of the network it travels through.

In order to get information before a link is used, probe wavelength-paths may be set up. Probe wavelength-paths may use idle regenerators as transmission sources. Alternatively/additionally, probe wavelength-paths may use ROADMs (reconfigurable optical add-drop multiplexers) to split existing wavelength-paths (probe or user) into their original path and one or more probe paths, although this is restrictive in that the probes will all be at the same wavelength as the original. Once the network has at least one traffic-carrying wavelength on each link, there is no further use for probe wavelength-paths – i.e. there is no long-term requirement for probing equipment.

While the network is in operation, monitoring can continue on traffic-carrying and probe wavelength-paths to detect performance drifts over time.

In terms of the parameters for evaluation:

- Speed of viability calculation:
- Accuracy of results: Section 4.3 is dedicated to this question.
- Constraint of network design: No constraints. Requirement for enough hardware (spare transponders) at initial deployment for network to characterise itself before use, although this requirement goes away when network is fully in use (all links have at least one wavelength). Requirement for monitoring equipment at each node which has cost. The Ciena system has an Optical Spectrum Analyser (OSA) - as part of its optical performance monitor (OPM) function - present at every ROADM site anyway as part of the wavelength power-control/gain-flattening control system, so this can be used at no extra cost by a control plane.
- Efficiency in minimizing OEO regeneration: Makes full use of system reach, except due to false-negatives due to inaccuracy on viability.

This technique is similar to the drafts currently proposed in the IETF standards body [Bernstein 10], [wson-impairments], and by the ITU in G.680. However, these standards currently only describe how to model the impairments of each component and calculate cumulative impairments of all the different types (noise, PMD, polarization-dependent loss (PDL) etc.) without the required final step of an actual BER prediction such as is provided in the next section.

4.2.4.1 Example measure-and-predict system

The example system was built as a test-bed at the Kao-Hockham laboratories (now closed) in Nortel Harlow. A more analytical presentation and an error analysis are performed in section 4.3.

This section uses the concept of Optical Signal-to-Noise Ratio (OSNR). This is simply the ratio of the average signal optical power to the average signal noise power [from Agrawal 97]:

$$OSNR = 10\log_{10}\left(\frac{P_S}{P_N}\right) \tag{4-1}$$

Where *OSNR* here is given in dB.
P_S is the signal power (in any units)
P_N is the noise power (in units to match P_S).

Practically, this measurement is made over a given bandwidth Δf as the receiver will only pick up noise (or indeed signal) over a finite bandwidth.

An example of a measure-and-predict system is described in this section. This is chosen as it is evaluated further in section 4.3. Figure 4-1 shows the configuration of the system. At each photonic cross-connect or ROADM, each wavelength is periodically measured as it enters and leaves the transmission fibre. Two measurements are performed. The first measurement is an Optical Spectrum Analyser (OSA). This is used to measure change in optical signal to noise ratio across the link (Δ-OSNR) – from which can be extracted the impairment due to optical noise added by this link. The second measurement is a Q monitor. This measures the overall differential impairment across the link. Subtracting the noise-based impairment from the total impairment across the link gives the distortion impairment – described in the figure as Δ-distortion. See section 4.3 for a mathematical treatment of this, and path performance based on this information. For cost reasons, the OSA and Q monitor are shared between all of the wavelengths at a site and a photonic switch is used to apply them to all of the input/output ports of that site in turn. A passive optical tap from each line means that such monitoring is non-intrusive.

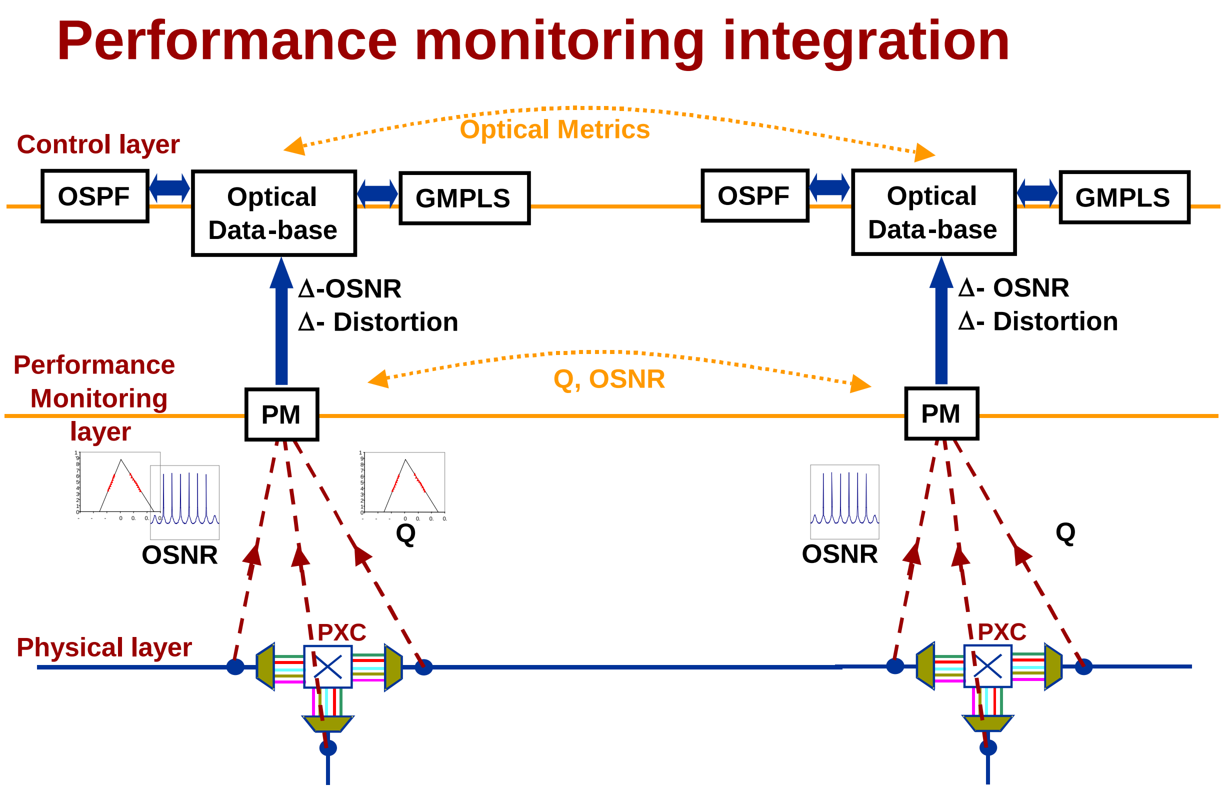

Figure 4-1 Passive taps from the optical cross-connects feeding into a shared performance monitor (one per node) giving Q and OSNR measurements. Reproduced from [Friskney02a] with permission.

It is significant that in terms of OSNR measurement, it is the OSNR *contribution* of the link being measured rather than absolute OSNR values. This is because OSNR is defined as the ratio of the signal to the noise within that wavelength. However, the noise within the wavelength cannot be separated by an OSA (it measures what power is there, not where it comes from); therefore the OSA measures the noise to either side of the wavelength signal and extrapolates the noise floor under the signal. When going through wavelength-separating filters, the noise floor between wavelengths will be changed – "noise floor shaping". Therefore the absolute OSNR measurements will be invalid.

However, measurements are taken at wavelength-multiplexed points – just before the first amplifier and just after the last amplifier. Therefore, the *comparison* of these two measurements is still valid, even if the absolute values are not.

The distortion values measured will include any inter-channel effects such as XPM. However they will not capture how those impairments will change as more channels are added later. A margin must be added to compensate for that depending upon the channels which can be added from the current fill level to the maximum fill level anticipated within the period that the wavelength-path will be used.

4.2.5 Specify and predict

This method takes the manufacturer specifications of all of the equipment in the path and then predicts the end-to-end wavelength performance. Some options for path performance prediction:

- Full split-step propagation simulation (such as discussed for example in [He 10])
- A simple noise + impairment-estimate model such as provided in 4.3.
- Some hybrid of the above.

The photonic planning tools produced by Ciena use an accelerated split-step Fourier propagation simulation by using a proprietary approach of pre-calculated lookup tables where possible.

Advantages of specify-and-predict over measure-and-predict:

- More accurate measuring equipment is available in a factory than in an operational network and more insightful characterisation can be performed. This assumes such per-unit factory calibration data can be stored in and read from the equipment. Passive equipment (DCMs, fibre) may not have a mechanism to report such characterisation data.
- No additional measurement equipment required in the network.
- Fixed information over the lifetime of the network so impairments can be precalculated if required.

Disadvantages of specify-and-predict over measure-and-predict:

- If there is significant performance variation between instances of the same product, the specification data will have to incorporate this – unless per-unit calibration data is included as discussed above.
- Performance data will have to include ageing margin for the product's lifetime.

4.2.6 Comparison table of viability methods

Table 4-1 provides a comparison of the viability methods listed in previous sections, evaluated against the criteria provided in section 4.2.1.

	Optical Islands	Trial & error	Measure & predict	Specify & predict
Speed of response of OVE	No calculation required.	N * Wavelength turn-up and measurement time.	Negligible (*)	Negligible (*)
Additional margin (and thus utilisation inefficiency) required (**)	Built in at planning stage	For ageing only.	For ageing only	For ageing + component variation tolerance.
Additional measurement equipment	None	None	OSA/Q monitor per switching site.	None
Network design constraints	Requires islands	No constraints.	No constraints.	No constraints.
Suitability for fast switching such as WROBS	Yes	Requirement for multiple attempts may result in unacceptable delay.	Yes	Yes

Table 4-1 Summary of viability assessment methods measured by comparison parameters

(*) –This assumes that both measure & predict and specify & predict use the simple impairment model described in the next section. In our experiments this model took an imperceptible time to execute compared to the seconds required by the photonic switch. Without having measured it, this only allows the characterisation of << 1 second.

(**) – Margins for PDL and similar fast-moving variations are not noted, as they are common to all options.

4.2.7 Conclusions of comparison of viability methods

At present, A-WRON systems tend to assume viability e.g. [Um 08][Tinter 08] (and trivially, as it is PON-based [Segarra 06]), which limits their applicability to small networks, or networks with an optical islands design approach.

Presently, one of the limiting factors in WROBS is the worst-case path set-up time. [Um 08] [Zapata 03][Zapata 04] Therefore, increasing this by one or several additional path set-up times with the trial-and-error method seems unattractive – it will increase intrinsic network latency, thereby decreasing the buffer fill to trigger a burst, decreasing network efficiency.

While the measure/specify & predict methods would require more complex routing algorithms in WROBS to take account of the possibility of non-viability, the additional computation time should still be negligible (with the assumptions stated in section 4.2.6) by comparison with the path setup delay. [Guild 06] does a similarly elaborate calculation for OBS/OPS.

Theoretically, measure & predict should out-perform specify & predict because there is no need to include further margin for component unit variation (although recording of per-unit factory calibration data may eliminate this issue for specify & predict as discussed above), and with knowledge of the target wavelength hold-time, there can be a significant reduction in ageing margin.

Considering how the additional cost of the Q monitor and OSA might decrease over time in the all-optical future:

- There will always be additional components versus the other viability options and so have non-zero extra cost.
- Only one Q monitor/OSA is required/cross-connect site. Extrapolation may be possible if the network is 100% populated, although the accuracy impact of this sub-population is not considered in the calculations below.
- Speed of measurement is not critical, as this measurement is not part of the turn-up workflow.
- Alternative approaches for deriving OSNR and Q are arriving via developments such as [Ye 07] and his multi-Gaussian curve-fitting to histograms of signal levels. [Skoog 06] believes that such things can be both cost-effective and revealing. These are samples from a huge body of work on performance characterisation. The purpose of this comparison is to discuss the general case of the different approaches and so review of that field is out of scope.

Where a network may be segmented into optical islands without adding additional regenerators, this approach is simplest of those considered and should be used. For the general case of networks, assuming that in the all-optical future it becomes affordable to have a compact OSAs and Q monitor at a high proportion of the nodes, measure-and-predict should theoretically produce the best performance. The next section considers what this performance could be and the influence of the accuracy of the measurement equipment on it.

4.3 Accuracy of On-Off Keying (OOK) measure-and-predict algorithm

A summary version of this section was published as [Friskney 02] and in more detail as internal report [Friskney 02a]. Where elements are Copyright Ciena from that internal report, they are reproduced with permission.

In this section equations behind the measure-and-predict algorithm are derived and then novel error propagation calculations are performed on them. A simplification/instantiation of this is offered based on current measurement equipment, showing that current accuracy is very poor, and setting new targets for future measurement equipment.

The objective of this section is to establish how accurate these calculations are given known measurement equipment capabilities. It is emphasised that the contribution of this section is that error analysis rather than presentation of this particular measure-and-predict framework. The framework essentially models nonlinear distortion as horizontal eye-closure, assuming that vertical eye-closure comes predominantly from noise. However, [Thiele 00] shows that the effects of XPM are seen mainly through vertical eye-closure, with negligible timing jitter (horizontal eye-closure). This was not known to the experimenters at the time, but better-reflects modern systems with many wavelengths (XPM pumps), high bitrates and non-dispersion-compensated systems (so causing the interference time of a pump data-bit A with a signal bit B to be lower than with older low-rate/fully-span-compensated line systems).

4.3.1 Calculating a link noise metric

This metric has physical significance in that it measures the amount of noise power or distortion that will be experienced by a signal traversing this link.

The link metric is derived along similar lines to that in [G.680] (the ITU standard on calculation of an impairment metric) “Impact of cascaded ONEs (Optical Network Elements) on line system OSNR”. This standard does not bring together the impairments into a predicted BER or perform an error analysis on the result. See for example [Qin 10] who does predict a BER but does not perform an error calculation.

At each tap, signal power and OSNR is measured. The node at the downstream end of the link (remote) passes these measurements to the node at the upstream end (local) of the link where they are combined as follows (paying careful attention to the units used):

$$Loss_{link} = Power_{Local\_dBm} - Power_{Remote\_dBm} \quad \textbf{(4-2)}$$

This is often negative, indicating a net gain over the course of the link due to amplification.

First, the absolute noise power is measured at the start and end of the link – note that no wavelength multiplexers or demultiplexers must be between these two points or noise-floor shaping effects will cause error in the results, assuming that the usual interpolation-based OSNR measurement equipment is used. The loss adjustment on the local measurement is such that this is the noise *as would be seen at the remote end*, if no noise were added in this link.

$$Noise_{Local\_mW} = \frac{Power_{Local\_mW}}{Loss_{Link\_linear} OSNR_{Local\_linear}} \quad \textbf{(4-3)}$$

$$Noise_{\mathrm{Re}mote\_mW} = \frac{Power_{\mathrm{Re}mote\_mW}}{OSNR_{\mathrm{Re}mote\_linear}} \quad \textbf{(4-4)}$$

A simple subtraction yields the noise power attributable to this link, which is propagated as a property of the link l: $Noise_l = Noise_{Remote\_mW} - Noise_{Local\_mW}$.

4.3.2 Using link noise metrics for path calculations

In the final path calculations, the total anticipated noise power for a given path p is:

$$Noise_{Path\_mW} = \sum_{l \in p} \frac{Noise_l}{\prod_{k \in S(l)} Loss_k} \quad \textbf{(4-5)}$$

where *S(l)* is the set of links in the path strictly succeeding *l*, i.e. all those links between it and the destination, from the perspective of following the path. In incremental path calculations (e.g. Dijkstra), this has the convenient feature that for each new link added, a running path noise total can be kept by dividing the current total by the new link loss, then adding the link noise power contribution:

$$OSNR_{Path\_linear} = \frac{Launch\_power_{mW}}{Noise_{Path\_mW} \prod_{l \in p} Loss_l} = \frac{Launch\_power_{mW}}{\sum_{l \in p} Noise_l \prod_{k \in P(l)} Loss_k} \quad \textbf{(4-6)}$$

$$k \in P(l) = (k \in p) \cap (k \notin S(l))$$

Again, for incremental path calculations it is useful to keep a record of a running path OSNR. This equation shows that by storing the denominator and cumulative loss, the OSNR for a new link *z* can be calculated readily with four operations:

1) Update the cumulative loss with the loss of the new link z.
2) Multiply the noise from link z by the new cumulative loss.
3) Add the noise factor from 2) to the cumulative denominator.
4) Divide launch power by the new cumulative denominator.

In fact, the actual measurable OSNR will be: $OSNR_{Measurable}=1/(Noise_{Initial}/Launch\_power_{mW}+1/OSNR_{Path\_linear})$, where $Noise_{Initial}$ is the measured noise floor at the ingress to the managed domain, e.g. the input of the first PXC. $OSNR_{Path\_linear}$ is useful only for path optimisation calculations, i.e. where relative numbers are all that matter.

4.3.3 Error propagation in noise calculations

The standard error propagation formula to find δA (error on parameter A) where $A=B+C$, $(\delta A)^2=(\delta B)^2+(\delta C)^2$ is used in this section. From this, the error in per-link noise figure is:

$$\delta Noise_{link} = \delta(Noise_{Remote} - Noise_{Local}) = \sqrt{\left(\delta \frac{Power_{Remote}}{OSNR_{Remote}}\right)^2 + \left(\delta \frac{Power_{Local}}{OSNR_{Local} Loss_{Link}}\right)^2}$$

$$= \sqrt{\begin{aligned} &Noise_{Remote}^2\left[\left(\frac{\delta Power_{Remote}}{Power_{Remote}}\right)^2 + \left(\frac{\delta OSNR_{Remote}}{OSNR_{Remote}}\right)^2\right] \\ &+ Noise_{Local}^2\left[\left(\frac{\delta Power_{Local}}{Power_{Local}}\right)^2 + \left(\frac{\delta OSNR_{Local}}{OSNR_{Local}}\right)^2 + \left(\frac{\delta Loss}{Loss}\right)^2\right]\end{aligned}} \quad \textbf{(4-7)}$$

$$= \sqrt{\begin{aligned} &Noise_{Remote}^2\left[\left(\frac{\delta Power_{Remote}}{Power_{Remote}}\right)^2 + \left(\frac{\delta OSNR_{Remote}}{OSNR_{Remote}}\right)^2\right] \\ &+ Noise_{Local}^2\left[\left(\frac{\delta Power_{Local}}{Power_{Local}}\right)^2 + \left(\frac{\delta OSNR_{Local}}{OSNR_{Local}}\right)^2 + \left(\frac{1}{Loss}\right)^2\left[(\delta Power_{Local})^2 + (\delta Power_{Remote})^2\right]\right]\end{aligned}}$$

With algebraic shorthand of:

$$Z = Noise_{Initial} + \sum_{l \in p} Noise_l \prod_{k \in P(l)} Loss_k \quad \text{and:} \quad L = \left(\frac{\delta Launch\_power_{mW}}{Launch\_power_{mW}} \right)^2$$

The error in the calculated path OSNR is:

$$\begin{aligned}
\frac{\delta OSNR_{Path_linear}}{OSNR_{Path_linear}} &= \sqrt{L + {\delta Z / Z}^2} \\
&= \sqrt{L + {1 / Z^2} \left(\delta (Noise_{Initial} + \sum_{l \in p} Noise_l \prod_{k \in P(l)} Loss_k) \right)^2} \\
&= \sqrt{\begin{aligned} & L + {1 / Z^2} (\delta Noise_{Initial})^2 \\ & + \sum_{l \in p} \left(Noise_l \prod_{k \in P(l)} Loss_k \right)^2 \left[\left(\frac{\delta Noise_l}{Noise_l} \right)^2 + \sum_{k \in P(l)} \left(\frac{\delta Loss_k}{Loss_k} \right)^2 \right] \end{aligned}}
\end{aligned} \tag{4-8}$$

Note: this method of error calculations adds statistically on the assumption that all errors are from Gaussian noise sources.

This is an unwieldy result. Worst-case addition gives a slightly simpler but still a cumbersome formula.

If it can be assumed that there is no (net) loss in each link (i.e. $loss_l = 1$) – e.g. normalised sections or appropriately power-balanced, Z simplifies to the total noise power introduced, i.e. $Z_{lossless} = Noise_{Initial} + \sum_{l \in p} Noise_l$. The overall equation then simplifies to:

$$\begin{aligned}
\frac{\delta OSNR_{Path_linear_lossless_links}}{OSNR_{Path_linear_lossless_links}} &= \sqrt{L + {\delta Z_{lossless} / Z_{lossless}}^2} \\
&= \sqrt{L + {1 / Z_{lossless}}^2 \left(\delta (Noise_{Initial} + \sum_{l \in p} Noise_l) \right)^2} \\
&= \sqrt{L + {1 / Z_{lossless}}^2 \left[(\delta Noise_{Initial})^2 + \sum_{l \in p} (\delta Noise_l)^2 \right]}
\end{aligned} \tag{4-9}$$

The error in noise measurements is equal to the error in OSNR, assuming loss-less links and accurate knowledge of launch power:

$$\frac{\delta OSNR}{OSNR} = \frac{\delta\, S/N}{S/N} = \sqrt{\left(\frac{\delta S}{S}\right)^2 + \left(\frac{\delta N}{N}\right)^2} = \sqrt{\left(\frac{0}{S}\right)^2 + \left(\frac{\delta N}{N}\right)^2} = \frac{\delta N}{N} \qquad \textbf{(4-10)}$$

As a check, taking this to the extreme case, where there is no wavelength filtering (i.e. no wavelength demux/ROADM), that is to say it is simply concatenating together multiple sections of transmission line (i.e. fibre + amps), using one link's end measurement as the next link's start measurement, this reduces substantially to:

$$\frac{\delta OSNR_{Path\_linear\_lossless\_links\_no\_WDMs}}{OSNR_{Path\_linear\_lossless\_links\_no\_WDMs}}$$

$$= \sqrt{L + \delta Z_{lossless}/Z_{lossless}^{\;2}} = \sqrt{L + 1/Z_{lossless}^{\;2}\left(\delta(Noise_{Initial} + \sum_{l\in p} Noise_l)\right)^2} \qquad \textbf{(4-11)}$$

$$= \sqrt{L + 1/Z_{lossless}^{\;2}\left(\delta Noise_{Initial} + \delta Noise_{Final} - \delta Noise_{Initial}\right)^2} = \sqrt{L + \frac{\left(\delta Noise_{Final}\right)^2}{\left(Noise_{Final}\right)^2}}$$

i.e., as it should, this reduces to the error of the simple signal to noise ratio.

