Gridless Optical Networking Field Trial: Flexible Spectrum Switching, Defragmentation and Transport of 10G/40G/100G/555G over 620-km Field Fiber

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Abstract: We report the first gridless networking field trial with flexible spectrum switching nodes over 620 km field fibre links. Successful transport, spectrum switching and defragmentation achieved for mixed line signals including 555G and coherent 100G.
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1. Introduction

Future transport networks will need to deal with a mix of providers traffic representing services (i.e. 10Gb/s legacy channels), core traffic (i.e 400 Gb/s and beyond super-channels), as well as alien traffic (arbitrarily variable bit rate and format channels). Hence, optical nodes would need to allocate resources in a flexible and efficient manner to support a mix of super-channels and lower speed channels. The nodes' complexity will largely depend on the network segment (i.e. inner core, metro), and should also facilitate transparent interoperability between segments. In addition, metro segments might carry legacy 10 Gb/s requiring dispersion compensated (DC) links whereas inner core segments might just deploy coherent compensation techniques (e.g. DSP) to support super-channels. To address increasing traffic growth, advances in modulation formats enable a 100G channel to fit in a standard 50-GHz WDM slot. However, this may not be the case for higher bit-rate channels. For instance, super-channels at 400 Gb/s [1], 1Tb/s [2] and beyond [3,4] will occupy broader spectrum, which neither fits within the existing ITU grid nor is supported by conventional optical network infrastructures. Moreover, simultaneously supporting a combination of high-capacity super-channels and lower bit rate channels is critical [5].

Flexible and gridless optical networking is proposed to address such diverse requirements so as to switch and transport mix line rate technologies ranging from 10 Gb/s (25GHz spectrum) for better spectral efficiency to 555 Gb/s (650GHz spectrum). However, transporting mixed signal bit rates and modulation formats in such a flexible manner could lead to spectral fragmentation and increased blocking. To overcome this, a super-channel or multiple lower bit rate channels need to be moved to a different spectral region. Wavelength conversion could provide a vital network function for such spectrum defragmentation optimizing spectral efficiency. To represent this evolving network scenario, we report results from the first, to the best of our knowledge, gridless optical networking field trial with adaptive and flexible spectrum inner-core node as well as flexible spectrum switching nodes placed in different geographical locations, connected by several field fibre links totaling 620 km. We successfully demonstrate flexible switching and transport of mixed traffic including a high-speed super-channel at 555 Gb/s (650 GHz), coherent

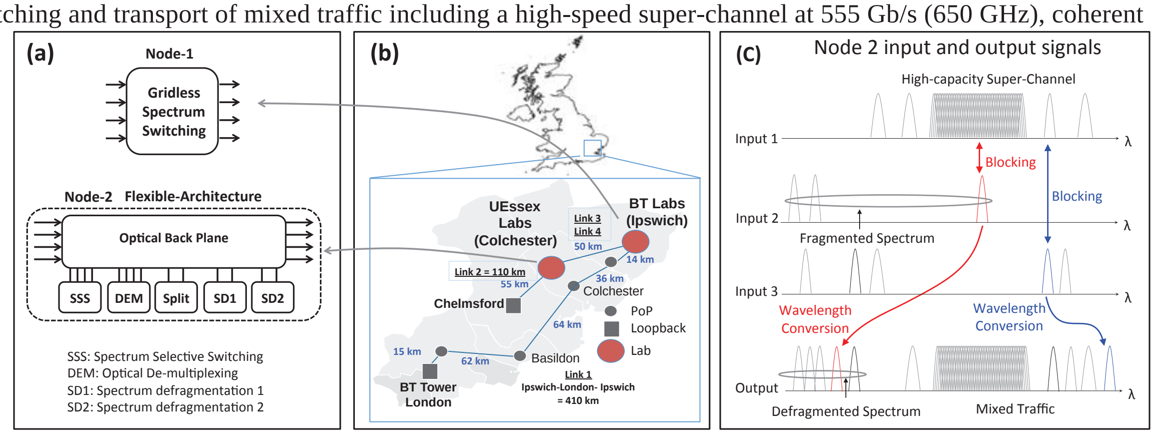

Fig.1 (a) Gridless optical network setup and scenario, (b) field network trial map, and (c) flexible spectrum switching and defragmentation.

