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Dispersion Based Highest-Modulation-First Last-Fit Spectrum Allocation Scheme for Elastic Optical Networks

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ABSTRACT This paper proposes a spectrum allocation scheme based on highest modulation-first last fit (LF) for elastic optical networks in order to suppress the call blocking in the network. The proposed scheme searches the available spectrum slots from the highest indexed spectrum slots and selects the slot position with the modulation level as high as possible, which guarantees the least spectrum slots consumption. It provides higher preference of the less robust modulation technique in order to minimize the number of required slots. The last fit spectrum allocation policy is used to keep lower indexed position slots available as much as possible, which have less dispersion effect, for incoming lightpath requests and gives them the opportunity to use the less number of slots. We introduce a dispersion-based highest modulation-first LF algorithm for allocation lightpath requests. The numerical results indicate that the proposed scheme outperforms the conventional schemes in terms of blocking probability, modulation usage ratio, and average number of required spectrum slots.

INDEX TERMS Blocking probability, dispersion based, elastic optical networks, spectrum allocation.

I. INTRODUCTION

The development of bandwidth-consuming applications, such as video streaming, cloud computing, and inter-datacenter transmissions, leads to increase the volume of Internet traffic [1]. An optical network has the potential to support the continued demands for communication bandwidth [2]. The advances in optical transmission technologies have significantly improved the transmission channel bit rate. Due to the fixed rigid granularity with ITU-T frequency-grid standard, traditional wavelength-division multiplexing (WDM) networks cannot efficiently utilize spectrum resources under diverse traffic. By adopting finer granularity (e.g., 12.5 GHz) with optical-orthogonal frequency division multiplexing (O-OFDM), elastic optical networks (EONs) can flexibly allocate spectrum resources and improve the spectrum efficiency compared with fixed-grid WDM networks [3].

EONs with O-OFDM technology allocate spectrum for lightpath requests by satisfying the spectrum contiguity and continuity constraints [4]. During network operations, bandwidth fragmented slots are generated due to dynamically allocating and releasing of lightpath requests with the varied bandwidth requirement of clients under the constraints of spectrum contiguity and continuity. These fragmented slots are difficult to be utilized for incoming lightpath requests, which reduces the spectrum utilization [5]. When the bandwidth demand of a lightpath request is not fulfilled, the incoming lightpath request is rejected or blocked. The call blocking in the network is measured in terms of blocking probability, which is defined as a ratio of number of blocked lightpath requests to the number of total lightpath requests in the network [6].

To overcome the bandwidth fragmentation problem, several routing and spectrum allocation (RSA) algorithms have been presented. Taking this direction, Zhang *et al.* [7] and Yao *et al.* [8] developed bandwidth defragmentation schemes, which greatly reduce the blocking probability in EONs. However, they assume the green field scenario, where lightpath requests are totally and partially rerouted, respectively, which trigger traffic disturbance.
Distance-adaptive

spectrum allocation scheme has been considered as a key attribute in EONs [9]. Distance-adaptive transmission entails the choice of a modulation for an incoming request, which is adaptive to the transmission distance of the lightpath. A higher-level modulation is selected for shorter distance lightpaths and a lower-level modulation is selected for longer distance lightpaths. Compared to the non-distance adaptive spectrum allocation scheme, spectrum resources of the fiber are effectively utilized as the necessary spectrum slots are always allocated to each lightpath.

To achieve a lower blocking probability without rerouting of lightpath requests in EONs, various studies on distance-adaptive spectrum allocation scheme have been reported in [10]–[13]. In these papers, there are diverse assumptions regarding the maximum transmission reach of lightpath requests. However, the given transmission reach of a modulation can have a huge impact on the utilization of spectrum resources in distance-adaptive transmission [14]. In order to increase the accuracy of the transmission reach in the selection of a modulation for lightpath requests, the work in [15] considers the constraint of physical impairments, namely, fiber loss, optical signal to noise ratio (OSNR) limits, and nonlinear effects, such as cross-phase modulation and four-wave mixing.

