Highly Dense Elastic Optical Networks Enabled by Grouped Routing with Distance-Adaptive Modulation

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***Abstract*—We propose highly spectrally efficient grouped-routing networks with distance-adaptive modulation. The proposed scheme can realize highly dense wavelength-division-multiplexing networks under the constraint of the spectrum narrowing caused by optical-node traversals. Its effectiveness is confirmed by extensive computer simulations using 400-Gbps dual-polarization QPSK, 8QAM, and 16QAM signals. The fiber-utilization efficiency is improved by 18.0%.**

***Index Terms*—Elastic optical network; higher-order modulation format**

I. Introduction

THE optical-path networks based on wavelength routing can process wavelength-division-multiplexed (WDM) signals without costly optical-to-electrical and electrical-to-optical conversion. To accommodate the ever-increasing network traffic cost-efficiently, the spectral efficiency must be increased. This is possible with high-order modulation formats, highly dense WDM, and/or elastic optical networking [1-3]. However, such spectrally efficient systems are susceptible to transmission impairments such as fiber nonlinearity in links and spectrum narrowing at nodes, which limits the available transmission distance and node-hop count [4]. To enhance the spectral efficiency, distance-adaptive modulation was proposed [3]; the highest-possible-order modulation format that suits the transmission distance of each path is adopted. Previous research, however, did not adequately examine the impacts of the spectrum narrowing induced by wavelength-selective switches (WSSs) at each node. As a result, distance-adaptive modulation cannot be applied to highly dense WDM systems given their narrow guard bands. A straightforward solution is to adaptively assign a modulation format and path bandwidth to each path according to both its distance and hop count; however, this assignment process is quite complicated because we need to identify the best combinations of modulation formats and path bandwidths for all path candidates while considering their distances and hop counts.

Another solution is to apply grouped routing in which express paths are routed in a bundle and add/drop operations are done in a path-by-path manner [5]. Multiple wavelength paths are densely packed in a group called Grouped Routing Entity (GRE). Since the express paths are routed on a GRE basis, broad guard bands are placed only between adjacent GREs. In other words, paths can be densely multiplexed in a fiber. Here, the add/drop operations at the wavelength-path level can relax the routing restriction of the grouped express routing; however, they cause spectrum narrowing on the adjacent-wavelength paths. We, therefore, developed a routing-and-wavelength assignment (RWA) algorithm that maximizes fiber-utilization efficiency while limiting the number of adjacent-path add/drop operations [5].

This paper proposes a highly spectrally efficient network architecture that exploits grouped routing in conjunction with distance-adaptive modulation. Since the number of adjacent-path add/drop operations is controlled, modulation-format optimality is determined by just the transmission distance of the path; the hop count is not a metric in the RWA process. First, we numerically evaluate the transmission characteristics of 400-Gbps signals, where four-subcarrier 32-Gbaud dual-polarization (DP) QPSK, two-subcarrier 43-Gbaud DP-8QAM, and two-subcarrier 32-Gbaud DP-16QAM signals are considered [6]. Second, we evaluate the fiber utilization efficiency attained by the proposed network. The results show that, to accommodate the same traffic demands, the number of fibers can be reduced by up to 18.0% compared to the previously proposed network based on distance-adaptive modulation without grouped routing [3].

II. Proposed Network Architecture

A. *Problem of distance/hop count-adaptive networks*

Fig. 1 depicts possible adaptive networking technologies. In distance-adaptive networks shown in Fig. 1(a), the optimum modulation format, the one that maximizes the spectral efficiency, is assigned to a path according to its transmission distance; the guard-band bandwidth must be broad enough so as to avoid spectrum narrowing. To further enhance spectral

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efficiency, the guard-band bandwidth must be reduced; unfortunately, the maximum hop count is then strictly limited by the spectrum narrowing caused by traversing each WSS. This can be resolved by using the distance-/hop count-adaptive modulation method shown in Fig. 1(b), where the modulation format and channel bandwidth are assigned according to both the transmission distance and hop count of each path. The distance-/hop count-adaptive scheme is expected to offer higher spectral efficiency compared to the distance-adaptive scheme. However, this scheme necessitates intensive analyses of the transmission performances of all path candidates, which depend on both the transmission distance and hop count.

