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All-Optical Grooming for 100 Gbit/s Ethernet

J. Leuthold[1], R. Bonk[1], P. Vorreau[1], S. Sygletos[1,5], D. Hillerkuss[1], W. Freude[1], G. Zarris[2], D. Simeonidou[2], C. Kouloumentas[3], M. Spyropoulou[3], I. Tomkos[3], F. Parmigiani[4], P. Petropoulos[4], D.J. Richardson[4], R. Weerasuriya[5], S. Ibrahim[5], A.D. Ellis[5], R. Morais[6], P. Monteiro[6], S. Ben Ezra[7], S. Tsadka[7]

[1]*Institute of Photonics and Quantum Electronics, Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany*
[2]*School of Computer Science and Electronic Engineering, University of Essex, CO4 3SQ, United Kingdom*
[3]*Athens Information Technology, Athens, Greece*
[4]*Optoelectronics Research Centre, University of Southampton, United Kingdom*
[5]*Photonic Systems Group, Department of Physics, University College Cork, Cork, Ireland*
[6]*Nokia Siemens Networks Portugal S.A., Rua Irmãos Siemens 1, 2720-093 – Amadora*
[7]*Finisar Israel, 3 Golda Meir St., Lev Hakongresim, Nitzan Building, Nes Ziona 74140, Israel*
Project web page at http://www.ipq.uni-karlsruhe.de/research/projects/TRIUMPH/

ABSTRACT

A regenerative optical grooming switch for interconnecting 100 Gbit/s networks with lower bit-rate networks and switching functionality in time, space and wavelength domain is demonstrated. Lab and field demonstrations show the feasibility of the new concept. Q-factors above 20 dB are reported.
Keywords: all-optical, networks, optical switches

1. INTRODUCTION

Future transparent networks should provide transparent interconnection of networks operating at different speed. This actually means that there is a need for grooming switches and routers, i.e. edge-switches and routers that are not only able to switch or route traffic but are as well able to aggregate traffic from one network at one speed onto a new network at another speed . Current solutions are costly due to the high energy consumption of the many optical-electrical-optical (O-E-O) conversions required [1][2].

In this paper we demonstrate an energy efficient grooming switch (Fig. 1) enabling full transparency between lower bit-

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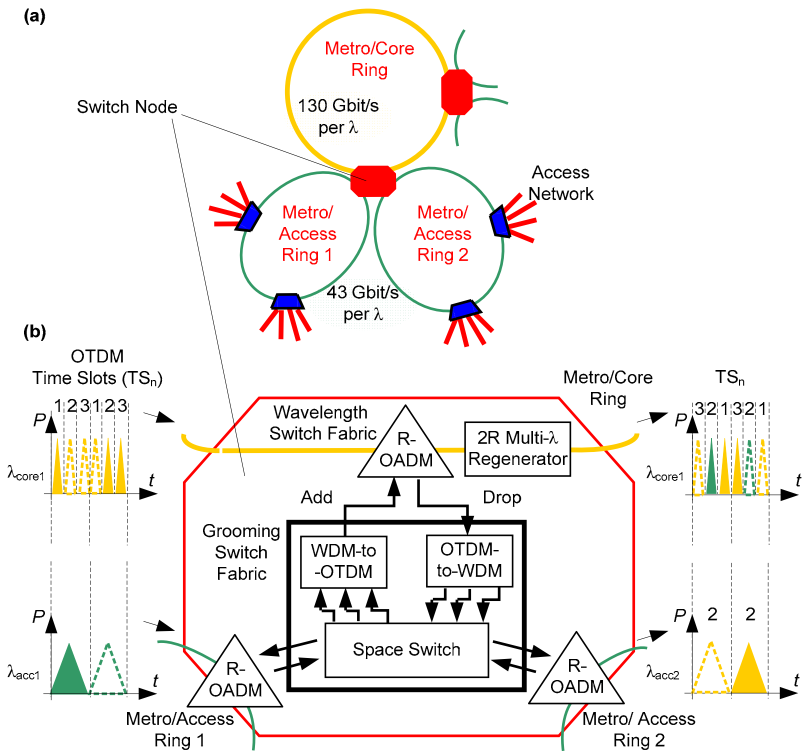


Fig. 1. Network scenario and switch node. (a) Two metro/access rings are interconnected to a metro/core ring via the grooming switch. Each ring carries a multiple of WDM channels, either at 43 Gbit/s or 130 Gbit/s per wavelength. (b) Grooming switch: key building blocks are the space switch, the WDM-to-TDM module, the OTDM-to-WDM module and the 2R multi-wavelength regenerator.