The work in [16] introduced a dispersion-adaptive first-last fit (FLF) spectrum allocation scheme to suppress the call blocking in EONs. It suppresses the call blocking by allocating the longer distance lightpath requests to the spectrum slots having a lower dispersion effect, and the spectrum slots having a higher dispersion effect are allocated to the shorter distance lightpath requests. The lightpath requests are categorized as longer and shorter based on the distance threshold value provided by network operators. If the distance of the lightpath requests is longer than the distance threshold, they are allocated using the first fit (FF) policy, and otherwise the lightpath requests are allocated using the last fit (LF) policy. The performance of the introduced scheme in [16] depends on the distance threshold value. If the distance threshold value is not correctly determined, the gain of the scheme introduced in [16] will not be maximized. In addition, the shorter distance requests may be faced with lower-level modulation for transmission even though they can be transmitted by higher-level modulation at lower-indexed slots, and hence the required slots for the shorter distance requests can be reduced.

To avoid the dependence of the distance threshold value and allocate the shorter distance requests more efficiently in [16], this paper proposes a spectrum allocation scheme based on highest-modulation-first last-fit (HMF-LF) for EONs in order to suppress the call blocking in the network. The proposed scheme searches the available spectrum slots from the highest-indexed spectrum slots and selects the slot position with the modulation level as high as possible, which guarantees the least spectrum slots consumption. We introduce a dispersion based highest-modulation-first last-fit algorithm for allocation lightpath requests. We evaluate the proposed scheme through simulation studies. The numerical results observe that the proposed scheme reduces the blocking probability in EONs and improves admissible traffic compared to the conventional schemes.

Note that the proposed scheme aims to suppress the dispersion effect for each lightpath request without using any dispersion compensating device. It is envisaged that the dispersion effect can be managed in a transmission system at the receiver side using digital signal processors (DSP) for coherent and characteristic dispersion compensation in electronics. Using coherent and feature dispersion compensation through the DSP requires extra cost. The proposed scheme is applicable to the transmission systems where any dispersion compensating device is not adopted.

The rest of the paper is organized as follows. Section II describes the EONs system that we consider the network model and assumptions, physical layer modeling, and distance-adaptive modulation. In Section III, the proposed HMF-LF scheme is presented. Section IV evaluates the performance of the proposed scheme and analyzes the simulation results. The conclusions of this paper are presented in Section V.

II. SYSTEM DESCRIPTIONS

A. NETWORK MODEL AND ASSUMPTIONS

We model the physical topology of EONs as undirected graph $G(V, E)$, where the set of nodes is denoted as V, and the set of bi-directional optical fiber links connecting two nodes in V is denoted as E. Each fiber link has a finite number of spectrum slots. The capacity of a slot, denoted by C_{slot}, depends on the used modulation technique. The capacity of a slot according to single bit per symbol Binary Phase Shift Keying (BPSK) is C_{slot} Gbps, and hence Quadrature Phase Shift Keying (QPSK) relates to $2C_{\text{slot}}$, 8-Quadrature Amplitude Modulation (8-QAM) relates to $3C_{\text{slot}}$, and so on. M is the set of modulation techniques, having C_{slot} as the base capacity, where $M = \{1, 2, 3, \cdots\}$, used for BPSK, QPSK, 8-QAM, etc.

We assume that each fiber link carries an equal number of spectrum slots, which is denoted as n, and the network does not have any frequency conversion capability. Two lightpaths sharing the same optical fiber link must be allocated with different spectrum slots. The guardband is required to avoid interference effects between adjacent lightpaths, which guarantees the transmission performance demand.

B. PHYSICAL LAYER MODELING FOR EONS

As channel bit rate increases, the dispersion plays a critical role in quality of transmission (QoT) degradation. The degradation of QoT from dispersion has a direct effect on the maximum transmission reach of lightpath requests. Typically, the total dispersion is subdivided into chromatic dispersion (CD) and polarization mode dispersion (PMD) [17], which are presented in the following.

CD is resulted from the variations in group velocity for different optical spectral components traveling in an optical fiber. It has several limitations on the optical fiber link, such as pulse broadening, limiting the data rate of an optical communications system, restricting the available wavelength region, increasing of bit-error rates, and affecting transmission performance [18].