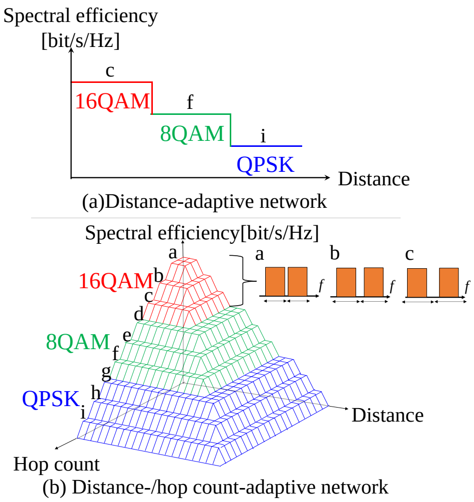


Fig. 1. Adaptive networking technologies. (a) distance-adaptive network and (b) distance-/hop count-adaptive network. The same channel bitrate is assumed for simplicity.

B. *Grouped routing with distance-adaptive modulation*

To resolve this complexity while realizing high spectral efficiency, we propose a novel network framework in which grouped routing is synergistically combined with distance-adaptive modulation. Fig. 2(a) overviews the grouped routing network. Multiple wavelength paths are bundled into groups (GREs) and express routing is done on a GRE basis as shown in Fig. 2(b). Since broad guard bands are inserted only between neighboring GREs, fiber-utilization efficiency can be high. It should be noted that this scheme differs from super-channel signals; paths in a GRE can be added/dropped in a path-by-path manner, whereas subcarriers in a super-channel signal must have the same source and destination nodes. The path-granular add/drop operations relax the routing restriction of grouped express routing. However, optical paths suffer from spectrum narrowing when adjacent-wavelength paths are added/dropped as shown in Fig. 2(c). Since the number of adjacent-path add/drop operations can easily be controlled by applying the RWA algorithm, signal quality is independent of the hop count. Thus, selecting the optimum modulation format of a path requires only its transmission distance.

In elastic optical networks, spectrum fragmentation degrades the spectral efficiency of the networks [7]. The fragmentation inherently derives from the excessive flexibility used in assigning the signal spectrum. In the grouped-routing network, the routes and spectra of optical paths are controlled so that signals with the same channel bandwidth are packed in each GRE whenever possible. Thus, the fragmentation effect is minimized in the grouped-routing network.

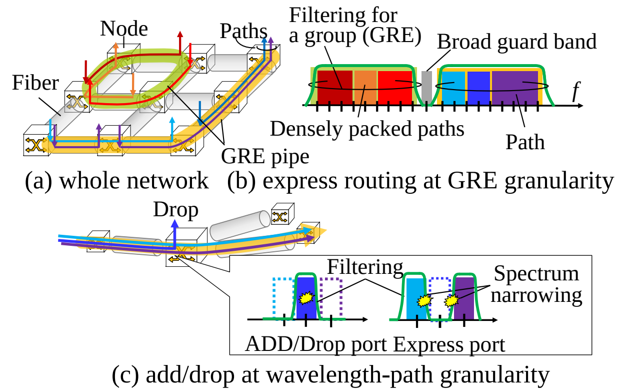


Fig. 2. Overview of grouped routing networks.

III. Simulations

A. *Overview*

To evaluate the performance of our proposed networking scheme, our transmission analyses and network analyses are based on computer simulations. First, we examine the transmissible distance and hop count for various modulation orders and channel bandwidths. Thereafter, we execute network simulations, where the optimum modulation order and channel bandwidth are assigned to each path according to the results obtained by the transmission analyses. For reference, the distance-/hop count-adaptive method is also examined though its calculation complexity is quite high as shown in Fig. 1(b).

