Flexible-Granularity Switching Node Architecture for Spatial-Division and Multi-Band Optical Networks

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Abstract A summary of the network architecture that adopts flexible path bundling and bundled path routing is provided in this paper. This architecture can also support spatial division multiplexing and multi-band transmission. Numerical simulations and transmission experiments confirm its validity.

Introduction

The continuous and exponential traffic increase [1,2] motivates the development of technologies enabling broad bandwidth transmission and efficient optical networking. The explosive growth will continue with emerging applications such as autonomous vehicles and remote machinery and 5G and future mobile communications, which will support the digital enterprise, Industry 4.0, and smart cities. The capacity of single mode fibres (SMFs) had been enhanced by the introduction of dense wavelength division multiplexing (DWDM). The use of digital coherent transmission and the introduction of the ITU-T flexible grid [3] can boost the frequency utilization efficiency further. In order to achieve further network capacity enhancement, the use of frequency bands which have yet to be adopted [4-8] and the introduction of spatial parallelism to links [9-12] have been extensively studied. However, optical cross-connects (OXCs) at nodes can be large and complex given the sheer number of single mode fibres and/or multi-core fibres (MCFs) and route optical paths distributed over multiple frequency bands.

Routing via coarse granularity where grouped optical paths are routed together as routing entities, has been studied to realize large scale OXC nodes [13-17]. A typical approach is to split the available frequency band into several blocks with the same bandwidth and route paths in each block together. The groups of paths are often referred wavebands. In fixed grid optical networks, by taking advantage of the bandwidth uniformity of wavebands, waveband granularity routing can reduce the number of switches and demultiplexer / multiplexers. However, such a strategy is not valid for flexible grid optical networks with WSS-based OXC nodes as we cannot assume any regular structure in bundled paths with non-uniform bandwidths.

In order to reduce the hardware scale of OXC nodes in flexible grid optical networks, we have proposed an optical network architecture which adopts flexible wavebands [18-21]. We refer to this architecture and the nodes as the flexible waveband routing network and flexible waveband routing nodes. A two stage switching scheme with WSSs and optical switches was introduced for flexible waveband routing nodes where the WSSs bundle any combinations of optical paths and the optical switches route these grouped paths. This switching structure allows us to introduce the spatially-jointed path grouping by using the spatial joint switching mode at WSSs [22]. Moreover, by using multiple WSSs for different frequency bands in parallel, we can bundle optical paths distributed over multiple bands and route these path groups without modifying optical switches. It has been verified that similar routing performance to conventional optical nodes can be achieved even if the number of path groups for each input is small (2~4). As the number of path groups gives the necessary degree of WSSs and the number of switches in the flexible waveband routing node, the hardware scale is substantially reduced by the introduction of flexible waveband routing. Some transmission experiments have been conducted that demonstrate the validity of flexible waveband routing. In [20], a spatially-jointed flexible waveband routing node prototype (21core/fibre, 4x4) was developed and achieved 2.15Pbps throughput. We also developed a 16x16 prototype for multi-band networks [21]. The prototype successfully routed bundled paths on multiple bands (C+L) and achieved 300+Tbps throughput / 2000+km transmission.

Flexible Waveband Routing Node Architecture

In this paper, we assume that optical paths are located on the ITU-T flexible grid and multiple frequency bands can be used. Each link between an adjacent node pair consists of multiple single-mode fibres or multi-core fibres (MCFs). For notational simplicity, we assume that each optical path is accommodated to one of the fibres / cores on each link. However, spatial super-channels can be accommodated in flexible waveband routing networks.

Large-scale WSS-based OXC nodes whose degrees exceed these of WSSs used necessitate the cascading of WSSs; however the number of WSSs necessary increases almost in the square order of node degree. If we adopt WSSs for different frequency bands for multi-band transmission, the minimum degree among these WSSs characterizes node scalability. Thus we have to develop a node architecture that can limit the degree of WSSs to a small integer. The use of large-scale optical switches instead of WSS-based OXCs has been discussed [23,24]; however severe routing performance deterioration occurs in dynamic network operation cases [25].

