Scalability Analysis and Switching Hardware Requirements for a Novel Multi-Granular SDM/UWB 10 Pbps Optical Node

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Abstract *Optical network node designs must change to address burgeoning traffic loads. We propose a novel, high-throughput, low-loss, reconfigurable, hierarchical architecture capable of switching whole fibres, flexible-defined bands, down to individual wavelengths, achieving ~10 Pb/s throughput, which will be required by decade end.*

Introduction and Related Work

Forthcoming network capacity scaling [1-2] dictates the use of both Space Division Multiplexing (SDM)-based optical links and Ultra-Wide Band (UWB) transmission, e.g., over S+C+L bands. Scaling current free-space technology wavelength-selective switches (WSS) used in ROADM nodes in support of UWB and high output port counts [3], is challenging, costly and will require large volume packaging and installation. Future SDM/UWB networks shall require new traffic switching modalities adapted for Spatial Channel Networks – SCNs ([4-5]).

The ideal optical network node would exhibit a cost-effective [6], multi-granular, multi-band and reconfigurable architecture. Several optical node architectures have been proposed ([5], [7], [8]). These are hierarchical (Optical Cross Connect) OXC architectures (of two and three layers) specially designed for specific data flows.

A modular optical node architecture using Photonic Integrated Circuit (PIC)-based multi-band WSS was suggested in [9]. The PIC implements S/C/L band-separating Bragg filters cascaded with channel-resolving micro-ring resonator filters, followed by MZI switching tree architecture and high output fibre-port count. Scalability and node connectivity for this solution has not been thoroughly investigated.

Another node architecture serving the transition from multi-band to multi-rail core networks and from wavelength switching to band/fibre switching, was presented in [10]. This solution hard-wires fixed band separation filters, limiting flexibility and forfeiting full fibre switching with a single switching element, hence impacting implementation with superfluous hardware.

As multiband transmission seems promising [5, 9, 10], WaveBand-Selective Switches (WBSS) become vital. Previous WBSSs deployed concatenating cyclic waveguide grating routers (WGR) with optical switches [11, 12] and thus are not bandwidth adaptable. Furthermore, these older WBSSs carved bands from within the C-band, not addressing UWB spectral support.

The missing optical networking element is a *flex*-WBSS, whereby the switch can flexibly carve the UWB spectrum to a few flexibly-defined contiguous bands (with few being reconfigurable down to one output, i.e., supporting full fibre content switching), and routing each filtered band to a desired output fibre port. Using such flex-WBSS enable us to propose a multi-granular optical node (MG-ON) architecture that supports flexible and adaptable band-switching to cover, on demand, a variety of spatial/spectral granularities, from a wavelength channel to the entire S+C+L-bands and everything in-between. Scalability studies reported herein reveal the MG-ON's switching hardware requirements and high net-throughput.

Innovative UWB/SDM MG-ON's Features

The novel MG-ON architecture is designed to fill the technology gap between current wavelength channel and future full-fibre switches. MG-ON shall incorporate PIC-based, state-of-the-art flex-WBSSs with small footprint, expected low insertion losses (few dB), high switching speeds (less than 10 μs with piezo actuators on SiN waveguides), ≥23 dB crosstalk suppression, and finally, low cost. As depicted in Fig. 1, it

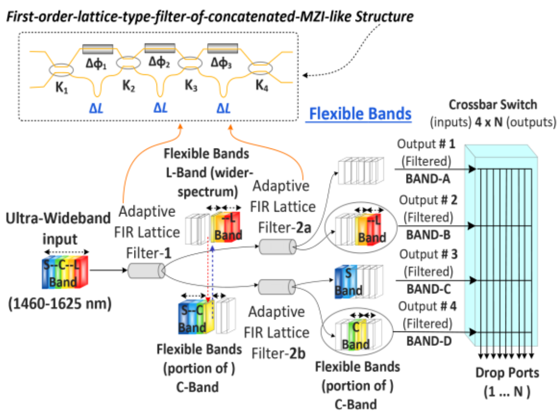

Fig. 1: Internal structure of Flexible WaveBand Selective Switch (flex-WBSS), comprising adaptive filtering stage followed by spatial crossbar switch to output fibre ports.