4.3.4 Calculating a link distortion metric

In this section is characterised all consistent non-ASE noise signal impairments for a link into one aggregate 'distortion' metric.

At each tap, $Q_{Measured}$ and $OSNR$ are measured.

Given a distortionless link, Q can be approximated directly from a measured OSNR by:

$$Q_{Measurable} = \frac{1}{\sqrt{1/4F.OSNR^2 + 1/Q_0^{\;2}} + \sqrt{\frac{4OSNR+1}{4F.OSNR^2} + 1/Q_1^{\;2}}} \qquad \textbf{(4-12)}$$

Equation (4-12) shows Q in terms of OSNR for a distortion-free link, incorporating receiver noise. The following, which are taken as constant calibration factors for a given physical receiver, are used:

- $F=\Delta f/B$, where Δf is the optical bandwidth used when measuring the *OSNR* and *B* the electrical bandwidth of the receiver.
- Q_0 and Q_1 reflect the limit to the measurable Q caused by receiver noise on 0's and 1's, respectively.

A measurement of distortion at tap x is then taken as $D_x = \frac{Q_{Measured}}{Q_{Measurable}}$ where $Q_{Measured}$ and $Q_{Measurable}$ were as defined earlier in this section.

A measurement of the eye-opening that will be seen given a distortion-free signal injection into a given link starting at tap *x* and finishing at tap *y* is then $D_{xy} = \frac{D_x}{D_y}$. D_{xy} is propagated as a characteristic of the link.

4.3.5 Using link distortion metrics for path calculations

Distortion for the path is calculated as $D_{Path} = \prod_{ij \in P} D_{ij}$ - where *P* is the set of all links *ij* in the path. Possible sources of distortion are XPM, FWM etc.

NOTE: This assumes that there is no distortion as seen at the head end of the path. This is unlikely to be the case, so D_{path} must be multiplied by D_a (where 'a' is the head end tap point) to give the distortion actually seen at the end of the path.

The Q at the downstream end of the path can then be predicted from this and the Q predicted from the path OSNR (previous subsection) as: $Q_{Egress} = Q_{Distortionless\_path} D_{Path}$.

This value can be compared against a specified minimum receiver Q as an acceptability threshold for paths. In the absence of any other method, it can also be used as a preference value for the paths.

4.3.6 Error propagation in distortion and path calculations

See section 4.3.3 above for OSNR error propagation calculations.

First, a little expansion of the equation on the assumption that Q measurements are end-to-end, i.e. one Q measurement is taken and used for both the end of one link and the start of another:

$$\begin{aligned} Q_{Egress} &= Q_{Distortionless\_path} D_{Path} = Q_{Predicted\_End} \prod_{ij \in P} D_{ij} \\ &= Q_{Predicted\_End} \, D_1 / D_{End} = \frac{Q_{Measured\_1} \left(Q_{Predicted\_End}\right)^2}{Q_{Predicted\_1} Q_{Measured\_End}} \end{aligned} \quad \textbf{(4-13)}$$

This substantially simplifies the error calculation, although it assumes that one measurement instance is used to probe the whole path. Assume that, for error calculation purposes, Q_0 and Q_1 are known exactly and thus that $Q_{Predicted} \alpha \sqrt{OSNR_{linear}}$, also using the OSNR error calculation performed previously, obtain:

$$\begin{aligned} \frac{\delta Q_{Predicted}}{Q_{Predicted}} &= \frac{\delta \sqrt{OSNR_{linear}}}{\sqrt{OSNR_{linear}}} = \frac{\delta OSNR_{linear}}{2 OSNR_{linear}} \\ \frac{\delta Q_{Egress}}{Q_{Egress}} &= \sqrt{\left(\frac{\delta Q_{Measured\_1} \left(Q_{Predicted\_End}\right)^2}{Q_{Measured\_1} \left(Q_{Predicted\_End}\right)^2}\right)^2 + \left(\frac{\delta Q_{Predicted\_1} Q_{Measured\_End}}{Q_{Predicted\_1} Q_{Measured\_End}}\right)^2} \\ &= \sqrt{\left(\frac{\delta Q_{Measured\_1}}{Q_{Measured\_1}}\right)^2 + \left(\frac{2\delta Q_{Predicted\_End}}{Q_{Predicted\_End}}\right)^2 + \left(\frac{\delta Q_{Predicted\_1}}{Q_{Predicted\_1}}\right)^2 + \left(\frac{\delta Q_{Measured\_End}}{Q_{Measured\_End}}\right)^2} \\ &= \sqrt{\left(\frac{\delta Q_{Measured\_1}}{Q_{Measured\_1}}\right)^2 + \left(\frac{\delta Q_{Measured\_End}}{Q_{Measured\_End}}\right)^2 + 4\left(\frac{\delta Q_{Predicted\_End}}{Q_{Predicted\_End}}\right)^2 + \left(\frac{\delta Q_{Predicted\_1}}{Q_{Predicted\_1}}\right)^2} \\ &= \sqrt{\left(\frac{\delta Q_{Measured\_1}}{Q_{Measured\_1}}\right)^2 + \left(\frac{\delta Q_{Measured\_End}}{Q_{Measured\_End}}\right)^2 + 4\left(\frac{\delta OSNR_{linear\_End}}{OSNR_{linear\_End}}\right)^2 + \left(\frac{\delta OSNR_{linear\_Start}}{OSNR_{linear\_Start}}\right)^2} \end{aligned} \quad \textbf{(4-14)}$$

All of these terms are direct properties of measurement equipment or calculated previously from such.

The object of path prediction from measurement is to be able to predict the properties of a path without having to light it, extrapolating from having measured each segment as part of other paths. Thus, the cancellation above does not work in the common case. In practice, particularly in networks with a low degree of connectivity, it seems likely that each ‘probe’ path would probably pass through – and hence give measurements for - several segments at once. The worst case, where each ‘probe’ touches only one link of our planned case is given here:

$$\frac{\delta Q_{Egress}}{Q_{Egress}} = \sqrt{\left(\frac{\delta Q_{OSNR}}{Q_{OSNR}}\right)^2 + \sum_{k\in(i,j)\in p}\left[\left(\frac{\delta Q_{Measured\_k}}{Q_{Measured\_k}}\right)^2 + \left(\frac{\delta Q_{\Pr edicted\_OSNR\_k}}{Q_{\Pr edicted\_OSNR\_k}}\right)^2\right]}$$
$$= \sqrt{\left(\frac{\delta OSNR}{2OSNR}\right)^2 + \sum_{k\in(i,j)\in p}\left[\left(\frac{\delta Q_{Measured\_k}}{Q_{Measured\_k}}\right)^2 + \left(\frac{\delta OSNR_k}{2OSNR_k}\right)^2\right]} \quad \textbf{(4-15)}$$

where the sum over k ranges over all measurement points, starts and finishes of links – i.e. for all but the first and last links, the error on the measurement at each end of each link is taken twice – once as a start, once as an end. Note that these calculations assume that the OSNRs used for each of the D_x have independent noise from each other and from that used for the Q_{OSNR}. This is not true in the general case – in particular for a given D_{xy}, the OSNR measurements for D_x and D_y and will be the same as the noise contribution for *x-y*.

This can be simplified by disregarding the effect of DWDM noise-floor shaping, which allows the direct use of the measured OSNR at each point for calculating the eye-openings D_x. This has the same issue as described above in that the path OSNR prediction will be based on the same measurements as the Q_{OSNR} in the D_x but this is disregarded again. The equation looks identical to *(iii)* but path predicted OSNR on the right hand side becomes the simple OSNR measurement error. Path OSNR predicted error comes from *(iii)* in section 4.3.3.

4.3.7 Calculation/logic description behind results

This section describes the approach taken to generate the results shown in the next section.

The Q path impairment calculations described above are implemented assuming that:

- OSNR measurements can be used directly to get eye closure, i.e. that there is no noise-shaping occurring *within* the links such that predicted path OSNR would need to be used instead. As noise shaping primarily occurs due to switching/wavelength filtering between links, this seems a reasonable assumption.
- Q measurements are taken at the start and end of a link. Each link is measured separately, i.e. the measurement from the end of one link in the path was not the same one as taken at the start of the next link, even though these would have been taken through the same tap – at different times. This assumption is one of the design rules of the system.
- Each span is identical.

Note that, due to the division factor of 2 in equation (4-12) deriving the path predicted distortionless Q from the path predicted OSNR, the effect of this is small compared to the effect of the error on the path predicted distortion, i.e. the error on the Q measurement.

The OSNR calculations follow the equations (4-13) and (4-15) above, assuming a loss-less system, although note that 1/OSNR is used instead of noise – they are equivalent in a loss-less system i.e. where the signal is constant at all points of measurement.

1. Representative values for OSNR at the start and end of a lightpath are used. It is worth noting that the number of spans is immaterial in this – the end OSNR must be not much below this or the receiver will have a significant error rate. However, if a lightpath was substantially beneath the maximum reach attainable, its receiver OSNR would be higher than this, so this calculation represents the maximum specified distance for the system.

2. Given this start and end OSNR, the calculation then apportions the noise power added to the signal equally between the links. While it is not valid to assume that all links will be exactly equal in this way, the case where links are very comparable is both normal and desirable – where one link dominates the overall noise, the error will be smaller but the link engineering may have been flawed!
3. Then the calculation takes two alternatives: the best case alternative is where all of the link data used for the path whose performance is being predicted comes from spans which were at the start of the probing lightpaths – i.e. where the difference in OSNR between the start and end of the span was largest, thus making the relative size of the error smallest. Alternatively, the worst case is where all of the link data used for the path being considered comes from measurements taken on spans at the end of the probing lightpaths. As can be seen, the difference in error is substantial, but as path OSNR makes so little difference to the predicted receiver Q there seems little point in further considering this issue – although clearly there are possibilities in the path probing strategy that would ensure a medium case or, with extra probing, move towards the best case.
4. On a given span, the absolute errors on the measurements taken at the start and end are calculated, and then combined to give an absolute error for delta 1/OSNR, i.e. the noise property associated with this link.
5. The absolute error is then calculated for the concatenation (by simple addition) of these link properties.
6. This is then converted to the a relative error for the path prediction against the final OSNR – which is the final desired result

4.3.8 Results from the error calculation

Figure 4-2 shows how the error of the final predicted path performance varies according to the errors in the Q and OSNR measurements used to calculate it. It assumes that there are 6 links within the path being considered. It is believed that the best of the technology of today gives OSNR accuracy of approx 0.25 dB (bench-based) and Q accuracy of 5%

(Nortel LH1600 OC192 receiver). Plotting these numbers on the graph it is apparent that this gives an error on the result of approximately 22%.

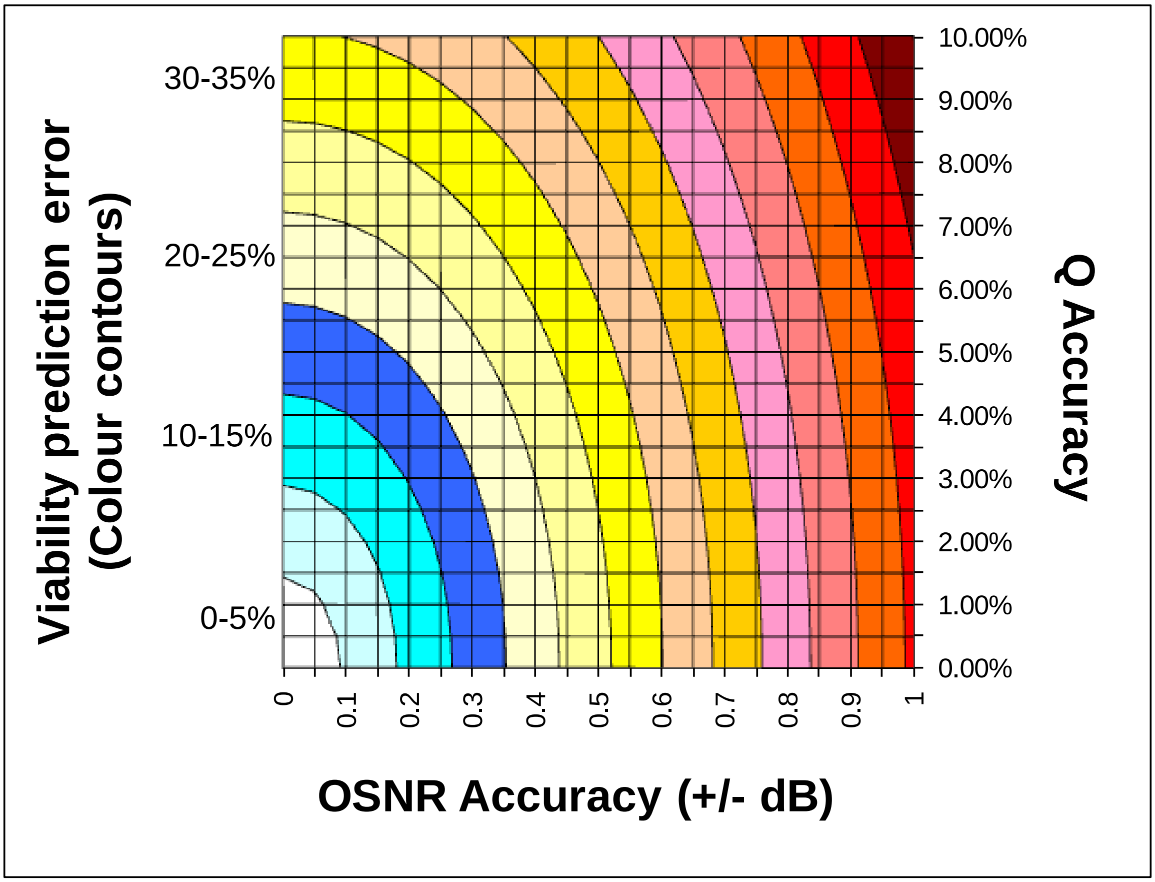

Figure 4-2 Showing how the overall path performance prediction varies with differing OSNR measurement accuracy and Q measurement accuracy. The viability prediction error is shown in terms of colour, with contours marked to be read out on the left-hand axis. To use this graph, pick an OSNR accuracy value and a Q accuracy value, find the point on the graph where these x and y values meet, then follow the contour around to the left-hand axis to read off the resulting prediction error.

Some assumptions made:

- Compact OSAs will achieve the performance of bench-based OSAs within the medium term.
- Equality between Qs measured by different receivers is achieved without adding any further error. [One of a series of best-case assumptions taken to find a minimum error result. This could be achievable if the receivers used for Q monitoring were calibrated and their ageing characterised]
- No automatic power-balancing is present.

No non-linear effects impair the signal. [Hiew 06] shows that for 40GBaud this assumption starts to break down for even smaller networks. However, as many 40Gbps systems are using QPSK and/or polarization multiplexing to achieve a symbol rate of as little as 10GBaud, the assumption is not broken by the 40Gbps systems of today. Making an estimate of what might be a reasonable generational improvement in equipment specification: 0.1 dB OSNR error and 3% Q error. This gives the dramatically more useful ~12% path error. ***Significantly, this result is more accurate than the specification-based planning-stage budgeting techniques of today***.

The purpose of the second graph (Figure 4-3) is to show that 6 spans is not a number of spans with any special significance – the error rises steadily with number of spans for both the example hardware specifications.

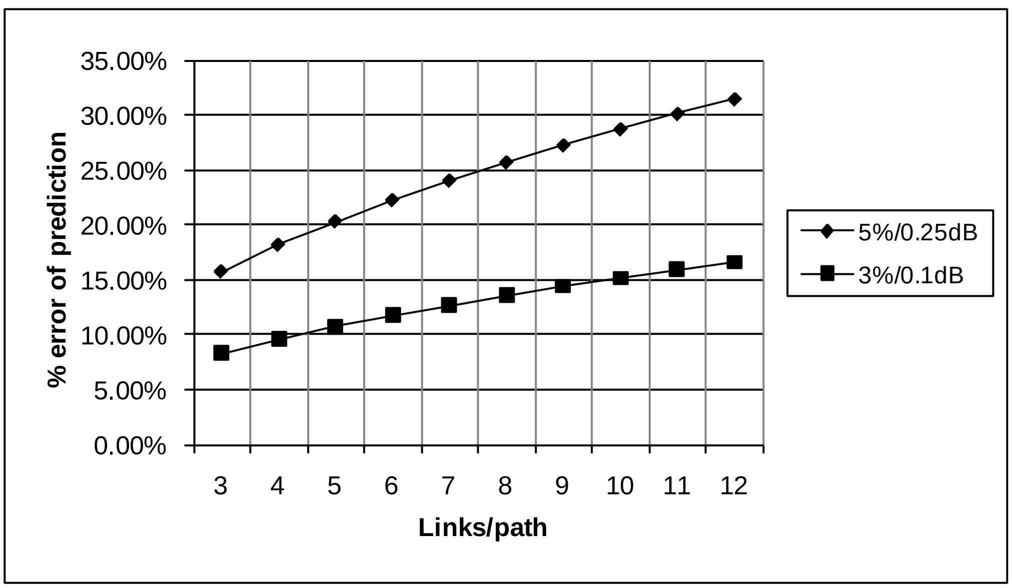

Figure 4-3 Performance prediction error rises steadily with the length of the path

4.3.9 The validity of measurements taken at a different fill level

Initial probing of the network is likely to occur at a lower fill level (number of wavelength slots occupied) than will finally occur – and indeed, some transmitters etc. may be installed as the network grows. In this and other circumstances, it is likely that the measured wavelength will be running in a link with a different fill level than the wavelength to be provisioned on that link – thus there is scope for the network performance experienced to be somewhat different due to increased inter-channel interference (e.g. FWM, XPM) as more wavelengths are added.

In the absence of per-wavelength dynamic VOA arrays, only two things change as the number of wavelengths increases:

- Amplifier pump power increases to maintain a given level of gain.
- Non-linear effects due to total power in the fibre and also localised effects to wavelengths adjacent to the newly added ones.

As has been previously stated, the latter point will be ignored as negligible at the power levels considered.

Amplifier manufacturers claim that amplifier noise figures are near-constant for a given gain, regardless of the pump power being used: a wavelength should suffer the same added ASE if on its own or with e.g. 39 others.

4.3.10 Unmeasurable signal quality workaround

During practical experimentation on this architecture, a problem became apparent: Near the transmitter, OSNR exceeded the ability of our OSAs to measure it accurately – the signal had to pass through one or two EDFAs before the OSNR had reduced to being measurable. To work around this, probe planning should note excessively high measurements, discard them, and re-measure the same link by using a different probe route whose transmitter is a few hops away. The consequence of this is that more probe wavelengths will be required to get full coverage of the network. It also means that links from terminal-only (i.e. no thru-capability) nodes cannot be measured.

4.4 Differences due to phase-modulated/coherent detection systems

As mentioned in Chapter 1, since the work described in this chapter was performed, the coherent 'revolution' has occurred. The impact of the development of coherent detection technology on this work can now be discussed. An example of the current commercial state-of-the-art using coherent detection is provided in Appendix A.

Key differences and similarities between a conventional 10G on-off keyed (OOK) and a Ciena 100G coherent (two-carrier dual-polarization quadrature phase-shift-keying, DP-QPSK, see [OIF-FD-100G-DWDM] for details of the 100G standard based on this) system are:

- Similarity: The symbol rate is approximately the same (12.5Gbaud/s) which gives the same fundamental tolerance to effects such as PMD.
- Difference: The coherent receiver and DSPs can fully compensate for chromatic dispersion and PMD in all new systems and most existing ones. This means that coherent receivers can be used where it would be too expensive to retrofit the network to support 10G OOK.
- Difference: As DP-QPSK is phase-modulated, the signal is affected by phase noise from effects such as XPM more strongly than OOK.
- Difference: Q and OSNR calculations are different (but equivalent) because they must take account of phase signal and noise rather than just amplitude.