rate (43 Gbit/s) circuit or burst switched access networks and a 130 Gbit/s (i.e. 100 Gbit/s with overhead) higher bit rate core ring network. Key functionalities of the node are WDM-to-TDM traffic aggregation, TDM-to-WDM demultiplexing of the high speed channels into lower bit rate tributaries, time-slot-interchange (TSI) of TDM tributaries, as well as multi-wavelength regeneration. A MEMS switch in combination with all-optical wavelength conversion guarantees non-blocking space and wavelength switching functionality for any tributary.

2. THE GROOMING SWITCH OPERATION PRINCIPLE

The grooming switch is depicted in Fig. 1. Fig. 1(a) shows two access networks carrying 43 Gbit/s data bursts that are connected with each other but may also be aggregated to higher-speed data bursts on the core ring carrying 130 Gbit/s. Vice-versa, data bursts from the core ring might be dropped to one of the access rings. Therefore, the node is designed to provide connectivity through optical wavelength switching and to offer traffic grooming and bit-rate adaptation. Disregarding any specific network scenario, the switch node can be classified as an all-optical multi-hop partial-grooming optical cross-connect (OXC)

The switch itself comprises Reconfigurable Optical-Add Drop Multiplexers (ROADMs), a MEMS switch, an OTDM-to-WDM unit [3][4] a WDM-to-OTDM unit [5][6] and a 2R multi-wavelength signal regenerator [7]. The various building block work as follows:

The MEMS Space Switch: Traffic from any of the access rings is switched by means of the MEMS switch to either access ring or via the add path to the core ring. Each MEMS-port to the core ring relates to a particular time-slot of the TDM tributaries. Time-slot interchanging (TSI) functionality is thus obtained by reconfiguration of add ports within the MEMS.

WDM-to-OTDM block: The WDM-OTDM consists of three dual-gate asynchronous digital optical regenerator (ADORE) units [5][6], each mapping one 43Gb/s on/off keying (OOK) channel onto one OTDM time-slot, see Fig. 2.

The ADORE provides retiming synchronization, wavelength conversion and pulse width adaptation by mapping the input tributaries onto a local mode-locked laser (MLL) pulse. Synchronization to one common clock is obtained by generating multiple copies of the input signals and selecting the signals which are best in sync with the local clock. This pulse selection is performed using a phase comparator circuit to select the optimum sampled clock phase using a 2x1 optical switch. The regenerated signal at the output of the switch will have the same pulse shape as the local optical clock in terms of pulse width and wavelength. It will also be aligned to a fixed output phase independent of the incoming data phase. In this way, the random and time-varying bit-slot phases of the input tributaries are translated in a fixed phase. The tributaries are subsequently bit-slot interleaved and coupled together to form the OTDM channel. It should be noted that since each ADORE unit is associated with a certain OTDM tributary, by reconfiguring the cross-bar switch (MEMS), time-slot interchange (TSI) can be performed.

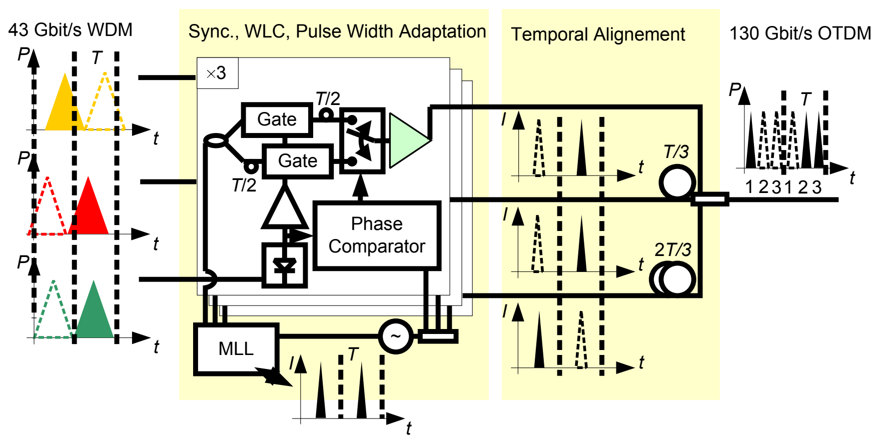


Fig. 2. WDM-to-OTDM conversion by means of mapping the incoming lower bit-rate data (yellow, red, green) onto three copies of a mode-locked laser (MLL) clock. The copies are then synchronized in time with the help of a phase-comparator. Lastly, the three synchronized clocks with the data are OTDM multiplexed onto a high-bit rate OTDM signal.