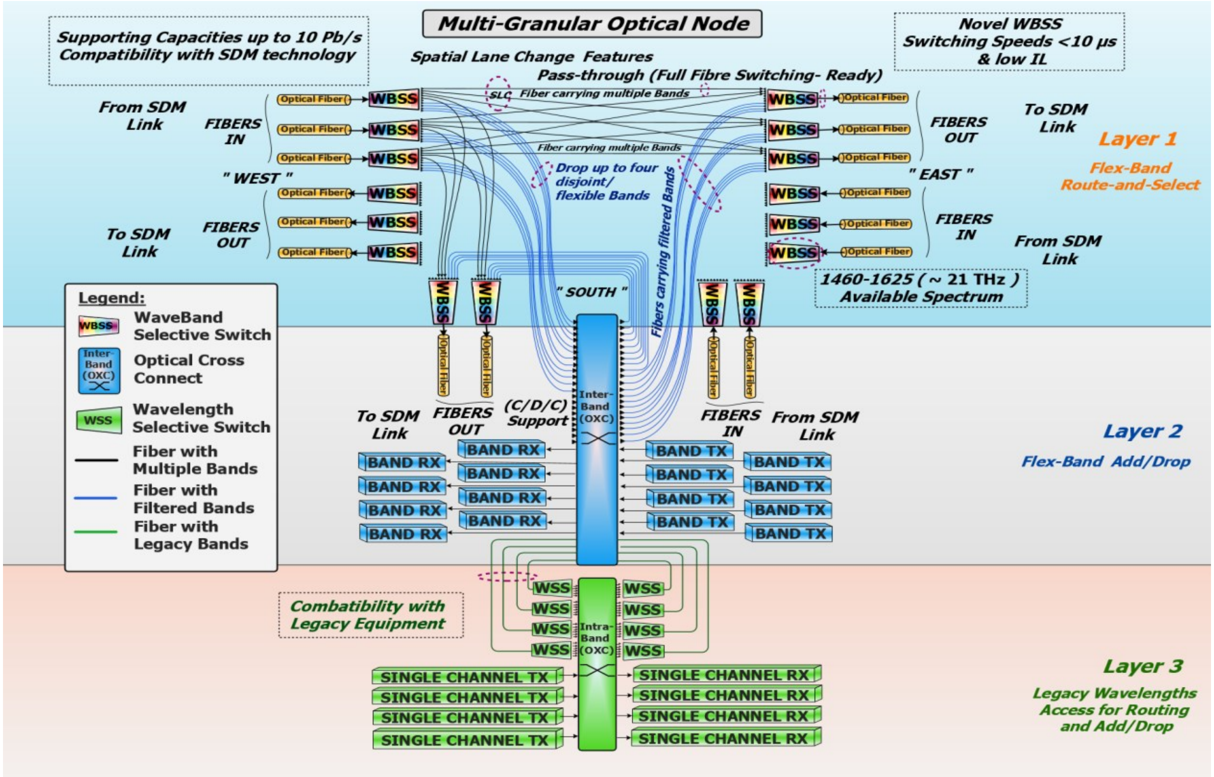

Fig. 2: Multi-Granular three-layered UWB/SDM-based Optical Node (MG-ON) architecture, offering route-and select with flex-WBSS modules at Layer 1, C/D/C band add/drop at Layer 2, and support of legacy wavelength routing and add/drop at layer 3.

comprises an adaptive filtering stage, implemented with cascaded optical FIR lattice filters [13] for carving the spectrum into 1-4 flexible disjoint bands, followed by a 4×N crossbar switch for routing each carved band to a designated output fibre port. The sharpness of the lattice filters is dictated by the number of filter taps, with sharper filters requiring finer resolution and a greater number of taps, and the optical delay is defined by the large bandwidth support of the filter (spanning 165 nm ~ 21 THz total bandwidth). Both the filters and crossbar switch use phase modulators for setting their state, which draw little power when implemented in piezo technology. While the flex-WBSS is theoretically lossless, in practice we expect its filter losses to scale with the number of taps (0.1 dB/tap) and its crossbar losses to scale with the number of junctions traversed (0.05 dB/junction).