Removing the need for DCMs (dispersion compensation modules) has the following effects:

- The elimination of the capital cost of the DCMs and the engineering required to calculate where to place them.
- The elimination of the significant power loss caused by the DCMs, and thus the noise added by amplifiers to compensate for this loss. This makes more and longer paths viable.
- Wavelength paths no longer need to achieve a narrow acceptable chromatic dispersion range and so many more wavelength paths are viable – the A-B-C

chromatic dispersion example in the previous section no longer applies. It is this advantage which is most significant for agile photonic networks because this key reason for non-viability disappears in most practical cases.

- Neighbouring wavelengths ‘walk off’ each other more quickly (find their bit-periods getting progressively more desynchronized as they are dispersed at every hop rather than re-compensated), thus reducing XPM.

It is important to note that coherent systems are not incompatible with DCMs. Therefore they may be used on existing fibre networks which mostly have DCMs present, still offering significant advantages in bitrate, PMD tolerance etc.

Greenfield coherent deployments (i.e. where there are no existing OOK wavelength-paths) have no requirement for DCMs. On non-dispersion-shifted fibre (e.g. the common SMF-28e), in the absence of DCMs, the XPM penalty is reduced relative to an equivalent fully-compensated modern many-channel 10G OOK system due to increased walk-off in time between the signals’ symbols ([Thiele 00] describes the effects of XPM generally and the interaction between XPM and walk-off length in depth), despite phase modulation being more-directly affected by the phase noise of XPM than non-phase-modulated OOK. This also applies to existing deployments where the DCMs and existing non-coherent wavelengths have been removed. As mentioned, coherent receivers can post-compensate for chromatic dispersion and polarization mode dispersion. Therefore, the remaining dominant impairment may be noise. Therefore, an approximate impairment calculation for coherent can be performed solely using OSNR as shown for OOK in section 4.3.2. Quantifying the size of the error in this approximation, and whether it can or should be approximated by some simple margin calculation, is discussed in the further work section of Chapter 5.

Modern transmitter/receiver pairs based on digital-to-analogue and analogue-to-digital converters are not fixed in hardware to any particular modulation format (e.g. QPSK, 8-PSK, 16-QAM) so it may be possible to change in software or firmware. As such, a trade-off between reach and bit-rate can be made. [Rival 11] demonstrates that by trading off between bitrate and reach, because of reduced regeneration, port-counts may be reduced. Rival et al. demonstrate up to a 21% reduction in the number of opto-electronic ports required to serve their example European network by using flexible-rate transponders. Such multi-format adaptive transmission is discussed further in [Friskney 02c], a US patent granted after examination, but otherwise out of scope of this thesis.

4.5 Chapter summary

A formal definition of optical viability within control planes was provided. Alternative methods of pre-determining viability were reviewed. A new calculation of the error involved in prediction based on live impairment measurement (a ‘measure-and-predict’ system) was provided.

This error calculation showed that given likely measurement accuracies (0.25dB OSNR error, 5% Q error), a measure-and-predict system was less accurate (22%) than the apparently more naive specify-and-predict approach, despite incurring the cost of additional measurement hardware. Therefore measurement accuracies would need to improve to make measure-and-predict a preferable choice. A combination that would achieve this would be 0.1dB OSNR error and 3% Q error.

Until measurement equipment can be improved, the two options available for viability calculation are then:

- Optical islands, only efficient where there are natural boundaries for other reasons that can be made to align with unregenerated reach limits.
- Specify-and-predict systems.

An alternative viability prediction calculation would have a different error result. In particular, if as has been speculated a purely noise-based viability calculation is sufficiently precise for a coherent system, the above accuracy result would not apply.

‘Try it and see’ was shown to be unsuitable for a system that may require regeneration.

Finally, differences in impairment calculations between traditional on-off keyed (OOK) modulation (the majority of the installed base of equipment) versus phase-modulation with coherent reception (the direction of newer products, notably at 100Gbits/s per wavelength) were described.

4.6 Statement of collaboration

The first (OOK) phase of the work described in this chapter was a project performed by my team at Nortel's Optical Communications Advanced Technology group and documented in [Friskney 02a] and published in [Friskney 02]. The measure and predict framework was proposed by Kevin Warbrick and Xiang Lu. The Q and OSNR equations were written by me from references provided by and with validation from Richard Hearth and Simon Poliakoff. The detailed error propagation equations were derived by me. The first simplification was done by Simon Poliakoff. The generalisation of this to the full range of input values, comparison with equipment behaviour and against network accuracy was performed by me. The write-up was done exclusively by me, re-using some material I contributed to [Friskney 02a] and [Friskney 02].

Work on viability approaches was done in collaboration primarily with Bram Peeters, Duncan Forbes and Jim Shields (all then at Nortel) and co-patented as [Peeters 03]. This write-up was provided by me, as a more comprehensive treatment than the summary provided by Bram Peeters in [Peeters 04], and with criteria for comparison. Related work was co-patented as [Shields 03].

The coherent section was written by me. I acknowledge very helpful conversations with David Boertjes, Michael Morey and Alan Robinson and suggestions from Kim Roberts (all while working for Ciena).

The principle of [Friskney 02c] was due to me, and then was developed in detail in collaboration with the help of my listed co-inventors.

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Chapter 5 Conclusions and further work

The work described in the thesis investigated the features of control plane functionality for routing wavelength paths in telecommunications networks. The objective of this routing functionality is to serve a set of changing sub-wavelength demands. Optimal efficiency in terms of wavelength capacity required to serve a given set of demands is the primary concern of this thesis. The work described in the thesis also takes account of routing problems not found in higher Open Systems Interconnect (OSI) layers (e.g. Ethernet, IP), notably physical transmission impairments. Agile wavelength-routed optical networks (A-WRONs) were investigated as being the closest to currently-deployed networks, and wavelength path sharing (WPS) as a variant on that that does not require fast (per-packet, per-burst) switching such as optical burst switching (OBS) or optical packet switching (OPS).

Firstly, the wavelength path sharing (WPS) scheme was discussed. WPS is a method of reducing the need for photonic agility by allowing semi-static wavelengths to be a unidirectional photonic shared-bus between multiple transmitters/receivers, allowing statistical packet multiplexing. An alternative hardware configuration was proposed in Chapter 2 (wavelength path sharing) which provided an additional benefit of photonic networking (format transparency) and savings in receiver/transmitter hardware, the quantitative benefit realised being according to the acceptable blocking probability threshold selected by the operator and traffic levels.

The routing ILP originally proposed with the WPS scheme was found to not scale to larger real-world networks. Therefore, a new heuristic was proposed.
This heuristic was shown to provide somewhat inferior performance (approx 50% more wavelengths) relative to the ILP in terms of wavelength consumption efficiency as would be expected, but still providing a significant gain (approx 20%) over the Baroni theoretical lower bound of wavelength usage for A-WRONs with faster execution time (approx 70%) with larger networks.

Further simulations were executed looking at first-fit wavelength allocation in terms of minimising continuous wavelength requirements, as this is a more practical parameter for network dimensioning than an abstract count of wavelengths. Validating the simulations using a new wavelength-allocation ILP showed that the first-fit algorithm noticeably favoured the routes found by the heuristic over those found by the routing ILP – by approximately 35%. This showed that comparing routing algorithms by combining them with the first-fit algorithm will give misleading results relative to an optimal (e.g. ILP) wavelength allocation, because the proportional 'cost' (sub-optimality in terms of wavelengths consumed) of first-fit may be systematically biased towards one algorithm, as it is here.

Using the optimal wavelength allocation results did not change the conclusion from the earlier simulations. However, introducing a novel WPS routing algorithm based on AUR-F offered a scalable algorithm at a low cost in wavelength utilisation (averaging 12% more wavelengths across all topologies tested) relative to the ILP formulation given the traffic and other assumptions stated in the chapter.

Secondly the question of how agile the WRON should be was addressed quantitatively in Chapter 3. A formal definition of network agility was provided, and a simple mapping to switch agility described. Modern switch technologies were compared in terms of agility and a categorisation by function – configuration/restoration/protection/OBS/OPS, noting that human provisioning does appear on this scale – was provided.

The quantitative network benefit that can be achieved by increased agility was assessed by simulation. It was observed that the benefit achieved depended significantly upon the network load – too low (negligible amounts of blocking) and there was nothing to improve on; too high and the network achieved inoperable amounts of blocking. Within the optimal window of load (with the network running at an average link-fill above 50%), an improvement of 46% usable network capacity could be achieved against a maximum acceptable blocking probability of 1% at the cost of a one thousand-fold increase in network agility – the equivalent of moving into the next technology category faster. This is a significant and worthwhile efficiency improvement. It was observed that for a given network size, the resulting signalling latency sets an upper bound on the value that can be achieved by faster switching.

Finally, photonic viability - the question of whether a path that the control plane can configure will work with sufficient bit error rate (BER) despite the physical transmission impairments encountered – was reviewed in Chapter 4, both for conventional networks and those based on the recently-commercialised coherent-receiver technology.

A formal definition of optical viability within control planes was provided. Alternative methods of pre-determining viability were reviewed. A new calculation of the error involved in prediction based on live impairment measurement (a ‘measure-and-predict’ system) was provided.

With this error calculation and given likely measurement accuracies, it was shown that a measure-and-predict system was less accurate than the apparently more naive specify-and-predict approach, despite incurring the cost of additional measurement hardware. Therefore measurement accuracies would need to improve to make measure-and-predict a preferable choice.

Until the measurement equipment (OSAs and Q monitors) can be improved, the two options available for viability calculation are then:

- Optical islands, only efficient where there are natural boundaries for other reasons that can be made to align with unregenerated reach limits.
- Specify-and-predict systems.

‘Try it and see’ was shown to be unsuitable for a system that may require regeneration.

Finally, differences in impairment calculations between conventional on-off keyed (OOK) modulation (the majority of the installed base of equipment) versus phase-modulation with coherent reception (the direction of newer products, notably at 100Gbits/s per wavelength) were described.

In summary, improved routing techniques for both the WPS and A-WRON cases have been provided, and recommendations were made for how to incorporate optical viability (also known as impairment awareness) into these algorithms. These answer the original research question of how a control plane routing algorithm can best serve sub-wavelength demands with a wavelength-routed network.

The significance of the work is that it has:

- **made WPS more practical** for control planes by providing an efficient heuristic algorithm for route calculation that is much faster than Myers' ILP. The latter is only really suitable for up-front planning where time is not an issue;

- **brought new understanding to the value of agility** by showing that under some conditions (operators who never allow network load to get high), there may be no value achieved – so they could buy a cheaper less-agile network. And to quantify the value for suitable networks;

- **determined the best viability calculation approach** for a photonic control plane to take (specify-and-predict - unless the network naturally splits into optical islands), having reviewed the alternatives and exposed a problem of accuracy with the proposed measure–and-predict approach.

Possible further work to extend that described in this thesis would be to:

- Calculate the viability error with a measure-and-predict system for a coherent system using a noise-only approach and (for comparison) using a noise + impairments approach. Theoretically the noise error calculation provided in Chapter 4 should translate without modification to the coherent case. However, the noise-only approach has not been publicly compared to measurement/simulation at the time of writing and so some refinement of it may be required to achieve usable accuracy which may invalidate the assumption in Chapter 4 of Gaussian noise for the coherent case and require an update of the calculations. The noise + impairments approach would additionally require an error calculation on the split-step Fourier calculation of the non-linear impairments.

- Quantify the value of agility in a WPS system. The A-WRON-based calculations of the value of agility should give an upper-bound on the value of agility in WPS because WPS uses wavelength-paths for its communication. However, the use of statistical multiplexing means that it is more tolerant to demand changes because each unit of spare capacity within a wavelength-path is available to two different demands. Simulations similar to that provided in Chapter 3 could be used to quantify how much difference this made.

- Provide routing algorithms that simultaneously optimise cost and achieve viability. The scaling problems of multi-objective optimisation are well known ([Reinhardt 11] is a very recent paper providing a survey). In the past, this has been avoided by assuming that cost and viability are correlated and optimising just for viability. It is indeed the trend that cost rises with distance (due to increased fibre and equipment traversed), and the probability of viability falls (due to increased accumulated impairments). Therefore many solutions have simply optimised on viability. However, the correlation is not total. As per the Deutsche Telekom PMD study [Breuer 03] discussed at length in Chapter 1, in older networks a lot of highly-impaired fibre exists which a solution optimising on viability would avoid. However, these fibres are likely to be lower-cost because the service provider wishes them to be used for any traffic that can to free up less-impaired links for wavelength-paths. For this reason, impairment should be treated as a binary threshold (as discussed in the next paragraph) rather than an optimisation parameter.

- Provide routing algorithms that achieve a given maximum cost goal. For viability as mentioned in the previous paragraph and cost factors such as latency – a requirement that I have seen become more commercially significant in my industrial experience – there is a threshold value above which a service is simply not useful (e.g. it exceeds the latency guarantee of a particular contract type, or the maximum tolerable latency of a particular application) and therefore highly costly routes become the only option. Techniques such as exception routing (described in many papers e.g. the Nortel-sponsored [Ahmed 09] and its references) can address this binary acceptability problem, at a cost in scalability – [Ahmed 09] gets the cost down to a constant factor which is the number of exceptions that need to be made (routes tried that are known not to be valid). These techniques are problematic in practice because the algorithms tend to try every variant on the failed path (all of which are also invalid), as these are of similar cost, before trying a different but slightly more costly approach, so the number of exceptions can become large. Therefore, there is opportunity for a viability-specific algorithm that understands viability to have a significant scaling advantage.

- Calculate the efficiency loss in wavelength usage terms of the viability calculation error. A worst-case model could be taken of a reduction in reach (and thus increased use of regenerators) equivalent to the size of the error bar in viability calculation.

- Develop a signalling protocol that would allow a distributed specify-and-predict algorithm to function. Extending OSPF-TE or ISIS-TE in this way would be straightforward. However, there could be some implications. In terms of propagation latency of impairment information, theoretically the loss and amplifier noise factors required for an OSNR-based solution are near-constant (decaying over the course of years rather than hours). If the nonlinear impairments were calculated using specify-and-predict based on equipment manufacturer data for a worst-case then these also would not vary, whereas with measure-and-predict they would vary with each added wavelength. If a coherent approach using an elaborate nonlinear impairment calculation approach with many parameters per link were used, then scaling might become a concern for larger networks.

- Devise multi-layer routing algorithms that would simultaneously optimise the photonic and client layers, still taking account of optical viability. This should produce better results than separate optimisation. For example, an alternative to setting up a lightpath A-B for a small amount of new traffic may be to indirect the traffic via existing lightpaths with spare capacity A-C and C-B. This has the benefit of decreasing the number of wavelengths required. It has the cost of requiring additional electronic switching capacity at C. However, this indirection should not always be done: it also hastens both A-C and C-B requiring an additional wavelength. Where C is not along an optimal path for A-B, this indirection action may at a later time therefore cause more wavelength-links to be consumed than if it had not been done.

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Appendix A A case study of the current state of the commercial art: The Ciena Photonic Layer with 40Gbps and 100Gbps/channel DWDM transmission

This appendix is frequently referenced in the main part of the thesis as an example of what is being deployed in volume commercially at the time of writing. The other chapters reference particular aspects and characteristics of the Ciena solution, this appendix gives context to those attributes. As will be seen, while most of the network functions used in the remainder of the thesis (amplifiers, DWDM multiplexers/demultiplexers, VOAs, power monitors etc.) are part of this real product, the way they are designed to be used here (e.g. with turn-up times reported in 2009 as “around 10 minutes” [Grosso 09], although current performance not public) is a long way from the millisecond or nanosecond timescales discussed in some papers at present (reviewed in Chapter 3). At the end of the appendix, the implications on control plane agility of the Ciena system design choices are described.

The Ciena coherent transmission system is a good example because it has been very commercially successful – [Ciena 11c] states that, as of 19th May 2011, Ciena “has shipped in excess of 7,000 coherent 40G/100G line interfaces to more than 80 customers across the globe with more than 5.5 million coherent kilometres deployed”.

A.1 Disclaimers

Disclaimers: No part of this thesis should be taken to form any kind of statement, claim, commitment or other form of communication by or on behalf of Ciena. This section is a summary of public information, and may not take account of commercially confidential information known to the author.

A.2 The Ciena Common Photonic Layer (CPL) and 6500 Photonic Layer

This section describes an example of the current state of the commercial art in the field.

Ciena CPL was formerly known as Nortel CPL.
Ciena 6500 Photonic Layer was formerly known as Nortel OME6500 Photonic Layer.
The Ciena 6500 Photonic Layer is, for the purposes of this thesis, a physically-repackaged version of the CPL – within a chassis capable of many higher-layer functions - and therefore they will not be separately described.

This section is a summary of [Nortel 07] and [Ciena 11a]. The Common Photonic Layer is the overall brand within Ciena for a system of optical amplifiers, DWDM multiplexers/demultiplexers (mux/demuxes) and related components. A diagram of the system is provided below in Figure A-1. It was introduced to simplify usage of the photonic layer through automation and network intelligence; to service a range of reaches (metro, regional and long-haul deployments); and to scale both up and down effectively – i.e. be suited to small initial deployments that could incrementally add wavelengths later without disrupting those already in service (e.g. by requiring them to be temporarily unplugged for additional components to be inserted into the line).

The Domain Optical Control (DOC) system is a software-based automatic wavelength turn-up and power optimisation systems. This is a significant part of CPL because some previous systems have required manual turn-up such as people with screwdrivers adjusting or adding/removing optical attenuators. Automatic turn-up not only decreases the time and cost taken to introduce new wavelengths, but reduces the risk of errors, i.e. decreases the chance that existing wavelengths will be disrupted. A reduced risk of disruption of existing traffic makes it more acceptable to introduce wavelengths during normal operation rather than in special maintenance windows that have to be agreed with all existing customers some time (e.g. weeks) in advance.

Part of the objective of CPL and DOC was to allow more sophisticated photonic topologies to be supported. In particular, to add support for photonic branching. This is defined as the point where at an OADM site, dropped wavelengths may then go into another line system (through amplifiers not on the first line system). This contrasts to local termination, where the optical receivers are physically co-located with the OADM device, so no further amplification is required. The reason that branching support is challenging is because the automatic power optimisation must simultaneously optimise the interlinked operation of multiple line systems, rather than being constrained to a simple linear segment.

A further benefit offered by DOC is that a planning tool is available that contains the DOC algorithm, plus continuous monitoring and re-optimisation allows initial performance to be increased by using initial link margins appropriate for the exact configuration used, rather than a conservative general-purpose figure. Note that this direct measurement of end-to-end BER is not what is in the link-by-link measurement model described in Chapter 4, where path prediction based on measured link-by-link characteristics was shown to be less accurate than specification-based predictions.

The CPL provides support for up to 88 wavelengths on the C-band with 50GHz wavelength spacing, or 44 wavelengths with 100GHz spacing, both using the standard ITU grid [G.694.1] of channel frequencies. This is achieved in two stages, a 4- or 8-channel (100GHz or 50GHz respectively) mux/demux (CMD) module, followed by a 9-way group mux/demux (GMD). The GMD also hosts the distributed power control plane (GMD). As discussed below, each of the channels may be up to 100Gbps, giving a total system capacity of 7.2Tbps/fibre. [Nortel 08] and [Ciena 10a] describes achieving 88 100Gbps wavelengths by using a passive splitter with amplifier to two 44-way splitters, giving a system capacity of 8.8Tbps/fibre. The previous Nortel long-haul transmission system (LH1600G) supported 80 C-band wavelengths and optionally allowed a parallel set of optical amplifiers/splitters/combiners to be used to achieve 80 wavelengths in the L-band, allowing 160 wavelengths in total. CPL makes no attempt to support any part of the fibre spectrum other than C-band at the time of writing.

