PSBT Field Trial at 40Gb/s

Martin Birk[1], Ted Schmidt[2] and Ross Saunders[2]

[1] AT&T Labs, Optical Systems Research, 200 Laurel Avenue South, Middletown, NJ 07748, USA, email birk@att.com
[2] StrataLight Communications, 2105 S. Bascom Avenue, Campbell, CA 95008, USA, email ross@stratalight.com

Abstract: This paper presents results of laboratory testing and field trial of 40Gb/s Phase Shaped Binary Transmission (PSBT) channel upgrades to installed 10Gb/s Dense Wavelength Division Multiplexed (DWDM) systems, supporting 50GHz channel spacing.

Introduction

As Internet traffic continues to grow, scaling the Internet backbone will continue to be a challenge. Although earlier claims of bandwidth doubling every 100 days were over-optimistic, Internet growth is still predicted to grow by 1.7x to 2.5x per year over the next decade [1]. With the commercial availability of next generation IP routers employing 40 Gb/s interfaces to support this growth comes the requirement to interconnect these routers across the WAN.

Due to the different capacities, service interfaces, and inherent reach of 10 Gb/s and 40 Gb/s DWDM systems, the most cost-effective transport solution will employ both in the network. For capacity demands with high growth rates and moderate reach (<1,000km), 40 Gb/s PSBT can be deployed without the need for intermediate regeneration. PSBT has unique capabilities for use in networks with a large number of intermediate ROADM filters. For sections of networks with ULH distances (1,000 – 2,000 km), connectivity is best supported with 10 Gb/s channels, and 40 Gb/s DPSK. Additional considerations are described below under the heading "Practical Challenges for 40 Gb/s Deployments".

This paper describes 10 and 40 Gb/s multi-haul DWDM testing in both laboratory and field environments, proving the viability and practicality of multi-haul transmission. Field trial testing over an installed 850 km 10 Gb/s system deployed between Seattle, WA to Bandon, OR showed error-free transmission with a Q margin exceeding 4dB. Error free transmission of the 40 Gb/s channels was also achieved over a 1700 km loopback configuration in the field trial, which included 3 intermediate OADMs supporting 50GHz channel spacing add/drop.

The DWDM system used in the trials supports any mixture of 10 Gb/s and 40 Gb/s wavelengths on a 50GHz ITU grid. The use of a spectrally efficient Phase-Shaped Binary Transmission (PSBT) modulation format for the 40 Gb/s channels offers a number of advantages over the use of NRZ or CS-RZ [2,3,4,5], such as:

1. Compatible with 50GHz channel spacing systems (0.8bit/s.Hz spectral efficiency), including Reconfigurable Optical Add/Drop Multiplexer (R-OADM)
2. Wide inherent chromatic dispersion tolerance of 300ps/nm, eliminating need for continuous CD optimization
3. Any mix of 10 Gb/s and 40 Gb/s wavelengths, no requirement for wavelength sub-bands or guard bands
4. Launch power compatible with existing 10 Gb/s design rules

Laboratory experiment

To prove the seamless upgradeability of this 10 Gb/s system to 40 Gb/s channels, tests were first performed in the lab with a pre-production version of the 40 Gb/s transponders over the existing 10 Gb/s system. A 1,000 km system with 3 optical add/drop multiplexers (OADM) along the transmission path was used for the lab tests. The transmission link consisted of 12 spans of 80 km Standard Single Mode fiber (SSMF of 1997 vintage), with each span attenuated to 21 dB. The transmission system was optimized for 10 Gb/s channels, with 80 of the 10 Gb/s channels in the C-band at 50 GHz spacing. For the multi-haul experiments, 78 channels were populated with 10 Gb/s NRZ transponders employing 25% overhead FEC. Two channels were populated with 40 Gb/s PSBT transponders employing 7% overhead E-FEC. The 40 Gb/s channels were added at the standard multiplexer ports and interleaved to 50GHz channel spacing (approximately 40GHz filter bandwidth). Launch power was comparable, at about +1 dBm, for the 10 Gb/s and 40 Gb/s channels. The amplifiers were three [two??] stage erbium doped fiber amplifiers (EDFA) with mid-stage access for chromatic dispersion

compensation. The system was running with full optical link control to balance optical gain tilt and spectral shape. The OADMs were based on a broadcast-and-select wavelength blocking architecture with a spectral width of approximately 35 GHz per channel.
The system was optimized for 10 Gb/s NRZ transmission, so the post-compensation was varied to determine the 40 Gb/s chromatic dispersion tolerance and optimize performance. Aside from the adjustment of the post compensation, the system was left untouched. The 40 Gb/s channels exhibited more than 2 dB Q margin over the link with an optical signal to noise ratio (OSNR) of 19.8 dB. Both channels were error free after FEC for 48+ hours, as measured via an OC-768 SONET test set connected to the client interface. The SONET test set was configured for OC-768c transmission with a 2^{31}-1 PRBS pattern in the payload.