100G and 40G (50 GHz), 40G OOK NRZ (100 GHz), 40G OOK RZ (150 GHz), 12.25 and 10 Gb/s NRZ (25 GHz) signals. Also, the flexible-architecture inner-core node demonstrates adaptive architecture reconfiguration as in [6], mixed channels' switching and spectral defragmentation using wavelength converters based on cross-gain modulation (XGM) in a semiconductor-optical-amplifier Mach Zehnder Interferomenter (SOA-MZI).

2. Gridless Network Scenario

As shown in Fig. 2, the field trial gridless network is comprised of 3 optical nodes placed in different geographical locations and connected by 4 field fibre links with total 620-km of installed standard SMF fibres (Fig. 1b). Link 2 – 3 are links of conventional design with in-line DCMs, whereas link 4 is a new DCM–less link of total 410km, which has 5 in-line amplifiers located in BT exchanges in Ipswich, Colchester, Basildon and London BT Tower, and looping back to Ipswich. The 3 optical nodes are flexible spectrum switching nodes using WaveShapers, Node-3 is an flexible-architecture node (Fig.1(a)) providing multiple functions inlcuding spectrum switching, on-demand architecture reconfiguration and wavelength conversion for defragmentation. Hence, the field trial optical network represents a potential future flexible network, with different types of optical nodes with varying level of network functionality, e.g. in Core and Metro, with both conventional in-line DCM design and new DCM-less design.

In Fig. 2 Tx-1 and Tx-2 coherent 40G (DP-QPSK) and coherent 100G (dual carrier, DP-QPSK) are generated by commercial transponders [7]. These are transmitted over Link-1 (410-km DCM-less) to Node-1. Also, channels from Tx-2 are input to Node-1 but without prior transmission. At Node-1 channels are combined using flexible spectrum switching, with a custom bandwidth allocation per channel, and transmitted over Link-3 (50-km dispersion compensated) to Node-2. Meanwhile, in Tx-3 channels 1x555 Gb/s, 3x42.7 Gb/s OOK RZ, 1x42.7 Gb/s OOK NRZ are generated and transmitted over Link-2 (110-km dispersion compensated) to Node-2. Also, Tx-4 generates channels 3x10Gb/s OOK NRZ. Node-2 provides a flexible-architecture platform whereby modules (subsystems) are interconnected through a backplane (3D-MEMS) to form optical nodes with on-demand (20ms) reconfiguration e.g. spectrum defragmentation when and where required. All input signals to Node-2 have to be transported over Link-4 to Node-3. However, there is contention between wavelengths, Fig.1 (c). Therefore, Node-2 implements spectrum defragmentation and the signals are successfully switched, using flexible spectrum switching, to Node-3. The signals originally generated by Tx-1 and Tx-2 are dropped and input to the receiver Rx-1 for performance evaluation. Signals originally generated by Tx-3 are spectrum-switched at Node-2, 3 and 1 and back to Node-2. At Node-2 they are dropped and input to the receiver (Rx-2) for performance evaluation.

