

PAPER

Architecture and Design of Coarse/Fine Hybrid Granular Routing Optical Networks

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SUMMARY A novel coarse and fine hybrid granular routing network architecture is proposed. Virtual direct links (VDLs) defined by the coarse granular routing to bridge distant node pairs, and routing via VDL mitigate the spectrum narrowing caused by optical filtering at wavelength-selective switches in ROADMs (Reconfigurable Optical Add/Drop Multiplexing) nodes. The impairment mitigation yields denser channel accommodation in the frequency domain, which substantially increases fiber spectral efficiency. The proposed network simultaneously utilizes fine granular optical path level routing so that optical paths can be effectively accommodated in VDLs. The newly developed network design algorithm presented in this paper effectively implements routing and spectrum assignment to paths in addition to optimizing VDL establishment and path accommodation to VDLs. The effectiveness of the proposed architecture is demonstrated through both numerical and experimental evaluations; the number of fibers necessary in a network, and the spectrum bandwidth and hop count product are, respectively, reduced by up to 18% and increased by up to 111%.

key words: coarse and fine granular routing, virtual direct links, routing and wavelength assignment, optical path networks

1. Introduction

The volume of Internet traffic is continuously increasing due to the penetration of video-related services, especially those offering 4k quality videos [1]. This is accelerating the wide deployment of photonic networks from core to metro as they can eliminate expensive O/E and E/O conversion from the intermediate nodes of optical paths. Two technologies support the deployment; the development of wavelength selective switches (WSSs) enables simply configured reconfigurable optical add-drop multiplexers (ROADMs) for photonic networks while the introduction of digital coherent technology increases the transparent transmission reach.

The expected traffic growth necessitates further fiber capacity enhancement by improving fiber-frequency-resource utilization. Considering that the available frequency bandwidth is bounded in practice (ex. C- and L-band), denser channel multiplexing within the available bandwidth is an effective solution. Although the finely granular frequency bandwidth assignment has been standardized [2], channel density is limited due to the impairment caused by the

non-ideal optical filtering at WSSs; i.e. spectrum narrowing [3], [4]. Indeed, the super Gaussian order of current liquid crystal on silicon (LCOS) WSSs is approximately limited to 4-3 [5], and achieving higher orders is difficult and costly. The spectrum narrowing problem will be more and more serious as optical paths traverse more WSSs. First, the expansion of the transparent transmission area over core/metro networks will increase the number of nodes traversed by an optical path; a large number of nodes are included in such networks, and accordingly the number of nodes traversed by a path may reach 20 to 30 [6]. Second, since the traffic growth rate surpasses the fiber capacity enhancement, the number of fibers on each link inevitably increases, which triggers substantial ROADM node scale expansion. When ROADM port counts exceed the available WSS degree, the ROADMs need to utilize cascaded WSSs. The number of WSSs traversed increased as more WSSs are cascaded. In addition, the WSS-based ROADM node architecture should be changed from a broadcast-and-select (optical coupler (OC) + WSS) configuration to a route-and-select (WSS + WSS) one [3] to ease the high optical coupler loss and the accumulated crosstalk problem. This change doubles the number of WSSs traversed at ROADM nodes. As a result, the number of WSSs encountered with each node traversal will substantially increase. Therefore, to suppress this enhanced spectrum narrowing effect caused by the traversal of numerous WSSs, broad guard-bands are required between each pair of adjacent optical channels, which significantly degrades optical path density in the frequency domain.

A solution to this conflict between the need for broad guard-bands and reductions in the total bandwidth occupied by the guard-bands is to find a new transport mechanism that can reduce the number of guard-bands inserted. As traffic grows, multiple optical paths will be established between each pair of source and destination nodes but network physical topologies will not change. Thus multiple paths will take the same route between nodes. This encourages the use of coarse granular routing, in which a broad bandpass filter is applied to a group of optical paths that are routed as a group. A broad guard-band is required only between adjacent groups, while optical paths in each group can be packed densely with minimum spacing. This method simultaneously mitigates the spectrum narrowing effect and improves spectral efficiency. One of the excellent features of coarse granular routing is that no hardware modification at nodes is required to implement this; only the bandwidth control

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of conventional LCOS-based WSSs needs to be modified. Of course, the routing flexibility is reduced due to the use of coarse granular routing, and hence how to minimize this deficiency is the key to fully utilizing the benefits of coarse granular routing.

Optical networks that adopt coarse granular routing have been investigated: hierarchical optical path networks [7] and Grouped Routing networks [8]–[10]. Their major difference is how to fill the coarse granular routing entities with optical paths which may have different source and destination nodes. Hierarchical optical networks employ a mechanism similar to that of the electrical digital path hierarchy (ex. Virtual Container-x (VC-x) in SDH/SONET), to which is added the wavelength continuity constraint. Optical paths are always carried by coarse granular waveband paths and fine granular (path-by-path) add/drop and grooming operations are applied at end points of waveband paths. On the other hand, Grouped Routing networks combine coarse granular routing and fine granular add/drop operations at ROADMs. This routing scheme defines coarse granular pipes, named grouped routing entity (GRE) pipes [8], [9]; a pipe can accommodate paths if the source and destination nodes lie along the pipe. In these networks, spectrum narrowing can occur only when fine granular operations are applied, and hence, the impairment mitigation is realized by bounding the number of such fine granular operations for each optical path. However, coarse granular paths/pipes can only accommodate paths whose source and destination nodes are at GRE pipes' end points or along their routes. Thus the routing capability at just the coarse granularity level will limit responsiveness to traffic churn or the path distribution changes expected in future dynamic network services, and it is hard to keep the optimality of coarse granular routing entities [8], [9].

In this paper, we propose a novel coarse/fine hybrid granular routing optical network architecture that not only mitigates the spectrum narrowing by its use of coarse granular routing, but also take advantage of the flexibility of fine granular routing. The coarse granular routing defines virtual direct links (VDLs) that directly bridge distant node pairs and each VDL can carry optical paths without causing spectrum narrowing except at its edges. Thus network topologies are virtually (logically) changed by VDLs so that their diameters, which are the largest hop counts of shortest routes between all node pairs, will be small enough to bound the spectrum narrowing effect. On the other hand, fine granular routing is used for improving routing flexibility whenever the filtering impairment is acceptable. We propose a heuristic-based network design algorithm that considers impairment (i.e. spectrum narrowing) bounding and optimizes VDL locations in addition to solving the routing and wavelength/spectrum assignment problem, which is known to be NP-complete [11]. The algorithm sequentially searches for groups of paths that have neighboring source or destination nodes and establish VDLs to accommodate the groups of paths so that all paths satisfy a given hop count limitation while maximizing VDL utilization.

