was inserted into the groove and fixed in place with a UV-curable adhesive. The fiber-to-fiber insertion loss was 5.1 dB, including the 2 dB loss of the half-wave plate. The PDL remained at 0.2 dB. The driving voltage was 3.3 V DC (Fig. 4) and 4.5 V for 10 Gb/s signals. Fig. 4 shows that the same drive voltage and the drive point were obtained for each type of polarized input. The extinction ratio was 20 dB or more for both polarized input lights. An electrical 3-dB bandwidth was achieved at over 10 GHz.

4. Low drive voltage modulator
Current 40 Gb/s modulators require a drive voltage of about 5 V for single-drives and 3 V for dual-drives. Low drive voltage is required to reduce the cost, size and power consumption of 40 Gb/s transmitters.

We optimized the structure of the dual-drive modulator to reduce the drive voltage [3]. We measured Vπ and microwave attenuation and obtained their dependency on the interaction length and the gap between signal and ground electrodes. From these data, we found that a wide-gap and long electrode was effective for a low drive voltage. We defined the interaction length of 60 mm and gap of 50 µm that were twice as large as those of conventional modulators.

We fabricated and packaged a dual-drive modulator with a novel design. The optical fiber to fiber insertion loss was 6 dB and the extinction ratio 27 dB, these values being suitable for practical use. Fig. 5 shows the S-parameters and the optical response. The 6 dB bandwidth of S21 was 30 GHz. The S11 was low enough because impedance matching was obtained. An effective refractive index of 2.15 was estimated from the S21 response. The 6 dB bandwidth of optical response was 28 GHz. Eye diagrams of the driving signal and optical output in a PRBS 231-1 are shown in Fig. 6. Clear eye openings were obtained with a drive voltage of 0.9 V.

5. Conclusions
I believe that LiNbO3 modulator will continue to be a key device in future high speed and long haul communication systems. Therefore the small size and low cost are considered to be more important especially in the WDM systems.

References
The technique could in principle be useful to increase the repetition rate of several lower rate sources and share the upgrade cost of the FPF and SOA between them. This is especially since a single FPF may multiply simultaneously the repetition frequency of several laser sources and since single SOAs have been shown in multi-wavelength amplification [7] and multi-wavelength sources [8].

2. Concept and Experimental Setup

Fig. 1 shows the experimental layout of the proposed optical source. The initial pulse train was generated with a DFB laser source gain switched at 9.97163 GHz at 1549.2 nm, producing 8.8 ps pulses after linear compression in a DCF fiber of total dispersion of -54.27 ps/λ. These pulses were then nonlinearly compressed in a two-stage fiber compressor comprising of an EDFA and alternating sections of DSF and SMF fiber, so that after filtering in a 2 nm filter the signal pulses had a temporal width of 3.2 ps. The compressed pulse train was next further amplified and fed into the Fabry-Perot filter. The FPF was a coated fused quartz substrate with FSR equal to 39.88652 GHz and a modest finesse of 50. Assuming that the input to this FPF is the initial pulse train, its output is a periodic sequence of 4 pulses that are exponentially decreasing amplitudes and these are alternately filtered in a SOA between them. This is especially since a single SOA can multiply simultaneously the repetition rate of several lower rate sources. The technique could in principle be useful to increase the repetition rate of several lower rate sources and share the upgrade cost of the FPF and SOA between them.

3. Results and Discussion

VOA1 and VO2 were adjusted to provide 850 µW and 80 µW of power for the first and second pass respectively. At this input power the first pass through the SOA results in its heavy saturation and sets its point of operation in the non-linear regime. Pulses passing through the SOA for the second time and with the ODL adjusted so that the pulses meet with their respective pairs in amplitude in the SOA, the pulses experience the saturated gain and modify it slightly so as to have their amplitude modulation nearly, totally, eliminated. Fig. 2 shows the pulse trains at the output of (a) the fiber compressor, (b) the FPF, (c) after the first pass through the SOA and finally (d) after its second pass. Monitored on a 40 GHz photodiode and sampling oscilloscope, the amplitude modulation, defined as the ratio of higher to lower pulse, after the FPF was measured to be 1.65 dB, after the first pass through the SOA reduces to

Fig. 1. Experimental setup. FPF: Fabry-Perot Filter, FRM: Faraday Rotator Mirror, ODL: Optical Delay Line.

The technique is simple and lends itself to be employed for the easy upgrade from 10 GHz to 40 or higher repetition rates of laser sources, using one passive and one active (but dc driven) component and without the need for any high frequency microwave driver circuits and amplifiers.

Fig. 3. RF Spectra at the (a) Output of the Compressor, (b) Output of the Fabry-Perot filter and (c) Output of the 40 GHz Pulse Source. Amplitude Scale is 10 dB/div and Frequency Scale is 4 GHz/div.

Fig. 6. Eye diagram at 40 Gb/s.

Fig. 2. (a) Compressor output, (b) Fabry-Perot filter output, (c) Output after first SOA pass (d) Output after second SOA pass and (e) Second harmonic autocorrelation trace with the white dots indicating the fitted profile.
0.8 dB and finally is reduced to 0.15 dB.


We describe an optical frequency shifter that uses two 4-channel multiple quasi-phase-matched LiNbO3 wavelength converters. We obtained ten different outputs by varying the pump wavelength combination for the two wavelength converters.

1. Introduction

An all-optical wavelength converter is a key device for constructing future large-capacity and flexible wavelength-division multiplexed (WDM) networks. We have fabricated quasi-phase-matched (QPM) wavelength converters based on difference frequency generation (DFG) in periodically poled LiNbO3 (LN) crystals. These are promising because of their novel features, such as the simultaneous conversion of multiple WDM channels, high-efficiency, low noise, and transparency as regards bit-rate and data format [1]. We have already reported a dual-conversion optical frequency shifter (DC-OFS) that employs two QPM-LN wavelength converters [2]. This DC-OFS provides WDM signals with a uniform optical frequency shift from the input signal. We fabricated two 4-channel optical frequency shifters, with nearly the same amount of shift, by using two 4-element DFB lasers. Therefore we can obtain 10 different shifts in the QPM-LN wavelength converters with an appropriate frequency difference between the two pump lights.

2. Concept of DC-OFS

The DC-OFS is based on double wavelength conversion using DFG in QPM-LN wavelength converters. Figure 1 is a schematic drawing of the principle of the DC-OFS when it is operated in a cascaded-scheme. When a pump light (pump1) and a signal light (signal2) are injected into a QPM-LN wavelength converter, the pump light generates a second-harmonic (SH) light (2pump1). A converted signal light, νcomb (= 2νpump1 − νsignal2), is then generated by means of a parametric interaction between the SH light and the signal light. In multi-channel-conversion, each channel is converted in accordance with the relation described above [see Fig. 1(a)]. When two pump lights, νpump2 (= νsignal + A), and a signal light, which is the signal converted in the first conversion, are injected into a second QPM-LN wavelength converter, the frequency difference between the first input signal and the second converted signal is twice the large-pump light frequency difference [Fig. 1(b)]. This system provides a uniform frequency shift (2A) for all the input lights without changing their order in the wavelength dimension.

In conclusion, various number and frequency spacings can be designed and devised in the multiple QPM structure. The number of different shift destinations can be increased up to Mn by utilizing multiple QPM-LN wavelength converters for M- and N-channel multiple QPM conditions for the first and second conversions, respectively. The magnitude of the frequency shift can be varied in accordance with the optical frequency difference between the two pump lights.

3. Experimental

3.1 Fabrication

We used a 3-inch z-cut non-congruent LN substrates to fabricate the QPM-LN wavelength converters. The substrates were periodically poled by means of an electric field. The poling periods were 14.75 µm. Phase of the periodic poling was continuously modulated in order to satisfy the QPM condition at 4 different wavelengths. A typical structure is fabricated using the annealed proton exchange (APE) method. After proton exchange in pure benzoic acid using a SiO2 mask, the substrate was annealed in an oxygen atmosphere. We fabricated two types of 4-channel QPM-LN wavelength converter, one with a 210 GHz spacing, and the other with a 420 GHz spacing.

3.2 Experimental setup

Figure 2 is a schematic diagram of the experimental setup. All the light sources were CW tunable semiconductor lasers. We used a 64.4 GHz signal source (pump 1) amplified by an erbium-doped fiber amplifier (EDFA). Two pump lights, where A = 210 GHz, were injected into the first QPM-LN wavelength converter through a mode coupler. The converted signal lights in the L-band were used as input signals in the second conversion through an L-band-pass filter. Two input signal lights in the L-band and the pump light (pump 2) were amplified by two 4-channel EDFAs, and injected into the second QPM-LN wavelength converter. Signal lights converted in the second conversion were measured by an optical spectrum analyzer.

The operating temperatures were 100.5°C and 102.2°C for the first and the second QPM-LN wavelength converters, respectively. Each QPM-LN wavelength converter was excited by one different pump wavelengths. The wavelengths of pump 1 were 1548.6, 1550.3, 1552.0, and 1553.7 nm, and the wavelengths of pump 2 were 1547.0, 1550.3, 1553.7, and 1557.0 nm. Figure 2(b) shows the relation between the two pump lights, where A = 210 GHz. The individual pump wavelengths were denoted as 1a, 1b, 1c, and 1d for pump 1, and 2a, 2b, 2c, and 2d for pump 2. In this case, the 4x4 combination of two pump lights provides 10 patterns of frequency differences because some combinations exhibit the same values. Therefore we can obtain 10 different shifts from this DC-OFS by utilizing different combinations of the two pump wavelengths. The maximum number of patterns, (16), for the DC-OFS utilizing two 4-channel QPM-LN wavelength converters is provided by varying the wavelength and the spacing of the multiple QPM structures.

4. Results and discussion

First, we measured the spectra after the two 4-channel QPM-LN wavelength converters to confirm the principle of the DC-OFS. Figure 3(a) shows the output spectra after the first converter for 4 different pump wavelengths. It can be seen...
that the input signal was converted in accordance with the wavelength of pump 1. Figure 3(b) shows the output spectra after the second conversion when the input was the longest wavelength signal converted in the first conversion. A pump wavelength shift by 420 GHz relocated the converted signal by 840 GHz. We also confirmed that the remaining three signals converted in the first conversion could be converted appropriately by the second conversion.

Figure 4 shows the output spectra of the DC-OFS. We succeeded in demonstrating all the conversions of the 4x4 combination shown in Fig. 2(b). Note that the amount of shift is twice as large as the frequency difference of the two pump lights. All the signals exhibited a 420 GHz spacing from -10A to 10A with a reasonably small deviation resulting from the fact that the pump wavelengths were not tuned precisely. The magnitude of the shift agreed well with that expected from the principle. The direction of the shift was blue, red, and "0", and the output wavelength range was as broad as 30 nm.

Although we used one channel for the input signal in this study, it is clear that the DC-OFS can be operated with multi-channel inputs or a variable input [2]. Since the number of QPM structures in a single device for practical use is limited by the efficiency of the QPM-LN wavelength converter, the use of two multiple QPM-LN wavelength converters is an attractive way of providing flexibility with this type of DC-OFS.

### References
3. A 10 GHz, 5 ps pulse stream (λ₀=1554.8 nm) was wavelength converted in a Ti:PPLN channel waveguide by exploiting CSFG/DFG. The wavelength shift could be optically controlled in a 15 nm wide range by the wavelength of a control beam.

### Numerical Analysis
Fig. 1 shows the schematic diagram of the operation principle of the device exploiting CSFG/DFG process. In this process, five different waves interact with each other simultaneously in the Ti:PPLN channel waveguide. The signal (λ₀) and the pump (λₚ) generate the sum frequency (λₛ) perfectly phase matched. At the same time, a control wave (λₗ) interacts with the sum frequency wave (λₛ) to facilitate reconfigurable dynamic wavelength routing [1]. Cascaded three-wave mixing (2(2), 2(3)) processes in periodically poled LiNbO₃ (PPLN) waveguides are most promising to realise all-optical wavelength conversion with high efficiency. Two different methods have been demonstrated including cascaded difference frequency generation (cDFG) [2] and cascaded sum and difference frequency generation (cCSFG/cDFG) [3]. cDFG offers a wide range of transparency, negligible excess noise due to spontaneous parametric emission, a high conversion efficiency and polarization independent operation [4]. However, fast all-optical tuning of the wavelength shifted signal is not possible [5]. In order to achieve optically tunable wavelength conversion, we recently proposed and experimentally demonstrated wave length conversion and tuning based on CSFG/DFG [3]. Two cw pump waves of different wavelengths were used to convert a cw signal to the sum frequency and to generate a wavelength shifted idler by subsequent DFG with the second pump. As a consequence, the idler wavelength can be tuned by changing the wavelength of the second pump.

In this contribution, we demonstrated for the first time tunable all-optical wavelength conversion of 5 ps pulses based on CSFG/DFG in a single Ti:PPLN channel waveguide. The device was numerically analysed and wavelength conversion and tuning was experimentally demonstrated.
generate an idler ($\lambda_0$) by DFG. However, this process is slightly phase mismatched, but obeys of course energy conservation $1/\lambda_{sf} = 1/\lambda_i + 1/\lambda_c$. This relation is plotted as dashed line in Figure 1(b) for fixed $\lambda_p$. Though not ideally phase matched the DFG conversion efficiency is only slightly reduced in comparison to a phase matched interaction. For the numerical calculations, signal pulses ($\lambda_s$) were assumed as Gaussian-type 5 ps pulses with 10 GHz repetition rate; pump and control were considered as cw waves. The coupled wave equations for the nonlinear optical processes were numerically solved using a fast fourier transform (FFT) split-step propagation method. The (average) input power of the signal was 7.7 mW, the control power was assumed to be 161 mW as in the experiments. The length and width of the Ti:PPLN channel waveguide were assumed to be 6 cm and 7 µm, respectively. 19 pm/V was taken as $d_{33}$ value of LiNbO$_3$ and optical losses for infrared and sum frequency waves were assumed to be 0.15 dB/cm and 0.3 dB/cm, respectively.

Fig. 2 (a) presents the calculated sum frequency and idler power, respectively, as function of the pump power. The inset gives a magnified characteristic at low pump power levels to allow a comparison with experimental results. The maximum idler power of 2.6 mW is achieved with 150 mW of pump power. Fig. 2 (b) shows the temporal evolution of the idler pulse along the waveguide. The broadening of sum frequency and signal/idler pulses is due to the group velocity mismatch (3 ps/cm). At the output, the pulse width is 9 ps. The conversion efficiency defined as the ratio of generated idler power to the input signal power is -4.8 dB at 150 mW of pump power.

Experimental results and discussion

To demonstrate all-optical wavelength conversion by cSFG/DFG, a 8-cm-long Ti:PPLN channel waveguide of 16.6 µm microdomain period was fabricated. One side of the sample was angle polished in order to avoid internal multiple reflections. Phase matching wavelength and conversion efficiency for second harmonic generation (SHG) are 1549.45 nm and 650%/W, respectively, at 153.3°C. The effective nonlinear interaction length is -6 cm calculated from the SHG bandwidth of $\Delta\lambda=0.18$ nm; the waveguide propagation losses are 0.15 dB/cm around $\lambda=1550$ nm.