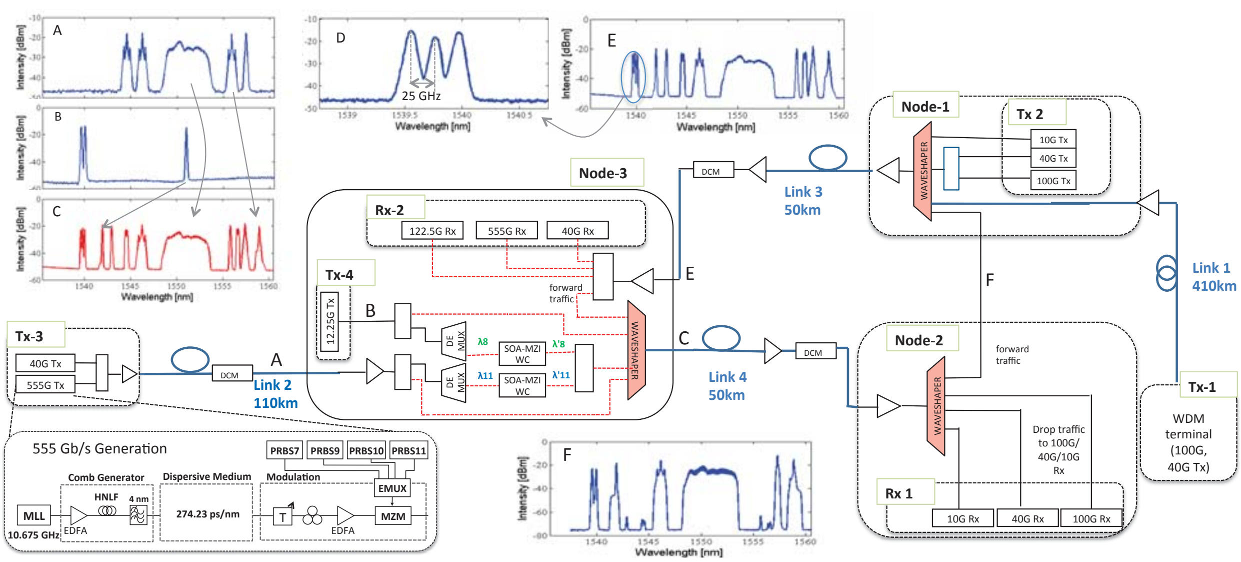

Fig. 2 Field trial gridless optical network configuration

3. Experimental Setup and Results

As shown in Fig. 2 inset A, the 555 Gb/s signal is generated from a 10.675-GHz 2-ps MLL pulse train followed by super-continuum generation in a HNLF, band-pass filtering and frequency-time transformation in dispersive medium (274.23-ps/nm to achieve a 23.4-ps delay between adjacent sub-carriers). Then, the signal is intensity modulated in a LiNbO3 MZM with a 42.7-Gb/s signal composed of four electrically multiplexed PRBS sequences of length 2^7-1, 2^9-1, 2^{10}-1 and 2^{11}-1, at 10.675 Gb/s each. Thus, adjacent sub-carriers are modulated with a different

PRBS. At Tx-1 and Tx-2, coherent DP-QPSK 100G and 40G signals are generated by commercial WDM transponders [7]. Additional 12.25 Gb/s and 42.7 Gb/s OOK signals are generated using LiNbO3 MZM. Table 1 lists the channels generated with their respective parameters, routes and bandwidth allocation. Nodes 3-4 are flexible spectrum switching nodes using an LCoS-based spectrum selective switch (SSS) implemented with a WaveShaper [8]. The SSS switches from 10-GHz up to 5-THz C band slots with a 1-GHz resolution. The flexible-architecture Node-2 is implemented with a 96x96 3D-MEMS optical backplane that interconnects amplification and signal-processing modules such as the SSS, and two SOA-MZI wavelength converter configurations at 12.25 Gb/s [9] and 42.7 Gb/s [10]. In Nodes 3, 4 and 7, signals are allocated a customized spectral bandwidth per channel. For instance, a 650-GHz frequency slot is allocated for the 555 Gb/s; 50 GHz for the 100 Gb/s DP-QPSK and 40 Gb/s QPSK; 100 GHz for the 40 Gb/s NRZ; 150 GHz for the 42.7 Gb/s RZ; and 25 GHz for the 12.25 Gb/s and 10 Gb/s signals.