The validity of the proposed architecture is verified from two different perspectives. First is a network-wide numerical evaluation where the impairment bounding constraint is formulated as a hop count limitation; i.e. the spectrum narrowing effect of linear transmission systems is considered. The metric used here is the minimum number of fibers necessary to create a network that accommodates a given traffic demand. The superiority of the proposed networks over conventional ones is verified by the improved metric demonstrated by four network topologies. Up to ~18% improvement is observed. Second is a verification of transmission performance including fiber nonlinearity. The transmission performance of a point-to-point system is generally evaluated by the product of transmission bit rate and length. In photonic networks that employ many ROADMs and ultra-dense WDM transmission, the product of spectral efficiency, which is defined by the averaged spectral resource utilization ratio of fibers in the network, and the transmissible hop count is an important measure that reflects the impact of spectrum narrowing and the wavelength/spectrum continuity constraint for optical paths. We name the metric the SH (spectrum-hop count) product. The BER variations subject to the number of physical hops are analyzed through transmission experiments for different channel configurations; i.e. conventional WDM configuration and ultra-dense WDM configurations with and without VDLs. The acceptable hop counts for three configurations subject to a given BER threshold confirm that the introduction of VDLs substantially reduces the hop count (filtering impairment). As a result, the SH product is improved by 13.7% and 111% compared to the conventional configuration and the ultra-dense WDM configuration without VDLs, respectively.

The paper is organized as follows. The motivation and background are explained in Sect. 1. In Sect. 2, two existing coarse granular routing networks are briefly compared. Then in Sect. 3, the proposed network architecture and its design algorithm are presented. Section 4 demonstrates performance verifications based on numerical simulations and the results of transmission experiments. Finally, Sect. 5 concludes this paper. Parts of a preliminary VDL proposal have been presented at international conferences [12]–[14].

2. Preliminaries

2.1 Coarse Granular Routing for Filter Narrowing Mitigation

Throughout this paper, we assume that all optical channels have the same bitrate & modulation format and all groups occupy the same bandwidth for simplicity; however the discussion can be easily extended to non-uniform bitrate and bandwidths with the adaptive bitrate and modulation format selection in [15]. No wavelength conversion or 3R regeneration is used. The static network design scenario is assumed; the objective is minimization of the number of necessary fibers in a network to accommodate given optical path demands. The validity of the proposed architecture in dynamic

optical path control scenarios was elucidated in [14].

The conventional fixed grid approach locates optical channels on a uniformly spaced (ex. 25/50/100 GHz) grid and channel bandwidths must not exceed the spacing. Recent standards on the flexible grid [2], which we assume throughout this paper, define a fine frequency grid (6.25 GHz spacing) on which channel center frequencies are located. Channel frequency bandwidths are multiples of 12.5 GHz ($= 2 \times 6.25$ GHz). This fine granular channel assignment provides room to improve the spectral utilization efficiency by reducing the gap between channels. For example, current DP-QPSK modulated 100 Gbps optical channels are accommodated on a 50 GHz spacing fixed grid; their net frequency bandwidths are around 30 GHz depending on FEC overhead. Thus if there is no filtering impairment, the flexible grid allows these channels to be densely located on a 37.5 GHz ($= 3 \times 12.5$ GHz) spacing grid. However, optical filters cannot yield passbands with ideal rectangular shape and hence dense optical path arrangements in the frequency domain incurs signal impairment at the edges of the filter passbands when the guard-band between adjacent channels is narrow (see Fig. 1(a)). While setting a broad guard-band between adjacent channels resolves the signal impairment, the number of channels accommodated in a fiber is reduced (see Fig. 1(b)).

If multiple paths are bundled and routed as an entity, a broad passband filter covering a routing entity, i.e. a bundle of optical paths, can be applied at each ROADM (see Fig. 1(c)). This passband concatenation in Fig. 1(c) is possible with commercial LCOS based WSSs and thus no modification of hardware is required. A sufficient and minimum bandwidth guard-band is inserted only between groups (bundles of optical paths), while optical paths in each group are packed densely with minimum spacing. The number of optical channels per fiber is determined by the number of optical channels per bundle. As the number of channels that can be accommodated in a bundle increases, the total bandwidth occupied by the guard-bands falls. Routing flexibility, on the other hand, is degraded. Thus the number of paths accommodated in a bundle must be carefully chosen to optimize the trade-off between fiber frequency utilization and routing flexibility. The grouping of channels of non-uniform bandwidths is possible as shown in Fig. 1(d); however we focus on the uniform bandwidth case as in Fig. 1(c) for simplicity as stated at the beginning of this section.

Here 100 Gbps optical channels in the C-band (bandwidth, 4.4 THz) with 37.5 GHz spacing are assumed. Each pair of adjacent bundles is separated by a 25 GHz guard-band. The number of channels per fiber for given number of channels per bundle, n , is given by

$$\begin{aligned} \# \text{ of channels per fiber} &= n \times \left\lfloor \frac{4400 + 25}{37.5 \times n + 25} \right\rfloor \\ &\leq \frac{4400 + 25}{37.5 + 25/n} \end{aligned}$$

where $\lfloor \cdot \rfloor$ is a flooring function. The relations of the number of channels per bundle and the upper bound in the above