Figure 3 shows the schematic diagram of the experimental set-up. Transform limited gaussian pulses ($\lambda_s=1554.82$ nm) of 5ps width and 10 GHz repetition rate of a mode-locked fiber laser were combined by a 3 dB-coupler with the cw pump wave ($\lambda_p=1544.12$ nm) of an extended cavity semiconductor laser (ECL1) and amplified simultaneously by an EDFA. The control wave delivered by the ECL2 was amplified by a high power EDFA (HP-EDFA). Amplified spontaneous emission (ASE) was to a large extent suppressed by a tunable band pass filter. All three waves were polarisation-controlled by fiber optic polarisation controllers (PC). They were superimposed by another 3 dB-coupler and launched together into the channel waveguide by fiber butt-coupling. The transmitted signal, pump, and generated idler were observed as function of the wavelength using an optical spectrum analyser. Fig. 4(a) shows the optical spectra for three different wavelengths of the control wave measured with 2 nm resolution; averaged optical power levels are given. The coupled (peak) power of signal and control were adjusted to be equal (161 mW). The coupled pump power was 2.8 mW. Pump and signal generate optical pulses at $\lambda_{sf}=774.7$ nm by SFG. These pulses serve as pump for the DFG-process with the control wave; idler pulses are generated. Their (calculated) evolution along the waveguide is shown in Fig. 2(b). The idler wavelength changes with the control wavelength according to energy conservation (see Fig 4a). Due to group velocity dispersion the idler pulses are broadened to about 9 ps half width according to our calculations. The average idler power was measured to be -24.6 dBm. Figure 4(b) shows the average idler power as function of the control wavelength together with a calculated normalised response. The wavelength of the control wave could be tuned from 1552.65 nm to 1567.30 nm.
Wavelength Converter Operating on Strict Frequency Grid Using a Single Side Band Optical Modulator in a Circulating Loop

A. Takada, NTT Network Innovation Laboratories, NTT Corporation, Yokosuka, Kanagawa, Japan; E. Yamazaki, J. Park, NTT Network Innovation Laboratories, NTT Corporation, Yokosuka, Kanagawa, Japan. Email: takada@exa.onlab.ntt.co.jp.

A wavelength converter and a variable wavelength light source that operate on strict frequency grid are proposed and demonstrated using a single side band optical modulator in a re-circulating fiber loop configuration.

1. Introduction

Wavelength conversion is attracting considerable attention for use in photonic routers that must be capable of setting "virtual wavelength paths" [1]. To date, many kinds of wavelength conversion techniques have been proposed: Optical-Electrical-Optical (OEO) conversion, cross gain modulation using nonlinear materials such as semiconductor optical amplifiers and optical fibers, and parametric conversion using χ(2) or χ(3) effect in parametric materials. Optical frequency shift type-wavelength conversion using a single side band (SSB) electrooptic modulator (EOM) [2-3] has several attractive features. It needs no other light source, its operation is independent of the optical modulation format of the input signal light, and it has capability of strict frequency shift identical to the modulation frequency injected into the EOM. However, the frequency shift is limited by the modulation-bandwidth of the EOM and driving circuit. This paper introduces a novel configuration for a wide-band wavelength converter that uses an SSB optical modulator in a fiber loop. The optical frequency of the input signal light shifts successively as the light circulates the loop. Therefore, a large degree of frequency shifting on a strict frequency grid is obtained.

The proposed configuration is also useful for a wide-band variable-wavelength light source or optical frequency comb generator. Experimental demonstrations show error-free 375 GHz frequency shift for wavelength conversion and 3.7 THz-wide variable-wavelength light source.

2. Configuration and principle

The configuration of the wavelength converter is shown in Fig.1. Input light, with wavelength of \( \lambda_i \), passes through circulator-1 and is reflected by the Fiber Bragg Grating-1 (FBG-1) whose reflecting center wavelength equals that of the input light. The reflected light passes through FBG-2, whose reflecting wavelength \( \lambda_o \) is longer or shorter than \( \lambda_i \), and experiences an optical frequency shift in the SSB-modulator (SSB-Mod). The frequency-shifted light is then passes FBG-1, because the reflection bandwidth of the FBG-1 is set to narrower than the frequency shift by the SSB-Modulator.

This means that the optical frequency of the input light is shifted successively as the light circulates the loop to the wavelength of the circulating light in the loop reaches the reflection wavelength of FBG-2. The circulating light, whose wavelength equals that of FBG-2, is reflected by FBG-2 and launched to the output port though circulator-2. Therefore, the required wavelength converted light that lies exactly on the frequency grid is obtained by adjusting the wavelength of FBG-2 to the one of the frequency grid and the modulation frequency of the SSB modulator to the grid spacing. The optical amplifier (E DFA in Fig.1) is inserted to compensate loop loss from passive devices and conversion loss of the SSB-Modulator. This configuration also acts as wavelength variable light source and optical frequency comb generator [4-5] that is needed is a CW light with standardized optical frequency as the input.

3. Experiment and results

A monolithic waveguide SSB-modulator [2] with the basic structure shown in ref [3] was used in the loop. The driving frequency of the SSB-modulator was 25 GHz. The optical spectra of unmodulated and modulated output light in single transmission are shown in Fig.2 (a). The input light is CW. The SSB-modulator is adjusted to shift the input light to the longer wavelength side. The suppression ratio of the fundamental input mode was larger than 45 dB and the required -1th (neighboring longer wavelength to the input light) to 1th, 2th, and -2th modulation side-band power ratios were larger than 25 dB.

We converted the wavelength of an input signal light modulated with 5 Gbit/s non-return to zero (NRZ) pseudo-random bit sequence (PRBS) format. The wavelength of the input light and center reflection wavelength of FBG-1 was set to the same 1549.8 nm. The reflection bandwidth (FWHM) and reflectivity of FBG-1 and -2 were 11 GHz and 95 %, respectively. The center reflection wavelength of FBG-2 was 1552.8 nm. Figures 2 (b) and (c) show the spectra obtained at the monitor port and output port of circulator-2, respectively. These spectra show that the input light circulated 15 times in the loop, was wavelength-shifted a total of 3 nm (375 GHz in frequency) and launched to the output. The bit error rate performance is shown in Fig. 3. The lines (a) and (b) show BERs for back-to-back and after wavelength conversion. An optical pre-amplifier EDFA followed by an optical band pass filter was used in the receiver. Error free wavelength conversion was confirmed. The power penalty is considered to be attributed to the spectral filtering effect in both FBG-1 and -2, degradation in signal to noise ratio of the circulating light due to ASE from loss compensating EDFA, and interference between required the output mode and the spurious sideband generated from the SSB-modulator. The wavelength conversion of 10 Gbit/s signal with lower power penalty may be available by using properly designed FBGs for 10 Gbit/s signal. Wideband optical frequency comb [4-5] was generated by removing output FBG-2 and introducing CW light into the loop. The monitored optical spectra are shown in Fig. 4. Figures (a) and (b) show the spectra for SSB-modulator adjusted to shift the input light to shorten longer.
wavelength sides, respectively. The adjustment is achieved by varying the DC biases of three Mach-Zehnder interferometers forming the SSB-modulator [2]. Fig. 4 (c) shows magnified portion of the spectrum around 1546 nm in Fig. 4 (a). The degradation in optical SNR is found from Fig. 4 (a), (b) to be about 0.18 dB/circuit. The optical frequency degradation in optical SNR is found from Fig. 4 (a), (b) spectrum around 1546 nm in Fig. 4 (a). The degrada-

We demonstrate GaAs integration of an encoder for optical DQPSK transmission. Experiments demonstrate application to dispersion-tolerant 10 Gb/s transmission over an uncompensated fiber span up to 250 km, and high spectral efficiency 20 Gb/s transport.

1. Introduction
There is currently renewed interest in the development of differential phase-shift key (DPSK) for optical transmission, with increasing evidence that DPSK exhibits superior transmission performance compared to on-off-key (OOK) in DWDM transmission systems [1]. While binary DPSK has been recognized for many years, we have recently demonstrated quadrature signaling - DQPSK [2,3] - where parallel bit streams are encoded to one of four possible phase states. Compared to conventional OOK, optical DQPSK offers improved tolerance to chromatic dispersion and polarization mode dispersion (PMD), together with increased spectral efficiency, while requiring the same OSNR for a given bit rate.

To enable wide application of optical DQPSK, integration of optical functionality is required to provide high performance, compact size and cost-effective manufacturing. Here we describe the realization of a high-functionality GaAs/AlGaAs single-chip DQPSK encoder, which we employ to demonstrate key features of optical DQPSK. We utilize the inherent advantages of DQPSK to address multiple applications: transmission of 10 Gb/s over 250 km, and high spectral efficiency 20 Gb/s with high spectral efficiency.

2. Single-Chip GaAs/AlGaAs Optical DQPSK Encoder
As outlined in [2], an optical DQPSK link consists of digital precoder, electro-optic encoder, and an optical delay-and-add decoder used with balanced detection. Here we focus on the development of the encoder. While there are alternative encoder realizations which can provide mapping of electrical bits to optical phase states, our simulations suggest that best performance is achieved using Mach-Zehnder modulators (MZMs) arranged within a Mach-Zehnder super-structure, as shown in Fig. 1. Each of the MZMs is biased for minimum de transmission and driven with a data signal with amplitude 2Vp at a bit rate B/2. An optical phase difference of ±π/2 is maintained between upper and lower branches, ensuring quaternary addition of the optical fields on recombination. A phase modulator (PM) is also shown in Fig. 1 after the recombiner, which can be driven with a sinusoidal clock signal to provide chirp on the DQPSK signal. As shown in the results below, additional chirp allows extended reach for uncompensated transmission.

For practical implementation, integration of these multiple functions is essential in order to reduce footprint, reduce assembly, and provide suitable stability. We have successfully integrated a DQPSK encoder like Fig. 1 onto a single chip using a GaAs/AlGaAs integration platform. This improves our previous design by incorporating the additional phase modulator, together with modifications which allow transmission experiments with long pattern lengths. The optical waveguides consist of ribs etched into the surface of a GaAs/AlGaAs slab-waveguide. Optical inputs to the twin, parallel MZMs are from a 1×2 splitter via compact 5-bends. Similar 5-bends furnished with phase-shift electrodes route the modulator outputs to the 2×2 optical combiner, a device that introduces a nominal π/2 phase difference between the two optical paths. Identical split and recombine elements are also used within each travelling-wave MZM. The MZMs use a microwave slow-wave technique to achieve the RF/optical velocity-match needed to achieve wide bandwidth with low drive voltage. The phase modulator at the output is a traveling wave structure similar to the Mach-Zehnder electrodes. A low-loss integrated two-photon absorption (TPA) monitor on the GaAs chip after the recombiner provides a photocurrent proportional to dI/dt, where is the instantaneous output intensity. The TPA photocurrent, ~ 1μA, is equivalent to detection of the output signal with a fast photodiode followed by an RF diode detector. The RF power carried by the optical signal under DQPSK modulation is minimum at optimum bias, and provides a convenient error signal for closed loop control of the phase difference between upper and lower optical paths. The 52mm × 3.5mm GaAs/AlGaAs chip was co-packaged together with a DFB laser to provide a high-performance small-footprint module, shown in Fig. 2. Typical optical output power of 1 mW under DQPSK modulation was realized for several modules.

This indicates that a light with arbitrary wave-lengths over a 30 nm (3.75 THz in frequency) range that exactly follow a frequency grid can be achieved with a variable FBG.

4. Conclusion
A novel configuration for a wavelength converter and a variable wavelength light source operating on strict frequency grid was proposed and demonstrated. The 375 GHz frequency shift as a wavelength converter and 3.7 THz-wide variable-wavelength light source are successfully demonstrated. A part of this study was supported by the Telecommunications Advancement Organization of Japan (TAO).

References

Integrated DQPSK Transmitter for Dispersion-Tolerant and Dispersion-Managed DWDM Transmission
R. Griffin, R. Johnstone, R. Walker, S. Wadsworth, A. Carter, M. Wake, Bookham Technology, Towcester, United Kingdom, Email: roger.griffin@bookham.com.

Figure 1. Schematic illustration of optical DQPSK encoder, showing configuration for 10Gb/s transmission.
generator were used, with a relative time delay of 2.2 ns to approximate uncorrelated data. For a net transmission rate of 10 (20) Gb/s, the pattern generator was clocked at 5 (10) GHz. The MZMs exhibited bandwidths ~ 15 GHz, with $V_p < 3.5V$. Standard 10 Gb/s devices were used to amplify the signals to 7V peak-peak, corresponding to $2V_p$ for the MZMs. RF phase shifters were used to synchronize and data terms. Each MZM was biased for minimum optical output in the absence of an RF signal.

A simplified decoder consisting of a single Mach-Zehnder interferometer (MZI) with balanced detection was used, and either output or could be measured by direct adjustment of the decoder phase. The MZI was a fiber interferometer with a commercial fiber receiver with 15 GHz bandwidth. For 10 (20) Gb/s operation, the nominal MZ delay was 200 (100) ps. For decoder stabilization, a control loop was implemented using a second pilot tone together with an RF diode detector after the balanced receiver. No precoder circuit was employed for measurement, and hence there was a deterministic mapping of data from input to output. To allow BER measurements, the error detector was programmed with the expected data sequence incorporating the DQPSK mapping. For transmission of real traffic, a precoding function is required as given in [2].

4. Dispersion-Tolerant Transmission

For many architectures in metropolitan networks, dispersion-tolerant transmission is an attractive feature, since dispersion compensation adds considerable cost and complexity. DQPSK provides inherent dispersion tolerance since data is transmitted at a symbol rate half that of the channel bit rate. For transmission at 10 Gb/s over standard singlemode fiber with dispersion $\sim 17$ ps/nm.km, DQPSK can provide reach up to 150 km, providing significant improvement over conventional on-off keying. Further improvement is realized, however, by additional chirp generated by a phase modulator at the encoder output. With a small sinusoidal modulation of $\sim 0.2$ rad amplitude, correctly phased with the data, substantially greater reach can be achieved. Whereas this synchronous phase modulation can improve dispersion tolerance, even small values of chirp within the individual MZMs of the encoder are detrimental to transmission. Transmission was performed over SMF28 fiber with dispersion 15.8 ps/nm.km at 1535 nm. Measurements were performed for 10 Gb/s transmission using 21-length PRBS patterns. Excellent back-to-back sensitivity of DQPSK was achieved, demonstrating the high waveform quality achieved from the transmitter. By driving the phase modulator at the clock frequency and optimizing amplitude and relative phase, low dispersion penalty was recorded for spans up to 250 km, as shown in the results in Fig. 3a and 3b.