OTDM-to-WDM: Conversely, an OTDM channel may be dropped via the ROADM to the OTDM-to-WDM unit which maps the OTDM onto distinct wavelength channels. We have implemented both a scheme with wavelength interchangeability where tributaries are mapped onto clocks from tuneable sources [4] or a scheme with wavelength interchangeability limited to permutations [3]. The latter scheme is schematically shown in Fig. 3. Details on the operation principle of the scheme are given in the figure caption of Fig. 3. Subsequently, the three low bit-rate WDM tributaries are guided into the MEMS switch and can be switched to either one of the access rings or back to the core ring.

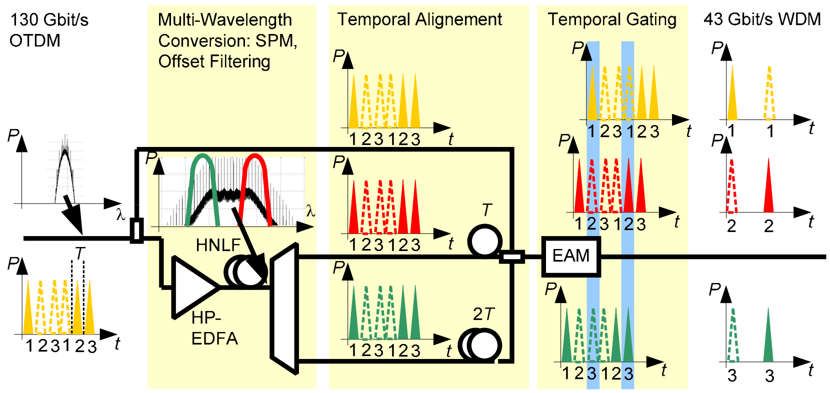


Fig. 3. Operation principle of the OTDM to WDM conversion. The OTDM signal is first broadened in a HLNF by means of SPM. Subsequently three spectral ranges are selected by means of filtering. The three copies are combined into a single fiber after adjusting the time delays of the three copies such that the three OTDM tributaries overlap in time. Lastly, gating is performed with an EAM such that only one tributary for each colour is retained. (HNLF – highly-nonlinear fiber, SPM – self phase modulation, EAM – electro absorption modulator) [3].

Multi-Wavelength Regenerator: Finally, to guarantee the quality of the traffic in the core ring, an all-optical multi-wavelength regenerator, operating at 130 Gbit/s traffic, is also included [7], see Fig. 4. We have implemented a scheme relying on self-phase modulation (SPM) induced spectral broadening, that takes place in a highly non-linear fiber (HNLF), and subsequent filtering at an offset wavelength. This Mamyshev principle is well known for single channel operation and is extended for two wavelengths in this node. To avoid interchannel distortions by cross-phase modulation (XPM) or four-wave mixing (FWM) a bidirectional propagation of the two data signals are used to achieve a rapid "walk-through" of the data pulses within the adjacent channels.

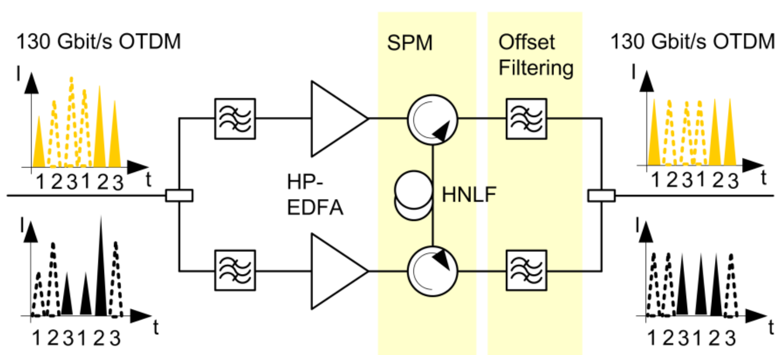


Fig. 4. Operation principle of the fiber-based 2R regenerator. The two degraded 130 Gbit/s input signals are individually amplified and counter propagate in the HNLF, where self-phase modulation (SPM) induced spectral broadening takes place. In combination with subsequent offset filtering this leads to the regenerated output signals [7].