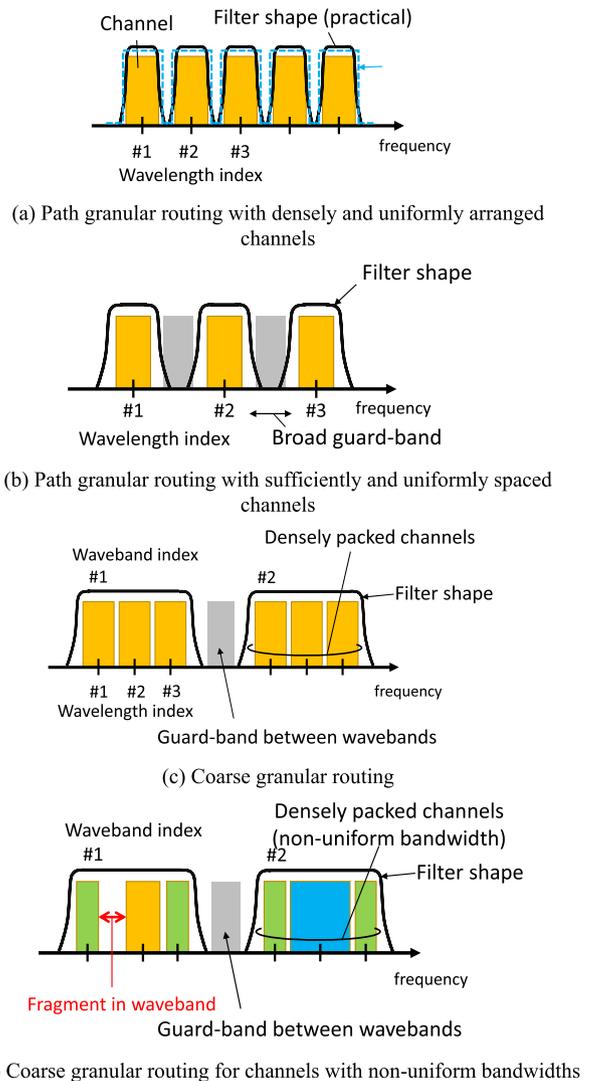


Fig. 1 Optical channel arrangements and spectrum narrowing effect.

equation are shown in Fig. 2. Solid green bars without hatching in the figure show that the channel number accommodated in a fiber rises as the bundles become smaller. Solid green bars with hatching show the configurations that should be avoided, as the other configurations with narrower bundles can achieve the same or larger channel numbers. Purple bar is for 50 GHz spaced channels without bundling; i.e. conventional configuration. The figure shows that the number of channels per fiber increases steeply when the number of channels per bundle is small, however it saturates when the channel number per bundle is around ten.

For each channel accommodation configuration in Figs. 1(a)–(c), the locations of center frequencies are labeled by positive integers (i.e. 1, 2, 3, ...) in ascending order of frequency and these labels are referred to as wavelength indexes. The frequency ranges for bundles of paths in Fig. 1(c) are referred to wavebands in all coarse granular routing architectures; hierarchical, Grouped Routing, and Virtual Direct Link, and the positive integer labels (called waveband

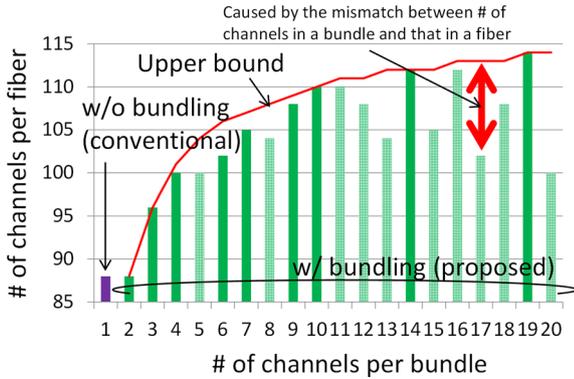


Fig. 2 Variation of number of channels per fiber (100 Gbps channels in the C-band (4.4 THz width)).

indexes) are also assigned to the wavebands.

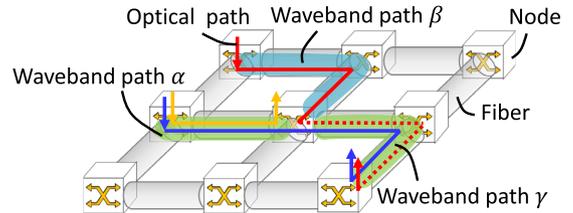
2.2 Conventional Coarse Granular Routing Network Architectures

(a) Hierarchical optical path networks

A higher-order optical path, a waveband path or a bundle of multiple wavelength paths, is shown in Fig. 3(a). A waveband path offers path functions, higher order path, as defined by ITU-T.G.783 [16] and hence waveband path edges are defined. Each optical path is generally routed along the way from each source to each destination on one or more waveband paths, and adding/dropping optical paths is allowed only at the edge nodes of waveband paths. If an optical path traverses multiple concatenated waveband paths, these waveband paths must have the same waveband (WB) index; i.e. the same frequency allocation (See Fig. 3(b)). Moreover, a common wavelength should be assigned to each optical path along the sequence of waveband paths traversed. In Fig. 3(a), a blue optical path traverses two separate waveband paths, α and γ , having the same waveband index WB #1, while the red path included in waveband β , which has a different index (WB #3), cannot be accommodated in Waveband path γ . This severe constraint hinders optical paths from traversing multiple waveband paths. This wavelength continuity constraint differentiates hierarchical optical networks from present hierarchical electrical path networks such as SDH/SONET, and can substantially degrade the utilization of waveband paths. To enhance the accommodation efficiency, some studies introduce wavelength/waveband conversion [17]; however, the high cost of converters can be an issue that must be resolved before they can be utilized.

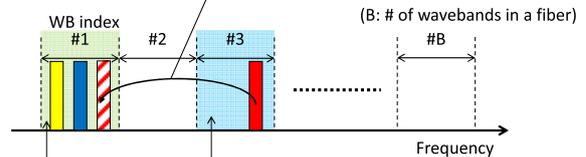
(b) Grouped Routing networks

Grouped Routing networks were proposed and investigated in [8]–[10]. In those studies, the coarse granular routing entities are called Grouped Routing Entities (GRE). Routing is done at the GRE granularity level and each GRE (called a GRE pipe) can be regarded as a virtual fiber (small bandwidth fiber). GRE pipes do not branch or join at intermediate nodes and connect nodes on their way. Different



(a) Path routing in hierarchical optical path network

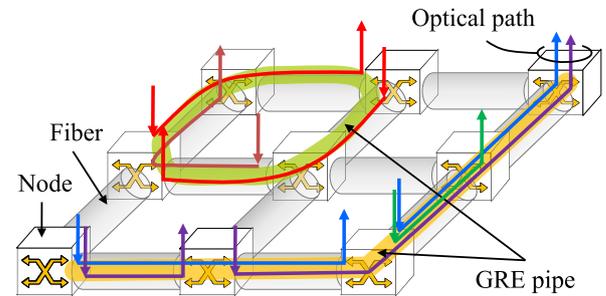
Wavelength conversion is necessary for the red path to be carried by the Waveband path γ .



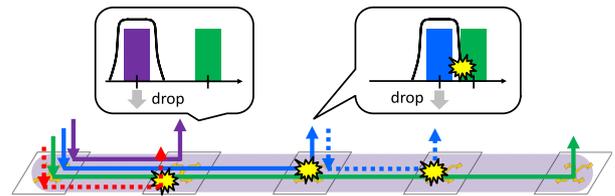
This range is commonly assigned to the Waveband paths α and γ .