Disabling the two 50 GHz-spaced 10 Gb/s channels adjacent to the 40 Gb/s channels improved the Q margin by approximately 0.5 dB. Disabling the next adjacent channel on either side had no further impact on the 40 Gb/s performance. The impact of adding a 40 Gb/s channel to the existing 10 Gb/s channels was found to be minimal, comparable to that of adding a 10 Gb/s channel at the same frequency and channel spacing.

Field experiments at 850 km

Next, a 10/40 Gb/s multi-haul field trial was conducted over the AT&T network connecting Bandon, Oregon and Seattle, Washington. The transmission distance for the link was 850 km, and the link consisted of 12 fiber spans in each direction. Two of the fiber spans were TrueWave-Classic fiber, 10 were SSMF. Span lengths ranged from 50km to 88km. Insertion losses ranged from 15 to 22 dB, with an average loss of 17 dB. The polarization mode dispersion (PMD) of the route was below 0.1 ps/sqrt(km). On this route, a ROADM was present in Portland, OR. A total of seven transponders were equipped in each direction, one 40 Gb/s PSBT transponder at 193.5 THz, two 10 Gb/s transponders on either side (193.4, 193.45, 193.55 and 192.6 THz) for a total cluster of 5 wavelengths at 50 GHz spacing. The other two wavelengths on the system were towards the end of the C-band, used for other testing.

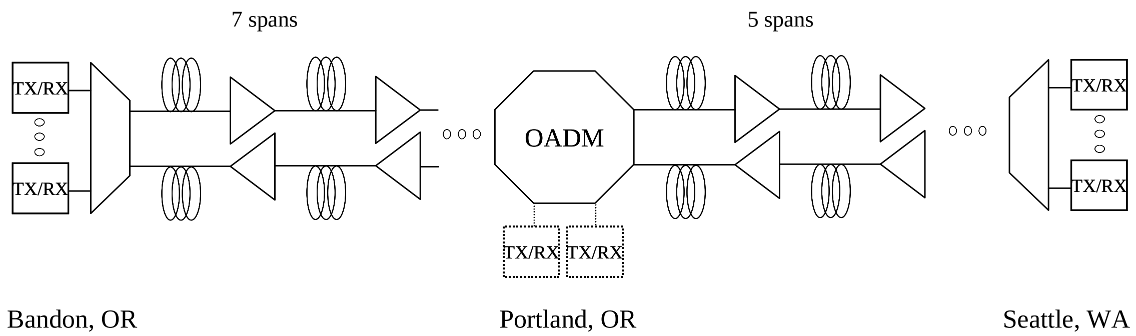

Fig. 1: Diagram of the field-installed system over installed fiber between Bandon and Seattle.

The transmission system was the same type as used for the lab experiments. All link optimizing control loops were running and no adjustment was made to accommodate the 40 Gb/s channels, apart from adjusting the pre- and post compensation, which did not influence the existing system. To monitor the post-FEC BER, an OC-768 SONET test set was connected to the 40 Gb/s transponder in Seattle with the client interface on the 40G transponder in Bandon in optical loop-back on itself. The SONET test set was configured for OC-768c transmission with a 2^{31}-1 PRBS pattern in the payload.

A newer generation of the fully C-band tunable 40 Gb/s PSBT transponder was used for the field trial, with enhanced performance (improved transmit/receive electronics) relative to the generation used in the lab trial. Pre/post compensation for the 40G channels was varied by inserting DCMs between the 40 Gb/s transmitter/receiver and the mux/dmux, respectively. A chromatic dispersion tolerance greater than 150 ps/nm was measured for a 0.5dB Q penalty on this route (see Fig. 2). This large CD tolerance eliminates the need for tunable dispersion compensation and makes 40 Gb/s deployments practical.

For initial experiments, the 10 Gb/s channels at 193.45 THz and 193.55 THz were disabled. Approximately 3.5 dB and 4.5 dB Q margin was measured for the southern and northern routes, respectively, at 100 GHz channel spacing. In comparison to lab trial results over similar links, it is estimated that the ONSR margin on the southern route exceeded 6 dB for this 100 GHz experiment. The post-FEC BER was verified to be error free. The two 10 Gb/s channels were then activated at 193.45 THz and 193.55 THz, providing the cluster of 5 channels at 50 GHz channel spacing centered on the 40 Gb/s channels. The margin of the 40 Gb/s channels was reduced by approximately 1 dB due to the presence of these 50 GHz-spaced 10 Gb/s channels, but significant margin was still present over the link. In previous lab experiments over this system, the impact of the 40 Gb/s channels on the 10 Gb/s channels has been found to be negligible so the impact was not measured during the trial. Performance of the 40 Gb/s channels could have been improved by optimizing the 40G channel launch power, but this was not within the scope of the trial.