B. *Simulations on transmission characteristics*

We examine transmission performance of 400-Gbps signal-format candidates recommended by OIF, *i.e.*, four-subcarrier 32-Gbaud DP-QPSK, two-subcarrier 43-Gbaud DP-8QAM, and two-subcarrier 32-Gbaud DP-16QAM signals [6]. The subcarriers of QPSK and 16QAM are aligned with a 37.5-GHz spacing and those of 8QAM are aligned with a 50-GHz spacing. The signal spectra are shaped by a root-raised-cosine filter with a roll-off factor of 0.05. After launch-power optimization with a 1-dB resolution, the signal is added to the transmission link through a WSS. To include inter-channel nonlinearity, eight channels closest to the target channel are considered. The channel frequency spacing is set to 150/162.5/175 GHz for the QPSK signal, 100/112.5/125 GHz for the 8-QAM signal, and 75/87.5/100 GHz for the 16-QAM signal. Each link comprises two or six repeater spans and each repeater span consists of a 100-km single-mode fiber (SMF) and an erbium-doped fiber amplifier (EDFA). The loss coefficient, nonlinear coefficient, and dispersion parameter of the SMF are 0.2 dB/km, 1.5 /W/km, and 16 ps/nm/km, respectively. The noise figure of the EDFA is 5 dB. The interactions among loss, fiber nonlinearity, and chromatic dispersion are calculated by the split-step Fourier method. After two or six repeater spans, the signal enters an adjacent node. The node consists of multiple WSSs in the route-and-select configuration. The peak loss of each WSS passband is 6.5 dB.

Note that the spectrum narrowing is caused by add/drop operations of the adjacent paths in a GRE as shown in Fig. 2(c). Therefore, we parameterize the number of add/drop operations of adjacent paths. The WSS passband was simulated by convoluting a rectangular function with an assigned bandwidth and a Gaussian function with a 10-GHz 3-dB bandwidth, where the Gaussian function defines the attenuation slope specific to the given WSS. We assume that all channel add/drop operations were performed using 400-Gbps granularity. The 3-dB bandwidth of the WSS passband is determined by the assigned channel bandwidth; the resulting 3-dB bandwidths are around 68.5/81/93.5/106/118.5/143.5/156/168.5 GHz for the assigned bandwidths of 75/87.5/100/112.5/125/150/162.5/175 GHz, respectively. After multiple node hops, the target signal is dropped at the destination node by using a WSS and detected by a digital coherent receiver. The signal is then demodulated by a digital-signal-processing (DSP) circuit. In the DSP circuit, the spectrum narrowing is partly equalized by 32-tap finite-impulse-response filters adapted by the least-mean-square algorithm. Finally, bit-error ratios (BERs) are calculated. The maximum hop count is the limit at which the signal can satisfy BER<1.0×10^{-2} as the use of forward-error correction (FEC) is assumed.

Fig. 3 shows examples of constellation maps of the DP-16QAM signals after 800-km transmission, where a 75-GHz or 100-GHz bandwidth is assigned for each path. We observe that the signal quality is degraded as the number of add/drop operations of adjacent wavelength paths is increased when the channel bandwidth is 75 GHz. In contrast, the performance of a signal with 100-GHz channel bandwidth is almost insensitive to the number of add/drop operations of adjacent-wavelength paths. Thus, we need to mainly consider the number of add/drop operations of adjacent-wavelength paths when the signals are densely multiplexed.

Fig. 4 plots the maximum distance/hop count calculated as a function of the number of adjacent-path add/drop operations. We find that the transmission characteristics are seriously degraded due to the spectrum narrowing when the assigned path bandwidth is insufficient. In highly dense networks, therefore, we should allocate a proper bandwidth to each path while considering both the distance and hop count. In contrast, our proposed grouped-routing network limits the number of adjacent-path add/drop operations. As a result, the hop count is no longer a metric in modulation-format assignment. In this way, our scheme significantly simplifies the path-assignment process.

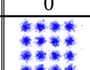
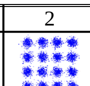
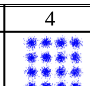
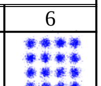
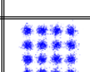
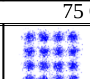
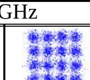
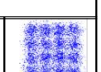
Path bandwidth	100 GHz			
The number of add/drop operations	0	2	4	6
Constellation diagram				
BER	0.00074	0.00078	0.00082	0.00082
Path bandwidth	75 GHz			
Constellation diagram				
BER	0.0011	0.0037	0.0136	0.0361

Fig.3. Constellation maps and BERs of two-subcarrier 32-Gbaud DP-16QAM signals after 800-km transmission, where the inter-node distance is 200 km.