Multi-Granular Optical Node Architecture

Fig. 2 depicts the proposed MG-ON architecture employing the new flex-WBSS that addresses the scaling challenge and is fully compatible with upcoming UWB/SDM technology. At the top of the hierarchy, Layer 1—Flex-Band Route and Select, ingress and egress fiber ports are mated to flex-WBSS modules that are interconnected to each other to enable a route-and-select (R&S) switch topology, at the filtered bands level (continuously scalable to full fiber when no filtering is applied). Black lines from “West” input to “East” and “South” output directions represent available connection paths that can be selected (the remaining lines are excluded for simplicity). Here, East/West and South links have SDM dimensions of three and two, respectively. The shown R&S options support spatial lane change features (a band can be relocated from one spatial input lane to another), which comes at a cost of greater WBSS output ports requirement.

At the middle hierarchy (Layer 2—Flex-Band Add/Drop), we position an Inter-Band OXC which facilitates the interconnectivity between added/dropped flexibly defined bands and shared banks of band transceivers. The OXC enables colorless/directionless/contentionless (C/D/C) [14] access to transceivers. Blue lines from the West ingress WBSS send selected flex-bands to the OXC which assigns each dropped band to an available band receiver, and blue lines from the OXC to the East/South egress WBSS represent add paths for signals originating from band transmitters, with the reconfiguration association performed by the OXC. The rest of the blue connection lines are excluded for simplicity.

Finally, the lowest hierarchy (Layer 3—Legacy Wavelengths Access for Routing and Add/Drop) provides compatibility with legacy equipment using, e.g., C-band transmission equipment. Bands requiring wavelength access are configured to conventional WSS that interface to an Intra-Band OXC for supporting routing and/or wavelength add/drop to single channel transceivers, also attached to the intra-band OXC. As wavelength access is expected to be gradually decommissioned, the resources at this layer can be removed over time.

Switch Port Scaling Analysis

The total number of deployed WBSSs for R&S per Degree (D) and spatial parallelism (S_i) is given by:

$$N_{WBSS} = \sum_{i=1}^{D} (2 \cdot S_i), \qquad D,S \in \mathbb{N}_1 \qquad (1)$$

The WBSS's port count per Degree (D) is given by:

$$P_{WBSS} = \left[\left(\sum_{j=1}^{D-1} (S_j)\right) + K_B\right] \quad K_B, D, S \in \mathbb{N}_1 \quad (2)$$

where K_B is port count per WBSS devoted to flex-band add/drop (between 1 and 4). Eq. 2 supports spatial lane changes (SLC) enabling full routing flexibility to any spatial dimension. Without it, $P_{WBSS}=D-1+K_B$. The port count for the Inter-OXC is given by:

$$P_{OXC\,(INTER)} = \left[\left(\sum_{i=1}^{D} (K_B \cdot S_i)\right) + N_{BTx}\right] \times \left[\left(\sum_{i=1}^{D} (K_B \cdot S_i)\right) + N_{BRx}\right] \qquad (3)$$

where N_{BTx} / N_{BRx} represents the number of band transmitters/receivers in the ON add/drop.

Fig. 3. depicts the total number and output port scaling of WBSSs for four different network node cases, by varying nodal degree, D, spatial lane count, S, and band add/drop port count, K_B.