3. GROOMING SWITCH OPERATION VALIDATION

The performance of the grooming switch with eye-diagrams and spectra is shown for a typical switching scenario in Fig. 5 [8]. In this scenario a first 130 Gbit/s signal (A) is passed through the node and the regenerator to the output (E). The eye diagram shows a signal quality improvement. A second 130 Gbit/s core signal (B) is simultaneously launched into the switch and guided into the OTDM-to-WDM, where the signal is demultiplexed into the three tributaries (C). Tributary 2 is then dropped onto access ring 2 and replaced by the new tributary 2 from access ring 1 (G). Tributaries TS_1 and TS_3 are looped back to the core ring by means of the switch and the WDM-to-OTDM module. The WDM-to-OTDM module synchronizes the three new tributaries, shortens their pulse width and maps them all onto a new wavelength $\lambda_{core2,add}$. After regeneration, a high quality 130 Gb/s signal is seen at the output of the router (F).

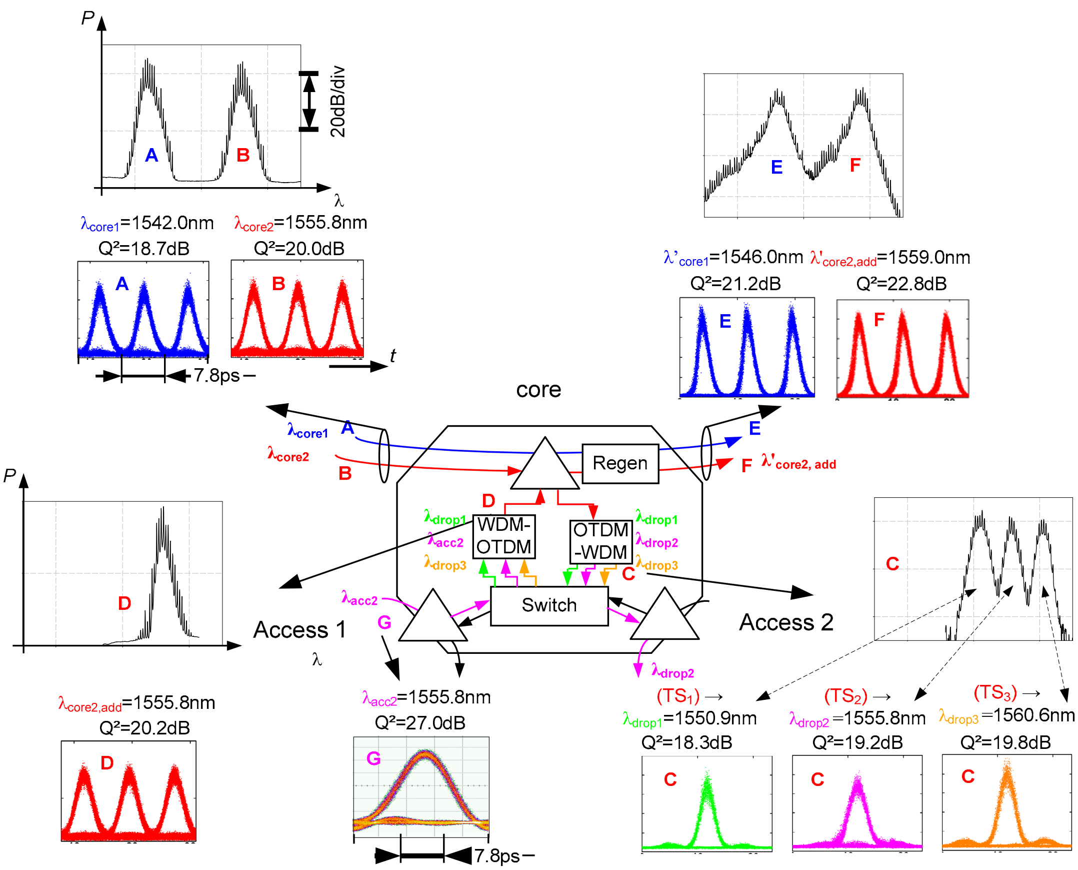


Fig. 5. Scenario where two 130 Gbit/s signals (A & B) are launched into the switch. (A) is passed through to (E), (B) is split into its tributaries (C). Tributary TS_2 is dropped and another access ring tributary (G) is added and aggregated with tributaries TS_1 and TS_3 (see D) and mapped back to the core (F) [8].

