“Broadcast and Select” OADM in 80 × 10.7 Gb/s Ultra-Longhaul Network

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***Abstract*—We report the first experimental realization of dynamically reconfigurable ultra-longhaul network using “broadcast and select” optical add–drop-multiplexer (OADM) architecture. We achieve 80 × 10.7 Gb/s nonreturn-to-zero C-band dense wavelength-division-multiplexing networking with 50-GHz channel spacing over 4160 km (52 spans × 80 km each) of all-Raman-amplified symmetric dispersion-managed fiber and 13 concatenated OADMs with 320-km spacing. Measured Q values exhibit more than 2 dB margin over the forward-error-correction threshold for 10^{-15} bit-error-rate operation. These results are obtained for the channels passing through the 320-km spaced OADMs when 50% add–drop occurs at an intermediate OADM located along the transmission path, as well as for the channels added at the intermediate OADM. Penalties due to filter concatenation and crosstalk are quantified. Q factor is also characterized after 8000-km transmission.**

***Index Terms*—Networks, optical communication, Raman amplification.**

THE RAPIDLY growing Internet traffic in major U.S. cities, and the need for a cost-effective interconnection of the traffic pipes originating from them, have created the demand for high-capacity ultra-longhaul (ULH) networks with transparent reach in excess of 2500 km and capability of dynamic add–drop of selected channels at each node [1]. These optical add–drop-multiplexer (OADM) nodes will need to accommodate an average add–drop traffic ratio of about 25%. High-capacity transport is realized by using dense wavelength-division-multiplexing (DWDM) technology and high data rate per channel, while ultralong transparent reach is enabled by new technologies such as optimized Raman amplification, dispersion management, advanced modulation formats, and forward error correction (FEC). With recent progress in these technologies, point-to-point multiterabit transmission over many thousands of kilometers has been demonstrated even for terrestrial amplifier spacing (e.g., see [2]). On the other hand, experimental reports of optical networking capabilities over ULH distances are scarce [3], [4].

In this work, we present a transport study of ULH networks using fully functional reconfigurable OADMs. The OADMs are based on a novel “broadcast-and-select” (B&S) architecture, enabled by a wavelength-selective blocker [Corning’s PurePath Dynamic Spectral Equalizer (DSE)] [5]. The transmission link employs a symmetric dispersion-managed fiber (DMF) and distributed all-Raman amplification. Our system’s performance is impacted by both transmission and networking impairments including amplified spontaneous emission (ASE) noise, filter concatenation, dispersion, fiber nonlinearity, and crosstalk.

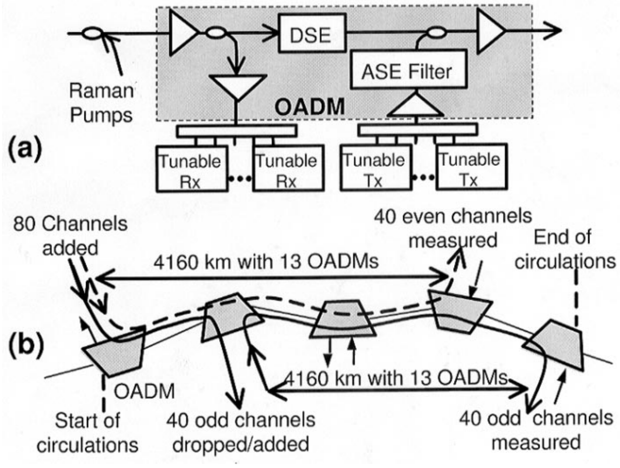

Fig. 1. (a) B&S OADM architecture. (b) Network model realized in our recirculating loop testbed.

The B&S OADM architecture used in our experiments consists of a 1×1 wavelength-selective blocker in combination with 1×2 power splitters–combiners to perform traffic add–drop and proper amplification to compensate for OADM losses. In this architecture shown in Fig. 1(a), all incoming traffic is split into two paths for drop and pass-through. In the drop path, the dropped traffic is selected by a combination of a power splitter ($1 \times N$, where N is the number of simultaneously accessible DWDM channels) and tunable filters. In the pass-through path, the dropped channels are blocked by the DSE and the available channel slots can be filled by the channels newly added from the add path. The add path may consist of N tunable transmitters and an $N \times 1$ power combiner. An erbium-doped fiber amplifier (EDFA) is used to compensate for losses in the add path (when high add–drop ratio and colorless multiplexers are used) and the amplifier noise in the empty channel slots is removed by an ASE filter (e.g., another DSE). Both DSEs in this architecture can block selected channels and simultaneously level the power for the pass-through or added channels. EDFAs are placed at the input and the output of the OADM to compensate for OADM losses. Fig. 1(b) shows the network model that we emulate in the lab using a recirculating