(b) Restrictions on assigning waveband paths

Fig. 3 Hierarchical optical path networks.



(a) Path routing in grouped routing networks



(b) Spectrum narrowing caused by an adjacent path drop

Fig. 4 Grouped routing networks.

from waveband paths, GRE pipes do not offer path functions such as termination as defined by ITU-T.G.783 [16] and hence they can form loops when necessary, similar to a fiber ring. Moreover, optical paths can be added/dropped at each node on the GRE pipe as shown in Fig. 4(a), unlike the waveband path. This fine granular add/drop can improve the accommodation efficiency of GRE pipes. On the other hand, optical paths suffer from spectrum narrowing effects when adjacent optical paths are dropped as shown in Fig. 4(b) and hence we need to control the number of filtering operations for each path. Therefore, when the traffic distribution changes dynamically, rather complex operations are needed so that all the paths meet the filtering operation

requirements, which can degrade GRE pipe utilization.

3. Proposed Optical Path Network That Adopts Virtual Direct Links

3.1 Network Architecture Utilizing Virtual Direct Links

Figure 5 shows a simple example of the network architecture proposed herein that adopts VDLs, where a VDL directly bridges distant node pairs (s_L and d_L) and carries three optical paths. Optical paths whose sources and destinations coincide with or are close to the VDL edges are accommodated into the VDL where wavelength granular routing (optical path level routing) is used outside the VDL or in the vicinity of the VDL edge. Intermediate VDL nodes use a broader passband filter so that the bundle of paths within the passband is routed as a group (See Fig. 1(c)). Accordingly, there is no spectrum narrowing at intermediate VDL nodes, and hence, traversing a VDL is regarded as one hop (Fig. 5). Each path may traverse multiple wavelength path routing nodes before and after traversing a VDL and hence bounding the total hop count is required to keep the impairment caused by spectrum narrowing to an acceptable level. This network combines coarse and fine granular routing in an integrated way that mitigates the degradation in routing flexibility stemming from the use of VDLs. Spectrum narrowing for paths in a VDL does not occur when an adjacent path is set up or torn down, which is different from grouped routing networks where optical path add/drop is allowed along a GRE pipe. As a result, path setup and tear down operations can be done without causing filtering impairment to the adjacent paths, and this makes the routing and wavelength/spectrum assignment to paths much simpler than that in grouped routing networks.

The number of VDLs traversed by a path is assumed to be one throughout the rest of this paper since a numerical experiment showed that the improvement in performance attained by traversing multiple VDLs was limited. Using VDLs can substantially reduce the hop count, however, the number of physical links traversed by the path may increase from its shortest route. This detour wastes the frequency resources of the network. Therefore, we need to manage not only the number of hops but also the number of physical links traversed. Let $\text{hop}(n_1, n_2)$ be the hop count of the shortest route between nodes n_1 and n_2 . Let H_{limit} be the maximum allowable hop count for a given spectrum narrowing condition. Then the search area in the vicinity of the source and destination nodes of the VDL is characterized by another parameter, search radius $R (= H_{\text{limit}} - 1)$ where the subtraction “-1” corresponds to the number of traversed VDLs; it is limited to one due to the aforementioned assumption. We introduce another parameter, h_{add} , which is an upper bound of the increment in the number of physical links traversed by the path due to detouring.

Figure 6 also shows that the number of optical paths to be accommodated in a VDL is increased by the individual optical path (wavelength granular) routing in the vicinity of

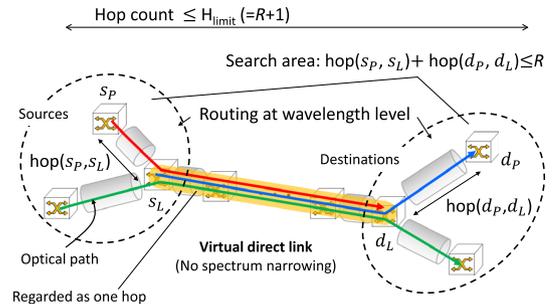


Fig. 5 Virtual direct link and corresponding search area.

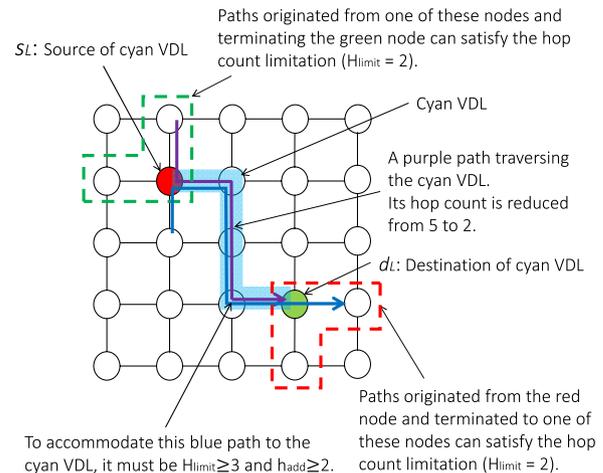


Fig. 6 Path accommodation in a VDL on a 5×5 network with $R = 1$ (i.e. $H_{\text{limit}} = 2$) and $h_{\text{add}} = 0$.

the VDL edges. The VDL can only accommodate paths whose source and destination are identical to those of the VDL if $R=0$. However, if R is increased to one and h_{add} is set to 0, the VDL can accommodate optical paths between five node pairs; three pairs between nodes in the dotted green area to the green node, and three pairs between the red node and nodes in the dotted red area, where one pair (red and green node) is included in both groups. Increasing R increases the number of paths that can be accommodated in each VDL and thus attains better accommodation efficiency. This characteristic is confirmed by the numerical simulations presented in Sect. 4.1.