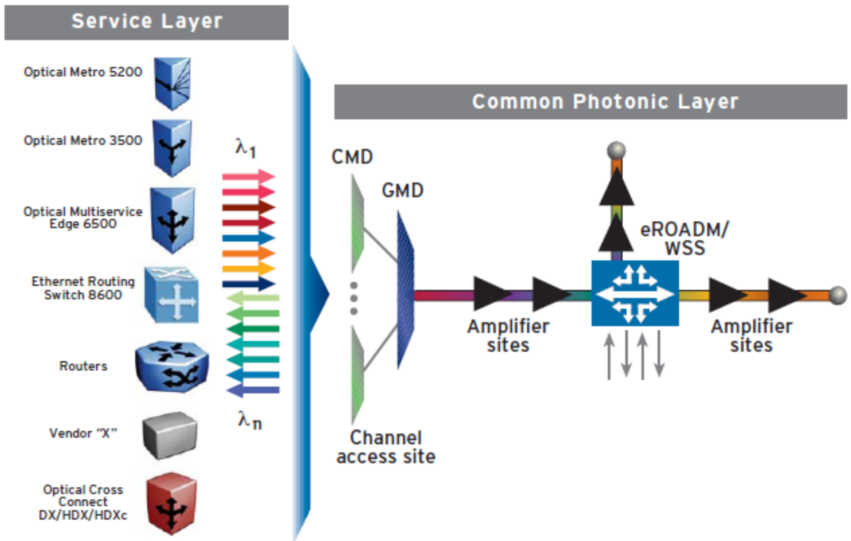

Figure A-1 The architecture of the Common Photonic Layer (CPL), showing that it can exclude transmitters/receivers from its control domain and so can support any terminal device supporting a support ITU grid wavelength – illustrated devices include metro photonics, long-haul photonics, SDH/SONET multiplexers (including of non-TDM traffic) and large-scale enterprise Ethernet switching. eROADM/WSS are discussed in the next section. Taken from [Nortel 07]

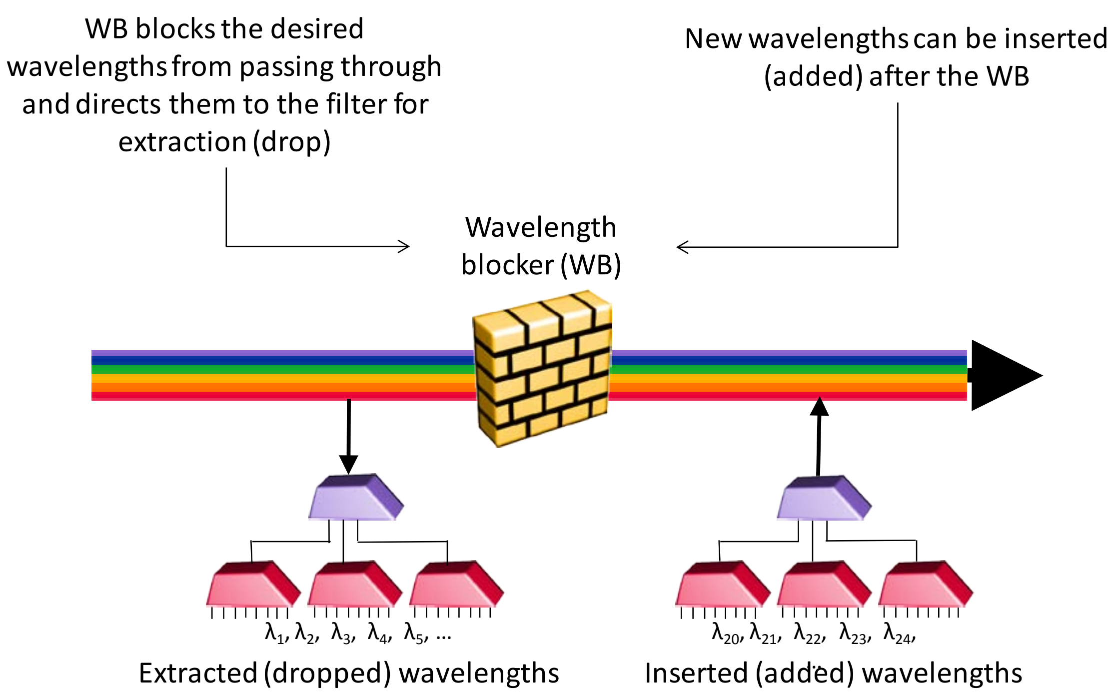

Figure A-2 Forming a ROADM for local termination/origination of wavelengths using a wavelength blocker. Reproduced from [Nortel 06a]

The CPL amplifier is locally gain-controlled but participates in the DOC and thus may have its gain adjusted by this control plane. The amplifier is also transient-suppressed. Both of these are to reduce the impact on existing wavelengths of addition/removal of new/defunct wavelengths, as a planned operation or due to an upstream fault.

The reasons for the ‘common’ in the name is that CPL is intended to carry wavelengths of all sources that can comply with the ITU grid as neighbours on the same fibre (designed for 1.25-40Gbps wavelengths, 100Gbps compatible as discussed below) – from short-reach traffic used by low-cost metro equipment, to extremely optically-performance sensitive ultra-long-reach wavelengths. In particular, a design goal is to carry non-Ciena-originated wavelengths - ‘alien’ wavelengths, as shown in Figure A-1. This new capability is significant because alien wavelengths cannot be expected to participate in the DOC control plane, or carry Ciena-proprietary health-monitoring data. Therefore, all DOC signalling is done out-of-band, all channels are controlled by electronically-controlled VOAs, and the DOC resides in the line system components rather than the transmitter/receiver cards.

A.2.1 Wavelength Selective Switches (WSSs) for Reconfigurable Optical Add/Drop Multiplexers (ROADMs)

This section provides a summary of [Nortel 06a] and [Ciena 10a]. For its latest ROADM product, Ciena has chosen to use micro electro-mechanical systems (MEMS)-based wavelength selective switches (WSSs), which it brands as Enhanced Reconfigurable Optical Add/Drop Multiplexers (eROADMs). WSSs allow the dropping of an arbitrary choice of wavelengths into one of – with this product – five different output ports. Each output port is truly ‘colourless’ and so can have any selection of wavelengths directed to it by remote configuration, avoiding the bandwidth stranding of systems without this capability such as PLC-based ROADMs. This makes branching sites simpler than with the older technology of wavelength blockers (WB), which were two port devices, selectively allowing/disallowing a wavelength through.

Figure A-2 shows an equipment configuration where a WB is used for local add/drop. It shows that selected wavelengths can be dropped when they reach the WB. A passive coupler before the WB allows reception of those wavelengths, once selected via DWDM demultiplexers. Selected wavelengths (either previously blocked or never inserted onto the line) can be inserted, via passive coupler, after the blocker.

As will be clear, to form an n-way non-blocking cross-connection, n.n-1 WBs would be required (one for each input to each output that does not loop back into the input fibre-pair), with losses caused by n-way couplers becoming quickly unacceptable. WSSes are preferable because only n would be required to provide a full cross-connection. The solution publicly advertised by Ciena offers five-way branching with WSSes and use of 50GHz spacing, but only two-way and 100GHz spacing with WB or planar lightwave circuits (PLC) approaches.

A.2.2 Colourless and direction-independent filters

Figure A-2 above includes traditional fixed multiplexer/demultiplexers. That is to say, any particular port a transmitter/receiver plugs into will be for a designated wavelength. Thus, if the transmitter is tunable, this facility cannot be utilised for route agility – tunable transmitters provide value only in that one spare does not need to be kept for each wavelength, as was the case with fixed transmitters.

This presents an obstacle to network agility when provisioning a new path – unless 88 spares (one/wavelength) are deployed, how can the control plane be sure it will find a terminal or regenerator on the correct wavelength? If a spare terminal/regenerator is installed on every wavelength, how can the network cost minimisation goals be met?

The solution to this is not to use fixed filters. Some vendors propose using tunable filters. At present, our competitive information is that these result in an expensive solution. Another solution would be to attach a transmitter/receiver directly to a ROADM port. This would allow full flexibility as to which wavelength could be added/dropped, but presently the cost of ROADMs and the number of ports they support makes this uneconomical/impractical, although technically feasible.

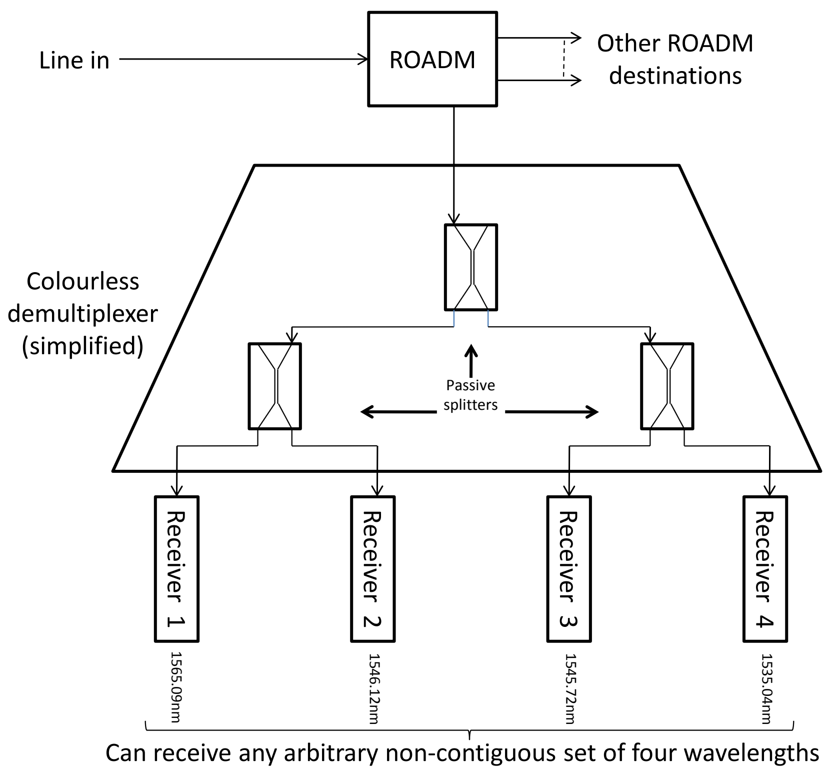

Figure A-3 The principle of a colourless wavelength demultiplexer configuration which can receive any arbitrary non-contiguous set of (in this case four) wavelengths

The solution taken by Ciena (first publicised by the company as a concept in [Nortel 06], demonstrated at OFC/NFOEC 2010 as described in [Lightwave 2010]) is to share the ROADM port between a number of terminals by using colourless filters. Colourless filters are passive splitters/combiners, sometimes with an amplifier to compensate for the loss. A conceptual diagram is shown in Figure A-3. Coherent receivers reject wavelengths that do not match the local oscillator, effectively providing an input filter. Each receiver can tune to any wavelength independent of the others. Therefore the ROADM can drop an entirely arbitrary set of wavelengths with no grouping constraints. The figure shows four such receivers receiving four randomly-selected wavelengths from the C-Band. Similarly, a transmitter can tune to any wavelength, and thus a group of transmitters can inject an arbitrary set of wavelengths into the ROADM. This is the exact converse of the figure.

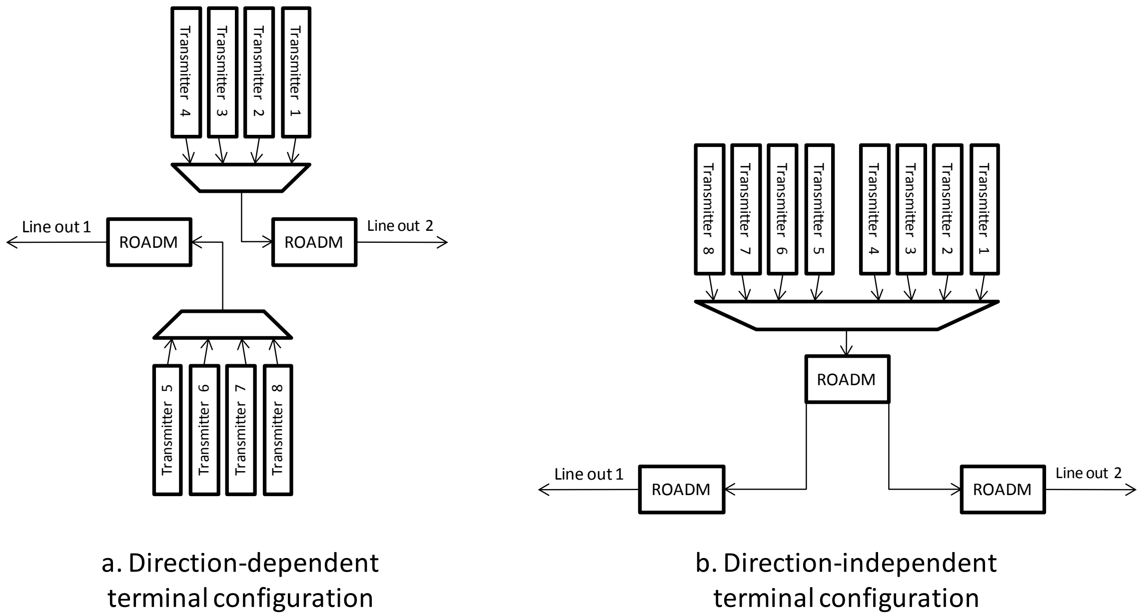

Figure A-4 The principles of direction-dependent versus direction-independent terminal configurations.

Directionally-independent operation is simply the concept that a particular transceiver is not bound to a specific ‘direction’ (a particular fibre at a ROADM site). This concept is illustrated in Figure A-4, which shows a subset of the hardware at a 2-direction (“Line out 1” and “Line out 2”) ROADM site. The subset is just to show the path from the local transmitters to their line systems. The diagram for receivers is just the converse, omitted for simplicity. Other inputs from the ROADMs are also omitted for simplicity. Diagram a shows an older-fashioned direction-dependent terminal configuration where e.g. transmitter 1 is unconditionally associated with line out 2. Diagram b shows a direction-independent (sometimes called ‘directionless’ in marketing material) node configuration where each transmitter can output to any direction according to switch settings. Diagram b requires a larger switching capability (an extra WSS as illustrated here, or one bigger WSS, or some such), which has cost relative to diagram a. However, it will be more efficient and flexible in how the transmitters may be used. Like colourless, direction-independent improves the value of speculative installation of transceivers/regenerators at a site, because any one transceiver can be used for more directions.

To be clear, direction-independence uses no novel hardware or concepts of any fashion - the innovation is to enable the power-balancing control plane to support this configuration, which previously it did not.

A.3 The Ciena 40G transmission system

The Ciena 100G transmission system is based on the 40G system, so that is described first. Both are currently implemented as transmitter/receiver cards for the 6500 chassis, that also supports many other card types for functions such as TDM switching, packet switching, adaptation of many traffic types (e.g. Ethernet, SAN, PDH, SDH, SONET), or simple regeneration. The associated line system components (e.g. amplifiers, mux/demuxes) form part of the previously-described Common Photonic Layer system or may also reside in 6500 chassis.

The Ciena 40Gbps transmission product is able to upgrade existing 10G infrastructure just by replacing transponders and achieve equivalent continental-scale (2000km+ [Nortel 08]) reach equivalent to Ciena's more traditional (i.e. simple non-return-to-zero (NRZ)-modulated) 10Gbps transmission systems[1]. By comparison, its competitors using other technologies, such as non-polarization DQPSK, achieve distinctly limited reach and require more constrained and idealised conditions – only certain fibre types, and more tightly constrained dispersion maps – such that upgrading 10G systems can only be done in rare circumstances, or by re-engineering the intermediate equipment. Therefore, while Ciena's approach results in more complex (and therefore potentially more expensive) transponders, less of them are needed, the system cost for upgrading to 40G can often be much lower, the upgrade can be done selectively per-wavelength rather than as one big

[1] Ciena now has an upgraded 10Gbps transmitter with electronic dispersion pre-compensation, branded as electronic dynamic-compensating optics (eDCO) [Nortel 06]. The 'traditional' transmitter is given as a reference point of the state of the art across the industry before digital signal-shaping/post-compensation started to be used.

replacement operation, and the upgrade can be done in more networks (as changing fibre type – which would usually involve physically replacing thousands of miles of it - is usually not regarded as an option). The solution is therefore achieving significant sales.

The key technologies used to achieve the benefits of the Ciena solution are DP-QPSK modulation and coherent reception. These are discussed in the next sections.

First, a numerical comparison of the performance achieved by Ciena's system is shown in Table A-1, noting that the Ciena DP-QPSK column is showing system performance rather than modulation performance, i.e. it includes the benefits of coherent reception and receiver digital signal-processing.

	10G NRZ reference system	**Nortel 2-POL QPSK**	**Duobinary**	**DPSK**	**DQPSK**
Normalised reach	1	1	.4	.8	.65
CD tolerance [ps/nm]	±500	±50,000	±90	±90	±200
PMD tolerance (<DGD>) [ps]	15	25	3.5	3.5	8
50-GHz filter/OADM tolerance [# of OADMs traversed]	>16	>16	3-5	3-5	8
100-GHz filter/OADM tolerance [# of OADMs traversed]	>16	>16	8	8	>12

Table A-1 The numerical performance achieved by the approaches to 40Gbps transmission discussed, with 10Gbps NRZ for comparison. From [Nortel 08a]. All system specifications mentioned are using the same end of life margin.

This compares with the Alcatel-Lucent 1625 LambdaXtreme single-polarization system currently publicly advertising 128x10Gbps (50GHz-spaced, 4000km claimed reach) or

64x40Gbps (100GHz-spaced, 1000km claimed reach) [AlcaLu 09][Lucent 04]. [Lucent 04] also shows that this performance is supported over a limited range of the most common fibre types, FITEL TrueWave, Corning LEAF and SSMF.

A.3.1 Dual-Polarisation Quadrature Phase-Shift Keying (DP-QPSK)

DP-QPSK modulation is used to achieve a symbol rate of 10GBaud (i.e. 10G symbols/s, by effectively having two channels – via polarization diversity – each sending 2 bits/symbol) – the same symbol rate as most existing 10Gbps transmission systems. In fact it is slightly higher than this, due to FEC. One publicly-disclosed FEC option [Ciena 11b] results in a symbol rate of 11.1GBaud.

Competitor systems use DQPSK (no polarization) for a symbol rate of 20GBaud, or even DPSK/Duobinary for a symbol rate of 40GBaud. Symbol rate is a dominant factor in determining susceptibility to chromatic dispersion (proportion to symbol rate squared), polarization mode dispersion (PMD – proportion to symbol rate) and other impairments. Additionally, symbol rate determines signal bandwidth, and thus the impairment suffered when travelling through the existing long-haul standard of 50GHz DWDM mux/demux spacing. This is illustrated in Figure A-5.

Figure A-6 graphically illustrates the two aspects of DP-QPSK, the polarization diversity, and the in-phase/quadrature modulation.

Since Ciena's decision to adopt it, DP-QPSK has been selected as the base for the 100Gbps long-haul (1000-1500km) transmission standard by the Optical Internetworking Forum, as reported in e.g. [Lightwave 2008].

A.3.2 Coherent reception and Digital Signal Processing (DSP)

Instead of directly detecting the light amplitude of the incoming wavelength with a photodiode, coherent reception first mixes it with a 'local oscillator' (a tunable laser, set to a fixed offset from the desired reception frequency) to generate an intermediate frequency (IF) containing the desired signal, much like a super-heterodyne radio receiver.

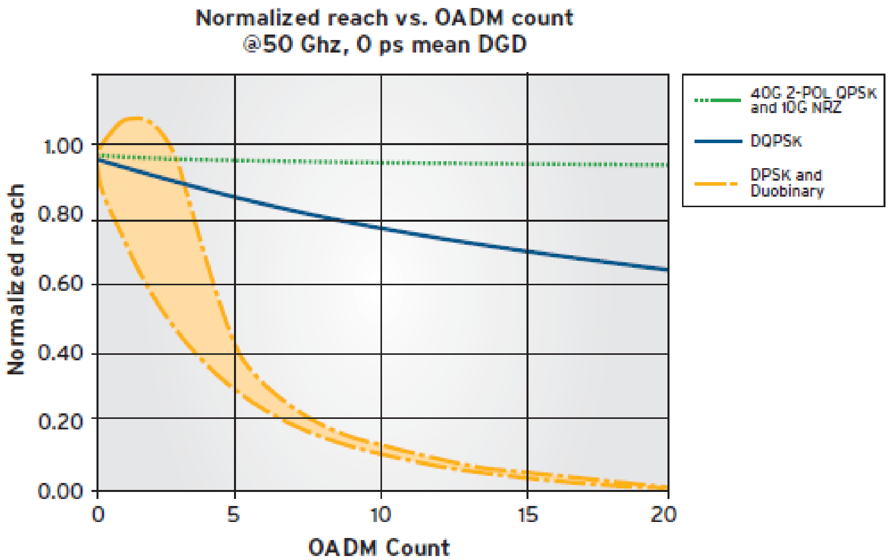

Figure A-5 Normalised reach impact caused by (R)OADMs comparing different 40G implications. From [Nortel 08b]

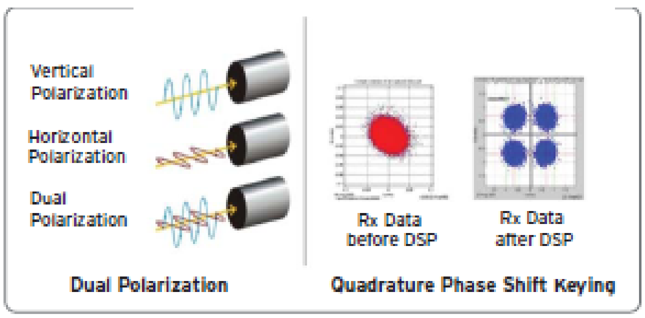

Figure A-6 The two new aspects of Ciena's 40G modulation versus its 10G modulation: dual polarization and quadrature phase-shift keying. Also empirically showing the signal improvement achieved by receiver DSP. From [Nortel 2009]

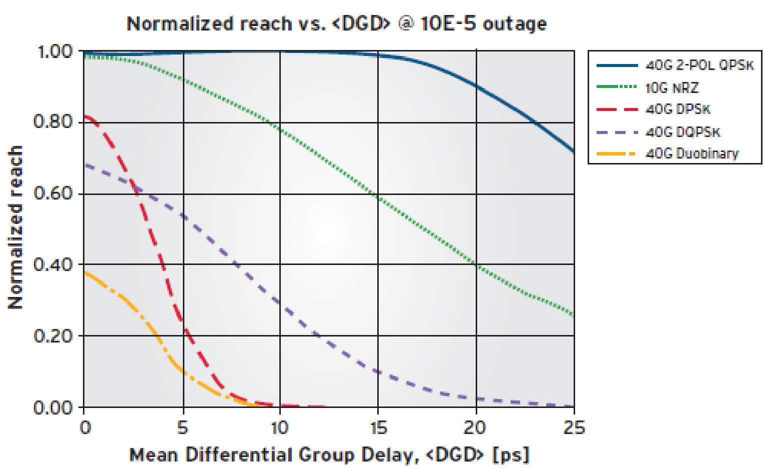

Figure A-7 Showed the normalised reach impact caused by PMD with different 40Gbps modulation formats. From [Nortel 08a]

This provides phase information as well as amplitude. Polarization diverse receivers allow polarization information to be extracted. Given this much richer information (amplitude, phase and polarization) than traditional systems (amplitude only), and digital signal processing (DSP) including polarization tracking, the DP-QPSK can then be demodulated. However, the DSP also has the information to undo chromatic and polarization mode dispersion to the extent shown in Table A-1. In fact, the 40Gbps system achieves better PMD tolerance (25ps) than the conventional NRZ 10Gbps system (15ps), the network system impact of this is shown in Figure A-7. This means that some fibres deemed unsuitable for 10Gbps transmission due to excess PMD can now be used for 40Gbps.