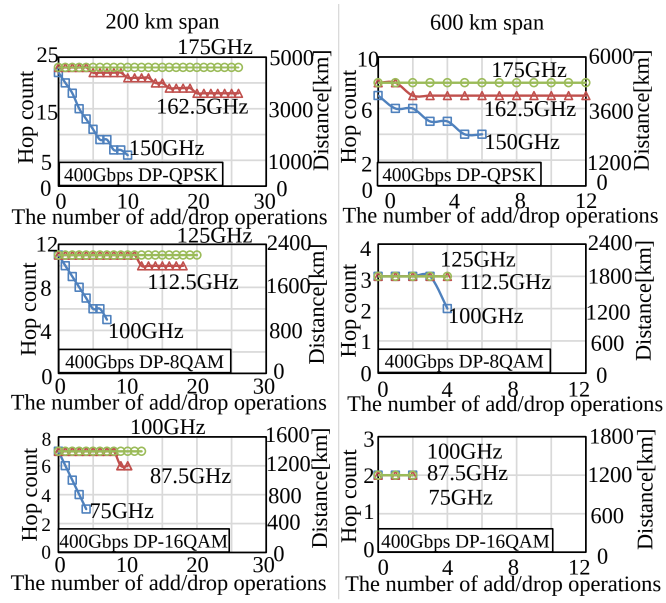


Fig. 4. Maximum distance/hop count vs. the number of add/drop operations of adjacent-wavelength paths, where the inter-node distance is 200 or 600 km.

C. Simulations on fiber utilization efficiency

According to the obtained transmission characteristics, we maximize the fiber-utilization efficiency of the following three networking schemes. Scheme A: individual path routing networks with distance-adaptive modulation (Fig. 1(a)), Scheme B: individual path routing networks with distance/hop count-adaptive modulation/path bandwidth (Fig. 1(b)), and Scheme C: proposed grouped-routing networks with distance-adaptive modulation (Fig. 2). The available bandwidth of each fiber is set to 4,400 GHz (C-band: 352 12.5-GHz slots). The tested network topologies are the 4×4 regular-mesh network, Japan network, and pan-European network. The network parameters are summarized in Fig. 5. For simplicity, we assume uniform inter-node distance in each network. The traffic demand is uniformly and randomly distributed and is represented as the average number of path demands between each node pair, which is parameterized. We test 20 random traffic patterns and average their results. We consider three modulation formats; 400-Gbps DP-QPSK, 400-Gbps DP-8QAM, and 400-Gbps DP-16QAM. In Scheme A and B, paths are routed individually, in a path-by-path manner. In Scheme C, the proposed scheme, paths are routed in a group-by-group manner, where the bandwidth of a GRE is set to 600 GHz (48 slots) and 25 GHz (two slots) are inserted between each neighboring GRE to avoid spectrum narrowing caused by routing. The allowable number of adjacent-path add/drop operations for each optical path is limited to 1. The number of required bandwidths/slots for each scheme are obtained from Fig. 4 and the results are summarized in Table I. Fig. 6 illustrates candidates of the modulation formats and channel bandwidths. We select the combination of modulation format and channel bandwidth from among the candidates for each scheme so as to maximize the spectral efficiency, *i.e.* alphabetical order. Fig. 7 shows the number of fibers necessary for accommodating the traffic demand, which is normalized against the counterpart in the distance-adaptive network

(Scheme A). When the average number of paths between each node pair is 20, the distance-/hop count-adaptive modulation/bandwidth assignment (Scheme B) can reduce the necessary number of fibers by 14.3% for 4×4 (200 km), 12.7% for 4×4 (600 km), 10% for Japan, and 13.5% for pan-European. In contrast, our proposed grouped routing with distance-adaptive modulation (Scheme C) can reduce the necessary number of fibers by 18.0% for 4×4 (200 km), 15.4% for 4×4 (600 km), 17.8% for Japan, and 16.3% for pan-European. We observe that improvement of Scheme C is more prominent when the inter-node distance is short and/or the maximum hop count is large since the signal quality is degraded by spectrum narrowing rather than by fiber nonlinearity.