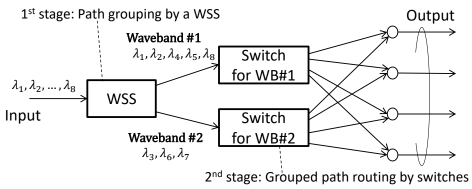

Fig. 1: Two-stage routing scheme.

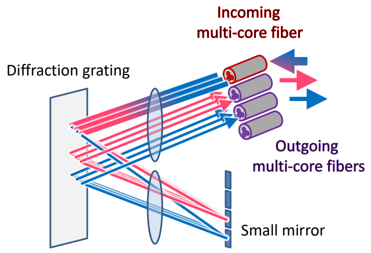

Fig. 2: Spatially-joint switching at a MEMS-based WSS.

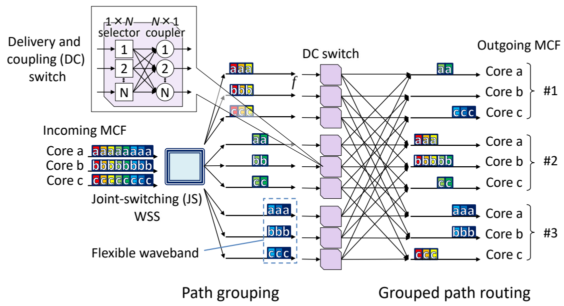

Fig. 3: Spatially-jointed path grouping and routing.

Figure 1 illustrate our two-stage routing scheme; optical paths in an input fibre are distributed to a small number (=B) of groups by a WSS and form path groups named flexible wavebands [18]. The flexible wavebands are routed by optical switches. Distribute-&-coupling switches can be used; merging multiple wavebands at the output sides is possible but the coupling loss is relatively high. The waveband number B gives the degree of WSSs necessary and the number of optical switches used, and thus, the development of network design algorithm which can suppress the value of B while keeping similar routing performance at nodes. We have proposed such an algorithm based on a graph-degeneration scheme; sufficient routing performance was achieved with B=2-4.

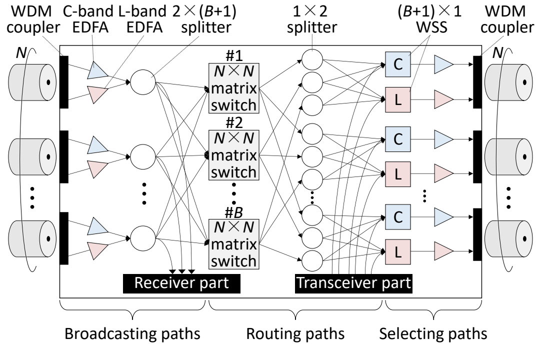

Fig. 4: Flexible Waveband Routing Node for Multi-band Networks [21].

The spatially-jointed switching mode of WSSs shown in Fig.2 divide the ports of a WSS into several port groups. Signals of the same frequency to the input grouped ports are switched together to one of output grouped ports. For example, a 1x(MN-1) WSS can be used an M-core joint-switching 1x(N-1) WSS. The use of the spatially-jointed switching mode enables path grouping over multiple SMFs / multiple cores of MCFs with a WSS (See Fig.3). Although the degree of spatially-joint switching WSSs, 1x(N-1), is not actually sufficient for OXC nodes, such WSSs can be used for the spatially-jointed waveband approach as the necessary degree B is small in general. With spatially-jointed flexible waveband routing, large-scale optical OXC nodes can be realized while suppressing B (See Fig.4).

Design and Performance Evaluation for Flexible Waveband Routing Networks

The routing and wavelength / spectrum assignment (RSA/RWA) to paths has been studied extensively and is known to be NP-complete. In order to evaluate the impact by the constraint given by flexible waveband routing, we have to develop a computationally efficient algorithm that can design networks with several tens of nodes while reducing the number of wavebands B. We have proposed a design algorithm based on a graph degeneration technique so that optical paths from each input fibre / core are routed together as much as possible. This algorithm iteratively accommodates and removes paths to/from the network and memorizes the number of paths routed together to the same output fibre / core. At each iteration, the number of paths routed together to an output fibre / core is translated into the weight for the input and output fibre / core pair, which encourages optical paths to concentrate on a small number of input and output fibre / core pairs. It was verified that this network design algorithm achieves almost the same routing performance as achieved with conventional nodes when B=3-4.