Coherent technology has therefore provided a revolution in:

- Increased spectral efficiency to allow higher bitrates without increasing baud rate and thus impairment sensitivity.
- Working with DSP to cancel out some impairments altogether, and ameliorate others, to increase reach and make photonic systems easier to plan.

A.3.3 The Ciena 100G transmission system

Following on from the 40Gbps transmission system described above, Ciena has made available its “40G/100G adaptive optical engine”. With the now-Ciena system, Nortel was able to announce the first commercially-supplied 100G wavelength, and (simultaneously) first commercial traffic to travel over 100G [Nortel 09] – the 893km Paris-Frankfurt link for Verizon, added alongside in-service 10G wavelengths in the same fibre. Further sales and field trials have followed, such as TelstraClear [Ciena 10] and Surfnet [Ciena 11c].

As described in [Nortel 08], the Ciena 100G system uses similar modulation to the 40G system, DP-QPSK, up-rated to 50G, then runs two such wavelengths 20GHz apart to form a combined bit-rate of 100Gbps[2] (although the two wavelengths are produced,

[2] As with 10 and 40Gbps, this is not exactly 100Gbps due to FEC and other overheads. In particular, a key published rate is ITU OTU-4, an OTN wrapper for 100GE, at 112Gbps before FEC.

received and managed as if they were one, from the black-box perspective of the network operator) as shown in Figure A-8. As can be seen, the sidebands of the two wavelengths overlap significantly, and with the generation of technology used for 10G receivers, the two wavelengths would dramatically interfere. However, due to the frequency selectivity of the coherent receiver, it is possible to separate out the two wavelengths from each other. Further, despite achieving a 100Gbps bitrate, the combined signal can still be transmitted through already-deployed 50GHz filters – as described in the previous section, this allows use on already-installed line systems, and interworking with neighbouring wavelengths of other bitrates. Transmission reach of 1000km is advertised, as is support of 88 wavelengths. For the same reasons as in the 40Gbps product, no inline dispersion compensation or PMD compensation is required, as the receivers can post-compensate for these impairments. The electronic dynamically-compensating optics (eDCO) brand is applied to the 40/100G system, as well as the pre-compensating 10G system [Nortel 06].

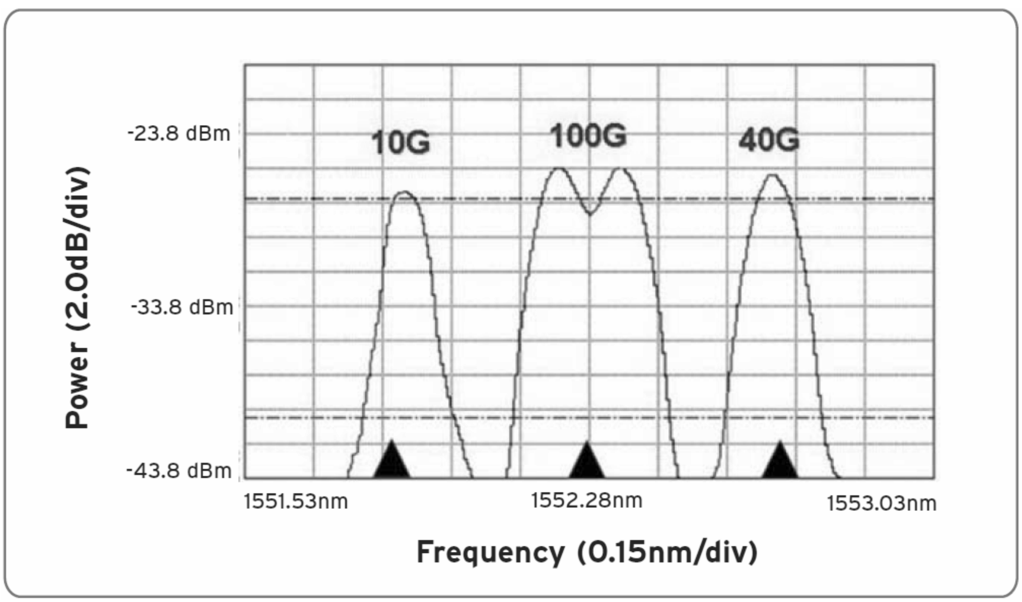

Figure A-8 Comparison of spectrum consumed by Ciena's 10G, 40G and 100G transmission systems. From [Nortel 08]

A.3.4 Ciena system design choices, impact on wavelength agility

Traditional (such as NRZ, without DSP) optical transmission systems used for agile wavelength route-switching have always suffered from a need for carefully planned dispersion compensation – that the net dispersion over a path should be a precise value (whatever amount of dispersion is naturally compensated for by the configured laser chirp). If the net dispersion does not exactly match this target, the link budget will be impaired and thus some paths will cease to work. Thus, net dispersion needs to be tracked in such systems' viability calculators or planning restrictions introduced with their own negative consequences, such as exactly compensating each fibre span (requires very fine granularity of DSCMs, or dispersion compensation fibre to be cut to length and spliced on site, increases the non-linear interference between co-propagating wavelengths by bringing them back into temporal correlation) or limiting the size of the network such that the net dispersion is bounded.

However, if lumped dispersion compensation is not required, as in the Ciena system, this problem simply does not exist. This applies both to new-build networks with no DSCMs at all, and existing networks with DSCMs designed for statically-routed 10G wavelengths – which can now be upgraded to flexibly-routed 40G paths. This is because, as well as compensating for large amounts of dispersion, electronic dispersion compensation is also useful for compensating for residual dispersion that varies with the route chosen, as can occur in partially-compensated systems.

Eliminating bulk fibre dispersion slope compensation modules (DSCMs) has the additional benefit of reducing latency (less distance for the light to travel) and OSNR degradation caused by the additional amplifier required to compensate for the DSCM's loss.

The Ciena transmitters and receivers are tunable to the full-C-band of wavelengths. Other transmission systems are not (such as the predecessor of CPL, the Nortel LH1600 system), which places restrictions upon routing and wavelength assignment.

In 2009 [Grosso 09] reported a complete wavelength turn-up time of "around 10 minutes" using a Nortel CPL system – CPL being the previous branding and physical packaging for the Ciena 6500 photonic capability. 10 minutes would be fast enough for time-of-day based rerouting, but does not provide sufficient switching speed for OBS/OPS. The current switching speed of the 6500 is not public information.

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Appendix B Topologies used for simulations

The topologies that were used in the simulations of Chapters 2 and 3 are shown in this appendix.

The choice of topologies is based on the standard analytical set used in many papers, as used in [Zapata-Beghelli 06]. [Myers 01], the work on which Chapter 2 is based, uses NSFNet, TOR3 and ARMNet, as well as some randomly connected networks. Of these, NSFNet is already included in Zapata-Beghelli's set and ARMNet is trivial. However, TOR3 is added to this chapter as being challenging for routing algorithms due to its many circular paths. Chapter 2 included an exploration of the axis of α for a network size matching NSFNet, so a range of randomly connected networks were generated and used. These are illustrated at the end of the section.

Let a graph have ***N*** **nodes** and ***L*** **links**.

The following definition for the level of network connectivity in a network (α), introduced in [Baroni 96], is used in the network simulations later, showing the close relationship between α and the number of wavelengths required for S-WRON routing:

Define α as the normalized number of bi-directional links with respect to a fully-connected mesh topology:

$$\alpha = \frac{L}{L_{FC}} = \frac{2.L}{N.(N-1)} \qquad \textbf{(B-1)}$$

where LFC is the number of links in a fully-meshed network.
Define Δ as the mean nodal degree in the graph. All alpha and delta values are to 2 decimal places.

All of these topologies satisfy the Baroni requirement of nodal degree greater than or equal to 2 for all nodes.

B.1 TOR3

[Myers 01 page 66]

$n = 9$, $L = 18$, $\alpha = 0.5$, $\Delta = 4$.

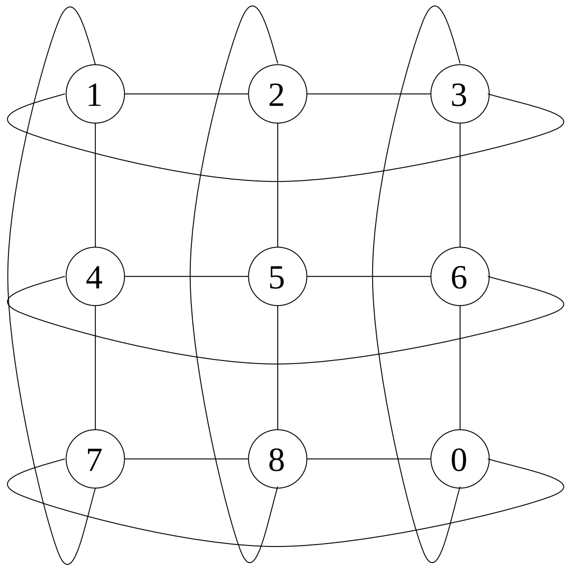

Figure B-1 TOR3

B.2 Eurocore

[Zapata-Beghelli 06]

n=11, L=25, $\alpha = 0.45$, $\Delta = 4.55$.

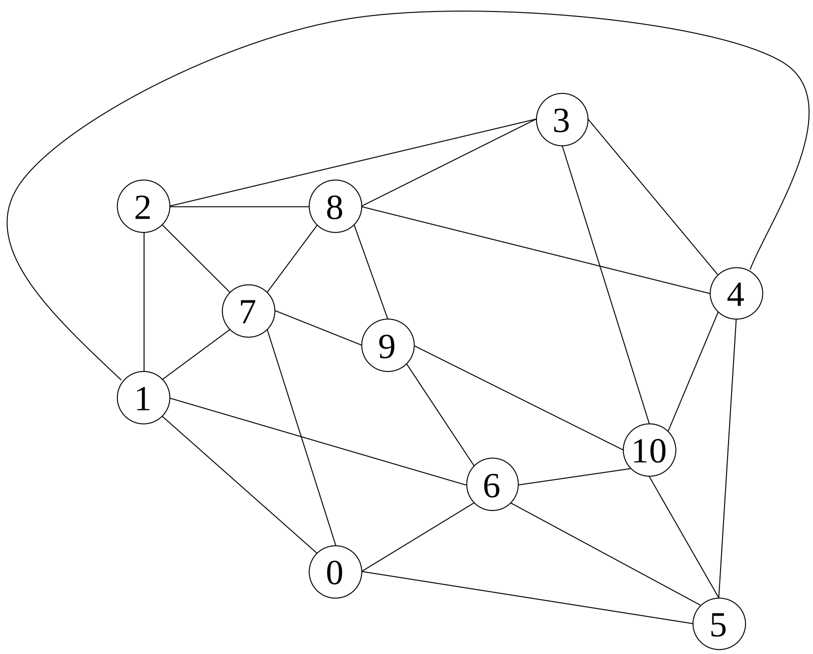

Figure B-2 Eurocore

B.3 NSFNet

[Myers 01 page 66], [Zapata-Beghelli 06], [Baroni 98]

n = 14, L = 20, α = 0.22, Δ = 2.86.

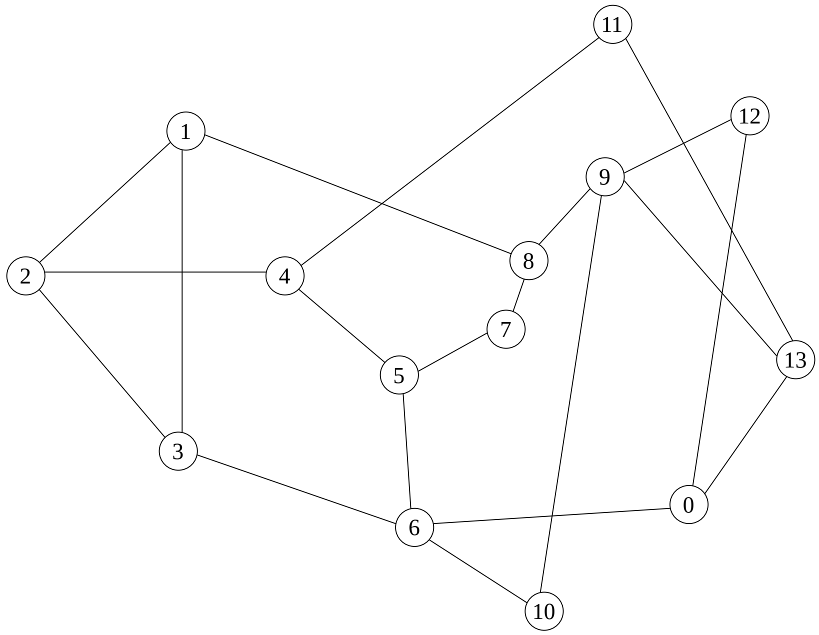

Figure B-3 NSFNet

B.4 EON

[Zapata-Beghelli 06], [Baroni 98]

n = 20, L = 39, α = 0.21, Δ = 3.90.

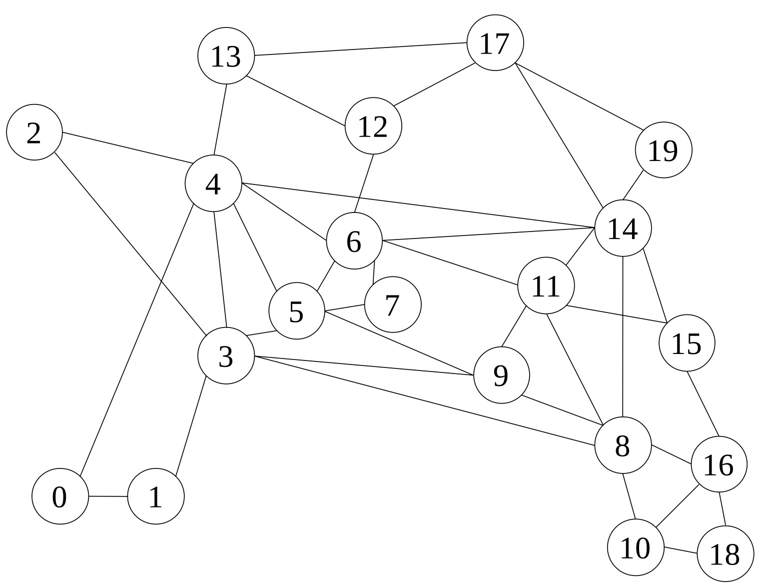

Figure B-4 EON

B.5 UKNet

[Zapata-Beghelli 06], [Baroni 98] n = 21, L = 39, α = 0.19, Δ = 3.71.

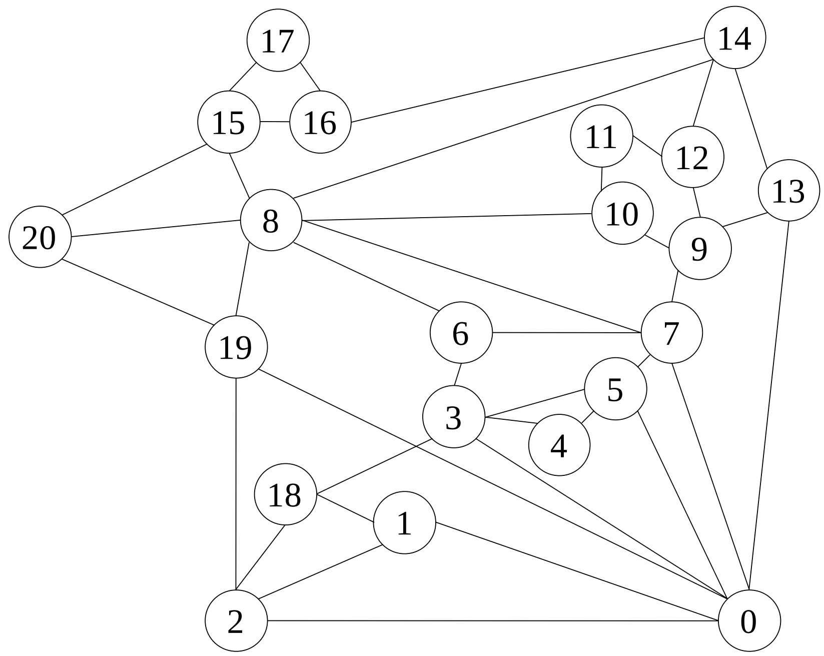

Figure B-5 UKNet

B.6 ArpaNet

[Zapata-Beghelli 06], [Baroni 98]

n = 20, L = 31, α = 0.16, Δ = 3.10.

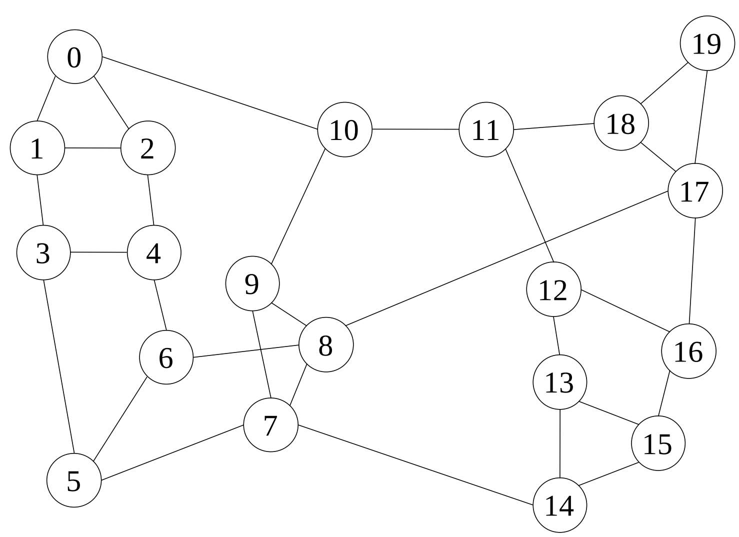

Figure B-6 ArpaNet

B.7 USNet

[Zapata-Beghelli 06], [Baroni 98]

n = 46, L = 76, α = 0.07, Δ = 3.30.

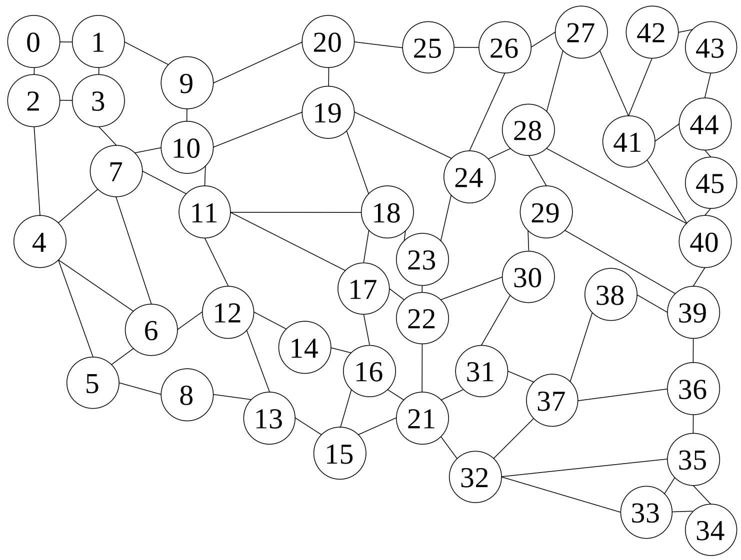

Figure B-7 USNet

B.8 EuroLarge

[Zapata-Beghelli 06], [Baroni 98]

n = 43, L = 90, α = 0.10, Δ = 4.19.