3.2 Design Algorithm of Optical Networks That Introduce VDLs

The routing performance of the proposed optical network strongly depends on its design algorithm; we must carefully decide the locations of VDLs and which VDL should be used to carry each optical path. In this section, we propose an algorithm that designs a network for a given network topology and a set of path demands between nodes; i.e. static network design. The objective is to minimize the number of fibers necessary in the network by effectively establishing VDLs and performing route and wavelength (or spectrum) assignment to each optical path. The routing

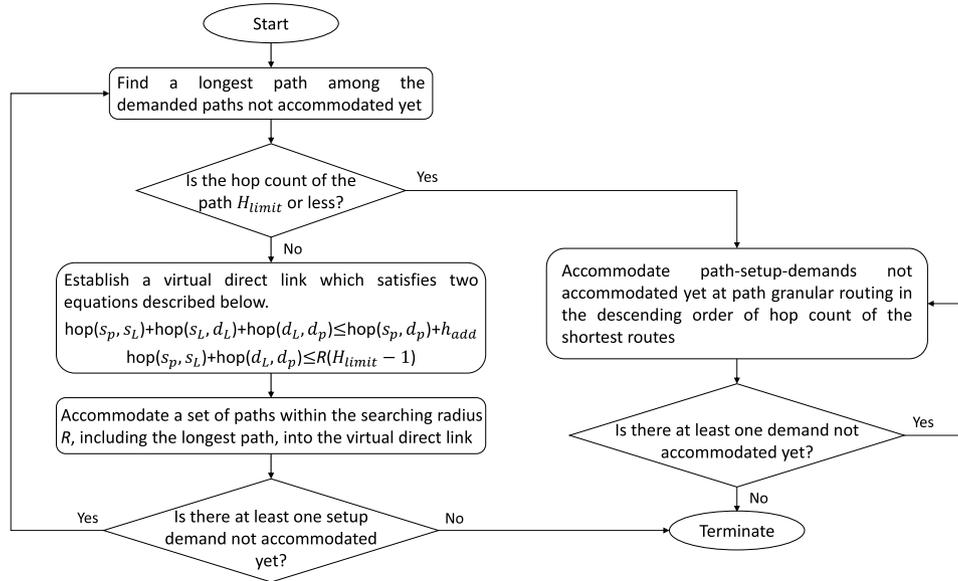


Fig. 7 Flow-chart of the proposed network design algorithm.

and wavelength assignment problem for conventional optical path networks is known to be NP-complete [11], and the introduction of VDLs makes the problem more complicated. Thus we need a computationally efficient heuristic algorithm. The proposed network design algorithm iteratively locates VDLs considering the path demand distribution as described below. The flow chart is shown in Fig. 7.

⟨Designing hybrid routing-granularity optical path networks that use VDLs⟩

Step 0: Parameter selection

Set appropriate values for design parameters: the maximum allowable hop count H_{limit} for a given channel spacing and impairment condition, the search radius $R (= H_{limit} - 1)$ (See Fig. 5), and the additional physical hop count h_{add} that stems from detours caused by virtual direct link accommodation. Go to Step 1.

Step 1: Find the longest path demand

Among the demanded paths not yet accommodated, find a path-setup-demand whose source and destination nodes (s_p and d_p , respectively) are the most distant (i.e. the longest path demand). If multiple longest path demands are found, select one randomly. If $\text{hop}(s_p, d_p) < H_{limit}$, go to Step 3. Otherwise, go to Step 2.

Step 2: Establish VDLs and accommodate paths

Step 2.1: Select source and destination nodes of VDLs

For the source and destination node pair (s_p, d_p) of the path-setup-demand found in Step 1, list all of its neighboring node pairs (s_L, d_L) such that $\text{hop}(s_p, s_L) + \text{hop}(s_L, d_L) + \text{hop}(d_L, d_p) \leq \text{hop}(s_p, d_p) + h_{add}$ and $\text{hop}(s_p, s_L) + \text{hop}(d_L, d_p) \leq R (= H_{limit} - 1)$ (See Fig. 5). The listed node pairs are regarded as end point candidates of a VDL. In other words, the hop count is reduced to $\text{hop}(s_p, s_L) + \text{hop}(d_L, d_p) + 1$, in terms of filtering number, by establishing a VDL

between (s_L, d_L). Select one of these candidates (\tilde{s}_L, \tilde{d}_L) so as to maximize the number of path-setup-demands that are not yet processed and whose source and destination nodes are within the search radius, R ; i.e. demands that can be accommodated by the VDL. If multiple candidates maximize the number, select one that minimizes the total reduced hop count if a VDL is set between the candidate node pair (An example of hop count reduction is shown in Fig. 6). Fix a set of neighboring path-setup-demands to be accommodated to the VDL between (\tilde{s}_L, \tilde{d}_L).

Step 2.2: Assign route & wavelength/waveband and accommodate paths in VDLs

Search for available routes and waveband/wavelengths for the VDL between (\tilde{s}_L, \tilde{d}_L) and the neighboring path-setup-demands selected in Step 2.1. Note that the wavelengths to be assigned to these paths must be included in the waveband for the VDL (See Fig. 6). Routes are searched in ascending order of hop count while waveband/wavelengths are searched in descending order of waveband/wavelength indexes. Select the best routes and waveband/wavelengths so that the number of newly added fibers is minimized. If multiple parameter sets minimize the newly added fiber number, then select the first one found. Establish the selected VDL between (\tilde{s}_L, \tilde{d}_L) and the corresponding paths on the selected routes and waveband/wavelengths and install new fibers if necessary. If at least one path-setup-demand has not been processed yet, go back to Step 1. Otherwise, terminate.

Step 3: Accommodate remaining optical paths

Sort remaining path-setup-demands in descending order of hop counts of their shortest routes. For each demand, routes are selected in ascending order of hop count and a vacant wavelength is searched in ascending order of wavelength indexes. From the pairs of route and wavelength that minimize newly added fibers while ensuring path accommodation, select the first one. Use the selected route and

wavelength to accommodate the path. Repeat this procedure until no demand remains unassigned. Terminate.

Remark

1. With the hybrid granular routing proposal, the impairment management issue in network control is simplified as it translates to the hop count bounding constraint. Another simplification in path operation is that set up or tear down of a path does not affect the spectrum narrowing level of the other paths.
2. Path detour is managed by parameter h_{add} in the proposed algorithm. Detouring may improve the utilization ratio of VDLs but increasing the hop number will waste more network resources. This trade-off has been evaluated numerically for several topologies, and $h_{\text{add}} = 0$ gives the best results for almost all cases. Therefore, the following analyses in Sect. 4 commonly use $h_{\text{add}} = 0$.
3. In this paper, conventional (1xN) WSS based nodes are assumed to elucidate the impact of VDLs in general situations. However, the introduction of VDLs is independent of optical node architecture. For example, we can combine VDLs with the subsystem-modular optical node architecture that uses recently developed multiple-input and multiple-output WSS [18]; this reduces the link and node cost simultaneously. The resulting optical networks not only accommodate large traffic volume but also have graceful modular-growth (pay-as-you-grow) capability.