Many more switching scenario are possible. We have plotted two more scenario in Fig. 6. Scenario 2 and 3 show the capability of the switch to perform time slot interchanging. The switching scenario actually are identical except for the interchanged time slot of tributaries TS_1 and TS_2. Perfect eyes (F) are found in all scenarios.

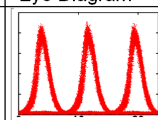
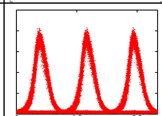
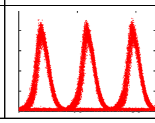
Switching Scenario	$\lambda'_{core2,\ add}$ Tributaries			$\lambda'_{core2,\ add}$ Result at F	
	TS_1	TS_2	TS_3	Q^2[dB]	Eye Diagram
1	λ_{drop1}	λ_{acc2}	λ_{drop3}	22.8	
2	λ_{drop2}	λ_{acc2}	λ_{acc3}	22.9	
3	λ_{acc2}	λ_{drop2}	λ_{acc3}	21.4	

Fig. 6. Three switching scenario with variation on how tributaries are dropped and looped back onto the core and access network. Scenario 2 and 3 show time-slot-interchanging. The signal quality of the eyes after OTDM multiplexing is excellent in all situations [8].

4. FIELD TRIAL

Field trials were performed using two dispersion compensated SMF-28™ dark fibre sections, Fig. 7(a) [9]. The first section, Colchester-Ipswich, was 100% pre compensated using slope matched dispersion compensating module and had a round trip length of 80 km and represented an access link transmitting 42.7 Gb/s channels. The second, Colchester-Chelmsford represented a link in the core network with a round trip length of 110 km. It was 80% pre compensated and 20% post compensated and carried 130 Gb/s channels.

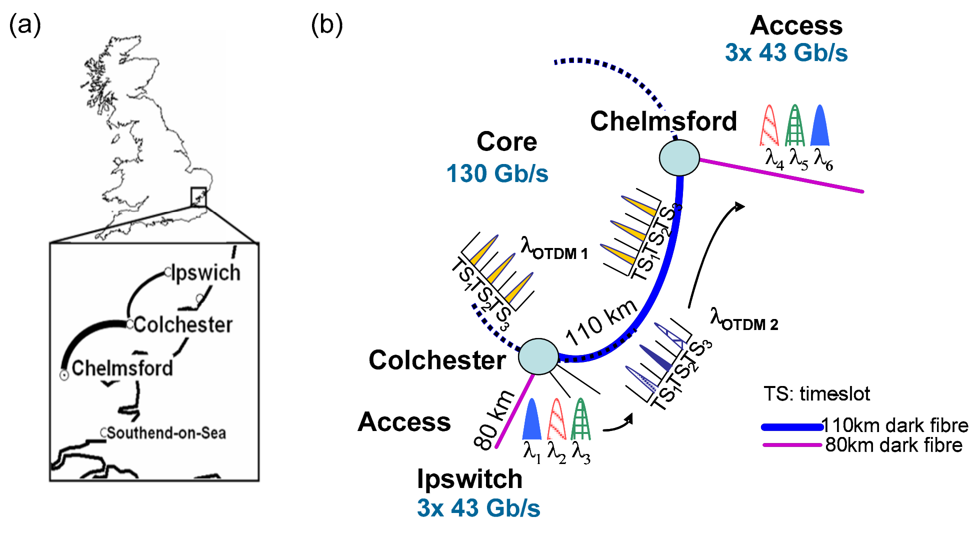


Fig. 7. (a) Dark fiber network, (b) Network scenario with traffic mapped from Ipswitch across the access network to the core node in Colchester. From Colchester the signals are transported on the core ring to Chelmsford where one channel is dropped off to the access network [9].

Several experiments were performed with the aim of demonstrating key network functions. Here we only report on one exemplary experiment in which the node at Colchester performs WDM-to-OTDM grooming of traffic which originates in an edge 43 Gbit/s WDM domain and the node at Chelmsford performs 2R multi-wavelength regeneration of two 130 Gbit/s channels and also the OTDM-to-WDM demultiplexing of the originally groomed OTDM channel, Fig. 7(a).
In detail, in the experiment three 33% RZ 43 Gbit/s OOK channels were transmitted from the Ipswich link to Colchester. The data pattern consisted of a repeating 2^7-1 pseudo random bit sequence (PRBS) of 1 ms duration, and a single