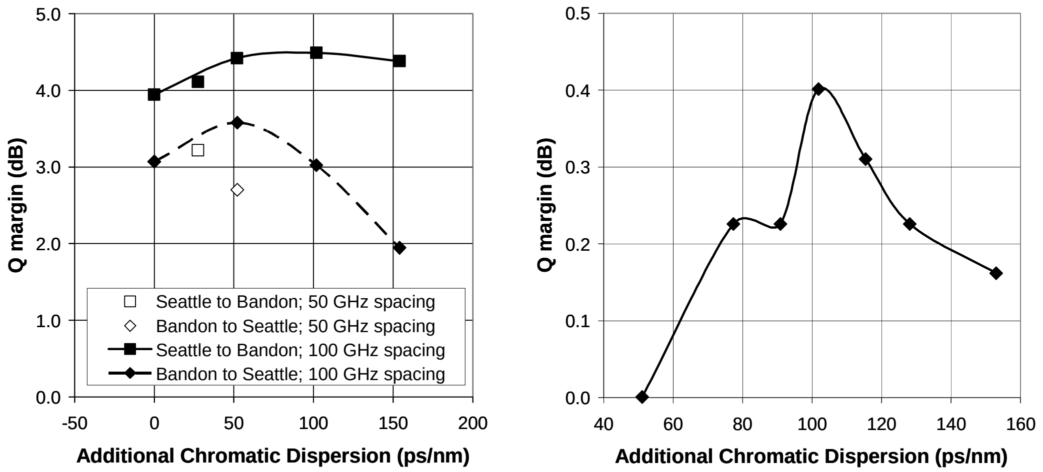

Fig. 2: Q margin as a function of link chromatic dispersion for the 850 km field trial link (left graph) and 1700 km loopback field trial link (right graph). Q margin is measured relative to the FEC correction limit. Chromatic dispersion values are given relative to the residual link dispersion.

Field experiments at 1700 km

To further evaluate the performance of the 40 Gb/s PSBT channels over the system, the 40 Gb/s channel was optically looped back at the Bandon site to provide a total transmission distance of 1700km. An optical amplifier was added between the mux/dmux to overcome the loss associated with the loop-back. For these experiments, the 10 Gb/s channels at 193.45 THz and 193.55 THz were disabled. The pre- and post dispersion compensation stayed the same as in the 850 km experiment, with a DCM inserted at the loop-back prior to the amplifier. As before, all control loops were enabled. In this configuration, the 40 Gb/s channel traveled 1700 km and passed through three 50 GHz OADMs (2 broadcast-and-select OADMs and one full mux/dmux OADM) without regeneration. The margin over the link was 0.4 dB and the post-FEC BER was error free for this 100 GHz experiment, measured by the OC-768 test set (see Fig. 2). Enabling the 50 GHz spaced channels again, we could decode the FEC error free, but got bit error hits on small adjustments of the optical link power balance control, showing that there was no excess margin.

Practical challenges for 40Gb/s deployments

This field trial has shown that 40Gb/s technology is now approaching maturity and that network deployments are feasible. For 40Gb/s to achieve widespread use the following issues must be addressed:

1) Compatibility with existing fiber and DWDM architectures
2) Complexity of turn-up and maintenance
3) Cost-effectiveness

The first and second constraints indicate the design target should be to enable 40Gb/s deployment within existing 10Gb/s design rules. In reality this target cannot be achieved due to the physical constraints of 4x capacity increase, but the use of novel modulation formats accompanied by electrical and optical compensation schemes allow minimal deviation from existing design rules and make 40Gb/s deployments a practical reality. Practical challenges for 40Gb/s deployments with 10Gb/s design rules are:

1) Wide CD tolerance (typical 10Gb/s systems have around 1,000ps/nm tolerance)
2) Large PMD tolerance (typical 10Gb/s systems have around 8ps mean DGD tolerance)
3) Optical reach (typical 10Gb/s systems have 1,500km reach)
4) Channel count (typical 10Gb/s systems support 80 channels per band on a 50GHz grid)

The use of PSBT optical modulation at 40 Gb/s fully supports 4) and partially supports 1) and 3) , however PMD is not addressed. This is not a concern for more recent fiber builds (late 90s onwards) but can severely limit the 40Gb/s reach on older fiber. The use of optical PMD compensation can improve the PMD tolerance by a factor of 4.