4. Numerical and Experimental Evaluations

To evaluate the effectiveness of the proposed network architecture, we conducted two different evaluations. First, numerical evaluations used the metric of the number of fibers necessary. Second, we evaluated both spectral efficiency and hop count reduction based on numerical simulations and transmission experiments.

The available fiber bandwidth of each fiber was set to 4.4 THz in the C-band. We assumed a frequency granularity of 12.5 GHz as determined by ITU-T [2]. The baud rate of each channel is 30G baud with DP-QPSK modulation and 20% overhead is assumed for forward error correction (FEC). Thus the net bit rate of each optical path is 100 Gbps (30G baud \times 3 bit/symbol \times 1/1.2). Each ROADM node uses WSSs with the route-&-select configuration, so two filtering operations are done with each node traversal. The tested network topologies are a 7×7 regular mesh network, the US long-haul network [19] (Fig. 8(a)), the Phoenix network (Italian national network) [20] (Fig. 8(b)) and the pan-European network (COST266) [21] (Fig. 8(c)). For all these topologies, there are always sufficient numbers of route candidates between node pairs and hence throughout the following evaluations, no detouring is necessary for paths and VDLs; i.e. the hop count increment h_{add} was set to 0, as explained in the remark at the end of Sect. 3. The proposed network design

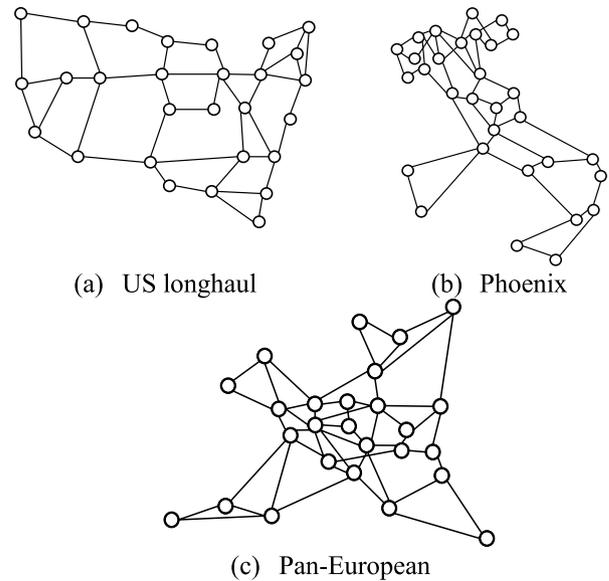


Fig. 8 Network topologies.

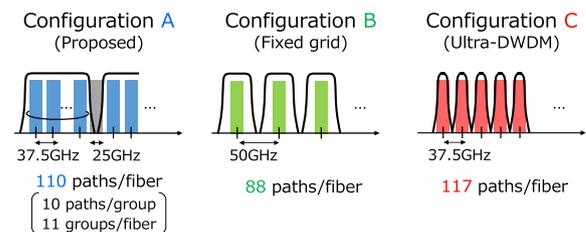


Fig. 9 Assumed 100 Gbps DP-QPSK channel configurations evaluated in Sect. 4.

algorithm is implemented as tailor-made software written in C++ and Intel Xeon E5 servers are used to run the software. The running time of each evaluation is around several seconds, even in high traffic intensity areas.

We evaluated three channel configurations as shown in Fig. 9. Configuration A represents coarse granular routing networks (hierarchical optical path networks, grouped routing networks and VDL optical networks), in which ten 37.5 GHz spaced channels/paths form a grouped entity and 11 entities are accommodated in a fiber (See Figs. 1(c) and 2 and the second paragraph of Sect. 2.1). Between each pair of adjacent groups, a 25 GHz guard-band is inserted [11]. As a result, each fiber can accommodate 110 paths. Configuration B corresponds to current photonic networks in which 88 paths are located on the 50 GHz spaced grid (Fig. 1(a)). Configuration C is an example of denser WDM where 117 paths are located on a 37.5 GHz spaced grid (referred to as ultra-DWDM in this paper, Fig. 1(b)).

4.1 The Number of Fibers Necessary

We conducted network-wide numerical simulations on the different topologies to clarify the effectiveness attained with the proposed architecture. Section 4.1 assumes linear impairment caused by spectrum narrowing, which imposes a

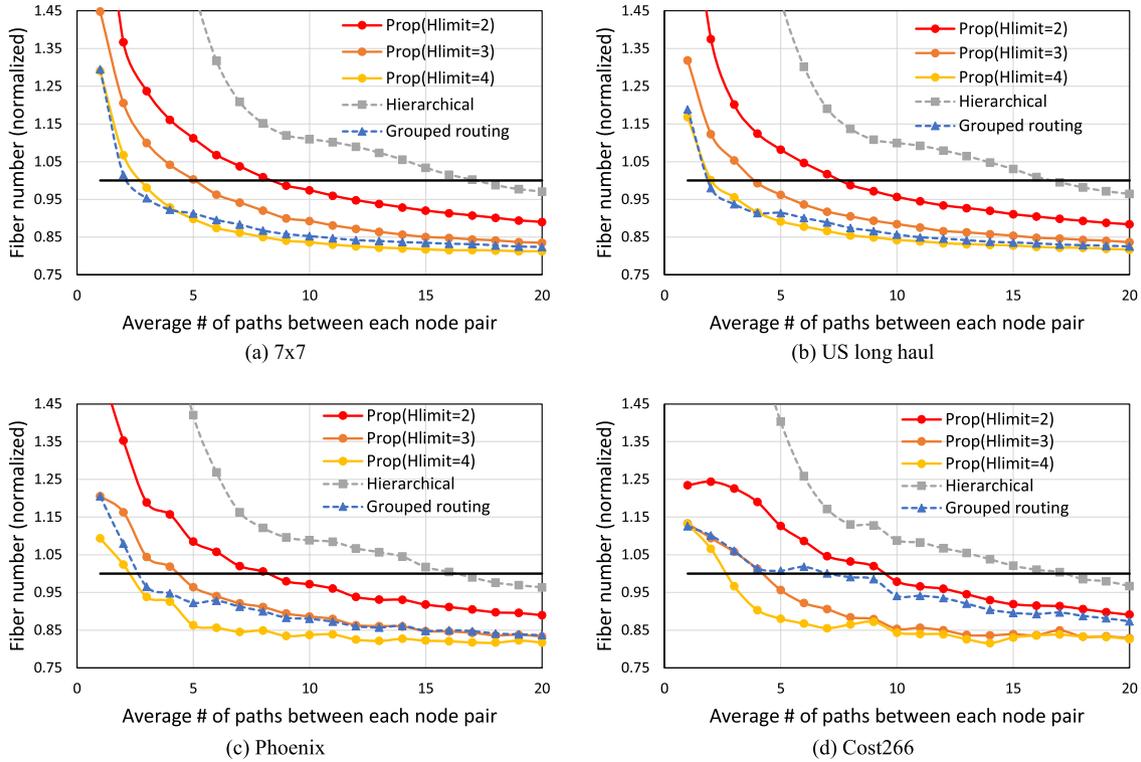


Fig. 10 Variations in number of fibers necessary for different topologies.