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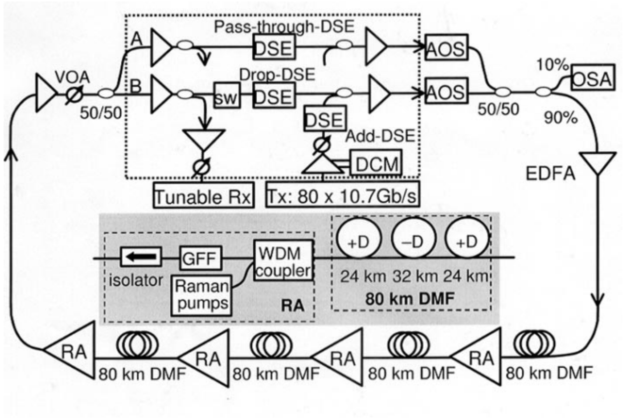

Fig. 2. Schematic of experimental setup.

loop setup. We assume that 80 channels are added at the first OADM. The 80 channels propagate over 1600 km of fiber (passing through four OADMs) and at the sixth OADM, 50% of the traffic (odd numbered channels) is dropped. The OADM adds 50% new traffic at these wavelengths so that a total of 80 wavelength-division-multiplexing (WDM) channels are sent to the next spans. Fig. 2 shows a schematic of a novel recirculating loop setup used in our experiments. The 80 DWDM channels (1530.33…,1561.82 nm) are obtained by interleaving two sets of 40 channels, each with 100-GHz channel spacing. A LiNbO$_3$ Mach–Zehnder modulator is used to encode a $2^{31} - 1$, 10.664 Gb/s nonreturn-to-zero pseudorandom bit-sequence data on each set of 40 channels. An EDFA is used to amplify the DWDM signals that are fed at the add path of the OADM. A dispersion-compensating module (DCM) is placed in the mid-stage of the EDFA to precompensate the signals by -986 ps/nm and -1315 ps/nm for transmission over 4160 and 8000 km, respectively. No postcompensation is used in the drop path for a reach of 4160 km, while for 8000-km reach we use 820 ps/nm postcompensation. Preemphasis of the powers of the transmitted DWDM signals is performed to achieve optimum flat optical signal-to-noise ratio (OSNR) for all channels after transmission through one loop. An EDFA is used before the first span to compensate for losses specific to the loop architecture (i.e., losses from the acoustooptic switches (AOS) and the 3-dB coupler). The average launch power per channel in each fiber span is -6.8 dBm. The loop consists of four 80-km spans of DMF with a very small overall dispersion slope, each comprising 32 km of a negative dispersion fiber positioned between two 24-km sections of positive dispersion fiber. Such DMF design has shown remarkable advantages in terms of Raman noise-figure and multipath interference performance [6]. The per-span residual dispersion is 28 ps/nm on average, and the total accumulated dispersion per loop is 110 ± 8 ps/nm across the entire C-band. All fiber spans are made transparent by using distributed Raman amplification only (six backward pumps—three wavelengths, two polarizations). The pump powers are adjusted to achieve minimum gain ripple. Each Raman amplifier (RA) also includes a fixed gain-flattening filter (GFF) (see inset in Fig. 2). The average Raman gain to compensate for losses of the fiber, splices, connectors, WDM coupler, GFF, and an isolator is 20.5 dB. After passing through the spans, the signals are fed to the OADM (dotted line in Fig. 2). In the drop path of the OADM they are demultiplexed, preamplified, and selected by a bandpass filter.

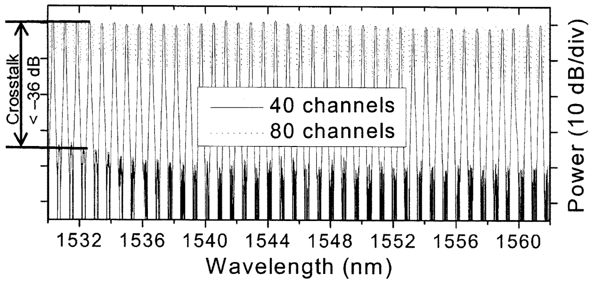

Fig. 3. Spectra at the DSE output with and without blocking.

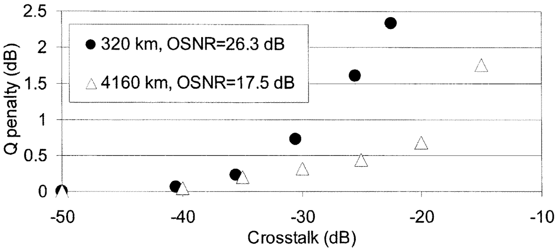

Fig. 4. Crosstalk penalty for channel 25 (1539.77 nm) after 320 and 4160 km.