Wavelength circuit	**λ1**	**λ2**	**λ3**	**λ4**	**λ5**	**λ6**	**λ7**	**λ8/λ'8**	**λ9**	**λ10**	**λ11/λ'11**	**λ12**
Source node	Tx-1		Node-1 (Tx-2)			Tx-4			Tx-3			
Destination node	Node-2		Node-2			Node-3			Node-2			
Route	Node-1, Node-3		Node-3			Node-2, Node-1			Node-3, Node-2, Node-1			
Wavelength (nm)	1556.55	***1555.75***	1544.53	***1542.94***	1539.77	1539.57	1539.97	***1550.92/ 1541.75***	1546.12	1550.92	***1555.75/ 1558.98***	1557.36
Bit rate (Gb/s)	100G	**40G**	100G	**40G**	10G	12.25G	12.25G	**12.25G**	40G	555G	**42.7G**	42.7G
Modulation	DP-QPSK, 2 subcarriers	**DP - QPSK**	DP-QPSK, 2 subcarriers	**DP - QPSK**	NRZ	NRZ	NRZ	**NRZ**	RZ	NRZ	**RZ**	NRZ
Bandwidth (GHz)	50	**50**	50	**50**	25	25	25	**100**	150	650	**150**	100
Links on the route	1, 3, 4	***1, 3, 4***	3, 4	***3, 4***	3, 4	2, 4, 3	2, 4, 3	2, 4, 3	2, 4, 3	2, 4, 3	2, 4, 3	2, 4, 3
Route length (km)	510	**510**	100	**100**	100	210	210	**210**	210	210	**210**	210

Table 1. Summary of the traffic in the gridless optical network field trial

The performance of 100G was measured over the field trial network switching and transport and compared with the point to point transmission. Error free performance was achieved with long term stability as shown in Fig. 3(b). Figure 3(a) shows the spectrum of the 555 Gb/s signal at the input to Node-3 and the end-to-end performance shows BER below 10^{-4}, which is a comfortable margin to the FEC limit of $2x10^{-3}$. The performance of the wavelength converters is evaluated by means of bit error rate measurements and results are presented in Fig 3(c). The power penalty at a BER = 10-9 is 1.5 dB for the 10-Gb/s SOA-MZI converter and 6 dB for the 42.7-Gb/s SOA-MZI converter.

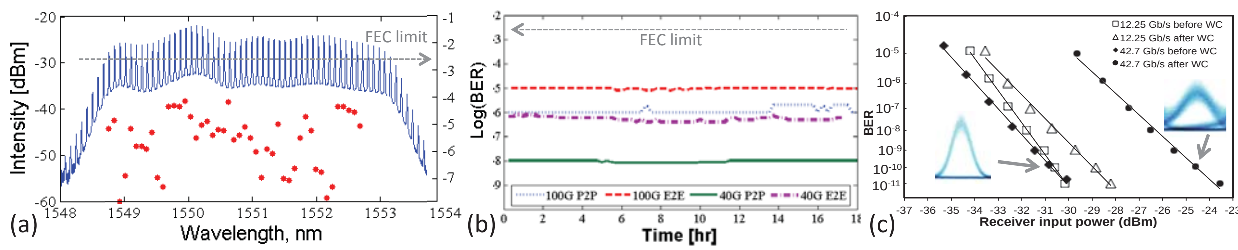

Fig.3 a) 555 Gb/s signal at Node 3 and its BER, b) BER of coherent 40G and 100G channels (P2P: 410km, E2E: Gridless network 510 km) and c) 40G/10G wavelength conversion BER.

5. Conclusion

This paper presents results from the first gridless optical networking field trial with geographically scattered flexible-spectrum-switching nodes linked by 620-km of field fibre, and spectrum defragmentation functionality. We have successfully demonstrated flexible spectrum switching and transport of mixed traffic with different bit rates and modulation formats including 555G, coherent 100G and 40G, as well as intensity modulated and converted 10G and 40G signals with good end-to-end BER performance. All channels are switched and transported using custom and finely shaped frequency slots to optimize utilization (e.g. 555Gb/s on a 650 GHz slot, 2x 10Gb/s signals on a 50GHz slot) and yet guarantee error free operation.

6. Acknowledgements

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