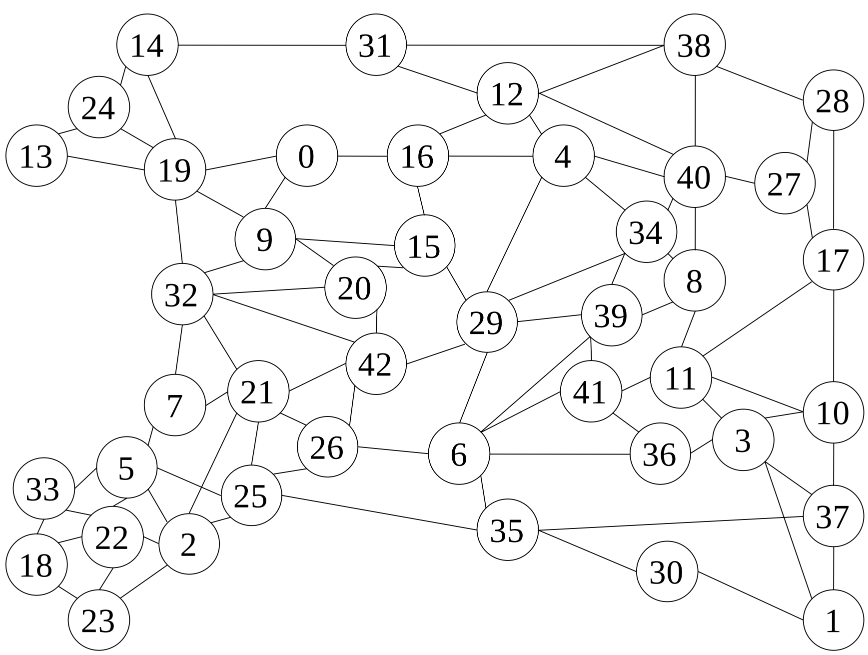

Figure B-8 EuroLarge

B.9 Randomly-Connected Networks (RCNs)

This section shows a sample of the RCNs used in Chapter 2. The alpha values may appear arbitrary, but represent unitary increments in *L* – this is every achievable value of alpha from *L*=15 to *L*=33. Reasons for choosing this range are discussed in Chapter 2 and not replicated here.

For reasons of space, only the first network representing each alpha value is shown, comprising 19 of the 38 networks used. Only one network was used representing the two extreme values as the target was the range of α (where the duplication in the middle was caused by *L* being rounded up or down) rather than *L*, as described in Chapter 2.

A sub-set of the illustrated networks were used in Chapter 3, as described there.

B.9.1 RCN with $\alpha = 0.16$

$n = 14$, $L = 15$, $\alpha = 0.16$, $\Delta = 2.14$.

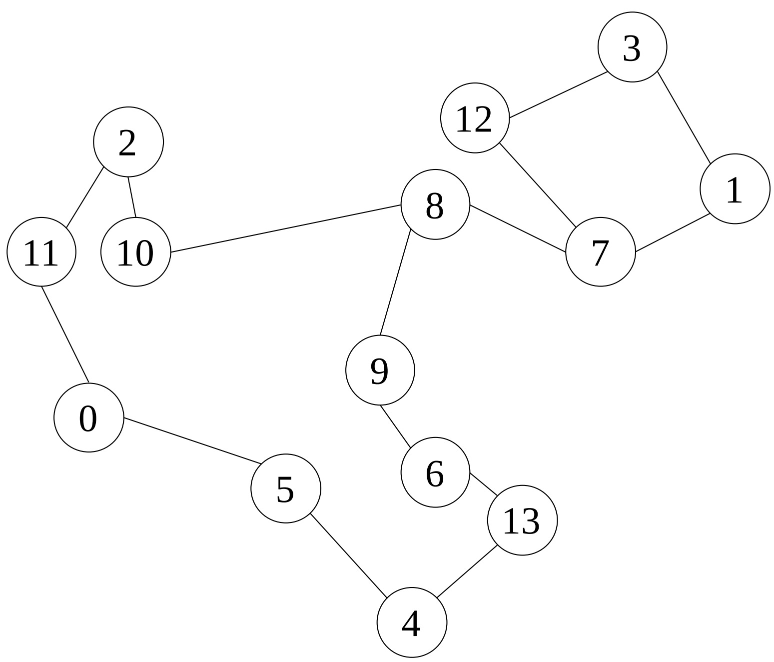

Figure B-9 RCN with α = 0.16

B.9.2 Sample RCN with $\alpha = 0.18$

$n = 14$, $L = 16$, $\alpha = 0.18$, $\Delta = 2.29$.

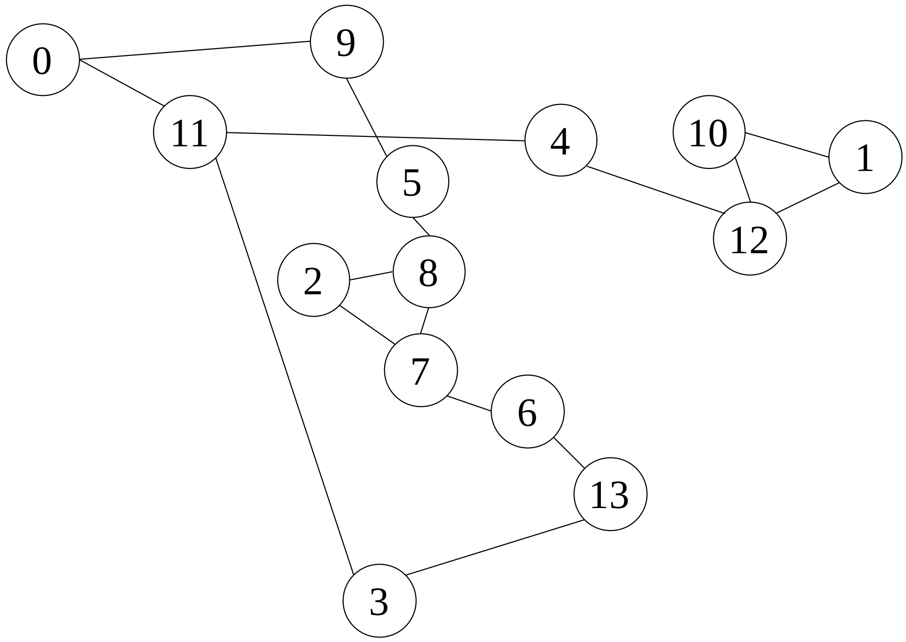

Figure B-10 Sample RCN with $\alpha = 0.18$

B.9.3 Sample RCN with $\alpha = 0.19$

$n = 14$, $L = 17$, $\alpha = 0.19$, $\Delta = 2.43$.

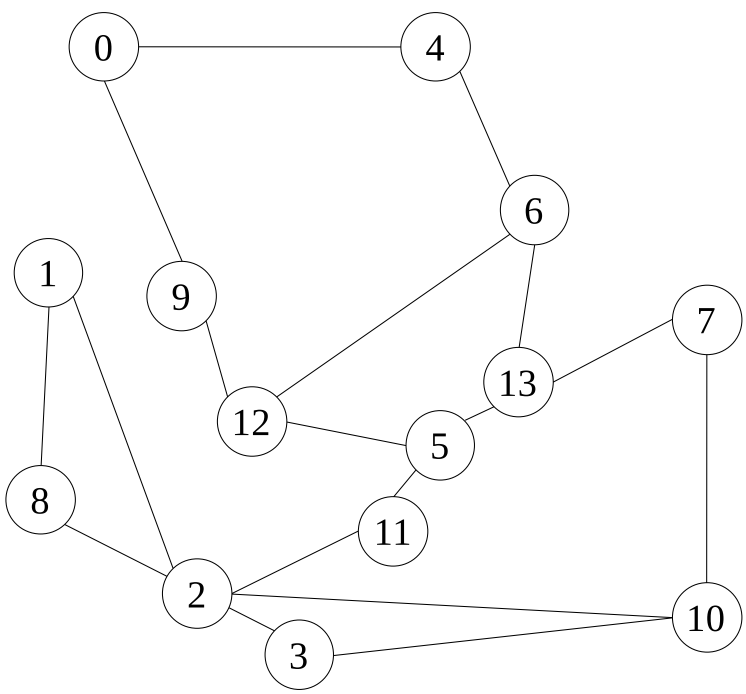

Figure B-11 Sample RCN with $\alpha = 0.19$

B.9.4 Sample RCN with $\alpha = 0.20$

$n = 14$, $L = 18$, $\alpha = 0.20$, $\Delta = 2.57$.

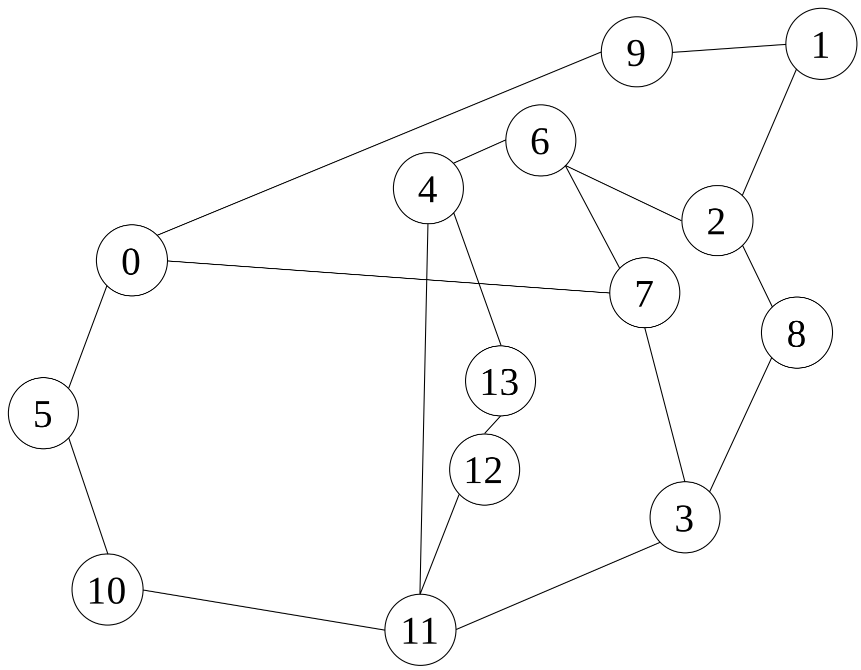

Figure B-12 Sample RCN with $\alpha = 0.20$

B.9.5 Sample RCN with $\alpha = 0.21$

$n = 14$, $L = 19$, $\alpha = 0.21$, $\Delta = 2.71$.

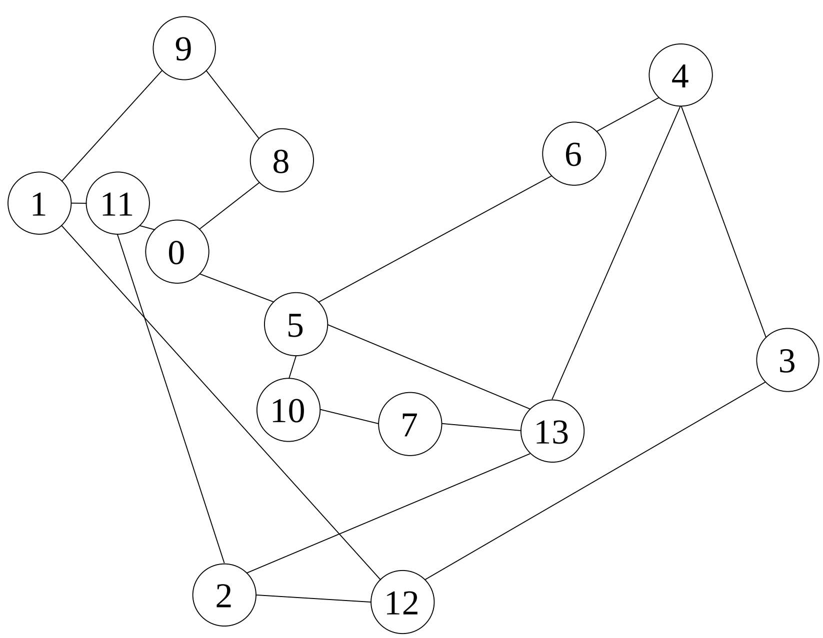

Figure B-13 Sample RCN with $\alpha = 0.21$

B.9.6 Sample RCN with $\alpha = 0.22$

$n = 14$, $L = 20$, $\alpha = 0.22$, $\Delta = 2.86$.

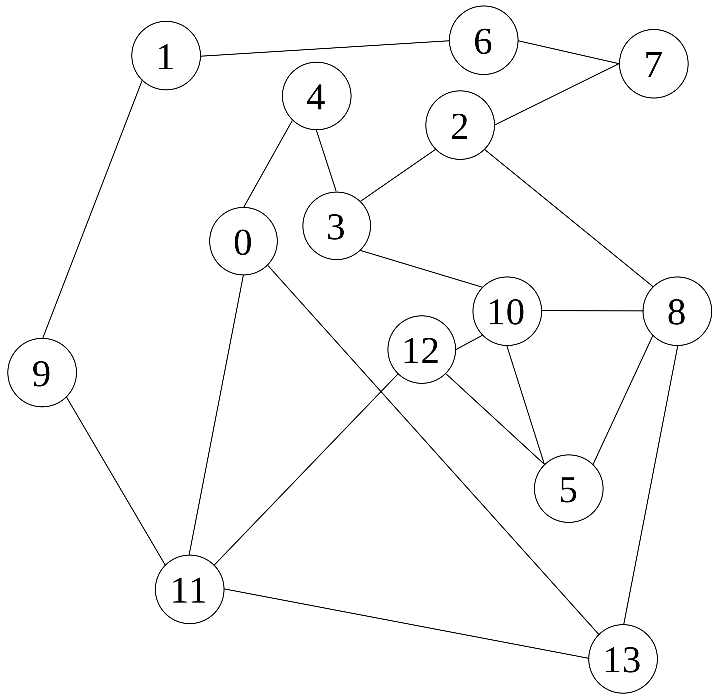

Figure B-14 Sample RCN with $\alpha = 0.22$

B.9.7 Sample RCN with $\alpha = 0.23$

$n = 14$, $L = 21$, $\alpha = 0.23$, $\Delta = 3.00$.

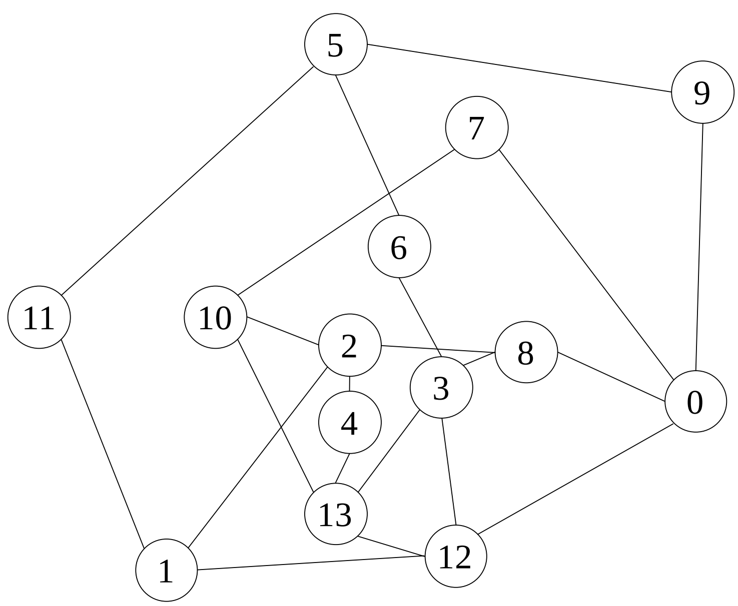

Figure B-15 Sample RCN with $\alpha = 0.23$

B.9.8 Sample RCN with $\alpha = 0.24$

$n = 14$, $L = 22$, $\alpha = 0.24$, $\Delta = 3.14$.

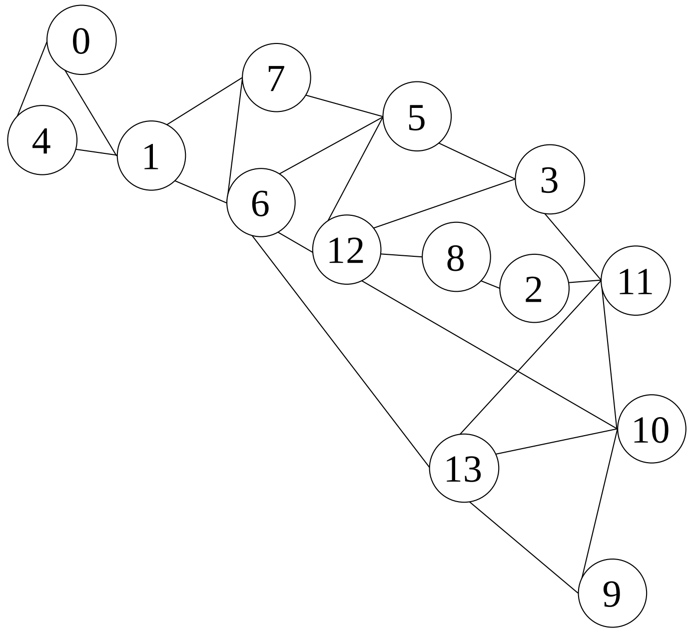

Figure B-16 Sample RCN with $\alpha = 0.24$

B.9.9 Sample RCN with $\alpha = 0.25$

$n = 14$, $L = 23$, $\alpha = 0.25$, $\Delta = 3.29$.

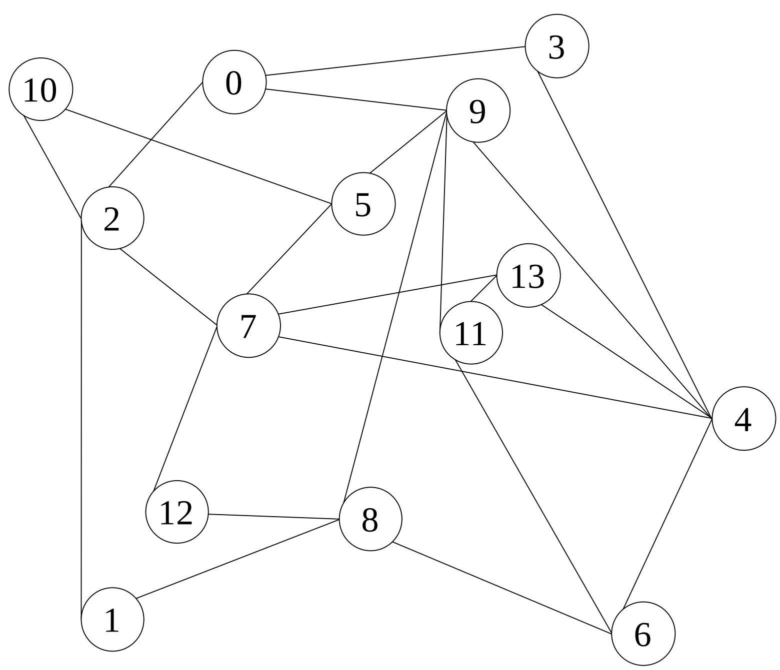

Figure B-17 Sample RCN with $\alpha = 0.25$

B.9.10 Sample RCN with $\alpha = 0.26$

$n = 14$, $L = 24$, $\alpha = 0.26$, $\Delta = 3.43$.

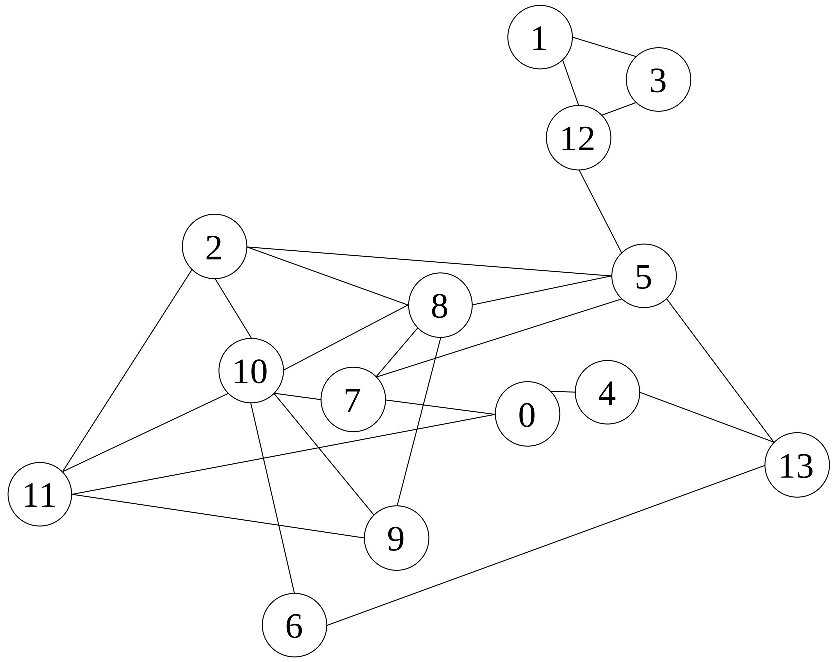

Figure B-18 Sample RCN with $\alpha = 0.26$

B.9.11 Sample RCN with $\alpha = 0.27$

$n = 14$, $L = 25$, $\alpha = 0.27$, $\Delta = 3.57$.