modified 2^{19}-1 PRBS serving as a 1 µs guard-band with mark ratio 52.5%, see Fig. 8. WDM-to-OTDM grooming was performed in Colchester with the assist of the ADORE unit. The ADORE actually first detected the guard-band by simple power measurement, and performed resynchronization of the three tributaries to the local clock within 440 ns only during the guard-band intervals. In this way, data block integrity was assured during natural variations of input data phase in the dark fiber. Point A in Fig.6 shows ADORE output eye that forms together with two pulse width adapted, wavelength converted onto the same MLL and interleaved local channels the OTDM channel at 1556 nm (Spectra in Point C). The groomed channel was then combined with another 130 Gbit/s signal (Point B) which transited the node and sent over the core ring to Chelmsford, where it was 2R regenerated, dropped (Point E) and OTDM-to-WDM demultiplexed (Spectra Point F). The eye diagram signal qualities and spectra at the different nodes are depicted in Fig.6 (Point G). Excellent eye diagrams and bit-error ratios were measured at all nodes of the field experiment. The BER curve in shows results for of the back-to-back EAM-demultiplexed 1556 nm OTDM channel and the OTDM-WDM demuliplexed wavelength channels. The power penalty is around 2 dB and mainly induces by small leading pulses from the MLL source affecting the CRU performance. The values of the signal qualities and eye diagrams have been measured with the picosolve sampling scope.

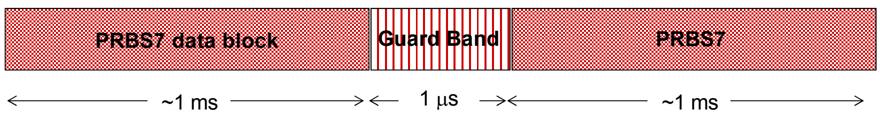


Fig. 8. (a) The data frame and guard bands of the burst switched networks.

The eye diagrams, signal qualities and spectra at the different nodes are depicted in Fig. 9. Excellent eye diagrams and bit-error rates were measured at all nodes within the field experiment. The values of the signal qualities and eye diagrams reported here have been measured with the picosolve sampling scope and not with a real bit-error rate measurement tools.

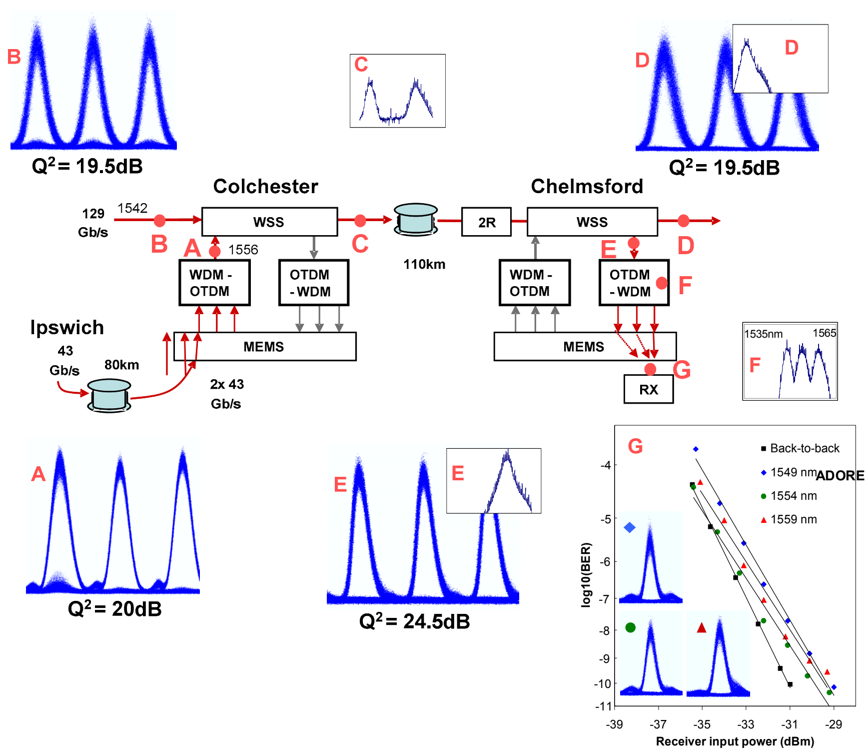


Fig. 9. (a) Eye diagrams, signal quality values and bit-error rate measurements at various points.

5. CONCLUSIONS

We have demonstrated a 43/130 Gb/s heterogeneous transparent burst-switched network with grooming switch functionality both in the lab and in a field trial experiment.

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