Another concern, particularly for installed systems that may not have tight dispersion compensation granularity and slope-matched DCMs, is that the intrinsic CD tolerance (300ps/nm) of 40Gb/s PSBT is not sufficient. To increase the CD tolerance, tunable Fiber Bragg Grating (FBG) or etalon based devices can be used with the PSBT format as set-once adjustable compensators to significantly improve 40Gb/s CD tolerance to > 2,000ps/nm.

For ULH network applications, particularly those sections of core networks in the USA with longer link distances, a reach of 1,000km results in O-E-O regenerators being required. For maximum reach, Differential Phase Shift Keying (DPSK) offers a 3dB improvement in OSNR sensitivity, which increases the reach to > 1,500km. The added receiver complexity of DPSK does add cost, but deploying PSBT for demands < 1,000km and DPSK for demands > 1,000km offers one solution to manage the total network cost through the use of complementary 40Gb/s technologies.

	10Gb/s	**40Gb/s PSBT**	**40Gb/s PSBT + TDC**	**40Gb/s PSBT + TDC + PMDC**	**40Gb/s DPSK + TDC + PMDC**
CD tolerance (ps/nm)	1000	300 (**X**)	2,100 (√)	2,100 (√)	1,000 (√)
PMD tolerance (ps)	8	2.5 (**X**)	2.5 (**X**)	8 (√)	6 (**X**)
Reach (km)	1,500	1,000 (**X**)	1,000 (**X**)	1,000 (**X**)	1,500 (√)
Channel count	80	80 (√)	80 (√)	80 (√)	40 (**X**)

Fig. 3: Summary comparison table of different 40Gb/s modulation formats and optical compensation technology options. A comparison is given versus typical 10Gb/s network design rules.

A summary of 40Gb/s PSBT and DPSK modulation format compatibility with 10Gb/s design rule targets is shown in Figure 3. Although there is not a perfect match to 10Gb/s design rules, selective deployment of the right modulation format and optical compensation technologies does allow the existing 10Gb/s fiber/DWDM infrastructure to support 40Gb/s deployment and appeases network operators' primary feasibility concerns.

Summary and conclusions

Lab and field trials have been performed, proving the viability and practicality of spectrally efficient 10/40 Gb/s multi-haul DWDM transmission using production 40 Gb/s PSBT transponders. Seamless 40 Gb/s upgrade to the existing 10 Gb/s transmission system was demonstrated in lab and field trial environments using spectrally efficient 40 Gb/s PSBT transponders. These 40 Gb/s PSBT transponders supported OC-768c framing, which was used for all testing reported here. The first field trial, consisting of an 850 km link with one intermediate OADM showed up to 4.5 dB of Q margin and a large chromatic dispersion tolerance. The second field trial was over a 1700 km link with 3 OADMs. Margin above the FEC threshold was achieved and error free performance after FEC was confirmed via an OC-768 SONET test set connected to the client interface. Further field trials using 40 Gb/s DPSK are being planned.

References

[1] A. M. Odlyzko, "Internet traffic growth: Sources and implications," http://www.dtc.umn.edu/~odlyzko/doc/itcom.internet.growth.pdf.

[2] W. Kaiser, A. Ehrhardt, W. Rosenkranz, and N. Hanik, "Field trial of duobinary transmission over 1720 km at 10 Gb/s," in Proc. Eur. Conf. Opt. Communication (ECOC'02) Copenhagen, Denmark, vol. 3, Paper P3.3, 2002.

[3] N. Hanik, A. Ehrhardt, A. Gladisch, C. Peucheret, P. Jeppesen, L. Molle, R. Freund, C. Caspar, "Extension of All-Optical Network-Transparent Domains Based on Normalized Transmission Sections," Journal of Lightwave Technology, vol. 22, pp. 1439 - 1453, June 2004

[4] H. Bissessur, L. Pierre, J.-P. Hamaide, "Enhanced PSBT: demonstration of dispersion tolerance and noise resistance over 300 km terrestrial link," Optical Fiber Communication Conference and Exhibit, OFC 2001 , vol. 3 , paper WDD36-1, 2001

[5] M. Birk, L. Raddatz, D. Fishman, S. Woodward, P. Magill, "Field trial of end-to-end OC-768 transmission using 9 WDM channels over 1000km of installed fiber," paper TuS4, Optical Fiber Communications Conference, 2003. OFC 2003, 23-27 March 2003, Pages: 290 - 291