The routing performance of flexible waveband routing nodes has been verified by numerical simulations [21]. Tested topologies were the 4x4 regular mesh, Kanto (Tokyo metropolitan), and US-metro networks in Fig.5. The metric is the number of fibres necessary to accommodate a given set of paths to be established. Source and destination nodes are selected randomly for these paths and the number of 12.5GHz slots to be occupied by each path is also randomly selected from {4, 7, 15} which correspond to 100G / 400G / 1Tbps. The baseline of the evaluation is the WSS-based conventional OXC node with ideal routing flexibility. Figure 6 shows the variation in terms of traffic intensity represented by the expected number of paths to be established between each node pair. The ratio of fibre number approaches 1 as the number of wavebands, Bayeux, is increased to 4. This result elucidates that flexible waveband routing networks can achieve almost the same routing performance in many cases and the value of B should be determined considering both the expected hardware scale reduction and achieved routing performance.

Transmission Experiments

Figure 7 shows the configuration of transmission experiments on a 21-core 4x4 node prototype [20]. Two 1x20 WSSs are used in the 7-core joint switching mode; they are translated to 7-core joint switching 1x2 WSSs. The number of wavebands B is set to 2. Each core / SMF accommodates 64 400Gbps signals (optical paths) in the C-band. The maximum throughput of the fully equipped prototype reached 2.15Pbps. The optical path successfully traversed the prototype and 100km SMF seven times (See Fig.8).

Another 16x16 prototype for multi-band optical networks was developed recently [21]. We have succeeded in transmitting 188 100Gbps signals in C+L bands over 2000+km. The total throughput of fully equipped prototype exceeded 300Gbps.

Conclusions

We reviewed our flexible-granularity routing node architecture that can be used for networks with spatial-division multiplexing and/or multi-band transmission. Its validity was verified by numerical simulations and transmission experiments. Our two-stage routing scheme realized scalability and hardware scale reduction at nodes and these advantages should make flexible-granularity routing an efficient scheme for next-generation extremely high-bandwidth optical networks.

Acknowledgements

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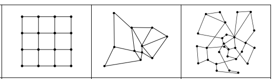

Network topology	(a) 4×4 regular-mesh	(b) Kanto	(c) US-metro
# of nodes	16	11	29
# of links	24	18	41
Max. node degree	4	5	7
Ave. node degree	3	3.27	2.83

Fig. 5: Tested network topologies.

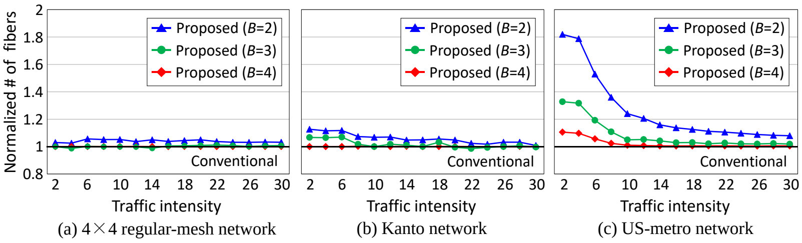

Fig. 6: The normalized number of necessary fibres relative to WSS-based node [21].

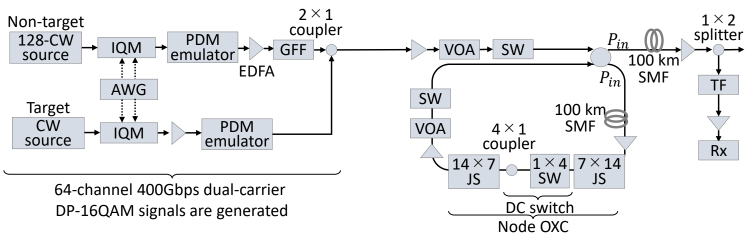

Fig. 7: Experimental configuration [20].

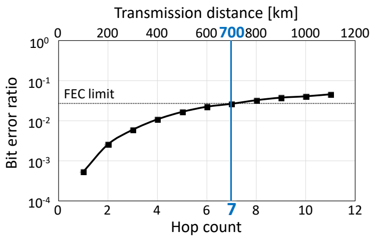

Fig. 8: BER variation [20].

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