Figure 3. (a) measured BER as a function of OSNR

Dispersion-Managed Transmission

To make most efficient use of fiber infrastructure for long-haul transmission, it is desirable to maximize the spectral efficiency of optical transport. For point-to-point systems where dispersion management is employed, 20 Gb/s DQPSK offers an attractive option. At this data rate, DQPSK effectively provides parallel transmission of two OC-192 data streams on a single optical channel, providing increased capacity while maintaining a standard interface. Since transmitting 2 bits per symbol inherently halves the optical spectral width compared to binary signalling, DQPSK offers increased channel packing, potentially allowing 20 Gb/s transmission with 25 GHz channel spacing without the need for polarization interleaving/multiplexing to reduce cross-channel interaction. To illustrate the potential spectral efficiency of DQPSK, we have demonstrated tolerance to tight optical filtering, which is a requisite for close channel spacing. A 20 Gb/s DQPSK signal was generated with the same encoder setup as above, but with the pattern generator clocked at 10 GHz. Here additional phase modulation was not applied. For decoding, an optical add-and-delay filter with 100ps delay was employed. To perform optical filtering, a 50 GHz de-interleaver operating in loop-back was used together with an optical circulator, providing an optical filter with FWHM 11 GHz. The 20 Gb/s DQPSK optical spectrum before and after optical filtering is shown in Fig. 4(a). The spectral width after filtering was 6.9 GHz, measured with 2 GHz resolution bandwidth. The narrow width of the DQPSK spectrum provides excellent tolerance to optical filtering, as demonstrated by the eye diagrams at the receiver shown in Fig 4(b) and Fig 4(c). Required OSNR to achieve a BER of $10^{-9}$ before and after filtering was measured to be 19.3 dB and 21.6 dB respectively. We expect that optimization of the optical filter will allow DWDM transmission with a spectral efficiency of 0.8 b/s/Hz.

Figure 4. (a) Measured 20 Gb/s DQPSK optical spectrum;

Figure 4. (b) 20 Gb/s received eye without optical filtering;

Figure 4. (c) 20 Gb/s received eye after optical filter with 11 GHz FWHM.

5. Summary

A multi-function single-chip DQPSK encoder fabricated in GaAs/AlGaAs has been co-packaged together with a DBR laser to realize an integrated DWDM DQPSK transmitter module. Experiments using the module have demonstrated key advantages of DQPSK for dispersion-tolerant and dispersion-managed operation. Transmission of 10 Gb/s over 250 km of uncompensated fiber has been demonstrated. For 20 Gb/s operation, optical filtering with 11 GHz FWHM has shown low power penalty, illustrating the potential for high spectral efficiency in long-haul DWDM systems.

6. References

[1] A. H. Gnauck et al, “2.5 Tb/s (64+42.7 Gb/s) transmission Over 40×100 km NZDF using RZ-DPSK format and all-Raman-amplified spans” OFC’02, paper FC 2 (2002).

T. Kawanishi, M. Izutsu, Communications Research Laboratory, Koganei, Japan, Email: kawanish@crl.go.jp.

For wavelength conversion using an optical SSB modulator, we proposed a novel technique for suppression of undesired harmonics, which gives the conventional theoretical limit of SNR, by feeding the fundamental and 3rd order harmonic rf-signals.

1. Introduction

In wavelength-domain-multiplexing (WDM) optical networks, wavelength conversion is a key technology for cross-connection at switching nodes [1]. Nonlinear effect between lightwaves whose wavelength are different, such as four-wave-mixing in optical fibers, cross phase modulation in semiconductor optical amplifier, and so on, are often used to obtain wavelength conversion, by which bit-stream data on a WDM channel can be copied to the other channel [2]. Pumping light sources are used in these techniques, so that the switching time from one WDM channel to the other channel is dominated by that of the pumping light source. The wavelength can be tuned by changing temperature or current density in the light source. But, it is difficult to change the wavelength in a few nano second without losing stability of the source. Recently, we reported wavelength conversion by using an optical single-sideband (SSB) modulator consisting of four optical phase modulators [3-6]. The wavelength of the output lightwave depends on rf-signal frequency and dc-bias voltage fed to the modulator, which can be electronically controlled. We demonstrated suppression of Optical Harmonics in Wavelength Conversion Using Optical Single-Sideband Modulator
2. Principle of operation

The SSB modulator consists of parallel four optical phase modulators as shown in Fig. 1. The phases of electric field induced on the phase modulators are 0, 90, 180 and 270 degrees. The SSB modulator has a pair of Mach-Zehnder structures, so that we can apply rf-signals of 0, 90, 180 and 270 degrees by feeding a pair of rf-signals with 90 degrees phase difference at two rf-ports (RF A/RF B) [6]. The rf-signals can be obtained by using rf 90 degrees hybrid couplers. The optical phase differences are also 90 degrees. Amplitudes of electric fields and lightwaves should be balanced. When the intensity of the electric field is so small that we can neglect high-order harmonic generation at the optical phase modulation, the output optical spectrum consists of only one component the first order lower or upper sideband. Thus, the optical frequency difference between the input and output is equal to the frequency of the rf-signal applied to the electrodes on the phase modulator. The unbalance in amplitude of lightwave in the phase modulators causes generation of undesired component. Phase fluctuation in electric signal and lightwave also decrease the SNR. For simplicity, we consider an ideal condition where the amplitudes are perfectly balanced and the phase fluctuations are zero. Even in this case, undesired components are generated by nonlinearity of optical phase modulator, which gives the theoretical SNR limit. In addition to the first order sideband component, high-order harmonic components whose optical frequency is \( f_0+nf_m \) (\( f_0 \): input lightwave frequency, \( n \): rf-signal frequency, \( n \) : order of harmonic), are generated at the phase modulators. Even order components \( (f_0+2nf_m) \) are eliminated by interference between the outputs of the phase modulators. On the other hand, half of the even order components come out from the output port of the SSB modulator. The first order lower \( (f_0-fm) \) or upper \( (f_0+fm) \) sideband is the major component, and is the desired component in the output lightwave from the SSB modulator. We can choose one from \( f_0-fm \) or \( f_0+fm \) components by adjusting the dc-bias voltage. Here, we consider that the major component is \( f_0+fm \) component. In this case, \( f_0-fm \) component is eliminated, but \( f_0+fm \) component comes out from the SSB modulator. Components of \( f_0+3fm, f_0+5fm, f_0+7fm, f_0+9fm \) and higher order are in the output of the SSB modulator. In experimental setups, the harmonic components higher than 5th order are so small that the SNR can be approximately expressed by \( J_1(A)/J_3(A) \), where \( A \) is the amplitude of the rf-signal. \( J_n \) is the \( n \)-th order the first kind Bessel's function. \( J_1(A) \) shows the theoretical limit of the desired component. Thus, in conventional configurations [3-6], the highest SNR we can get is \( J_1(A)/J_3(A) \).

Fig. 2 shows the principle of high order harmonic suppression. In addition to the rf-signal \((fm \text{ rf-signal})\), we add a phase \( \pi \)-modulated component \(( J(A) \text{ optical spectra components}) \). The rf-signal whose frequency is \( 3fm \) (3fm rf-signal, henceforth) fed to the modulator, in order to compensate \( f_0-3fm \) component. The amplitude of \( f_0-3fm \) component due to \( 3fm \) rf-signal is \( J_1(B) \), where \( B \) is the electric field intensity of \( 3fm \) rf-signal at the phase modulators. Thus, when \( J_3(A) \) is equal to \( J_1(B) \) and the phase difference between the components generated by \( fm \) and \( 3fm \) rf-signals is 180 degrees, the optical \( f_0-3fm \) component becomes zero. This is the basic principle of proposed method. The dc-bias voltage is adjusted to eliminate the first order lower sideband \((f_0-fm \text{ component generated by } fm \text{ rf-signal})\). Thus, \( f_0-3fm \) component due to \( 3fm \) rf-signal is also eliminated and \( f_0+3fm \) component is generated when \( 3fm \) rf-signal is just combined at the output port of the 90 degrees hybrid couplers. To generate \( f_0-3fm \) component and eliminate \( f_0+3fm \) component, the \( 3fm \) rf-signal phase of the port RF B should be 270 degrees with respect to that of the port RF A, when the rf-signal phase of the port RF B is 90 degrees with respect to that of the port RF A. Such signals can be obtained by using a pair of 90 degrees hybrid couplers and combiners. Here, we propose a simple setup using two input ports of a 90 degrees hybrid coupler, as shown in Fig. 3. A pair of \( fm \) and \( 3fm \) signals with 90 and 270 degrees phase delays can be taken out from a pair of the output ports of the hybrid coupler. In this setup, the hybrid coupler has three functions: 1) combine the \( fm \) rf-signal with the \( 3fm \) rf-signal, 2) make 90 degrees phase delay for \( fm \) rf-signal, and 70 degrees phase difference for \( 3fm \) rf-signal, 3) distribute the rf-signals to the two ports. We note that higher order components, for example, \( f_0+5fm \), and so on become larger due to nonlinearity, fm rf-signal modulation, so the \( f_0-3fm \) component becomes zero. Thus, we should minimize the total power of all undesired harmonics instead of elimination of the \( f_0-3fm \) component. The ratio of amplitudes of \( fm \) and \( 3fm \) rf-electric signals \((B/A)\) that gives maximum SNR is shown as a function of \( A \), in Fig. 4. The wavelength conversion efficiency \( J_1(A) \), which is also shown in Fig. 4, has a maximum of -4.70dB when \( A \) (normalized to be induced phase at a phase modulator) is 1.81rad. Fig. 5 shows numerically calculated SNR of our proposed technique and that of the conventional setup. SNR is defined as a ratio of the \( f_0+fm \) component and the sum of the \( f_0-3fm \) and \( f_0+5fm \) components. SNR with \( 3fm \) rf-signal is 36.3dB when the conversion efficiency is -6.2dB (\( A=1.2 \)), while SNR without \( 3fm \) rf-signal is 24.1dB.
Intelligence for network functions such as auto-
provisioning, topology and resource dis-
covery and failure recovery is being moved into
network elements through the emergence of dis-
tributed transport control planes. Proprietary
implementations are deployed, while overlapping
and competing standards bodies are developing
counterparts, by extending virtual circuit manage-
ment protocols from the packet realm. The Inter-
extnet Engineering Task Force (IETF) is extending
Internet Protocol (IP)-based protocols used in
the Multi-Protocol Label Switching (MPLS) control
plane to define Generalized Multi-Protocol Label
Switching (GMPLS). GMPLS is envisioned as a
common control plane managing multiple tech-
nologies, including IP / MPLS and a range of
transport technologies. The International Tele-
communication Union (ITU) is reviewing and
extending the IETF protocols to form an ITU
transport control plane standard. In addition, the
ATM forum and ITU are extending the PNNI pro-
tocols designed for controlling ATM networks to
provide another transport control plane standard.
Although restoration is a critical component of
emerging control plane standards, there are still
many challenges yet to be addressed. This paper
discusses some of these. We focus on restoration
within all-optical networks, and on internode
sharing challenges across technologies, and across
different control planes.

References
[1] H. Harati, M. Murata, and H. Miyahara, “Heu-
ristic Algorithm of Allocation of Wavelength Con-
gies for WDM network applications,” J. Light-

FQ1: 10:30 AM - 12:30 PM
Murphy
Network Protection and Restoration 2
Paul Bonenfant, Lucent Tech., USA, President

FQ1: (Invited) 10:30 AM
Challenges in Intelligent Transport Network Restoration
I. Yates, G. Li, AT&T Labs - Research, Florham
Park, NJ, Email: iyates@research.att.com.

Protocols and mechanisms developed for rapid res-
toration in intelligent transport networks require
careful design to ensure cost efficient, secure and
rapid failure recovery. This paper highlights many
of these challenges and some potential solutions.

1. Introduction
Rapid failure recovery is fundamental to building relia-
ble transport networks. Mesh restoration promises
cost effective failure recovery compared with legacy ring networks [1], and is now seeing large-scale deployment [1].
cross-connection is serial (i.e., a cross-connection can only be started once the previous cross-connection has completed), then the restoration time will be the sum of the time it takes to execute the desired cross-connections in a given XC. For example, if we have a cross-connection time of 5ms, and 200 connections being recovered through an XC, then the time to recover all connections exceeds 1 second if each one is executed in turn. Alternately, if cross-connections can be executed in parallel, then the restoration time can be dramatically reduced by as much as more than the signaling time (in fact, 5ms + signaling time). Thus, for “slow” cross-connections, it is crucial that multiple cross-connections are executed in parallel.

There are other technical challenges beyond what we have been able to discuss here [4]. For example, a reliable control plane software design is crucial to building a reliable transport network, and multi-service priority restoration is required to support multiple service types within a single restoration procedure.

3. Interworking issues

Ideally, a single standard with a limited set of restoration schemes would allow service providers to select equipment from different vendors and have their inter-working. However, the industry has created a plethora of standards, proprietary control plane implementations, and restoration mechanisms. This leads to immediate inter-working challenges – the Optical Internetworking Forum (OIF) and ITU are addressing these through the development of a Network-to-Network Interface (NNI) designed to provide distributed inter-working across different control domains all managed by a single service provider. A control domain (CD) is a sub-network in which all nodes run a common control plane. Figure 1 illustrates two control domains, interconnected by a two pairs of XC's. The NNI is addressing inter-working by aiming for a single standard that will allow provisioning across multiple control domains. Restoration can be achieved within each control domain without requiring complicated inter-working. However, this leaves nodes interconnecting control domains (known as border nodes) as single points of failure along each connection. Thus, it is desirable that control domains have dual interconnection (e.g., two links between CD A and CD B in Figure 1) and that there be restoration mechanisms to recover connections through a failed border node. Such restoration mechanisms are yet to be addressed, but must be designed to operate across a range of control domain control planes and transport.”
The figure illustrates five lightpaths Consider the example of Figure 3 below (3a through 3d.) The figure illustrates five lightpaths \{AD,CD,BC,AC,BD\} and their protections, routed in a 4-node ring network. All the protections traverse the same color if they are connected by an edge, since the corresponding restoration paths are conflicting and cannot share a channel. The objective is to minimize the number of protection channels required. An optimized coloring yields the solution shown in Figure 3d, which consumes only 3 colors. Comparing 1c and 1d, we observe that a new channel (R) should have been allotted to the protection path of demand (BC) instead of sharing channel (B) with the protection of demand (AD). This solution however is not considered because not optimal when the third demand is being provisioned (that is \{AD,CD,AC\} are routed and \{BD\} has not yet arrived) since at that time it would consume 3 channels instead of 2.

### 3. Implementation and Applications

The optimized channel reassignment is a low priority procedure. It can be a program thread running in background, or at regular intervals. The information necessary to accomplish this task is available locally in every OXC and independent of non-adjacent OXCs. Thus each OXC can run a copy of the algorithm in a distributed manner, locally and independently of other OXCs. A change in the allocation of a protection channel needs only to be propagated to its end-points. Since protection channels are “booked” and actually not cross-connected until a restoration occurs, the task amounts to no more than modifying and exchanging sharing databases between pairs of nodes. For every OXC-pair connected by at least one optical line, the OXC with highest IP address is delegated to perform the task. A byproduct of the optimized channel reassignment is that it can be used to migrate the protection paths of mesh dedicated protections to shared mesh protections if desired. By changing their protection type to shared mesh protections, we allow the thread to apply the channel reassignment optimization to these services. The algorithm does not optimize the routes of the backup paths however, and the resulting solution is thus not as efficient as a re-optimization algorithm that re-routes the backup paths to maximize sharing.[5]

### 4. Experiments

For our experiments we compare the benefits of local protection channel optimization on two realistic core mesh networks. Network A consists of shared-mesh capable optical switches in 46 cities interconnected by 75 fiber-trunks and loaded with 570 lightpaths. Network B consists of 61 switches, 88 fiber-trunks, and 419 lightpaths. For each network, we provision all the demands in sequence, using various values of demand churns (expressed in percent of the total demand), and perform a local channel optimization after all the demands are routed. We measure the amount of protection channel required before and after optimization and report the saving in % of total backup capacity in Table 2. Our measurements indicate that as the demand churn increases, the number of protection channels that can be freed becomes substantial.