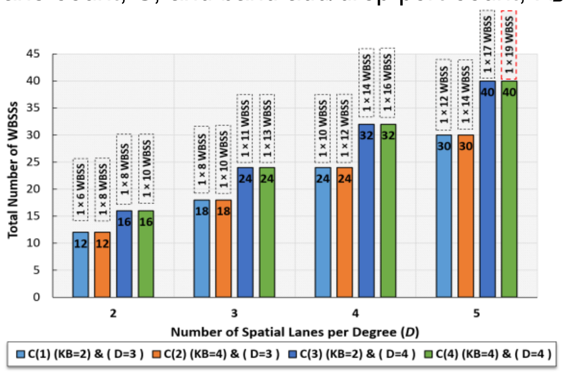

Fig. 3: WBSS unit count and their output port count for four different MG-ON network scales, with spatial lane changes.

Optical Node Capacity Evaluation

We evaluate different scenarios (number of spatial lanes, node degrees) to investigate the MG-ON throughput capacity (accounting both through and add/drop traffic). Fig. 4. depicts the net-throughput for small (D=3, 4), medium (D=5, 6) and large-scale nodes (D=7), having spatial dimensions S=2, 4, 6, 8, when using TRX's of SE=10 (bit/s)/Hz [15]. For example, a degree D=3 node with S=8 spatial parallelism supports 6.3 Pbps capacity, requiring 1×19 flex-WBSS and a 116×116 OXC. MG-ON supporting 10 Pbps throughput and beyond occur for high node degree count and spatial parallelism. For D=5, S=8, and K_B=3 we obtain 10.5 Pbps utilizing 1×35 flex-WBSS and 192×192 port OXC.

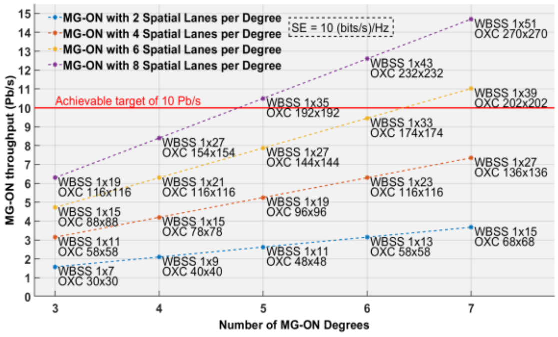

Fig. 4: Total MG-ON throughput for different scenarios

The Insertion Loss (IL) of the WBSS results from traversing two FIR lattice filters and the crossbar switch. The IL of each FIR lattice filter depends on its number of taps while IL of crossbar on the number of drop ports (N).

$$IL_{WBSS}\,(dB) = 2 \cdot IL_{FIR}\,(Taps) + IL_{CROSSBAR}\,(Worst, Average, Best) \quad (4)$$

Simulations for IL estimation (Fig. 5.) were conducted for WBSS implemented with 10, 20 and 30 taps respectively. Increasing the number of taps by factors of 2 and 3 offers a broader continuously-flat-top band shape and a smaller transition bandwidth respectively.

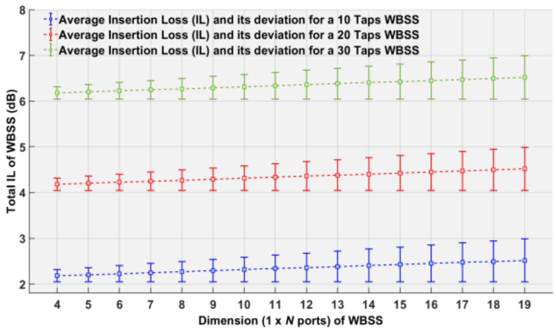

Fig. 5: Insertion Loss scale of WBSS for 10, 20, 30 taps.

Conclusions

We present a novel hierarchical multi-granular optical node architecture with the ability to switch flexibly-defined bands and support future SCNs. The scalability analysis reveals a low insertion loss modular approach, coupled with a high net-throughput. The MG-ON architecture is enabled by a new switching component, the 1×N *flex*-WBSS, implementable with emerging PIC-based technologies for defining and switching communication bands to their output ports.

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