For the demonstration purpose, we implement two OADMs with different optical paths in our loop experiment (see Fig. 2). The top path A is used for the traffic passing through the OADM. The bottom path B is used for adding and dropping traffic from the loop. The amplifier at the input of the OADM is placed to accommodate the 3-dB loss of the coupler that splits the signals in the two paths, without introducing OSNR degradation that would not be present in a real OADM design. The accumulation of gain ripple at the end of the loop is compensated for the pass-through traffic by using the pass-through DSE in a way that results in almost flat OSNR performance and maximization of the Q factor of the received signals. The AOSs, as well as the drop and add DSEs, are dynamically reconfigured to enable loading of the loop with traffic, circulation of signals in the loop, and add–drop functionality after the first five loops. Initially, the loop is loaded with 80 channels through the add DSE, while the light in the bottom path B is blocked by fast mechanical switch “sw.” The channels circulate for five loops using the OADM in the top path A with the pass-through DSE (AOS is ON in the top path A and OFF in bottom path B). After five loops, the AOS in the bottom path B turns ON and the AOS in the top path A turns OFF, which redirects the signals to the bottom path B. At that point, 40 odd channels are blocked by the drop DSE and are added by the add DSE. Then, the AOSs are reconfigured again and the signals circulate through the top path A.

Fig. 3 presents the optical spectra (measured with resolution of 0.12 nm) at the output of the DSE in the OADM when either all channels pass through or 40 channels are blocked. The crosstalk performance of the OADM, doing simultaneous blocking and power leveling (3.5–4.5 dB), is greater than 36 dB. The measured polarization-averaged Q penalty due to single-term crosstalk is shown in Fig. 4 for two propagation distances. As expected, because of the lower OSNR, the Q penalty after 4160 km is less than that after 320 km for the same crosstalk level. Figs. 5 and 6 show the measured

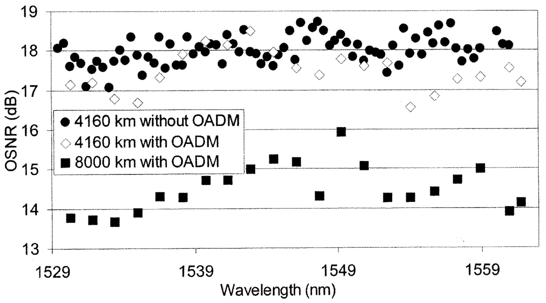

Fig. 5. OSNR in 0.1-nm bandwidth after 4160 and 8000 km.

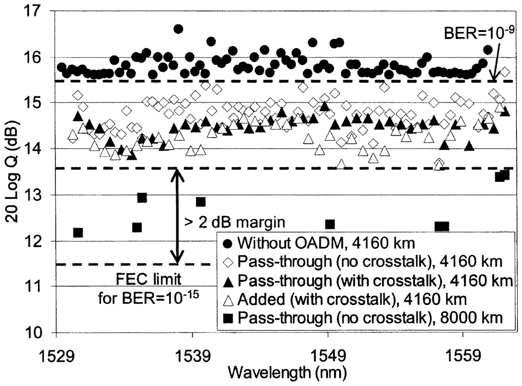

Fig. 6. Q-factor performance of pass-through and added channels after 4160 km, with and without 13 concatenated OADMs.