### 5. Conclusion

This document proposes a distributed method that rearranges the allocation of shared channels reserved for restoration, with objective to minimize the number of allotted channels. This algorithm can be implemented as an independent background process to supplement existing provisioning algorithms. It is effective to correct sub-optimality inherent to a first fit based provisioning, or seize on improvement opportunities that are brought forth by demand churn.

### 6. References

Capacity Requirements for Network Recovery from Node Failure with Dynamic Path Restoration

G Shen, W. Grover, TR Labs and Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada, Email: gshen@trlabs.ca

1. Introduction

Most studies of restorable networking consider span rather than node recovery as the primary class of failure scenario. It is, however, often noted that because of its end-to-end orientation, a path restoration mechanism has an inherent ability also to respond to node failures. The spare capacity that ensures 100% span restorability is not necessarily adequate to ensure any particular target level of recovery from a node failure, however. For example, planned full node protection (SBPP) [1] does inherently protect transiting flows against node loss if primary and backup paths are all node disjoint. But SBPP also generally requires more spare capacity than dynamic path restoration and, due to its fixed pre-planned nature, has an inherently lower availability against dual failure scenarios. It is of interest, therefore, to consider how much extra adaptive path restorable network needs to support node recovery, beyond that needed for span restorability. Other studies [2, 3, 4] have considered network recovery issues but to our knowledge the specific questions we ask, and the particular mechanism [6] and capacity design model [5] we consider are novel and useful. Note that in studies on “node restoration,” it is actually recovery of the transiting paths through a failed node that is intended. Service paths originating or terminating at the failed nodes cannot be restored by these methods. From one standpoint a node failure is like several concurrent node failures. This is the more challenging case for node restoration compared to span restoration alone.

2. Methods and Results

To address these questions, we extend the prior model for dynamic adaptive path-restorable capacity design [5] and assume that there is at least enough wavelength conversion at each OXC node to make wavelength blocking insignificant. Three new design models were developed. A) Design for 100% span and node failure restoration. This design model finds the minimal amount (and distribution) of spare capacity that guarantees 100% span restorability and 100% recovery of transiting demands at failed nodes. It is based on the conventional capacity design model for span restoration [5] with the addition of restorability and spare capacity constraints for each node failure scenario. This is the most straightforward (and potentially expensive) design approach.

B) Design to support Multi-QoP. This is an extension of the first model to consider three QoP levels. These are: (1) Rs restorability: this is a wholly best-efforts class with no assured restorability. (2) Rs+n: this class is assured of restorability against any failure, but receives only best efforts recovery for node failure. (3) Rsh+n: A lightpath in this class enjoys assured restorability against any span or node failure (other than the node that carries its own lightpath in the lightpath’s design model) places spare capacity so that all the affected traffic demands that require Rs or Rs+n restorability can be fully restored upon a span failure, and all the affected traffic demands that require Rsh+n restorability can be fully restored upon a node failure. Rs working capacity is effectively ignored in the spare capacity design problem, but would receive best-efforts restorability in real time within the spare capacity remaining after re-routing for Rs or Rs+n service classes. C) Maximal node recovery under a spare capacity budget. This design model allows us to set a budget on total spare capacity (above that where 100% span restoration is feasible) and optimize the distribution of spare capacity for the highest achievable node failure recovery level as well. In Models A and B the objective function is minimum cost or capacity, but here it is to minimize the total un-restored traffic across all the node failures.

By varying the budget amount this model can be used to systematically study the trade-off between cost and node recovery level. Each of these design models is also implemented with and without “stub release” (the conversion of surviving channels on failed paths into available spare capacity as per [5,6]). In the context of node recovery, stub release means that the surviving lightwave channels of paths transiting the failed node (which will be restored) and of paths sourced at the failed node (which will not be restored) are both available as spare capacity for the restoration effort. This is a failure-specific restoration response to exploit available capacity, in contrast to the fixed response of SBPP-planned paths to failure anywhere or transit node. The node-specific stub rerouting may be either found adaptively in real time [6], or pre-planned and stored in the OXC nodes.

We evaluate the performance of the design models on five well-known topologies: ARPA2 (21 nodes 25 spans), NSFNET (14, 21), SmallNet (10, 22) from [5], Cost 239 (11, 26), and the (55, 130) topology from www.level3.com. Lightpath demands were generated following a uniform random distribution on the range [1...20] for each node-pair. For the larger Level3 test case only the largest 30% of demand pairs volumes are considered. We consider a variety of cases, including full 100% node protection and 100% span protection. We also consider the case where there is a budget and no stub release available. The results are shown in Fig. 1 for each topology and Table 1 summarizes the results.

Table 1. Node failure restorability, redundancy increase, and total cost increase for various network design cases

<table>
<thead>
<tr>
<th>Network</th>
<th>ARPA2</th>
<th>NSFNET</th>
<th>SmallNet</th>
<th>Cost239</th>
<th>Level3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic node failure recovery</td>
<td>No stub release</td>
<td>91.35%</td>
<td>99.94%</td>
<td>85.30%</td>
<td>78.89%</td>
</tr>
<tr>
<td>Rs restorability</td>
<td>Sub release</td>
<td>88.43%</td>
<td>99.92%</td>
<td>89.40%</td>
<td>82.65%</td>
</tr>
<tr>
<td>Rs+n increase</td>
<td>No stub release</td>
<td>10.0%</td>
<td>0.02%</td>
<td>2.6%</td>
<td>3.42%</td>
</tr>
<tr>
<td>(Rs+n + Rs)</td>
<td>Sub release</td>
<td>9.7%</td>
<td>0.02%</td>
<td>2.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Total cost inc.</td>
<td>No stub release</td>
<td>5.2%</td>
<td>0.02%</td>
<td>1.7%</td>
<td>2.2%</td>
</tr>
<tr>
<td>(Rs+n + Rs)</td>
<td>Sub release</td>
<td>5.5%</td>
<td>0.02%</td>
<td>1.9%</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

Fig. 1. Node failure restorability change under different Rsh+n capacities

Fig. 2. Failure spare capacity required with different per cent of node failures.
additional spare capacity over the conventional designs, a network can still serve a large number of higher-level QoS services.

3. Concluding Remarks
This work shows that, overall, it is surprisingly easy to support node recovery in path-restorable networks. Very high levels of premium service class guarantees (services assured of both span and node recovery) can apparently be supported with no more spare capacity than needed to give all services span restorability alone. Conversely if 100% node recovery is desired by design it took at most 10% extra spare capacity to provide this. This knowledge and related design methods are useful in themselves and to further inform the comparison of failure-specific path restoration to the SBPP pre-planning scheme.

4. References

FQ4 11:30 AM
FASTeR: Shared Restoration Without Signaling
V. Poosala, C. Phadke, Bell Labs, Lucent Technologies, Murray Hill, NJ; A. Sandiluya, Univ. of Rochester, Rochester, NY; Email: poosala@research.bell-labs.com.

We present a novel technique for rapid restoration in optical/electrical mesh networks that does not incur additional signaling or cross-connect setup latencies. We show that it easily meets the 50ms requirement in most scenarios.

Introduction
The last few years have witnessed the introduction of optical and electrical mesh networks as an alternative to SONET ring networks. One of the key benefits of mesh networks is the improved bandwidth utilization coming from shared restoration. Unlike the traditional 1+1 protection schemes which reserve 50% of the bandwidth for protection, shared restoration allows multiple demands to share backup links and hence reserves less capacity. However, the speed of restoration is an issue with this scheme. Many classes of traffic, especially those with high bursty traffic requirements, have to be restored very fast, often within 50ms [2]. It is easy to meet this requirement with 1+1 protection - data is always sent on the primary and backup paths and the end node picks up the best signal. This is not the case with shared restoration where the backup paths are only set up after the failure. Typically, this process involves signaling to setup cross-connects (XCs) which can be time-consuming in large networks using slower XC technologies.

Motivated by these issues, we have developed a rapid restoration mechanism that works for both optical and electrical mesh networks, with a primary goal of eliminating the signaling and XC latencies.

Related Work: Much of the earlier work on shared restoration has focused on routing and design algorithms and our technique is complementary to those results. A mechanism called ROLEX for fast restoration was proposed in [1] and its implementation in GMPLS/RSPV was given in [3]. However, ROLEX also incurs cross-connect and signaling latencies, which are the primary bottlenecks addressed in our solution.

Solution
We consider a mesh network consisting of cross-connect nodes (XCs) connected by DWDM systems. Each wavelength between two adjacent nodes is considered to be a link. The edge nodes are assumed to have OXC capability. Traffic consists of unit-wavelength demands between the edge-nodes, protected through shared restoration. Each demand is associated with a primary path and a precomputed backup path for the entire path or per link. For clarity, we assume bi-directional traffic using the same path in both directions and bi-directional failures for our discussion and present the modifications for uni-directional cases where necessary.

The basic idea behind our solution, called FASTeR (FAST Signal-free Traffic Restoration), is as follows: Even before any failure occurs, all the backup paths are set up using certain special features of the XCs, in contrast with the traditional approach where the backup paths are only pre-computed but not until failure occurs. On failure, the end-nodes of the failed demand immediately start sending data on the backup path, without any prior signaling. The details are described next.

We present our solution to cover a wide-range of generic hardware with the following characteristics, rather than assuming specific XC technology like 3D MEMS [3].

1. Coupling/Multicasting: The node can generate multiple in-links (merge links) onto the same out-link, and multicast data from an in-link to multiple out-links.
2. Selection: The node will send light from only one of the merge links onto the out-link. One of the ways this may operate is as follows. All the merge links are in a "non-blocked" state when there is no light on any of them. When there is light on one of them it goes onto the out-link and in parallel the node blocks the others within certain blocking times (the blocking times being less than the guard band). The signal is multicasted on the split channel to stop the multicasting.

Node Details

Figure 1: Split Merge Node Configuration.

Figure 2: Message Format.

Outgoing L. The links L1, L2 in the outgoing fiber are configured as split links, with light from the incoming L multi-cast onto them. This is illustrated in Figure 1. By default, the backup links carry no light and hence all the merge-links are non-blocked. A protocol like RSVP can be extended to implement the necessary messages.

Restoration: On a network failure, the end-nodes of the failed demand (N1, N3 in the figure) send data out on their backup paths, preceded by a guard band equal to the blocking time and a header containing the destination node identifier (see Figure 2). When this light reaches an intermediate node over a merge link, it will be sent over the corresponding shared link while blocking the other merge links. If there are near-simultaneous failures in the network, multiple transmissions may arrive on the merge links before blocking is completed. This can result in garbling of data for that time duration. By choosing a guard band equal to the blocking time, the corruption is restricted to the guard band. The signal is multi-cast onto the split links when encountered, ultimately reaching the other end-node. Once the receiving light on the backup link, the end node skips the guard band, reads the header, and picks up the data only if the id in the header matches its own.

Essentially, blocking replaces the more complex cross-connect setups and multi-casting eliminates the need to process address headers in the internal nodes.

Note that, due to the multi-casting, data may go on parts of the network that were not in the backup path being restored. This can lead to unnecessary blocking if there are simultaneous failures. As an optimization, signals can be sent on a different channel to stop the multi-casting. This can be done after the data has been sent without impacting restoration times. If the hardware does not support automatic blocking on merge links, this signal can also be used to block the other merge links, of course at a higher blocking time.

Failure to Restore: Restoration may fail for various reasons, e.g. blocked merge link, failure in the backup path. It may even cause a deadlock where two simultaneously failed demands block each other on two different nodes. All these cases are handled through a time-out mechanism at the end-nodes. After sending the data out on the backup path, the end-nodes wait for a time equal to the maximum time for successful restoration. If data is not received on the backup path, the end node stops data transmission and retries after a random interval (similar to exponential backoff in Ethernet), up to a maximum number of attempts. This step differs for uni-directional traffic and failures, where the destination will need to send a signal to the source to notify the reception of data on
the backup path. We have also shown that there is no possibility of deadlocks with uni-directional traffic [4].

End of Backup Transmission: Once data transmission ends on the backup path, e.g., when the primary path becomes operational, the nodes unblock the merge links.

### Performance

The FASTeR scheme does not incur any signaling or cross connect setup latencies. The time taken to restore a backup path of n links after failure detection is (n * t_c + t_a), where t_c is the cross-connect setup time and t_a is the ACK processing time. If the node forwards the signal prior to setting up the cross-connect, the time taken is

\[(n-1) * (t_c + t_a) + n * t_a\]

For comparison, we have tabulated the above times for ranges of cross-connect times and blocking times for two different signal times. Here, n = 10, t_a = 1ms, t_c = 0.05ms.

### Table 1: Restoration Times For Various Schemes (all times in ms)

<table>
<thead>
<tr>
<th></th>
<th>FASTeR</th>
<th>Fwd-Before-XC</th>
<th>Fwd-After-XC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-35 ms</td>
<td>5-100 ms</td>
<td>10-45 ms</td>
</tr>
<tr>
<td>t_b</td>
<td>3-135 ms</td>
<td>5-100 ms</td>
<td>11-48 ms</td>
</tr>
<tr>
<td>t_f</td>
<td>3-135 ms</td>
<td>5-100 ms</td>
<td>11-48 ms</td>
</tr>
<tr>
<td>t_s</td>
<td>3-135 ms</td>
<td>5-100 ms</td>
<td>11-48 ms</td>
</tr>
<tr>
<td>Restoration Time</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note that even with an unrealistically large blocking time of 35ms, FASTeR still meets the 50ms requirement. In contrast, the signaling-based schemes fail to do so in most scenarios. All the schemes are likely to take longer when restoring several demands simultaneously - but the FASTeR scheme will suffer to a lesser extent due to fewer operations.

### Conclusion

Shared restoration is critical to the success of mesh networking. In this paper, we proposed a novel mechanism for ultra-fast shared restoration. The scheme requires certain additional support from XCs, but eliminates XC setups and signaling latencies. At the core of our solution is a technique for fast circuit switching which can be applied to other problems like burst switching. We are currently working on routing algorithms for FASTeR and further experimentation.

### References


4. C. Kalmanek, F. Yu, D. Wang, R. Sinha, G. Li, B. Dooverspike, C. Kalmanek, & T. G. J. Labs – Research, Florham Park, NJ, Email: fyu@seecs.berkeley.edu.


7. C. Kalmanek, F. Yu, D. Wang, R. Sinha, G. Li, B. Dooverspike, C. Kalmanek, & T. G. J. Labs – Research, Florham Park, NJ, Email: fyu@seecs.berkeley.edu.