constraint such that hop count is bounded by H_{limit} . Non-linear impairment was not considered, as this impact is considered in the next subsection. To assess the architectures, we compare the following: grouped routing [10], hierarchical (see Sect. 2.2(a)), proposal with configuration A, and conventional path granular routing with configuration B. No grooming operation (optical path transfer from one waveband path to another waveband path at ROADMs) is adopted for hierarchical optical path networks to highlight the impact of path granular add/drop in Grouped Routing networks. Configuration C is not used due to the severe limitation imposed by the number of hops.

The average number of path demands requested between each node pair was changed from 1 to 20. The source and destination node pair of each path was randomly assigned following a uniform distribution. The maximum allowable hop count H_{limit} and the search radius $R (= H_{\text{limit}} - 1)$ were set to $H_{\text{limit}} = 2$ with $R = 1$, $H_{\text{limit}} = 3$ with $R = 2$ and $H_{\text{limit}} = 4$ with $R = 3$, considering the typical super-Gaussian degrees, 4-3, of commercially available WSSs [13], [14]. All the results in Sect. 4.1 were derived by averaging the results of twenty runs.

Figure 10 shows the ratios of the number of fibers necessary for the different networks. The results of configuration A (Grouped Routing, hierarchical optical path, and proposed) are normalized by those of configuration B (the current standard channel accommodation) so as to demonstrate how well the dense channel packing with coarse granular routing improves the fiber utilization. In configuration A, optical channels are packed densely in each group as

depicted in Fig. 8, which enhances fiber spectral efficiency by up to 25% compared to configuration B. Thanks to this, the proposed network can successfully reduce the necessary number of fibers in all topologies. This improvement becomes more obvious as the traffic intensity rises. In other words, the proposed network suppresses the routing performance degradation that can be caused by grouped routing, especially when the traffic demand volume is large. As a result, the fiber number reduction of the proposed network reached 18.8% for 7×7 regular mesh, 18.3% for US long haul, 18.3% for Phoenix and 17.4% for COST266 compared to the conventional network (configuration B).

The performance differences between proposed and grouped routing networks were smaller in 7×7 and US long haul than in Phoenix and COST266. The former topologies have a perfect or almost uniform mesh structure which gives GRE pipes higher routing flexibility than the latter topologies. Since a GRE pipe can accommodate paths whose source and destination nodes lie along the route of the pipe, the high routing flexibility strengthens the performance of grouped routing in mesh-like topologies. On the other hand, in grouped routing networks, spectrum narrowing occurs only when adjacent paths are dropped as shown in Fig. 4 and thus the grouped routing networks will be less affected by reductions in the H_{limit} parameter than the proposed networks. Moreover, in addition to the performance superiority over grouped routing networks, the proposed architecture has the notable advantage that dynamic path operations over VDLs are simpler than those in grouped routing networks (See also Sect. 2).

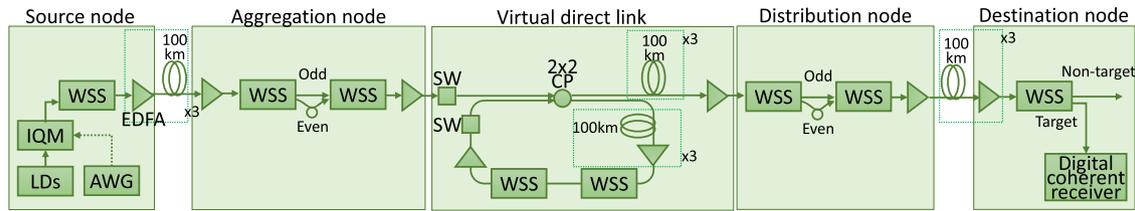


Fig. 11 Experimental configuration.

4.2 Evaluations of both Spectral Efficiency and Hop Count

In Sect. 4.1, we verified numerically that the proposed network (configuration A) improved network capacity by up to about 25% compared to conventional networks (configuration B). The numerical evaluations used a simple constraint, the upper bound of the number of hops as determined by an analysis of linear transmission systems. In order to verify the improvement in transmission performance achieved by the proposed architecture in detail, an analysis of the results of real transmission experiments is necessary. The transmission performance of a point-to-point system is generally evaluated by the product of bit rate and transmissible length. Due to the wavelength continuity constraint, unused wavelength/frequency slots in a fiber cannot necessarily be assigned to a path; the optical path requests a set of frequency slots commonly available (unused) on all fibers traversed. Thus, in order to ensure a practical evaluation of the spectral resource utilization of fibers, we jointly conducted a computer-based numerical evaluation (in Sect. 4.2.1) and an evaluation of physical transmission performance (in Sect. 4.2.2). As another important and natural measure to assess ultra-dense WDM photonic networks with many ROADMs, we introduce the product of spectral efficiency and the hop count (SH product) as is calculated in Sect. 4.2.1. The derived results are discussed in Sect. 4.2.3.

4.2.1 Simulations on Routing Performance

In order to measure the utilization efficiency of fiber spectral resources at the network level, we define the metric of spectral efficiency. Let the minimum frequency resource occupation for a path be the product of the frequency bandwidth (# of occupying slots \times 12.5 GHz) assigned to the path and the number of hops of the shortest route between source and destination nodes of the path. Spectral efficiency in a network is defined as the ratio of the sum of minimum frequency resource occupation for all paths to the product of available fiber frequency bandwidth and the number of fibers in the network.

The tested topology was a 7×7 regular mesh network. The optical paths were randomly established between each node pair, and the number of paths was changed from 10 to 20. The maximum allowable hop count and the searching radius were set to $H_{\text{limit}} = 3$ with $R = 2$. Simulations were conducted to derive the number of fibers necessary for each

traffic demand value and each channel configuration. The fiber number variations observed here are same as those shown in Sect. 4.1, and so are not shown here. However, they were used in deriving the spectral efficiency variation which is discussed in 4.2.3.