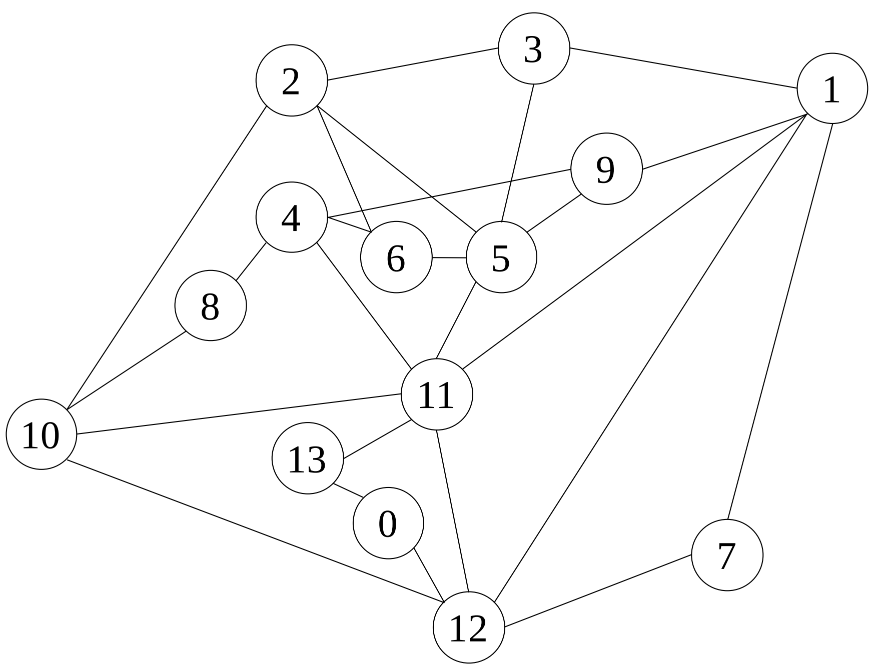

Figure B-19 Sample RCN with $\alpha = 0.27$

B.9.12 Sample RCN with $\alpha = 0.29$

$n = 14$, $L = 26$, $\alpha = 0.29$, $\Delta = 3.71$.

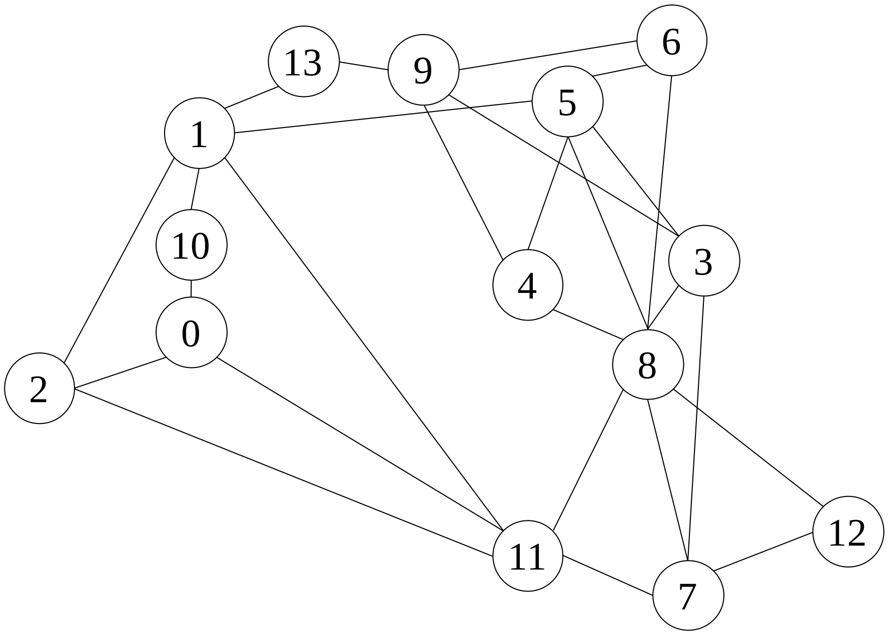

Figure B-20 Sample RCN with $\alpha = 0.29$

B.9.13 Sample RCN with $\alpha = 0.30$

$n = 14$, $L = 27$, $\alpha = 0.30$, $\Delta = 3.86$.

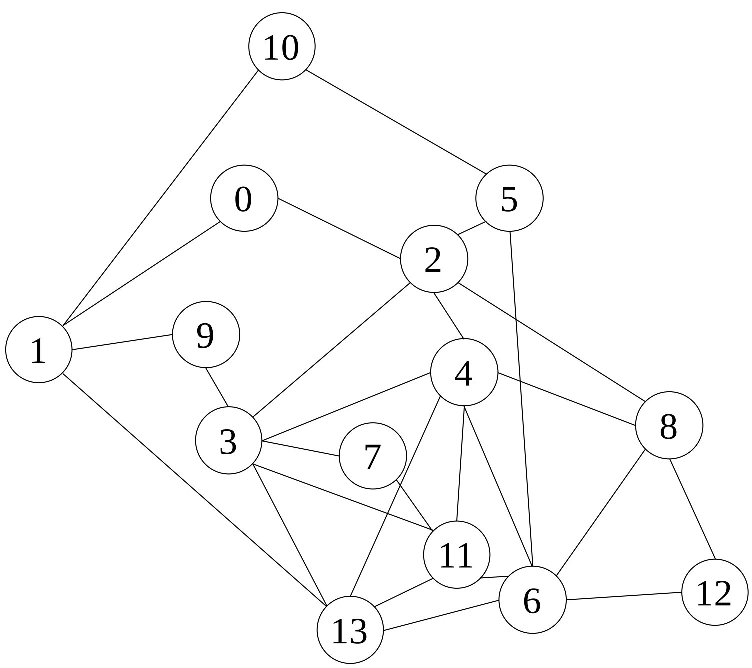

Figure B-21 Sample RCN with $\alpha = 0.30$

B.9.14 Sample RCN with $\alpha = 0.31$

$n = 14$, $L = 28$, $\alpha = 0.31$, $\Delta = 4.00$.

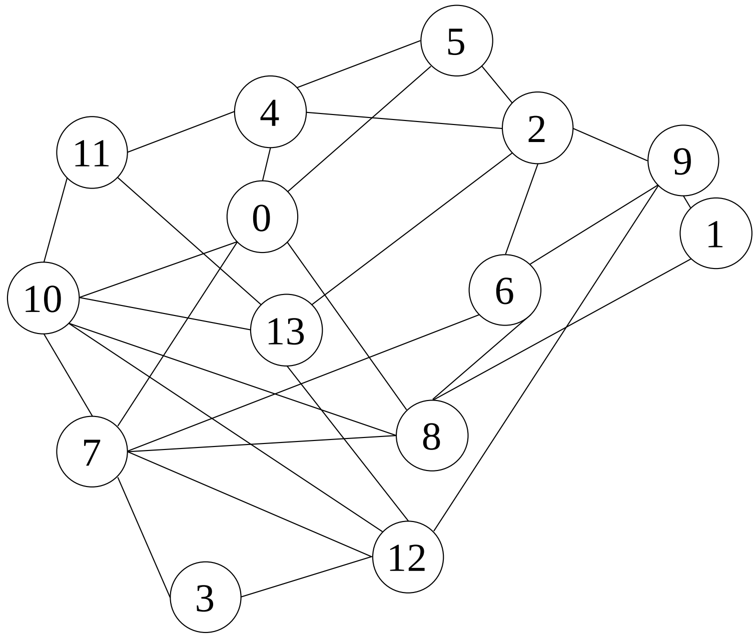

Figure B-22 Sample RCN with α = 0.31

B.9.15 Sample RCN with $\alpha = 0.32$

$n = 14$, $L = 29$, $\alpha = 0.32$, $\Delta = 4.14$.

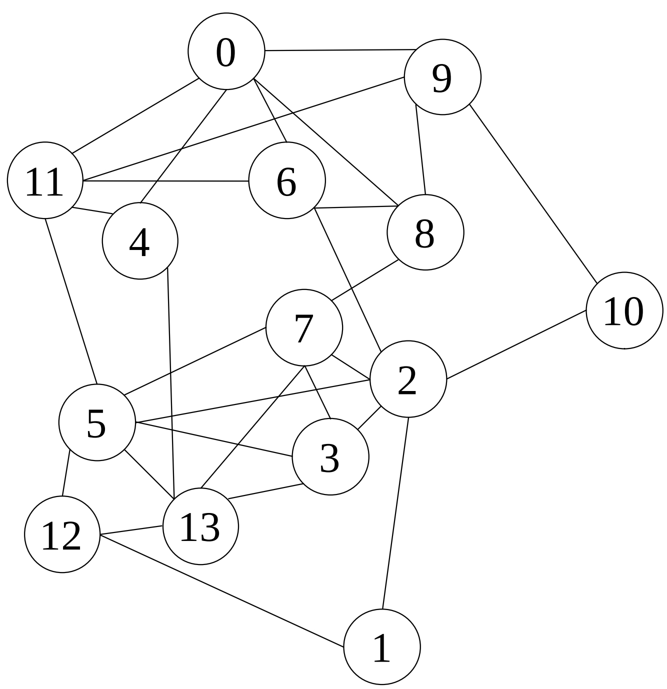

Figure B-23 Sample RCN with $\alpha = 0.32$

B.9.16 Sample RCN with $\alpha = 0.33$

$n = 14$, $L = 30$, $\alpha = 0.33$, $\Delta = 4.29$.

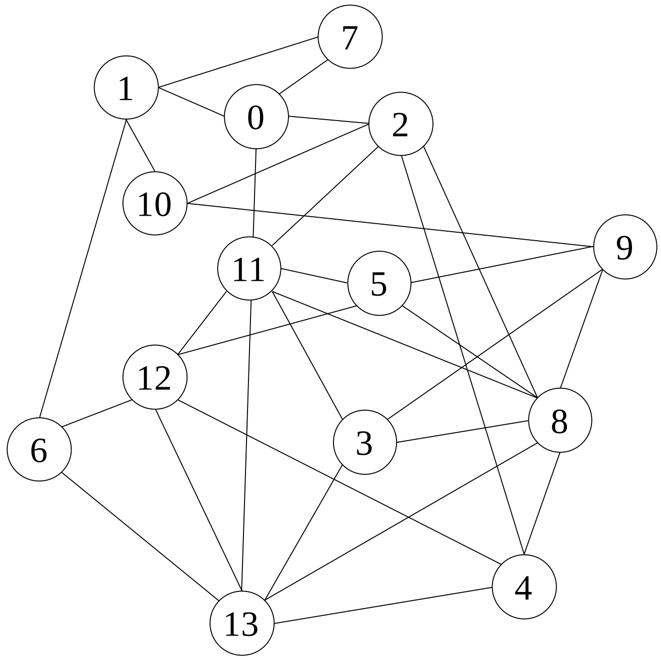

Figure B-24 Sample RCN with $\alpha = 0.33$

B.9.17 Sample RCN with $\alpha = 0.34$

$n = 14$, $L = 31$, $\alpha = 0.34$, $\Delta = 4.43$.

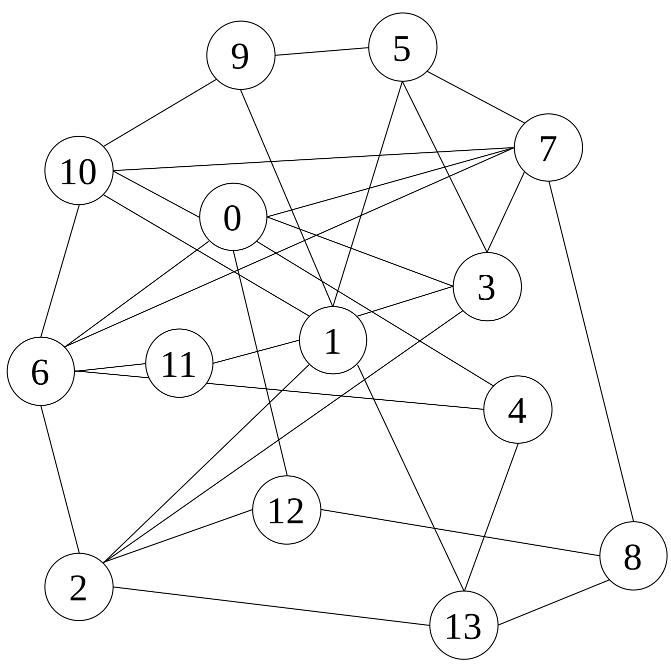

Figure B-25 Sample RCN with $\alpha = 0.34$

B.9.18 Sample RCN with $\alpha = 0.35$

$n = 14$, $L = 32$, $\alpha = 0.35$, $\Delta = 4.57$.

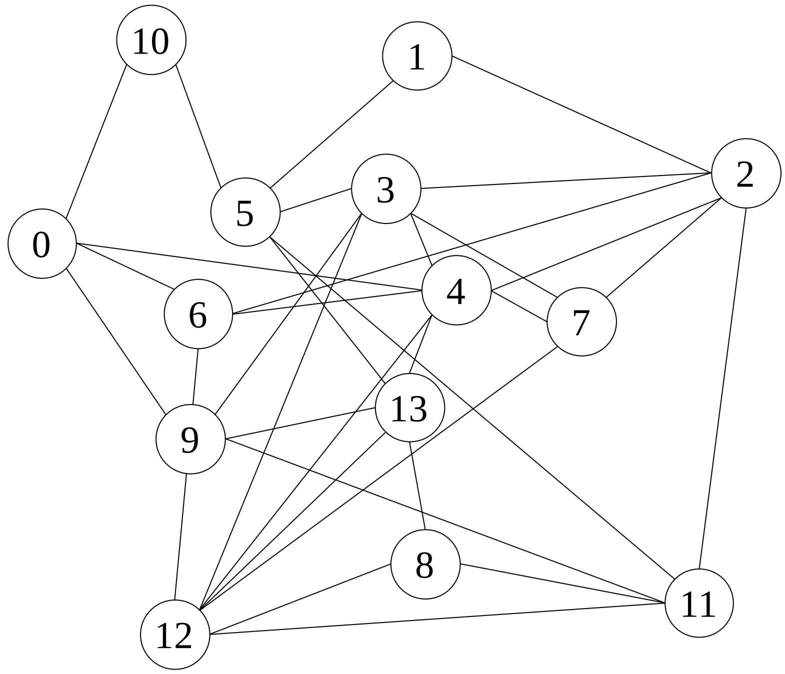

Figure B-26 Sample RCN with $\alpha = 0.35$

B.9.19 RCN with $\alpha = 0.36$

$n = 14$, $L = 33$, $\alpha = 0.36$, $\Delta = 4.71$.

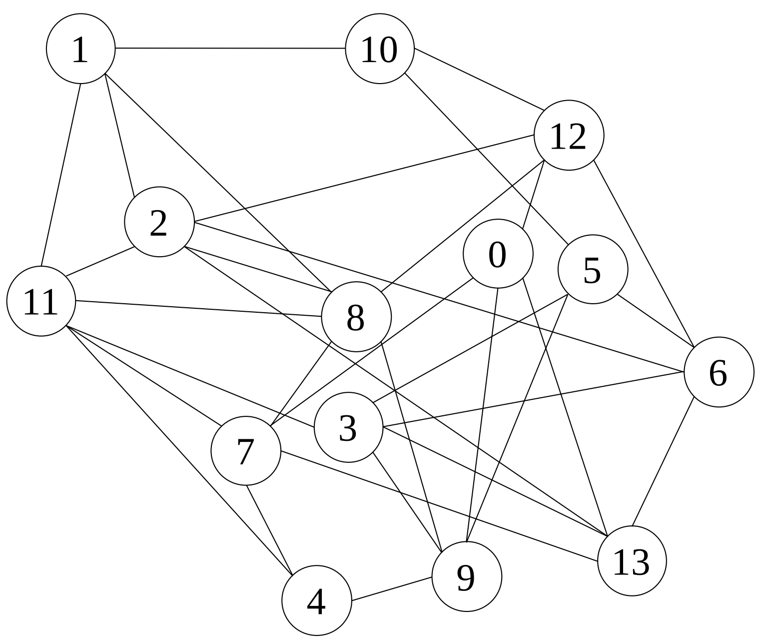

Figure B-27 RCN with $\alpha = 0.36$

B.10 Chapter references

[Myers 01] Alec Myers, "Architecture for Optical Burst Switching", MRes Thesis 2001, University College London.

[Baroni 96] S. Baroni, P. Bayvel, J. Midwinter, "Influence of physical connectivity on the number of wavelengths in dense wavelength-routed optical networks". Proc. Optical Fiber Communication (OFC) Conf. 1996, pp. 25-26.

[Baroni 98] Stefano Baroni, "Routing and wavelength allocation in WDM optical networks". PhD thesis, May 1998. University College London.

[Zapata-Beghelli 06] Alejandra Zapata-Beghelli, "Resource allocation and scalability in dynamic wavelength-routed optical networks". PhD thesis, 2006. University College London.

Appendix C Value of agility detailed results

This appendix provides the more detailed results referenced in section 3.4.7. Section 3.4.8 provides a summary.