10. C. Kalmanek, F. Yu, D. Wang, R. Sinha, G. Li, B. Dooverspike, C. Kalmanek, & T. G. J. Labs – Research, Florham Park, NJ, Email: fyu@seecs.berkeley.edu.


summarized here: (1) The network achieves both the speed of distributed restoration and the use of optimized restoration paths; (2) This capability can be implemented on the current network infrastructure without or minimal change to existing signaling mechanisms; (3) The path server allows carriers to customize restoration to their own specifications, with dedicated allocation to distributed restoration or end-to-end restoration for any single SRG failure, link when SRG failure occurs;

3. Centralized Path Selection Algorithm

In this section, we describe our capacity planning heuristic called pushed down that optimizes restoration paths to minimize the total restoration time. Suppose that capacity is purchased in units of OC-48, the OC employs STS-1 switching granularity, and the network supports two types of connection services: class 1 and class 2. Class 1 services have more stringent restoration time requirements than class 2 services. The inputs to the pushdown algorithm include the network topology, service connections in STS-1 service type, as well as service paths for all connections. The output is an SRG-disjoint restoration path for each service connection. Since the time to establish a restoration path is linear in the number of path hops [3], the pushdown algorithm selects minimum hop SRG-disjoint restoration paths for all connections. For class 2 connections, the pushdown algorithm selects a disjoint path, while attempting to minimize the total number of OC-48s.

The pushdown algorithm is based on a greedy online algorithm described in [2]. It operates in two phases. In the first phase, we consider one service connection at a time and apply a locally optimal algorithm. In the second phase, we try to do a global optimization. We maintain an array failed[\(e\)] for each link \(e\), where failed[\(e\)] denotes the needed restoration capacity on link \(e\) when SRG fails. In order to provide 100% restoration for any single SRG failure, link \(k\) must be added at least \(M_k = \max\{\text{failed}[\text{link } \text{states}]\} \text{ STS-1s}\). For example, if \(M_k = 49\) STS-1 units, then two OC-48s of capacity must be provisioned on link \(k\). However, it is possible that only one SRG failure routes two OC-48s and all the remaining SRG failures require only one OC-48 of capacity. Thus, we try to select alternative restoration paths for some of the service paths with a goal of bringing down the number of path hops [3]. Reducing one OC-48 from link \(k\) and fixing the required OC-48s on all other links accomplishes this. As a result, a few service paths can no longer be restored on link \(k\). Then we try to select alternative restoration paths for the service connections without increasing the required capacity on all links. If we succeed, we push down one OC-48. If we fail, we restore the original restoration paths and repeat this process with the next link. We iterate until no OC-48 can be pushed down.

4. Performance Evaluation

For our simulation study, we used a 95-node, 164-link network representative of an intercity backbone network. The demand sets are based on the private line demand distribution of a long-haul intercity backbone. We assume requests for bandwidth occur in units of STS-1, STS-3, or STS-12 and that 25% of connections are class 1 while 75% connections are class 2. We compare our pushdown algorithm with a solution that consists of disjoint shortest restoration paths and other published heuristics. For every demand set, we calculated the total number of OC-48s required for each restoration scheme. Figure 1 shows the restoration overheads for different demand sets. The top curve is the overbuild requirement for the SRG-disjoint minimum hop restoration path. The middle curve is the overbuild requirement using the algorithm provided in paper [2]. As shown, the pushdown algorithm reduces the restoration overbuild up to 50% compared with the shortest path algorithm, and 15% compared with the greedy algorithm in [2].

To evaluate restoration process efficiency, we compared our proposed approach with a fully distributed approach (using min-hop paths) with the same network and demand matrix models. We used the pushdown algorithm to plan the capacities and evaluated the restoration success ratio by simulation of the distributed restoration process. Both approaches restore nearly 100% of class 1 connections in the first attempt since we always give higher priority to class 1 connections in our simulation. Figure 2 shows the results for class 2 connections. Our approach restores 100% of class 2 connections at the first attempt. In contrast, the distributed approach can only restore 60% of class 2 connections at first attempt under high demand load.

5. Conclusion

We proposed a hybrid distributed/centralized approach for optical network restoration that combines the merits of centralized and distributed solutions. It avoids the scalability issues of centralized solutions by using a distributed control plane for service path computation and service/ restoration path provisioning. The hybrid approach improves the first restoration attempt success rate by 40% compared with the distributed approach. We also presented a restoration path computation algorithm. Simulation results show that our algorithm saves up to 50% of restoration capacity compared with the shortest path algorithm and 15% compared with a previously published greedy algorithm.

6. Reference


A Novel Bidirectional Wavelength Division Multiplexed Passive Optical Network with 1:1 Protection

T. J. Chan, Y. C. Ku, C. K. Chan, L. K. Chen, F. Tong, Chinese University of Hong Kong, Shatin, Hong Kong Special Administrative Region of China, Email: tjchan1@ie.cuhk.edu.hk.

We propose a novel network architecture for WDM-PO1N which offers 1:1 protection capability. In case of any fiber cut between remote ONU and the RN, the affected ONU will be unreachable from the optical line terminal (OLT), leading to enormous loss in data and business. In this paper, we propose a novel network architecture for WDM-PO1N which offers 1:1 protection capability in both downstream and upstream fiber connections. The traffic for both directions can be routed via the adjacent ONU if any fiber cut between the RN and an ONU occurs.

2. Network Design

Fig. 1: Proposed network architecture for WDM-PO1N architecture. The RN comprises an array-waveguide grating (AWG) and \(N \times 2 \times 3\)-dB couplers to route the wavelength channels to the ONUs. Every two adjacent ONUs are assigned to a group. Each ONU in a group is separately connected to the same output port of the AWG via the fiber coupler. In each group of ONUs, a single piece of fiber is used to connect two ONU to provide an alternative path whenever there is a possible fiber cut between an ONU and the RN, it can still route its upstream and downstream traffic to/from the OLT via its adjacent ONU in the same group. Thus an ONU can protect its adjacent ONU from being isolated due to fiber cut, although each of them can still serve their respective connected subscribers in both normal and protection modes. A mutual 1:1 protection is therefore achieved.

Under normal operation (see Fig. 1), the downstream wavelengths, \(B_i\) and \(D_i\), are carried on the fiber link connecting to ONU(2i-1) and the same composite signal is also delivered to ONU(2i). At the front-end of ONU(2i-1), its destined downstream wavelengths, \(B_i\), will be filtered out by the Red/Blue filter and so is \(D_i\) in ONU(2i). The use of the WDM coupler is to separate the upstream and the downstream wavelengths within the ONU. For upstream wavelength, \(A_i\) from ONU(2i-1) and \(C_i\) from ONU(2i) will pass through their own Red/Blue filters and their respective fiber links. They are then combined before being fed into the same output port of the AWG. Under normal operation, there will be no traffic running on the fiber link connecting two ONUs in the same group. For each ONU, two distinct wavelengths are assigned for upstream and downstream signals.
Moreover, as two adjacent ONUs in the same group are actually connecting to the same output port of AWG at the RN, we make use of the spectral periodicity property of AWG to support the set of working and re-routed wavelengths. The upstream wavelengths ($A_i$, $C_i$) and downstream wavelengths ($B_i$, $D_i$) in the ONU group, i.e. ONU(2i-1) & ONU(2i), are spaced by one free-spectral-range (FSR) of the AWG, thus one AWG port can support the transmission and routing of all four wavelength channels (see the inset of Fig. 1) simultaneously. Table 1 shows the example of the wavelength assignment for a WDM-PON with 10 ONUs.

In case of fiber cut at the fiber link connecting to ONU(2i), for example, the optical switches inside both ONUs in the same group would be reconfigured as illustrated in Fig. 2. Both upstream and downstream wavelengths of the isolated ONU(2i) will be routed to the ONU(2i-1) via the single fiber connecting between them. Conversely, ONU(2i) protects ONU(2i-1) in a similar way. With this protection mechanism, a fast restoration of the broken connection can be achieved, with minimal affect on the existing traffic.

### 3. Experimental Results

Fig. 3 shows the experimental setup to demonstrate the principles of the bi-directional transmission and protection operations of the proposed WDM-PON network. The 1550nm DFB laser diodes (LD) used were 2.5Gb/s, directly modulated, while each of the arrayed-waveguide gratings (AWGs) had 16 channels with 100-GHz channel spacing and had an FSR of 12.8nm. Each Red/Blue filter had a bandwidth of about 16nm in each passband. On the OLT side, EDFAs were inserted in front of the AWG in order to compensate the components' insertion losses and to achieve the required transmitted power. Using this setup, we measured the switching time in case of fiber cut between ONU #1 and the RN. The optical power of the downstream signals from RN and from ONU #2 were monitored and the result was shown in Fig. 4. The upper waveform showed the downstream signal from RN to ONU #1 while the lower was the re-routed downstream signal via ONU #2. The switching time was measured to be about 18ms and this corresponded to the network traffic restoration time. We have also measured the bit-error-rate (BER) performance using 2.5Gb/s 223 -1 PRBS data for both the upstream and the downstream traffic; and the measurement results were depicted in Fig. 5. In normal operation, both the upstream and downstream wavelengths having a transmission distance of 20km between the OLT and the ONU. Then, the fiber link between the RN and ONU1 was intentionally disconnected to simulate the fiber cut scenario. With our automatic protection mechanism, the fiber cut was detected and both the upstream and downstream wavelengths serving ONU1 were automatically switched to the fiber link (2km) between the two ONUs. Both wavelengths were then routed back to the OLT via the fiber link between ONU2 and the RN. Thus, the re-routed wavelengths travelled through a distance of 22km between the OLT and the ONU1. In all cases, the measured receiver sensitivities at 2.5-Gb/s varied from -25dBm to -26.5dBm. The additional 2-dB power penalty with respect to the back-to-back measurement was induced by fiber dispersion.

### 4. Conclusion

We have proposed a novel bidirectional protection scheme for WDM-PONs. By incorporating simple optical switches and optical filters into the ONUs; and by connecting two ONUs in the same group by a single piece of fiber, bi-directional signal re-routing can be achieved. Thus the isolated ONU can still communicate with the OLT in case of fiber cut. The automatic protection switching mechanism and the transmission aspect of the 2.5Gb/s signals were experimentally characterized.
NP. The NP in [2] divides a large network into different areas. Two areas can share some links if their corresponding working sub-paths belong to adjacent areas can share some links without checking the disjoint requirement because their working sub-paths belong to different areas. This motivates us to consider new partitioning configuration in order to improve the resource utilization.

Shared Sub-Path Protection with Overlapped Protection Areas in WDM Networks

J. Li, H. Park, Information and Communications University, Daejeon, Republic of Korea; H. Lee, Electronics and Telecommunications Research Institute, Daejeon, Republic of Korea, Email: jfil@ic.ac.kr.

A partitioning configuration that divides a given network into overlapped protection areas for shared sub-path protection is investigated. The performances of capacity requirement and restoration time are improved without any significant degradation of other performances.

I. Introduction

A sub-path is defined as a subset of the links along a path. To find protection paths for the sub-paths of a working path called sub-path protection. How to divide a working path into several sub-paths is an important problem in the sub-path protection scheme. One idea is to divide each working path into several protection domains [1]. The other idea is to partition a large network into several smaller areas [2]. However, partitioning configuration in [2] is not practicable for most actual networks. Moreover, over-sub-path protection requires more resources [2]. This is critical for network dimensioning.

We propose a new partitioning configuration that divides a given network into overlapped protection areas where wavelengths on the links that belongs to the overlap can be shared for protection sub-paths whose corresponding working sub-paths belong to different areas. The number besides each link is the length of the link. It is more practicable and guarantees higher resource utilization and decreased restoration time without any significant degradation of other performances.

II. Partitioning Configuration

We examine two ways of partitioning a working path in detail, and then give our new partitioning configuration. We only consider link failures in this paper. For convenient discussion, we call the way that divides a working path into several protection domains as Path Dividing (PD), and the way that partitions a large network into several smaller areas as Network Partitioning (NP). The main difference between PD and NP is that two protection sub-paths can share some links as long as their corresponding working sub-paths are link-disjoint for PD and two protection sub-paths that only belong to the same area can share some links if their corresponding working sub-paths are link-disjoint for NP. The NP in [2] divides a large network into several separated areas. We call this partitioning configuration as Separated Network Partitioning (SNP). However, two protection sub-paths whose corresponding two working sub-paths belong to adjacent areas can share some links without checking the disjoint requirement because their working sub-paths belong to different areas. This motivates us to consider new partitioning configuration in order to improve the resource utilization.

SNP has a requirement that the node degree of the Area Border Router (ABR) must be larger than 3. The node degree refer to the number of other nodes in the network to which a node is connected, which is also equal to the number of links connected to the node. As an ABR, it must guarantee that a working path that traverses it can be divided into two working sub-paths where each working sub-path and its corresponding protection sub-path belong to the same area. This means it must have more than 4 links connected to it and two links belong to one area, other two links belong to the other area. If the degree of a node is 2, it is not possible as an ABR. For a mesh network, it must have some nodes whose degree is larger than 2 otherwise it is a ring. If a large network does not have suitable nodes whose degree are more than 3 as ABRs, we cannot divide a large network into smaller separated areas according to SNP [2]. Most actual networks belong to this category. In order to partition this type of large networks, we need to choose some nodes whose degree are 3 as ABRs. If we divide the given network into overlapped areas, the partitioning problem can be solved. However, the complexity of the wavelength assignment for sub-paths on the links that belong to the overlap becomes high, since a wavelength on the link cannot be assigned for two working sub-paths and a wavelength on the links assigned for protection sub-paths must to check the link-disjoint requirement of their corresponding working sub-paths. This is not benefit for ILP calculation. In order to maintain the complexity of ILP calculation not to be increased significantly, we propose a new partitioning configuration.

Our partitioning configuration is described as follows. We also divide a given network into several areas, but areas for working and protection sub-paths are different. Areas for the working sub-paths are called as working areas. Working areas are separated. Areas for protection sub-paths are called protection areas. A protection area corresponds a working area. It can be bigger than its working area. Protection areas are overlapped. The objective of overlapping of protection areas is for high resource utilization. Our partitioning configuration is called Network Partitioning with Overlapped Protection Areas (NPOPA). The difference between NPOPA and SNP is that a working area and its corresponding protection area are different. The difference between NPOPA and PD is that a working area and its corresponding protection area can have many pairs of working and protection sub-paths for NPOPA and one protection domain only has one pair of working and protection sub-paths for PD.

For an example, consider a 16-node and 25-link NSFNET backbone in Fig. 1. It can be divided by several separated areas. We call this partitioning configuration as Network Partitioning (NP). However, two protection sub-paths whose corresponding two working sub-paths belong to adjacent areas can share some links without checking the disjoint requirement because their working sub-paths belong to different areas. This motivates us to consider new partitioning configuration in order to improve the resource utilization.