4.2.2 Experiments on Transmission Performance

The transmission performance was also evaluated using the experimental configuration shown in Fig. 11. This proof-of-concept experiment employed 10 wavelength channels and the center-wavelength channel was evaluated. At the source node, 10-ch 30-Gbaud QPSK signals were created with an IQ modulator (IQM) driven by an arbitrary-waveform generator (AWG). The signals thus obtained were added to a transmission link via a WSS. Each link comprised three repeater spans, each of which had a 100-km standard single-mode fiber (SMF) and an erbium-doped fiber amplifier (EDFA). The loss coefficient and dispersion parameter of the SMF were 0.19 dB/km and 16.5 ps/nm/km, respectively. The noise figure of the EDFA was around 5 dB. After three repeater spans, the signals were then input to the next node. To emulate optical path aggregation with fine granularity, the odd- and even-number wavelength channels were de-interleaved and de-correlated with a fiber delay line. The signal then traversed the VDL emulated by a recirculating fiber loop comprised of two synchronous loop switches (SWs), a 2×2 3-dB coupler, a 100-km SMF, EDFAs, and WSSs. In the VDL, signals were routed in a group-by-group manner and hence the spectrum narrowing at the WSSs was minimized. At the distribution node, the signals were routed with wavelength granularity. Finally, the target signal was dropped at the destination node and detected by a coherent receiver. After that, the received signal was sampled by a 4-ch analog-to-digital converter at 50 GSamples/s and delivered to a digital-signal-processing (DSP) circuit. The DSP circuit performed chromatic-dispersion compensation, polarization demultiplexing, carrier-phase estimation, and symbol decoding. Finally, we calculated the pre-FEC bit-error ratios (BERs) for every hop count and obtained the maximum number of acceptable hops that could satisfy the FEC threshold ($\text{BER} = 2.7 \times 10^{-2}$).

4.2.3 Discussions

Figure 12 shows the variations in spectral efficiency versus traffic volumes on the 7×7 regular mesh network for

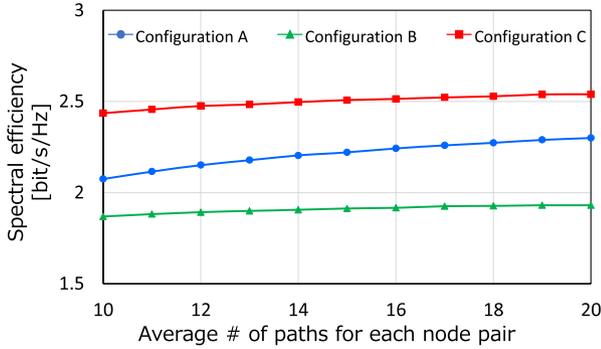


Fig. 12 Spectral efficiency of networks (simulations).

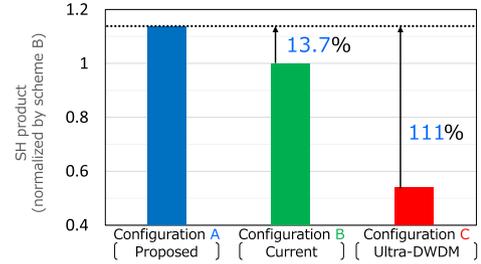


Fig. 14 SH (spectrum-hop count) product comparison.

Table 1 Comparison of tested configurations.

Configuration	# of channels per fiber	Spectral efficiency	Maximum hop count	SH product
A	110	2.30	21	1.137
B	88	1.93	22	1
C	117	2.54	9	0.538

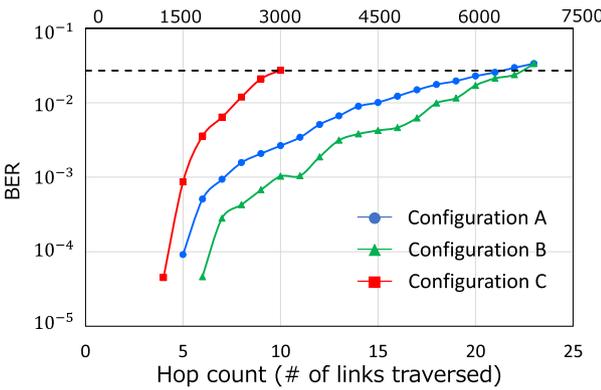


Fig. 13 BER (pre-FEC, limit = 2.7×10^{-2}) vs. hop count (experimental).

three channel configurations. Configuration C achieves the highest spectral efficiency because WDM signals are most densely multiplexed. On the other hand, Configuration A gradually improves in efficiency as traffic grows since VDL effectiveness rises with traffic demand.

Figure 13 shows the BER variations subject to hop counts observed during the transmission experiments in Sect. 4.2.2. Configuration C is severely impacted by the spectrum narrowing making it hard to introduce this configuration to large scale networks. Indeed, the maximum hop count for a 7×7 network is 12, while the BER after traversing 10 nodes exceeds the limit. On the other hand, configuration A achieves almost the same BER as Configuration B around the longest hop count area. Note that the number of traversed filters is constant for Configuration A while that of Configuration B increases linearly with hop count; therefore, the BER difference between Configuration A and Configuration B is reduced as the hop count increases. These figures elucidate the effectiveness of configuration A, not only in spectral efficiency but also in the number of nodes traversed.

Finally, we calculated the product of spectral efficiency and hop count (SH product), where the average number of paths for each node pair was 20. Configuration A can balance the spectral efficiency and hop count and hence its SH product is 13.7% higher than that of configuration B, and 111% higher compared to configuration C (see Fig. 14). Comparison results are detailed in Table 1. It is shown that our proposed routing scheme can substantially enhance the

overall network performance.

5. Conclusion

We proposed a novel optical network architecture based on virtual direct links. A network design algorithm that iteratively searches for VDL end points was proposed. The effectiveness of the proposed networks was verified through network-wide evaluations assuming a spectrum narrowing dominant case; i.e. linear transmission systems, and very detailed evaluations based on transmission experiments. It has been demonstrated that the proposed networks outperform conventional path granular routing networks in terms of not only the spectral efficiency but also the novel metric of the spectrum-hop count product; the number of fibers necessary in a network and the spectrum-hop count product are, respectively, reduced by up to 18% and increased by up to 111%. We believe that the proposal will be effective in creating the large scale and frequency-efficient optical networks needed in the future.

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