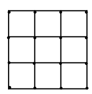
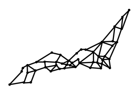
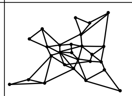
	4×4	JPN48	Pan-European Network
			
The number of nodes	16	48	26
Maximum hop count	6	14	6
Average link length (length in simulations)	(200 or 600 km)	154 km (200 km)	627 km (600 km)

Fig. 5. Network topologies and their characteristics.

TABLE I
FORMAT AND THE NUMBER OF ASSIGNED SLOTS

		A	B	C
Modulation format	The number of subcarriers	The number of assigned slots[a]		
32-Gbaud DP-QPSK	4	14	12,13 or 14	12
43-Gbaud DP-8QAM	2	10	8, 9 or 10	8
32-Gbaud DP-16QAM	2	8	6, 7 or 8	6

[a] Slot bandwidth: 12.5 GHz.

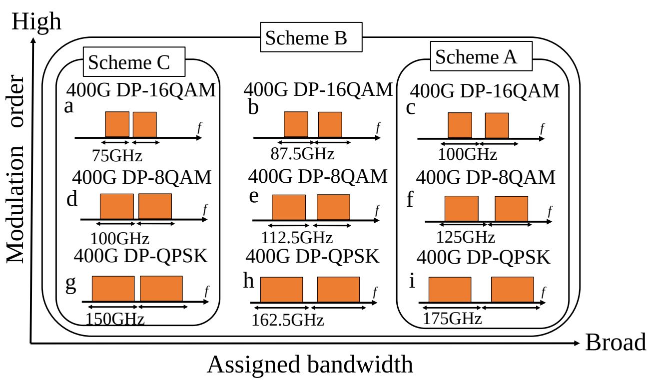


Fig.6. Priority list for assigning the modulation order and channel bandwidth, where the combination is selected from the candidates for each scheme in an alphabetical order.

D. Discussion

Table II compares the three networking schemes defined in Section III.C. With Scheme A, the path-assignment process is simple but the fiber-utilization efficiency is lower than Scheme B and C. Scheme B attains good fiber-utilization efficiency but its path control is complex. In contrast, Scheme C, which is our proposal, can attain the best fiber-utilization efficiency thanks to the relaxed spectrum-narrowing effect. In addition, the optimum modulation format is simply determined by the transmission distance; transmission characteristics considering path hop counts are not necessary in the path-assignment process.

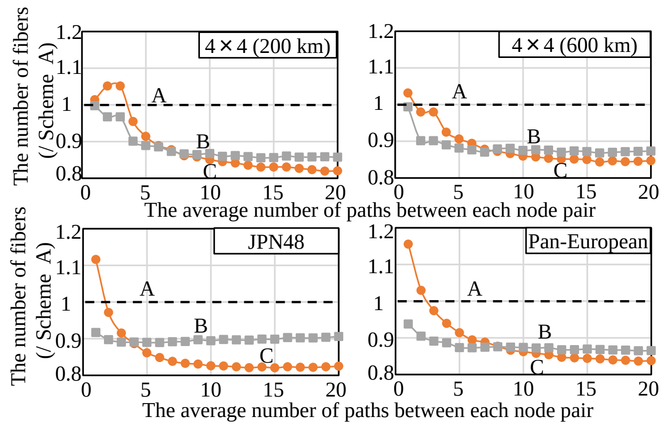


Fig. 7. The number of necessary fibers as a function of the average number of paths between each node pair, where Scheme A, B, and C are explained in Section III.C, Table I, and Fig. 6.

TABLE II
COMPARISON OF NETWORK SCHEMES

	A	B	C
Routing unit	Path	Path	Group (GRE)
Impairment-related metrics	Distance	Distance & hop count	Distance
Adaptive assignment	Modulation	Modulation & bandwidth	Modulation
Fiber utilization	Fair	Good	Excellent

IV. CONCLUSION

We proposed a highly spectrally efficient grouped routing network with distance-adaptive modulation. The path-assignment process is greatly simplified thanks to the introduction of grouped routing. Extensive computer simulations showed its effectiveness in enhancing the fiber-utilization efficiency. The number of necessary fibers was reduced by 15.4-18.0% compared to the previously proposed distance-adaptive modulation method.

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