SNP has a requirement that the node degree of the Area Border Router (ABR) must be larger than 3. The node degree refer to the number of other nodes in the network to which a node is connected, which is also equal to the number of links connected to the node. As an ABR, it must guarantee that a working path that traverses it can be divided into two working sub-paths where each working sub-path and its corresponding protection sub-path belong to the same area. This means it must have more than 4 links connected to it and two links belong to one area, other two links belong to the other area. If the degree of a node is 2, it is not possible as an ABR. For a mesh network, it must have some nodes whose degree is larger than 2 otherwise it is a ring. If a large network does not have suitable nodes whose degree are more than 3 as ABRs, we cannot divide a large network into smaller separated areas according to SNP [2]. Most actual networks belong to this category. In order to partition this type of large networks, we need to choose some nodes whose degree are 3 as ABRs. If we divide the given network into overlapped areas, the partitioning problem can be solved. However, the complexity of the wavelength assignment for sub-paths on the links that belong to the overlap becomes high, since a wavelength on the link cannot be assigned for two working sub-paths and a wavelength on the links assigned for protection sub-paths must to check the link-disjoint requirement of their corresponding working sub-paths. This is not benefit for ILP calculation. In order to maintain the complexity of ILP calculation not to be increased significantly, we propose a new partitioning configuration.

Our partitioning configuration is described as follows. We also divide a given network into several areas, but areas for working and protection sub-paths are different. Areas for the working sub-paths are called as working areas. Working areas are separated. Areas for protection sub-paths are called protection areas. A protection area corresponds a working area. It can be bigger than its working area. Protection areas are overlapped. The objective of overlapping of protection areas is for high resource utilization. Our partitioning configuration is called Network Partitioning with Overlapped Protection Areas (NPOPA). The difference between NPOPA and SNP is that a working area and its corresponding protection area are different. The difference between NPOPA and PD is that a working area and its corresponding protection area can have many pairs of working and protection sub-paths for NPOPA and one protection domain only has one pair of working and protection sub-paths for PD.

For an example, consider a 16-node and 25-link NSFNET backbone in Fig. 1. It can be divided by

Fig. 5: BER measurements of 2.5Gb/s upstream and downstream traffic in normal and protected modes.

Fig. 1 (a) 16-node and 25-link NSFNET backbone, (b), (c) and (d) are three areas of (a), working areas only include solid links, protection area include solid and dashed links, node 6, 7, 12, 13, and 14 are ABRs, the wavelengths on dashed links are permitted to be assigned only for protection sub-paths whose corresponding working sub-paths in this area. The solid (dotted) arrows from the working (protection) path between node-pair (6, 7).

5. References


Fig. 2 (a) 18-node and 29-link nationwide network, the number besides each link is the length of the link. (B), (c) and (d) are three areas of (a), working areas only include solid links, protection area include solid and dashed links, node 6, 7, 12, 13, and 14 are ABRs, the wavelengths on dashed links are permitted to be assigned only for protection sub-paths whose corresponding working sub-paths in this area.

NPOPA, but it cannot be divided by SNP. Besides the practicability, NPOPA has an important advantage that it provides high resource utilization compared to SNP. We give an intuitive example in Fig. 2. Consider a connection between node pair (6, 7) as shown in Fig. 2. The working path is <6,5,7>, the protection path is <6,3,4,7> according to SNP, and the protection path is <6,8,7> according to NPOPA. It is obvious that the resource utilization of the connection is 5 wavelength-links for SNP while it is 4 wavelength-links for NPOPA. If one wavelength on <6,8,7> has been assigned for other protection sub-paths whose corresponding working sub-paths in area b, the resource utilization is only 2 wavelength-links since a wavelength on the link belong to the overlap can be assigned for two protection sub-paths whose corresponding working sub-paths not belong to adjacent areas according to NPOPA.
The restoration time of our scheme is also less than or at most equal to that for SNP. The restoration time depends on the physical distance of working and protection paths [1]. It is obvious that the distance of working and protection paths for NPOPA is less than or at most equal to that for SNP. So the restoration time is also less than or at most equal to that for SNP. For an example, consider the connection between node pair 6-7. The distance is 2800 for NPOPA, while it is 4700 for SNP. The restoration time must be less than that for SNP.

Let A be the number of areas. If the independence of sub-paths is guaranteed, sub-path protection can survive up to A failures as long as there is at most one failure per area. If two areas overlap, the number of simultaneous failures that the protection scheme can survive becomes less than A. For example, area a and area b in Fig. 2 are not independent, and the network cannot guarantee to survive simultaneous failures in area a and b. However, if the failure probabilities of links are statistically independent, a single link failure counts for almost all link failures. The probability that more than two failures occur simultaneously is very low [3].

III. Assumptions and Calculation Procedures

The routing and wavelength assignment (RWA) problem in a WDM mesh network with shared sub-path protection can be formulated as an ILP. Our objective is to minimize the total number of wavelength-links. We assume that the network topology that is represented as a directed graph and the partitioning configuration NPOPA are given. Areas are numbered from 1 through A. We also assume that only the adjacent indexed protection areas can be overlapped. Protection area n can be overlapped with protection area n-1 and protection area n+1 when n = A. Protection area 1 can only be overlapped with protection area 2 and protection area A can only be overlapped with protection area A-1. It is not difficult to extend for the general case that a protection area can be overlapped with all adjacent protection areas. We also assume that ABRs have wavelength conversion capability and other nodes do not have wavelength conversion capability.

The procedures of calculating the total number of wavelength-links are given as follows. (1) transform of connection requests. For a given inter-area connection request that traverses some sub-areas, it is divided into some sub-paths according to working areas that it traverses, thus the inter-area connection is divided into several intra-area connections. (2) routing Problem. We calculate 2 shortest link-disjoint routes between each node-pair using the Bhandari’s algorithm [4] for all protection areas one by one. (3) wavelength assignment problem. We develop ILP formulation of the shared sub-path protection scheme. Due to space limitations, ILPs are not shown here.

IV. Illustrative Examples and Discussion

We apply our studies to the example network. The algorithm was evaluated on the same network as used in [2] (Fig. 2). We assume that the number of wavelengths on each link is 10. We run the ILP formulation on random demands, where each random demand has between 25 and 40 connection requests. We give the results of capacity utilization for the network in Fig. 3. It is shown, as expected, that our partitioning configuration NPOPA has higher capacity utilization compared to SNP. We give the results of average, maximum and minimum lengths of all sub-path pairs in Fig. 4. It is shown that they are less for NPOPA than that for SNP. It means that the restoration time for NPOPA is less than that for SNP.

The calculating complexity for NPOPA is almost same as that for SNP because we use the almost same time in calculation of the total number of wavelength-links for two cases.

References


Fig. 3. The total number of wavelength-links versus the number of the connections.

Fig. 4. The length of all sub-path pairs versus the number of connections.
the following wavelengths:

\( \lambda_{2a} = 1550.52 \), \( \lambda_{2b} = 1550.92 \), \( \lambda_{2c} = 1550.92 \), and \( \lambda_{2d} = 1551.12 \) nm.

The waveband was transmitted over approximately 100 km of SMF-28 fiber on a loopback path between the LTS and NRL through MEMS-based WSXCs located at each node. The entire waveband is received at the drop port, although the \( \lambda_2 \) sub-channel is attenuated slightly due to its proximity to the passband edge of the NE muxes and demuxes.

The recovered bit error rates (BERs) of all four sub-channels after transmission through the two WSXCs, 100 km of fiber, and optical amplifiers (integrated into the NEs) is shown in Fig. 4. For these BER results, the waveband sub-channels are modulated with decorrelated OC-48 (2.488 Gb/s) pseudo-random data streams (2^31-1). The average receiver sensitivity given a BER of 10^-9 is -34.4 dBm. Compared to back-to-back operation, the power penalty for the four sub-channels is only 0.1 dB. This experiment demonstrates that an existing transparent network infrastructure designed for 2.5 Gb/s capacity per passband can support 10 Gb/s per passband using waveform techniques at the edge of the network without requiring changes to core network elements or transmission fibers.

We also investigated the ability to modulate the individual sub-channels at 10 Gb/s, which provides a total passband capacity of 40 Gb/s within the transmission window. In this experiment, all four wavelengths were modulated by a common 10 Gb/s electro-optic modulator. Pre- and post-dispersion compensating fibers were used to support the 10 Gb/s sub-channels over the 100 km SMF-28 network span. The resulting BER performance for the four 10 Gb/s sub-channels is summarized in Fig. 5. The average receiver sensitivity at a BER of 10^-9 is -17.8 dBm. The average power penalty across the four sub-channels was 1.1 dB, with \( \lambda_2 \) having the largest penalty of 1.5 dB. The increased power penalty is likely to be a result of the channel proximity to the passband edge causing greater signal distortion due to fiber dispersion. It would not have been possible to achieve the transmission of a single 40 Gb/s wavelength within an ATDnet passband without subsequent compensation for PMD.

### Impact of polarization effects

An important physical layer issue to consider in a waveband switched network is the impact of how impairments may impact individual sub-channels of the waveband differently. In particular, polarization effects such as polarization dependent loss (PDL) can be particularly important for transparent NEs that use optical switch fabrics such as LiNbO_3. The ATDnet contains NEs with both MEMS and LiNbO_3 fabric technologies. The PDL for the loopback path for the MEMS-based WSXCs was less than 0.5 dB for waveband sub-channels \( \lambda_{2a}, \lambda_{2b}, \lambda_{2c} \) and did not vary significantly based on the launched polarization orientation of the subchannels. The first sub-channel (\( \lambda_{2a} \)) had a higher PDL value of 1.0 dB due to its proximity to the passband edge. In contrast, when the signal was sent through the LiNbO_3-based WSXC, the PDL varied within the range of 4.0-5.5 dB across the waveband. The amount of PDL experienced by each sub-channel was a function of the launch polarization orientation. Ensuring that the sub-channels of a waveband maintain the same amplitude is important for minimizing the waveband transmission penalty. Over longer spans and multiple hops through optical networks, the amount of PDL through a network element should be kept to a minimum especially since it can coupled with second order PMD (which introduces wavelength dependent depolarization [4]) to cause additional variation in the sub-channel amplitudes.

### Conclusion

Wavebanding is a technique that can be applied to existing transparent optical elements to increase the spectral efficiency within a passband without requiring costly impairment compensation or upgrades to photonic cross-connects. It can also be applied to new network designs in order to minimize the number of switch fabric ports. We have demonstrated 4-channel waveband transmission over 100 km of legacy fiber in ATDnet within a 200 GHz optical passband with aggregate capacities of 10 and 40 Gb/s. Understanding the impact of impairments and optical nonlinearities that may...
Cost-Effective WDM Backbone Network

Design with OXCs of Different Bandwidth Granularities

H. Zhu, K. Zhu, B. Mukherjee, University of California, Davis, Davis, CA; H. Zang, Sprint Advanced Technology Laboratories, Burlingame, CA; Email: zhuh@cs.ucdavis.edu

We propose a framework for designing a WDM backbone network with OXCs of different grooming granularities. Numerical examples are presented showing that granularity-heterogeneous networks are more cost-effective than granularity-homogeneous networks.

1. Introduction

As WDM technology advances, the capacity of a wavelength channel continues to increase (OC-48, OC-192, or OC-768). However, the bandwidth requirements of typical connection requests are versatile (e.g., STS-1, OC-3, OC-12, OC-48, and OC-192), and usually of small fractions of the bandwidth of a WDM channel. To efficiently use the bandwidth, grooming switches are introduced which can pack/unpack low-speed connections onto/from high-speed WDM channels and switch at sub-wavelength granularities. Different grooming switches may have different grooming granularities. For instance, some grooming switches can groom at STS-1 level, i.e., they are capable of unpacking a wavelength channel down to STS-1 timeslots, switching those STS-1 timeslots, and packing them back onto wavelength channels. Some other grooming switches may do grooming only at OC-48 level (assuming the capacity of a wavelength channel is greater than OC-48).

Although this kind of grooming switches provides less flexibility in grooming, the port cost may be less than that of STS-1 grooming switches. These two kinds of grooming switches are both opto-electro-opto (OEO) switches and need to be surrounded by transponders. Meanwhile, all-optical OXCs do not need transponders for OXC ports, which is a significant saving in optical transport networks, but at the price of no grooming capability and wasting channel capacities. Since the WDM backbone network topologies are usually irregular and traffic requests are of different bandwidth granularities, it is not necessary to deploy the same kind of OXC at all the nodes. If the granularities of all the OXCs in a network are the same, we call this network granularity-homogeneous network; otherwise, we call it granularity-heterogeneous network. When designing a WDM backbone network, it is desirable to take advantage of the benefit of all types of OXCs to accommodate the traffic while reducing the network capital expenditures.

In [1], the authors compared the network cost when using different node architectures, but they assumed all the grooming nodes have the same STS-1 grooming capability. In this paper, we focus on designing a WDM backbone network with OXCs of different bandwidth granularities to minimize the network-wide OXC port cost. Specifically, we determine the type of OXC at each node, compute the route of each traffic request, and calculate the total OXC port cost.

2. Problem Statement

Given the physical topology of a network, a traffic matrix which contains various bandwidth requirement between different nodes, the types of OXCs which can be deployed in the network, and the port cost of each type of OXCs, we need to determine the type of OXC at each node, as well as the route of each traffic request, and the objective is to minimize the total OXC port cost of the network while accommodating all the traffic demands. A traffic demand is represented by \(T(s, d, g, m)\), where \(s\) and \(d\) are the source and destination nodes, respectively; \(g\) is the granularity of the traffic demand, for instance, OC-48; and \(m\) is the amount of the traffic in units of \(g\).

3. Side-Effect of Routing Traffic in Granularity-Heterogeneous Networks

In a granularity-heterogeneous network, routing a connection request and representing the network state will become significantly more complex than in a network where only OXCs with STS-1 grooming granularity exist. In an STS-1 grooming granularity network, if there is a lightpath between two nodes, the free capacities on the lightpath can always be accessible by the end nodes of the lightpath. In a multi-granularity network, OXCs switch traffic at different granularities. For a given traffic demand requiring certain bandwidth, certain amount of timeslots on the lightpaths along the route of the traffic are allocated to the connection. At a STS-1 grooming switch, only the timeslots occupied by the traffic are switched from the incoming OXC port to the outgoing OXC port. However, at an OEO with a switching granularity coarser than the bandwidth granularity of the traffic request, some free timeslots may also be switched together with those timeslots taken by the traffic, causing these free timeslots to bypass this node and become unavailable to this node.

The fundamental observation is that the timeslots within the switching granularity of an OXC are transparent to the OXC and these timeslots can only be operated as a whole.

Table 1. Comparison of the three types of OXCs.