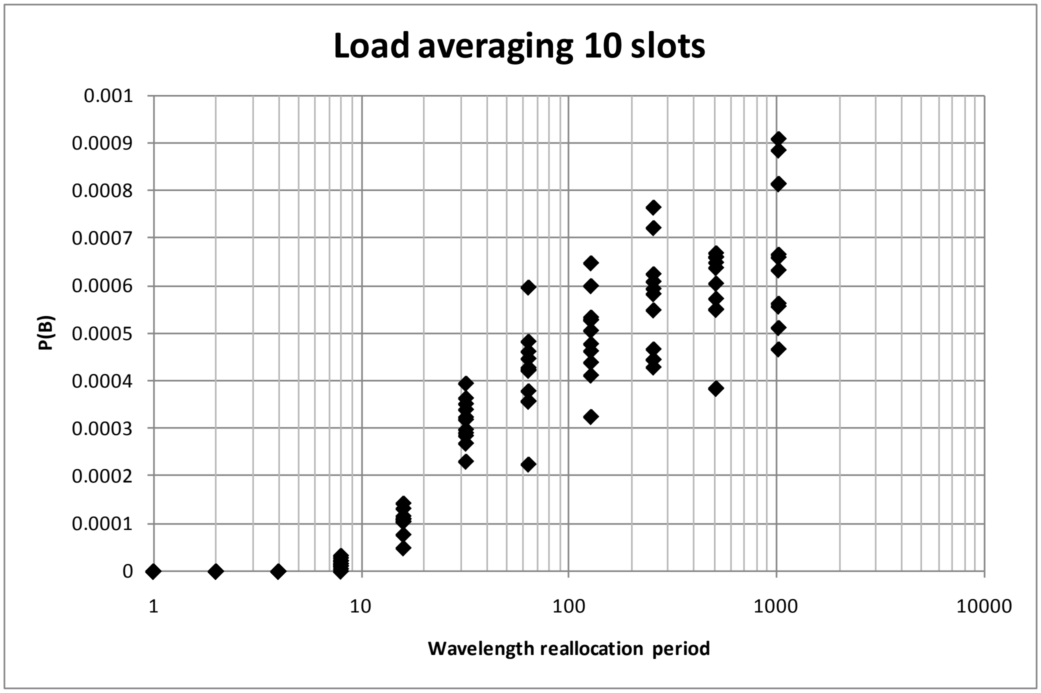

Figure C-1 Load averaging 10 slots/demand

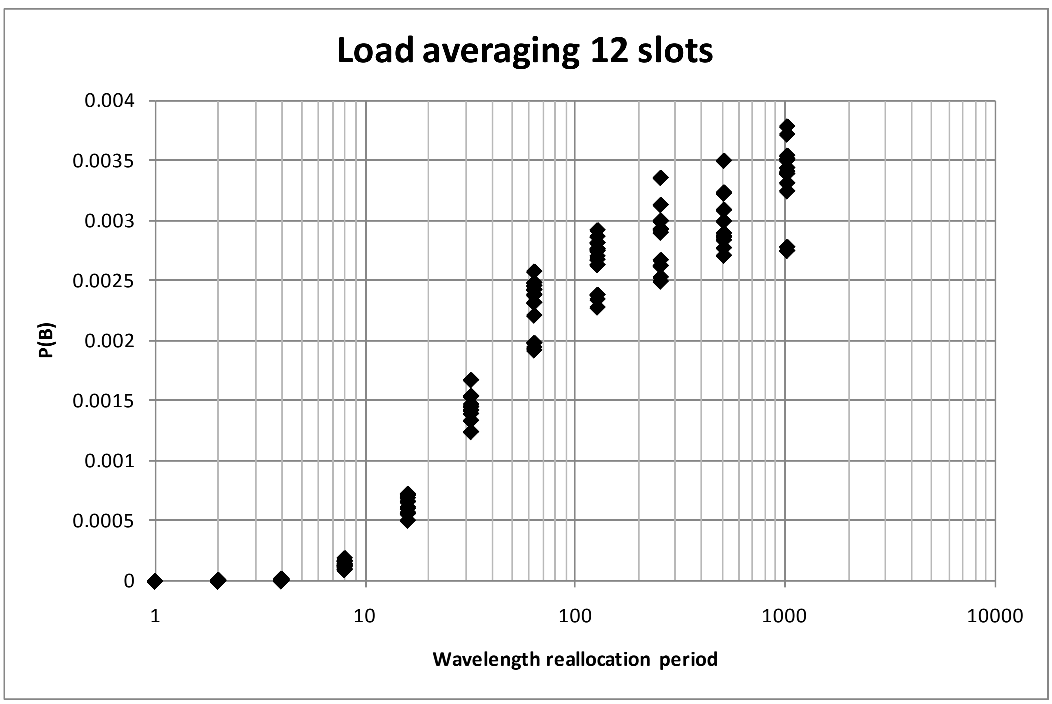

Figure C-2 Load averaging 12 slots/demand

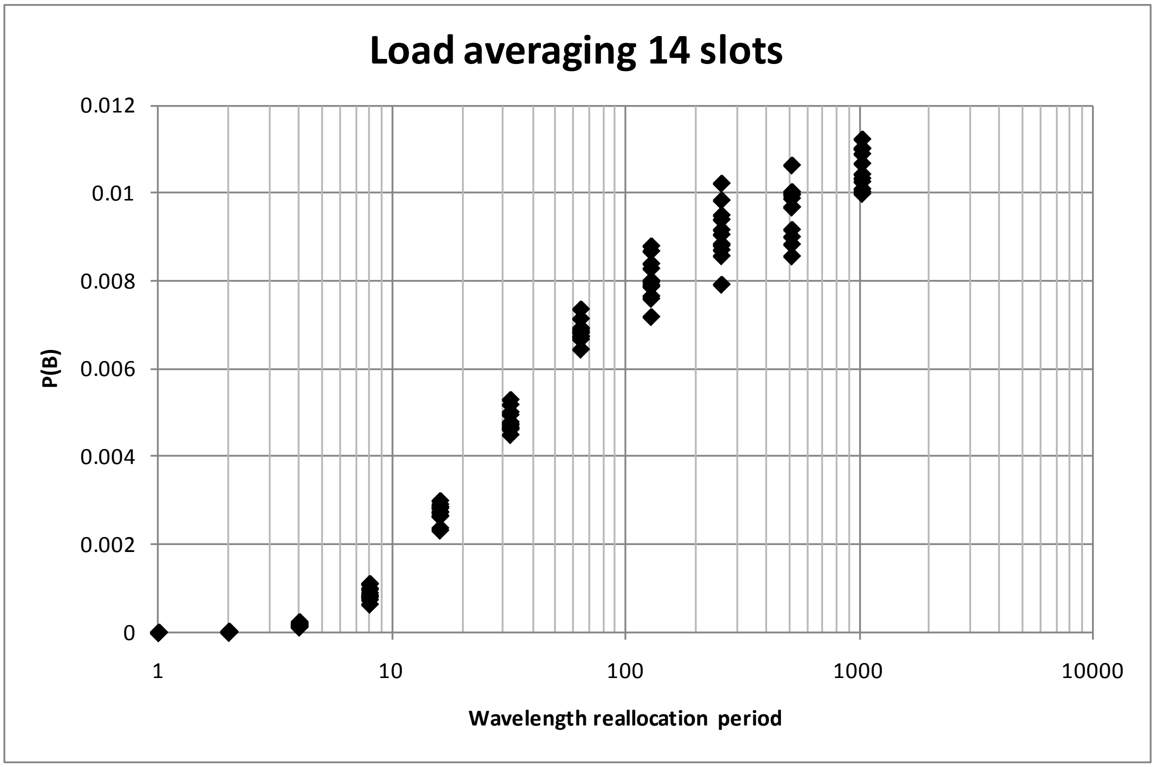

Figure C-3 Load averaging 14 slots/demand

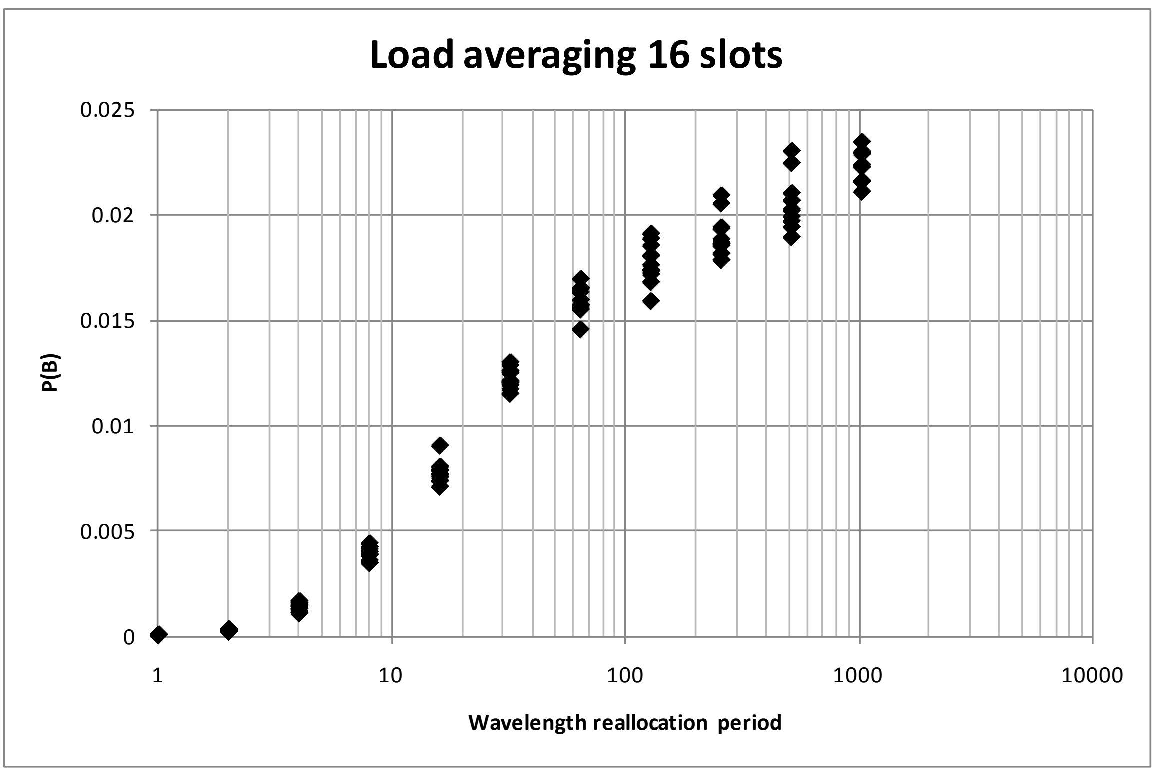

Figure C-4 Load averaging 16 slots/demand

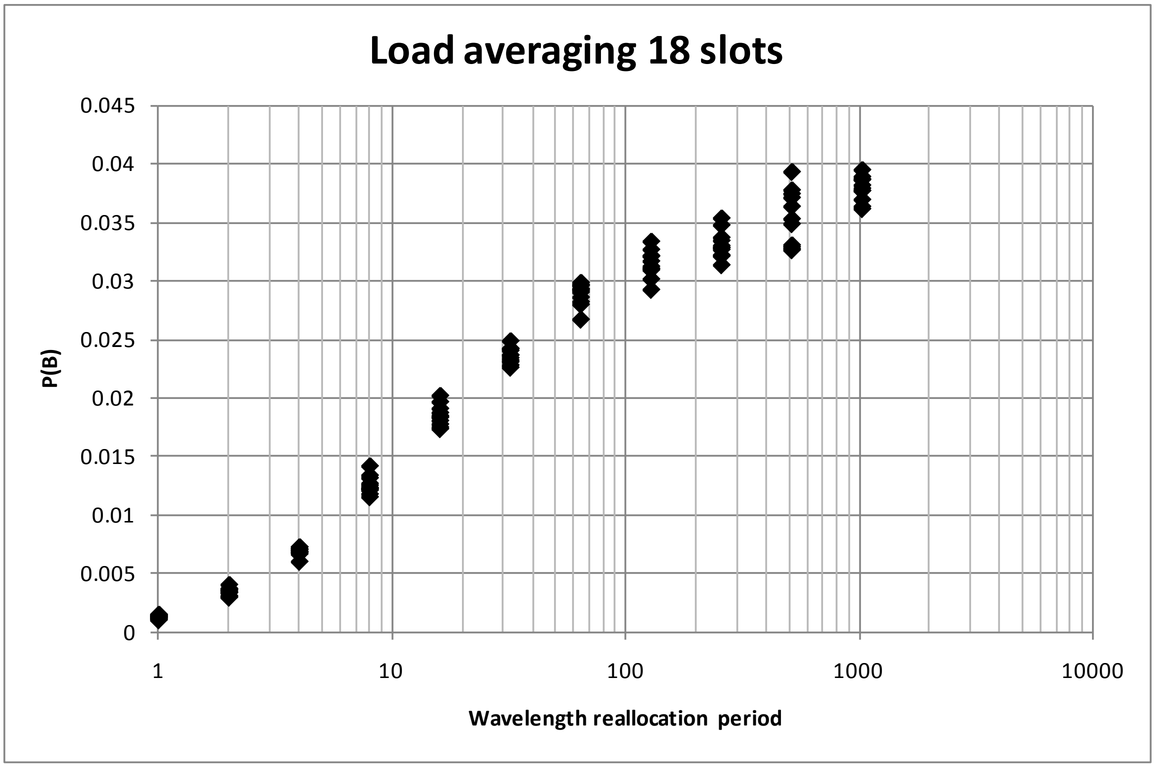

Figure C-5 Load averaging 18 slots/demand

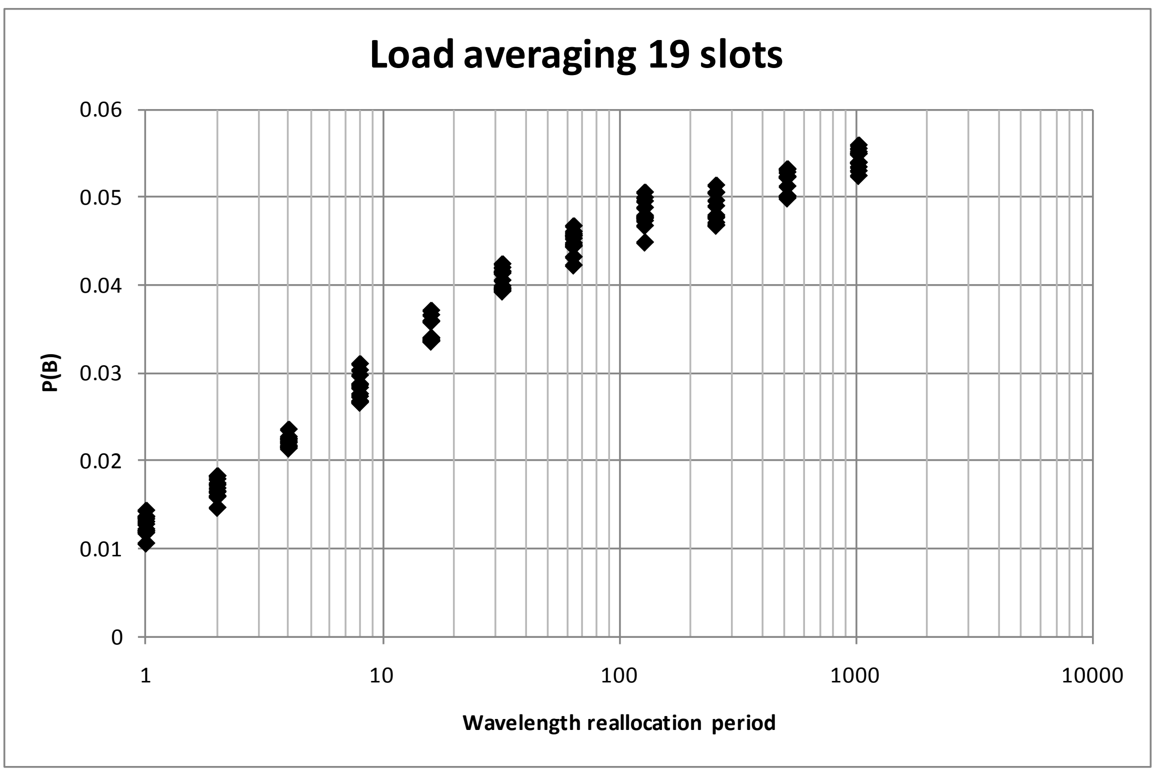

Figure C-6 Load averaging 19 slots/demand

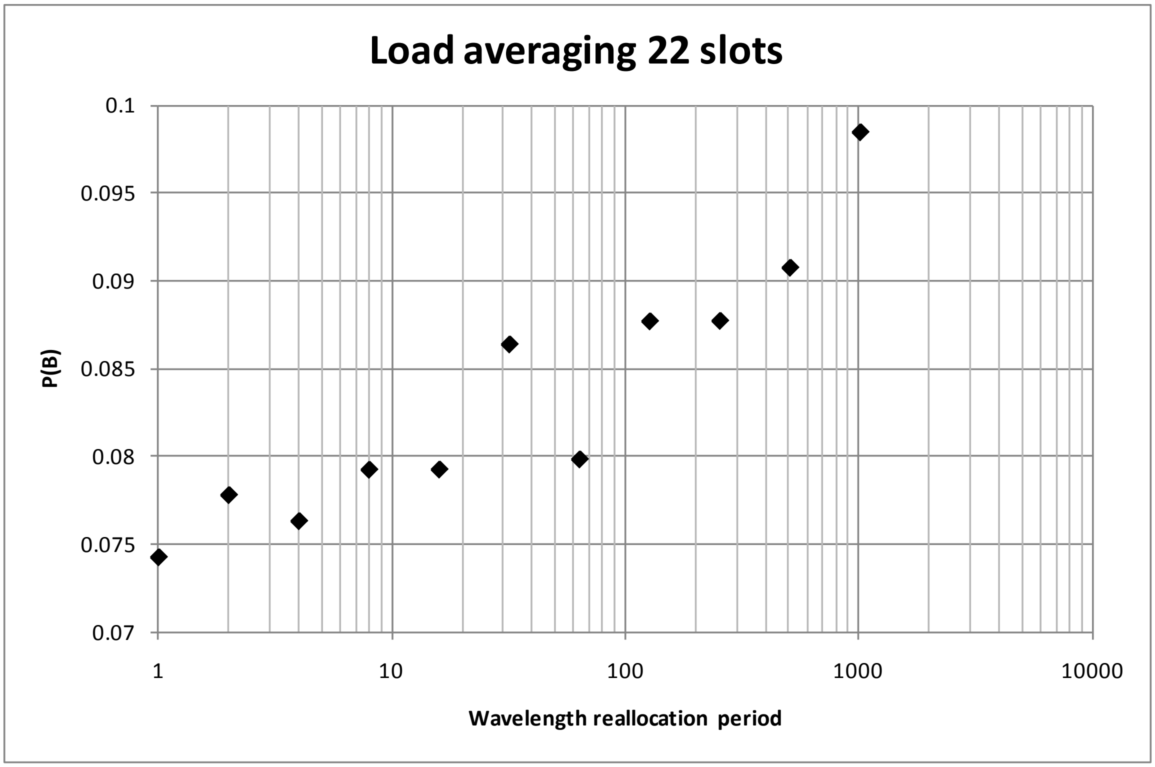

Figure C-7 Load averaging 22 slots/demand. Note non-zero y-axis origin.

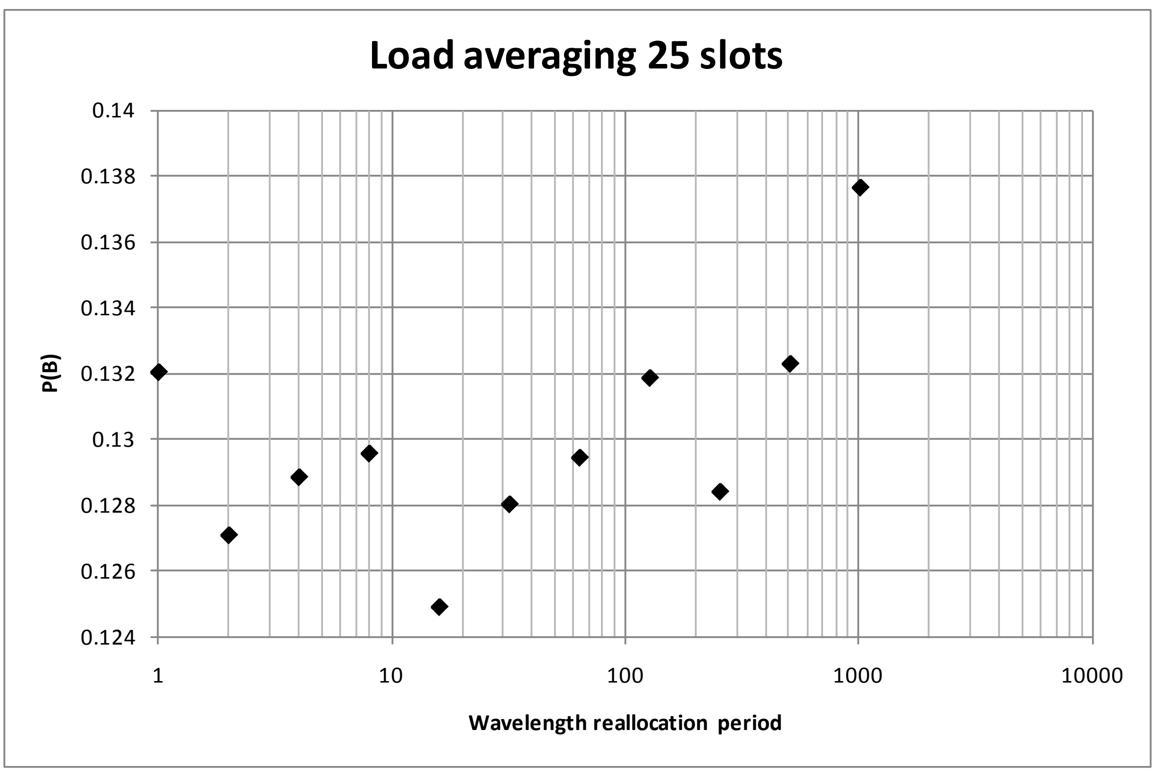

Figure C-8 Load averaging 25 slots/demand. Note non-zero y-axis origin.

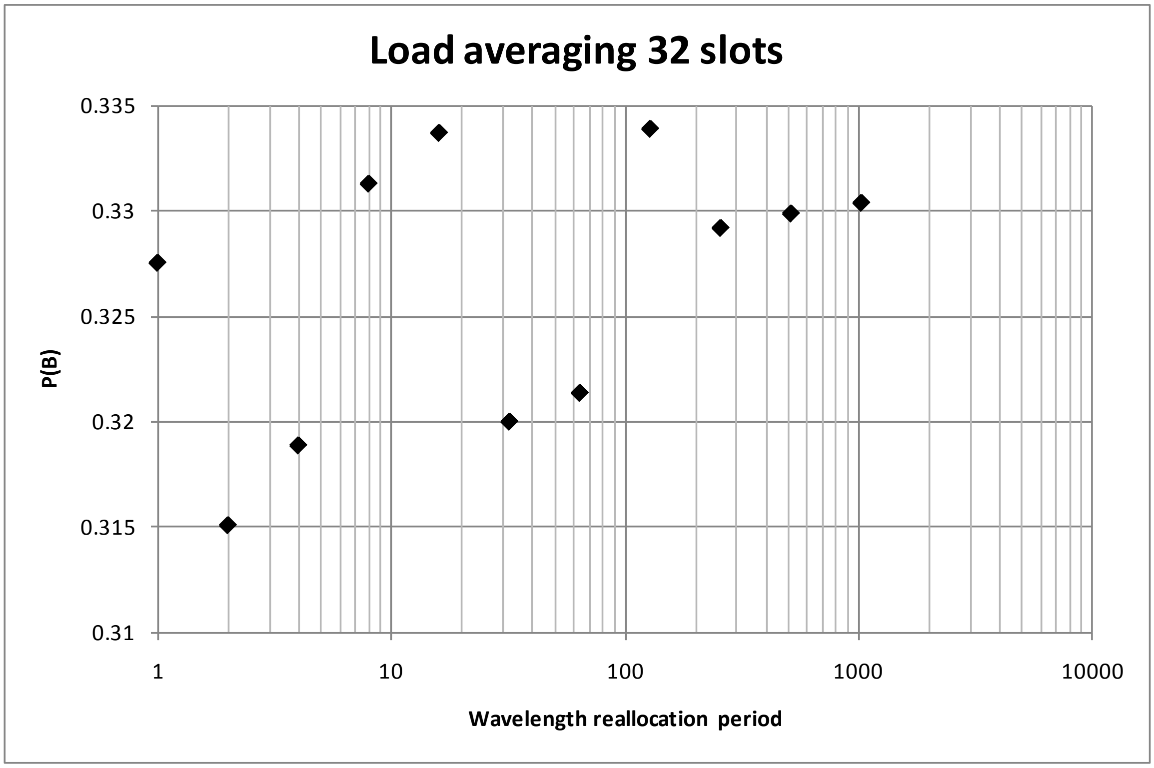

Figure C-9 Load averaging 32 slots/demand. Note non-zero y-axis origin.