OSNR and Q data ($Q[\text{dB}] = 20 \log Q_{\text{linear}}$) for three different system configurations. First, solid circles show the 80-channel results obtained from a 10-Gb/s 4160-km transmission test without any OADM, but with leveling performed by a dynamic gain-flattening filter at an EDFA mid-stage. Average OSNR in 0.1 nm is 18 dB, average $Q = 15.8$ dB and worst-channel BER $= 8 \times 10^{-10}$. Second, open diamonds in Figs. 5 and 6 show the 10.66 Gb/s performance with all 80 channels passing through 13 concatenated OADMs without introducing any crosstalk (0% add–drop). Average OSNR is degraded by 0.5 dB down to 17.5 dB, whereas average Q is reduced by 1.1 dB down to 14.7 dB, which captures OSNR, filter concatenation, and 10–10.66 Gb/s rate increase penalties. Third, for 50% add–drop performed at the sixth OADM, the performance of the pass-through channels (not added–dropped at the sixth OADM) measured after 4160 km and 13 concatenated OADMs is shown by solid triangles in Fig. 6. The performance for the traffic newly added at the sixth OADM (after 1600 km) is also measured after 4160 km transmission and 13 concatenated OADMs (open triangles in Fig. 6). The worst-case Q factor in the 50% add–drop case is 13.6 dB—more than 2 dB higher than the 7%-FEC threshold for 10^{-15} bit-error-rate operation. The average Q factor is 14.5 dB for the 40 pass-through channels and 14.3 dB for the 40 added channels. Both sets of channels in our experimental configuration exhibit the contribution of one crosstalk term. Thus, in agreement with the data in Fig. 4, the Q penalty due to the crosstalk added during the add–drop operation in our OADM system is less than 0.4 dB owing to the excellent extinction ratio of the DSE, which performs simultaneous blocking and leveling. In Figs. 5 and 6, we also present the OSNR and Q-factor performance of selected 10-Gb/s pass-through channels after 8000 km and 25 concatenated OADMs (solid squares). The measured channels include the worst performing channels at a distance of 4160 km (e.g., channel 69). The Q-factor performance is better than 12.1 dB, with average OSNR of 14.5 dB. The Q-factor penalty due to crosstalk is less than 0.2 dB in that case. In Fig. 7, we present the measured Q-penalty performance for channel 25 after 13 and 25 OADMs (4160 and 8000 km, respectively) as a function of frequency detuning of the transmitter around the ITU-grid. The results show the concatenation performance of the DSE. It can be observed that for less than 0.4 dB overall penalty, the allowable detuning is larger than ±7 GHz for the case of 13 concatenated DSEs and larger than ±4.5 GHz for the case of 25 concatenated DSEs. These measurements represent the worst-case performance due to concatenation of the same DSE. The allowable detuning is larger than the accuracy of a typical wavelength locker (±2.5 GHz), so the performance qualifies for real-life transmitter wavelength offset conditions.

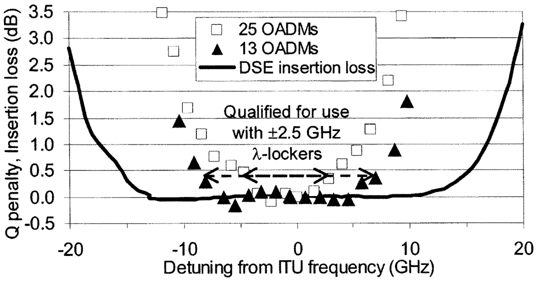

Fig. 7. Q-factor performance for channel 25 (1539.77 nm) as a function of transmitter frequency detuning from the ITU grid; also shown is the DSE insertion loss relative to that at the ITU frequency.

In conclusion, we have reported the first dynamically reconfigurable 10 Gb/s ULH network demonstration using a low-loss B&S OADM architecture. Our experiments have characterized the impact of both transmission and networking impairments and have shown the feasibility of this architecture.

REFERENCES

[1] A. Solheim and J. Frodsham, "Next generation backbone networks," in *Proc. NFOEC'01*, 2001, pp. 1283–1289.

[2] T. Tanaka, N. Shimojoh, T. Naito, H. Nakamoto, I. Yokota, T. Ueki, A. Suguyama, and M. Suyama, "2.1 Tbit/s WDM transmission over 7221 km with 80-km repeater spacing," presented at the Proc. European Conference on Optical Communication 2000, Munich, Germany, Paper PD1.8.

[3] I. Haxell, N. Robinson, A. Akhtar, M. Ding, and R. Haigh, "2410 km all-optical network field trial with 10 Gb/s DWDM transmission," in *Optical Fiber Communication Conf. Tech. Dig.*, Washington, DC, 2000, pp. PD41-1–PD41-3.

[4] D. Chen, S. Wheeler, D. Nguyen, B. Davis, M. Glavanovic, J. Khaydarov, I. Koruga, S. Hegarty, F. Cokic, and F. Zhu, "40 channels 4000 km DWDM ULH transmission field trial without Raman amplification and regeneration," in *Optical Fiber Communication Conf. Tech. Dig.*, Washington, DC, 2002, pp. PD FC10-1–PD FC10-3.

[5] A. Boskovic, M. Sharma, N. Antoniades, and M. Lee, "Broadcast and select OADM nodes: Application and performance tradeoffs," in *Optical Fiber Communication Conf. Tech. Dig.*, vol. 70, Washington, DC, 2002, pp. 158–159.

[6] M. Vasilyev, B. Szalabofka, S. Tsuda, J. M. Grochocinski, and A. F. Evans, "Reduction of Raman MPI and noise figure in dispersion-managed fibre," *Electron. Lett.*, vol. 38, pp. 271–272, 2002.