<table>
<thead>
<tr>
<th>OXC</th>
<th>Switching technology</th>
<th>Have grooming capability?</th>
<th>Capacity of the OXC port</th>
<th>Grooming granularity</th>
<th>Need transponders for bypass traffic?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>OOO</td>
<td>No</td>
<td>OC-192</td>
<td>N/A</td>
<td>No</td>
</tr>
<tr>
<td>Type II</td>
<td>OEO</td>
<td>Yes</td>
<td>OC-192</td>
<td>OC-48</td>
<td>Yes</td>
</tr>
<tr>
<td>Type III</td>
<td>OEO</td>
<td>Yes</td>
<td>OC-192</td>
<td>STS-1</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Here we give a small example. To carry a traffic demand \( T_1(1, 4, OC-1, 2) \), we set up lightpaths \( L_1 \) (from node 1 to node 2), \( L_2 \) (from node 2 to node 3), and \( L_3 \) (from node 3 to node 4), and then route \( T_1 \) onto these lightpaths. The switching granularities of the nodes 1, 2, 3, and 4 are STS-1, OC-3, STS-1, and STS-1, respectively. The capacity of a wavelength channel is OC-12 for this line. Figure 1(a) shows the switching state of the OXCs. Since the switching granularity of node 2 (OC-3) is coarser than the bandwidth granularity of the traffic demand (OC-1), there is a free STS-1 timeslot (timeslot 3 in \( L_1 \)) switched onto \( L_1 \) (timeslot 9 in \( L_1 \)) by the OXC at node 2. Although this timeslot goes through node 2, it cannot be accessed by node 2. Any traffic carried by this timeslot will bypass node 2 and directly reach node 3, where it can be switched to any free outgoing grooming port. This is equivalent to having an STS-1 circuit directly connecting node 1 and node 3. Figure 1(b) shows the network state (virtual connectivity) after routing \( T_1 \). These circuits form another topology above the virtual topology, and traffic demands should be routed on this topology instead of on the virtual topology.

4. Network Design Framework

To accommodate characteristics of multi-granularity networks, we extend the graph model proposed in [2]. The graph model can route a traffic demand according to the current network state, and update the network state after carrying the traffic. The extended graph model can also intelligently choose the appropriate type of OXC to carry the current traffic demand, given there are several types of OXCs at a node. Due to space limitation, the extended graph model is not shown here.

Based on the extended graph model, we propose a design procedure as follows.

1. Place one OXC of each type at each node.
2. Compute a route for each traffic demand, and choose the most suitable OXC at each node along the route using the extended graph model, until all the traffic has been carried.
3. For each type of OXC at each node, move the traffic going through the other types of OXC to this type of OXC, estimate the port cost of this type of OXCs, and choose the type of OXC with the least cost at each node.
4. After determining the type of OXC at each node, reroute all the traffic demands and calculate the network cost.

5. Numerical Results

We conducted experiments on a typical nationwide backbone network. The topology is shown in Fig. 2. It has 26 nodes and 40 bi-directional links. The capacity of a wavelength channel is OC-192. The bandwidth granularity of a traffic demand can be STS-1, OC-3, OC-12, OC-48, and OC-192, and the total bandwidth requirement distribution of these 5 granularities is \( a_1; a_2; a_3; a_4; a_5 \), respectively. The traffic is uniformly distributed between all the nodes. There are 3 types of OXCs, shown in Table 1.

The per-port cost ratio of Type I, Type II, and Type III OXCs is \( \beta_i; \beta_j; \beta_k \). We compare the port cost in four scenarios. In Scenario 1, there is only a Type I, II, and III OXC at each node, respectively. In Scenario 4, we use the above network design framework to determine the type of OXC at each node, and all three types of OXCs can coexist in the network. In the experiment reported here, the ratio of \( a_1; a_2; a_3; a_4; a_5 = 5:1:1:3:3 \), which is based on the projected traffic distribution of a typical nationwide WDM backbone network, and the per-port cost ratio \( \beta_i; \beta_j; \beta_k = 1:3:4 \). Note that these ratios are just inputs to our network design procedure, and more-accurate data, when available, can be plugged into our model.

Figure 3(a) shows the total port cost, which is normalized by the per-port cost of all-optical OXCs, in the four scenarios. The number of transponders and wavelength-links used in the network, and Fig. 3(c) shows the lightpath utilization in the four scenarios. For the given traffic distribution and port cost ratio, the total port cost of the network in Scenario 1 is the highest, followed by the cost in Scenarios 2 and 3, and Scenario 4 achieves the lowest port cost. In Scenario 1, since the OXCs do not have grooming capability, the lightpath utilization is very low (65.7%) and 3822 OXC ports are used, resulting in highest total port cost despite the lowest per-port cost. In addition, this scenario uses the largest amount of wavelength-links to carry all the traffic. In Scenario 3, although the per-port cost of the OXCs used is the highest, the total port cost is less than that in Scenarios 1 and 2. This is because Type III OXCs can efficiently pack low-speed connections onto high-speed wavelength channels, making the lightpath utilization relatively high (86%). Hence, the total number of OXC ports (354), with transponders used (160), and wavelength-links used (160) are lower than those in Scenarios 1 and 2. However, there is still room for improvement. For instance, not all of the nodes need such high flexibility in grooming fabric; some nodes may achieve similar performance with coarser grooming granularity or even no grooming capability, with the coordination of other nodes, thus further reducing the cost. This can be observed in Scenario 4. In this scenario, we choose an appropriate type of OXC for each node. Compared with Scenario 3, although more OXC ports may be used, the total port cost and the number of transponders used in the network channel is OC-12 for this line. Figure 1(a) shows the switching state of the OXCs. Since the switching granularity of node 2 (OC-3) is coarser than the bandwidth granularity of the traffic demand (OC-1), there is a free STS-1 timeslot (timeslot 3 in \( L_1 \)) switched onto \( L_1 \) (timeslot 9 in \( L_1 \)) by the OXC at node 2. Although this timeslot goes through node 2, it cannot be accessed by node 2. Any traffic carried by this timeslot will bypass node 2 and directly reach node 3, where it can be switched to any free outgoing grooming port. This is equivalent to having an STS-1 circuit directly connecting node 1 and node 3. Figure 1(b) shows the network state (virtual connectivity) after routing \( T_1 \). These circuits form another topology above the virtual topology, and traffic demands should be routed on this topology instead of on the virtual topology.

6. Conclusion

We proposed a framework for WDM backbone network design to better utilize the benefit of different types of OXCs, which have different bandwidth granularities. Our results demonstrate that using different type of OXCs will yield better network performance, and a design using our framework can reduce the network-wide OXC port cost.

References


Pre-Emptive Reprovisioning in Mesh Optical Networks

R. Ramamurthy, A. Akyamac, J. Labourdette, S. Chaudhuri, Tellium Inc., Oceanport, NJ, Email: aakyamac@tellium.com

Pre-emptive reprovisioning is a method to perform reprovisioning of a backup path in advance of a second failure, to reduce the time to recover service from seconds (reprovisioning) to milliseconds (restoration). We evaluate the tradeoff between benefits and operational complexity.

1. Introduction

In shared-mesh restoration [1,2,5], each working path has a diverse backup path. In one restoration architecture [1,2], backup routes are pre-computed, and shared protection channels on the backup path are pre-assigned at the time of path provisioning. Channels on the backup path may be shared between primary paths whose working paths are diverse. Upon a single failure event, the lightpaths whose primary paths are affected by the failure are restored on their backup paths. If restoration fails (because the shared-protection channels are either in a failed state or are already being used by another lightpath - which cannot happen in the case of a double failure), then re-provisioning of the backup path is attempted. If reprovisioning of the backup path is successful, then the newly re-provisioned backup path is used to carry traffic. If reprovisioning fails (due to lack of capacity), then the lightpath is not restorable. Reprovisioning is a time-consuming process since it is performed at a centralized management system, and lightpaths are sequentially reprovisioned to avoid contentions for capacity. Pre-emptive reprovisioning is a method to perform reprovisioning of a backup path in advance of a failure. The motivation for pre-emptive reprovisioning is to reduce the time it takes to restore service from several seconds to tens of seconds with reprovisioning to order of 10s to 100s of milliseconds with restoration. However, there is a tradeoff in pre-emptive re-provisioning. In this paper, we evaluate the trade-off between the benefits of pre-emptive reprovisioning and the additional operational complexity.

Step 1
Place one OXC of each type at each node.

Step 2
Compute a route for each traffic demand, and choose the most suitable OXC at each node along the route using the extended graph model, until all the traffic has been carried.

Step 3
For each type of OXC at each node, move the traffic going through the other types of OXC to this type of OXC, estimate the port cost of this type of OXCs, and choose the type of OXC with the least cost at each node.

Step 4
After determining the type of OXC at each node, reroute all the traffic demands and calculate the network cost.

Figure 3(a) shows the total port cost, which is normalized by the per-port cost of all-optical OXCs, in the four scenarios. The number of transponders and wavelength-links used in the network, and Fig. 3(c) shows the lightpath utilization in the four scenarios. For the given traffic distribution and port cost ratio, the total port cost of the network in Scenario 1 is the highest, followed by the cost in Scenarios 2 and 3, and Scenario 4 achieves the lowest port cost. In Scenario 1, since the OXCs do not have grooming capability, the lightpath utilization is very low (65.7%) and 3822 OXC ports are used, resulting in highest total port cost despite the lowest per-port cost. In addition, this scenario uses the largest amount of wavelength-links to carry all the traffic. In Scenario 3, although the per-port cost of the OXCs used is the highest, the total port cost is less than that in Scenarios 1 and 2. This is because Type III OXCs can efficiently pack low-speed connections onto high-speed wavelength channels, making the lightpath utilization relatively high (86%). Hence, the total number of OXC ports (354), with transponders used (160), and wavelength-links used (160) are lower than those in Scenarios 1 and 2. However, there is still room for improvement. For instance, not all of the nodes need such high flexibility in grooming fabric; some nodes may achieve similar performance with coarser
2. Pre-emptive Reprovisioning

Pre-emptive Reprovisioning automatically "reprovisions" a backup path for a demand whose backup path has become unavailable. As a result, upon a failure, pre-emptively reprovisioned lightpaths can be restored in the order of milliseconds as opposed to the reconfiguration times in the order of seconds to minutes. Backup paths can become unavailable due to several events that include:

- **Backup Channel Failure**: A backup shared-channel fails due to failure of electronics at one of the end-switches. In Fig. 1(b), a shared channel on the backup paths of P1 and P2 fails rendering the backups B1 and B2 unavailable.

- **Fiber Failure**: A fiber fails resulting in several lightpaths whose primary channels use the failed fiber to switch to their back-ups.

The value of pre-emptive reprovisioning is to allow to restore rather than reprovision upon a double failure. We evaluate the performance of pre-emptive reprovisioning on 3 representative real networks:

- Network 1 (45 nodes, 75 links, 72 shared-mesh demands, 97 shared channels)
- Network 2 (17 nodes, 26 links, 102 shared-mesh demands, 203 shared channels)
- Network 3 (50 nodes, 88 links, 300 shared-mesh demands, 476 shared channels)

The goal of the study is to evaluate the benefits of performing pre-emptive reprovisioning. The three failure events listed earlier are considered. Table 1 illustrates the "average" number of lightpaths whose primary and backup routes become unavailable for each of the three events. The averages represent the average over all possible events.

<table>
<thead>
<tr>
<th></th>
<th>Network 1</th>
<th>Network 2</th>
<th>Network 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backup channel failure</td>
<td>4</td>
<td>2.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Primary channel failure</td>
<td>13.6</td>
<td>7.6</td>
<td>25.1</td>
</tr>
<tr>
<td>Fiber failure</td>
<td>17</td>
<td>35</td>
<td>192</td>
</tr>
</tbody>
</table>

Table 1. Number of lightpaths that would benefit from pre-emptive reprovisioning for different types of failures (average over all possible failures).

For backup channel failure, the number of lightpaths that need to be pre-emptively reprovisioned is equal to the number of lightpaths that share a protection channel [3,4,6], which is about 4 lightpaths for the above networks. For a lightpath switch to back-up, the number of lightpaths that need to be pre-emptively reprovisioned is equal to the number of backup hops multiplied by the number of lightpaths that share a protection channel, which is about 20 depending on the size of the network, but is independent of the network loading. For fiber failure, the number of lightpaths that need to be pre-emptively reprovisioned is equal to the average number of lightpaths on a fiber multiplied by the average backup hops multiplied by the average lightpaths that share a protection channel, which is dependent on the network loading. Table 2 illustrates the "average" percentage of lightpaths that are successfully "pre-emptively reprovisioned" assuming that no extra capacity has been added for pre-emptive reprovisioning. Also included in the table is the percentage of lightpaths for which there is a "diversity violation" after pre-emptive reprovisioning. Diversity violation occurs when fully diverse primary and backup routes are not available and primary and backup routes have to share links. For backup channel failure, ~90% of lightpaths can be successfully pre-emptively reprovisioned (since there are only a few lightpaths that need pre-emptive reprovisioning), for lightpath switch, ~75% can be successfully pre-emptively reprovisioned, and for a fiber failure about ~50% can be successfully pre-emptively reprovisioned.

As shown in Tables 1 and 2, pre-emptive reprovisioning is not effective against fiber failures because a) a large number of lightpaths require pre-emptive reprovisioning (large operational impact) and b) only a limited percentage of lightpaths can indeed be successfully reprovisioned. In the remainder of this paper, we only consider pre-emptive reprovisioning in the case of an initial single channel failure. We now estimate the frequency of pre-emptive reprovisioning requests due to channel failures resulting from switch port failures. Given the FIT rates of switch ports, we can estimate the rate at which a given port fails within a certain duration (e.g., 1 week). We then estimate the number of channel failures in a given duration by multiplying the number of channels by the probability of a channel failure. We assume typical FIT rates for 2.5G, 10G ports and other equipment. We assume that 4 lightpaths need to be reprovisioned for a protection channel failure and 20 lightpaths need to be reprovisioned for primary channel failures. We find that the frequency of pre-emptive reprovisioning is dominated by primary channel failures, and the number of lightpaths pre-emptively reprovisioned depends on the size of the network. For example, we find that for Network 3, an average of 3 lightpaths are pre-emptively reprovisioned per week due to shared channel failures, whereas an average of 50 lightpaths are pre-emptively reprovisioned per week due to working channel failures. The likelihood that pre-emptive reprovisioning is beneficial is the likelihood of a second failure impacting a lightpath during the Mean Time to Repair (MTTR) of the first failure (that caused the lightpath to become unprotected). We consider the first failure to be a primary channel failure causing a lightpath to switch to its backup, thereby resulting in 20 lightpaths to become unprotected, and pre-emptively reprovisioned. We then consider the likelihood of a second failure (being either another channel failure or a fiber failure) impacting one of 20 pre-emptively reprovisioned lightpaths. The following figure plots the likelihood that pre-emptive reprovisioning is beneficial against the MTTR of the first failure. We find that when the MTTR is about 4 hours, the probability that pre-emptive reprovisioning will be beneficial is about 1 in 100 times. As the MTTR increases, the probability that pre-emptive reprovisioning is beneficial increases proportionally.

3. Conclusion

Pre-emptive reprovisioning of backup paths improves the restoration time upon multiple failures. We evaluated pre-emptive reprovisioning on several representative real networks. We find that the success rate of pre-emptive reprovisioning is about 90% for protection channel failures, 75% for working channel failures, and about 60% for fiber failures. We find that the likelihood that pre-emptive reprovisioning is beneficial, i.e., the chance of a second-failure impacting the network within the MTTR of the first-failure, and is proportional to the
MTTR and is about 1 in 100 when the MTTR is 4 hours. The decision to support pre-emptive re-provisioning is thus a trade-off between the operational complexity of re-provisioning after single failures and the chances that re-provisioning would be beneficial in those (rare) cases of double failures before the first failure is repaired. The benefit is that the lightpath would then be restored (10s to 100s of msec) rather than re-provisioned (sec.) after a double failure. This work provides some preliminary results on the benefits of preemptive re-provisioning.

References

FR4 11:15 AM

Implementation of Statistical Lambda Multiplexing Network (SLAMNet)

H. Nakamura, H. Yokoyama, S. Nomoto, KDDI R&D Laboratories Inc., Saitama, Japan, Email: nakamura@kddilabs.jp

This paper discusses implementation of a novel signaling-free DWDM network architecture that provides multi-wavelength service. In the service, the number of assigned wavelengths is dynamically modified according to the volume of traffic on a best-effort basis.

I. Introduction

In a future large-scale Dense Wavelength Division Multiplexing (DWDM) network, multiple wavelengths will be used by a pair of routers to transmit high-volume traffic. A basic concept of a novel architecture called Statistical Lambda Multiplexing Network (SLAMNet) was proposed for providing multi-wavelength service in the DWDM network [1]. In comparison with the other architectures proposed for the DWDM network [2-5], the most striking feature of the architecture is signaling-free wavelength path switching to dynamically adjust the number of wavelengths to the varying volume of traffic. Taking the advantage of the signaling-free wavelength path switching, the SLAMNet can afford to be implemented to a part of a network with keeping its scalability, to be operated and maintained in a simple and economical way, and also to shorten the switching cycle regardless of round trip time necessary for signaling. Furthermore, the signaling-free wavelength path switching can harmonize with signaling-based wavelength path management mechanisms such as GMPLS.

II. Basic Concept of SLAMNet

A basic concept of the SLAMNet is illustrated in Figure 1. A pair of routers uses two types of optical channel (OCH) paths, referred to as initial paths and additional paths. The initial paths are fixedly established between the router pair and are used for transmission of traffic at all time. The other hand, the additional paths are temporally utilized for transmission of burst traffic that overflows the capacity of the initial paths. The additional paths are dynamically setup and released by a pair of OCH path switches (OPSWs) and timeshare wavelength resources assigned via optical cross-connects (OXC)s between the OPSWs. A basic configuration of an OPSW is illustrated in Figure 2. A monitor measures the volume of traffic transmitted by established initial and additional paths and observes its variation on a real-time basis. Additional paths are set up and released by making use of the variation of traffic volume as a trigger in source and destination OPSWs independently. Although the OPSWs exchange no signal with each other for management of the additional paths, they control to connect XC paths according to a common algorithm that selects the same path to be connected with the target path at the same status in cross-connect of the paths. Furthermore, for the purpose of keeping logical consistency in operation of the source and destination OPSWs, the algorithm employs several techniques to avoid incorrect actions and to guard against unexpected events, such as path selection based on a hash table [6].

A key point of the path switching mechanism is the difference in transmission delay among the OCH paths used by the same router pair. The difference has to be guaranteed in order to operate the switching mechanism properly and also to limit the ratio of reverse in a sequence of packets transmitted by multiple OCH paths. In this architecture, the initial and additional paths for the same router pair is routed in the physical network so that the difference in transmission delay among the paths is guaranteed to a certain extent. In the case where the paths are set up on the same physical route, the guaranteed difference is limited to that among wavelengths when they go through it. Based on the guaranteed difference in transmission delay, additional paths are managed in a sequence as shown in Figure 3. The guard time

Figure 1. Basic Concept of SLAMNet

Figure 2. Configuration of OPSW

Figure 3. Basic Flow of Signaling-Free Path Management.
the XC path network and makes use of the guaranteed difference in transmission delay of the XC path bundle in management of SW paths. The SW paths are dynamically set up and released by switching the XC paths in the OPSWs with taking a configuration of the XC path bundle into account. The SW path network is designed to change its configuration more frequently than the XC path network that is operated in a conventional way. Statistical multiplex gain is expected in use of wavelength resources between a pair of OPSWs. Therefore, it is important for efficient network operation to implement the OPSWs with taking a tradeoff between the statistical multiplex gain and cost for implementation and operation of the OPSWs into account.

A SW path that consists of multiple XC paths is managed by multiple pairs of OPSWs as shown in Figure 5. Since each pair of OPSWs operates a XC path independently, it is not ensured that all the XC paths necessary for a SW path can be established when they are requested. The major target of this path management is transmission of burst traffic that requests wide bandwidth during a very short time period, such as high-speed download of huge files and aggregated traffic of individual streams that are apt to be highly concentrated. Furthermore, when the initial paths are established as a point-to-multipoint connection set and traffic is broadcasted via the paths, the additional path management mechanism of the SLAMNet can be simply applied for broadcasting the traffic.

IV. Harmonization with Wavelength Label Switching

The SLAMNet is applicable to a network that employs GMPLS function and can afford to work with the function in a harmonization scenario. In the scenario, initial paths and XC paths of the SLAMNet are managed as LSPs (Label Switched Paths) with signaling process by the GMPLS function. Based on the LSPs, additional paths are dynamically set up and released as SW paths by the signaling-free path management of the SLAMNet. Figure 6 illustrates a configuration of a node to support both the GMPLS function and the path management mechanism of the SLAMNet. In this configuration, a GMPLS router needs additional functions to set a cross-connect for the XC paths to be used in the additional paths according to setting of the initial paths and to control forwarding packets in output buffers of a packet switch with observing the volume of traffic. Furthermore, it is necessary for the GMPLS router to set a guard time before transmission of traffic through a newly established additional path and also to interwork with the OPSW in order to keep consistency of correspondence between the initial and additional paths.

V. Test System

For the purpose of demonstrating performance of the SLAMNet, a test system is developed as shown in Figure 7. This test system emulates the case where four router pairs share four or fewer OCh paths as additional paths on a best-effort basis. The additional paths are dynamically set up and released by a pair of OXCs representing OPSWs. Two routers in each side of the OXCs emulate four routers that share the additional paths. The router directly connected with hubs gives a tag to such the IP packet that overflows the capacity of an initial path and the other router distributes the traffic between the initial and additional paths according to the tags. A PC connected with the OXC works for monitor of traffic volume and control of the cross-connect. In a trial of this hardware, it is confirmed that the additional paths are dynamically managed in the cycle less than 28 milliseconds [6]. The cycle is expected to shorten in the further trials.

VI. Conclusions

The concept of SLAMNet is applicable to specific parts of the network, such as dense areas and bottleneck sections, and allows reduction of the necessary wavelength resources only in such portions. Thus, the architecture and path management mechanism can be introduced to conventional WDM
networks in a step-by-step manner according to their usage status and operation plans. Furthermore, the SLAMNet has the possibility to shorten the cycle of additional path switching to the order of transmission time of a burst in an optical burst switching network. Based on the SLAMNet, the short cycle operation is also pursued for optical burst switching.

References

FR5 (Invited)11:30 AM

Core Mesh Optical Networks: A European Carrier’s Perspective
A. Gladisch, Deutsche Telekom T-Systems Nova Technologiezentrum, Berlin, Germany, Email: Andreas.Gladisch@telekom.de.

Figure 7. Test system of SLAMNet

Experiences with mesh restoration in a former SDH network are presented. Results of mesh core networks design studies are given with respect to opaque and transparent scenarios and problems of inter-working of mesh restoration domains are discussed.

FR6 (Invited)12:00 AM

A National Mesh Network Using Optical Cross-Connect Switches
P. Charalambous, C. Dennis, Dynegy Global Communications, Englewood, CO; G. Ellinas, E. Bouillet, J. Labourdette, A. Akyamac, S. Chaudhuri, M. Morokhovich, D. Shales, Tellium Inc., Oceanport, NJ, Email: pambos.charalambous@dynegy.com.

This paper presents Dynegy’s long-haul national network utilizing intelligent optical switches. This network offers end-to-end point-and-click provisioning, shared mesh restoration, re-provisioning of connections and network re-optimization.

Networks that transport optical connections using Wavelength Division Multiplexed (WDM) systems and route these connections using intelligent optical cross-connects (OXC’s) are firmly established as the core constituent of next generation long-haul networks. In such networks, preventing and restoring link and node failures is increasingly becoming one of the most important network features [1-4]. Dynegy’s network implements shared mesh restoration using intelligent optical switches to protect against single link and node failures. In shared mesh restoration (Figure 1), backup paths can share capacity if the corresponding primary paths are mutually diverse. Diversity of routes in Dynegy’s optical network is defined using the notion of Shared Risk Groups [5]. A set of optical channels that have the same risk of failure is called a Shared Risk Group (SRG). SRGs are configured by Dynegy’s network operators with the knowledge of the physical fiber plant of the optical network. Compared to dedicated protection, this scheme allows considerable savings in terms of capacity required [5,6]. In addition, the backup resources can be utilized for lower priority preemptible traffic in normal network operating mode. However recovery is slower than dedicated protection in some cases, yet still within the realm of SONET restoration times, essentially because it involves signaling and path-setup procedures to establish the backup path. In particular, we note that the restoration time will be proportional to the length of the backup path and the number of hops, and if recovery latency is an issue this length must be kept under acceptable limits. However this constraint may increase the cost of the solution, as it is sometimes more cost-effective to use longer paths with available shareable capacity than shorter paths where shareable capacity must be reserved. This tradeoff can be handled by an appropriate cost model in the route computation algorithm [7-8].

For routing purposes, the algorithms utilized by the intelligent optical switches use a cost model that assigns costs to the links in the network. The policy used for assigning costs to the links is different for primary and backup paths. The weight of a link for a primary path is the real cost of using that link in the path. This is a user-defined cost that reflects the real cost of using a channel on that fiber. The weight of a link for a backup path is a function of the primary path [7-9]. Backup link $w_b$, if new capacity is required to provision the path, and (3) Weight $w_c = \varepsilon w_b$, $0 \leq \varepsilon \leq 1$, if the path can share existing capacity reserved for pre-established backup paths. The routing of each lightpath attempts to minimize the total cost of all channels in the lightpath route, i.e., the goal is to share the existing capacity amongst multiple backup paths.

Mesh Restoration

Provisioning of shared mesh restored lightpaths in Dynegy’s live network that utilizes Tellium’s intelligent Aurora Optical Switches, was achieved by calculating the working and backup paths using the weight assignment as described above. Dynegy’s network is on the order of 45 nodes and 75 trunks, and is carrying shared mesh restored demands amounting to several hundred gigabits of service. Upon a single link or single node failure, restoration times ranging from a few tens to a couple of hundred msec were observed. The maximum restoration times observed were less than 200 msec in the worst case (when a large

Figure 1. Shared Mesh Restoration: (a) Network connections before a failure occurs (b) Network connections after a failure occurs.
number of lightpaths have to be restored simultan-
eously as a result of a single failure). As expected, restoration latency generally increases as more lightpaths are failed, even though there could be variations for a relatively similar number of failed lightpaths. A study presented in [10] is representative of such a scenario and determines the range of restoration latencies that can be expected from a network upon single link or node failures.

Mesh Re-provisioning

In the case of multiple failures, Dynegy’s net-
work, utilizing intelligent OXCs, also supports lightpath re-provisioning. Lightpath re-provision-
ing establishes a new backup path when restora-
tion on the original backup path does not succeed. Re-provisioning uses existing spare capacity and unused shared capacity to find a new backup path on which to immediately restore the failed lightpath. There are three conditions that result in lightpath re-provisioning: (A) A failure of the primary path followed by a failure of the backup path prior to repair of the primary path, (B) A failure of the backup path followed by a failure of the primary path prior to repair of the primary or backup path, and (C) A failure of the primary path of a lightpath (B) sharing backup capacity with a lightpath (A), followed by a failure of the primary path of lightpath (A). In this case, lightpath (B) is restored onto its backup path after the failure, thus occupying the shared backup resources. When lightpath (A) fails, it cannot restore onto its backup (because resources are being used), resulting in a re-provisioning attempt. Note that re-provisioning may fail if there is not enough capacity available. Re-provisioning a lightpath that becomes unavailable after a double failure will improve the service availability of the network, by reducing the time that the service is unavailable from hours to tens of seconds. Simulation studies showed that compared to default protection, mesh restoration provides higher reliability due to the implementation of re-provisioning after a second failure, resulting in up to a 48% decrease in unavailability [11].

Mesh Re-optimization

During the network operation, requests for ser-
dvices are received and provisioned using an online routing algorithm with the cost model defined above. Both the primary and backup paths of each new demand request are computed according to the current state of the network. As the network changes with the addition or deletion of fiber links and capacity and traffic evolve, the routing of the existing demands becomes sub-
optimal. Re-optimization by re-routing the backup and/or primary paths gives the network operators the opportunity to regain some of the network bandwidth that is currently in use. In particular, re-routing only the backup paths is an attractive way to regain some of the protection bandwidth and reduce backup path length while avoiding any service interruption. Figure 2 illustrates how re-optimization temporarily eliminates the drift between the current solution and the best-
known offline solution that is achievable under the same conditions.

Table 1 shows the gains achieved when the backup paths in Dynegy’s live network are re-
outed during a maintenance window. In this case, the network consisted of 45 nodes, 75 links, and 70 shared mesh restored demands with their routes provided by the network operator, and all backup paths were re-optimized and tested. The complete re-optimization procedure, including testing took approximately 5 hours. Note that Table 1 only refers to ports used for the protection channels and it shows the port counts and number of backup hops measured before and after re-opti-
mization. Clearly, re-optimization is beneficial both in terms of number of protection ports used, as well as the length of the backup paths. Specifically, as shown in the table, backup path re-optimization saved 31% of the protection ports which in turn translated to 20% savings of the total number of ports. Also, the average length of the backup paths decreased from 5.87 to 4.88 hops [12]. The importance of re-optimization to the network is threefold. Firstly, the reduced number of protection ports used translates in freed protection capacity, which could then be used to carry new services. Secondly, the reduction in backup path length translates to the reduction in protection latency. In particular, in the re-optimization of Dynegy’s network, the reduction of the average length of the backup path reduced the backup latency (restoration time) by 25.61% (cal-
culated using the average length of the backup path in miles before and after the re-optimization) [12]. Finally, re-optimization allows network operators to make use of new nodes and links that are deployed in the network.

![Figure 2. Current cost versus best possible cost with cost-benefit of re-optimization.](image)

Dynegy’s long-haul national network utilizing Tellium’s optical switches has clearly become an intelligent network. It offers end-to-end point-
click provisioning, shared mesh restoration with a few tens to a couple of hundred msec restora-
tion times, re-provisioning of connections in the event of double failures and network re-opti-
mization to regain some of the network capacity that is not optimally used.

References

er 2002.
pean Conference on Networks & Optical Communications (NOC), Darmstadt, Germany, June 2002.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Backup port count</th>
<th>Avg. backup hops</th>
<th>Max backup hops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>% save</td>
</tr>
<tr>
<td>Dynegy Network</td>
<td>310</td>
<td>214</td>
<td>30.97%</td>
</tr>
</tbody>
</table>

Table 1. Backup Path Re-optimization.