First, we define some basic terms that are used throughout the paper. The occupied wavelength of lightpath requests is denoted by λ. The CD of a wavelength is the combination of material and waveguide dispersion, which is denoted by $D_{\mathrm{CD}}(\lambda)$ [19], [20]. The material dispersion is an invariable characteristic of a specific material due to the varied refractive index with the change of optical wavelength, which is denoted by $D_{\mathrm{md}}(\lambda)$. Whereas, the waveguide dispersion denoted by $D_{\mathrm{wd}}(\lambda)$, occurs due to the wavelength dependence of the group velocity on the mode, which can be adjusted by choosing an appropriate refractive index profile of the fiber. The arising effects of both material and waveguide dispersion are indispensable in designing high channel bit rate optical communication systems. The amount of total CD in optical fiber can be estimated as given in (1) [20].

$$D_{\mathrm{CD}}(\lambda) = D_{\mathrm{md}}(\lambda) + D_{\mathrm{wd}}(\lambda), \tag{1}$$

where

$$D_{\mathrm{md}}(\lambda) = \frac{\lambda}{c} \cdot \frac{d^2(n_1)}{d\lambda^2} \tag{2}$$

$$D_{\mathrm{wd}}(\lambda) = -\frac{2(n_1 - n_2)u^2}{c\lambda v^2}(1 - \frac{\lambda}{n_2} \cdot \frac{d(n_2)}{d\lambda}) \tag{3}$$

$$u^2 = a^2(\frac{4\pi^2}{\lambda^2} \cdot n_1^2 - \beta^2) \tag{4}$$

$$v^2 = \frac{4\pi^2 a^2(n_1^2 - \beta^2)}{\lambda^2} \tag{5}$$

$$\beta = \sqrt{k^2 n_1^2 b + k^2 n_2^2 (1 - b)} \tag{6}$$

$$b = \frac{\beta - n_2 k}{n_1 k - n_2 k} \tag{7}$$

In (2)-(7), c represents the speed of light in vacuum, n_1 and n_2 indicate the refractive index of the core and cladding, respectively. u and v represent horizontal transmission propagation constant of guided wave in the core and cladding, respectively. β represents longitudinal transmission propagation constant of guided wave in the optical fibers. a represents the radius of the fiber core. $k^2 n_1^2$ and $k^2 n_2^2$ represent the plane wave propagation constants in the core and the cladding, respectively, and b is the normalization propagation constant.

For the following Sellmeier equations (8)-(10), ω_i and φ_i represent the ith constant related to material oscillator strengths and oscillator wavelengths, respectively. The value of j is 1 and 2, and the value of Z is 3.

$$n_j^2(\lambda) = 1 + \sum_{i=1}^{Z} \frac{\omega_i \lambda^2}{\lambda^2 - \varphi_i^2} \tag{8}$$

$$\frac{d(n_j(\lambda))}{d\lambda} = -\frac{\lambda}{n_j(\lambda)} \sum_{i=1}^{Z} \frac{\varphi_i^2 \omega_i}{(\lambda^2 - \varphi_i^2)^2} \tag{9}$$

$$\frac{d^2(n_j(\lambda))}{d\lambda^2} = -\sum_{i=1}^{Z} \frac{\varphi_i^2 \omega_i}{(\lambda^2 - \varphi_i^2)^2 n_j(\lambda)} [\frac{\varphi_i^2 + 3\lambda^2}{\lambda^2 - \varphi_i^2} + \frac{\lambda^2 \sum_{i=1}^{Z} \frac{\varphi_i^2 \omega_i}{(\lambda^2 - \varphi_i^2)^2}}{n_j^2(\lambda)}] \tag{10}$$

As CD is a deterministic effect, an eye-opening penalty (EOP) is used to estimate the degradation of the pulses. EOP can be expressed as given in (11) [21].

$$EOP = 10 \log_{10} \sqrt{1 + (D_{\mathrm{CD}}(\lambda) \cdot L(\lambda) \cdot \frac{\sigma_\lambda}{\sigma_0})^2}, \tag{11}$$

where $L(\lambda)$ represents transmission fiber length with λ. σ_λ and σ_0 are the spectral width and pulse width, respectively.

PMD occurs due to small disruptions of the symmetry of the optical fiber, which can originate not only from the production process but also from changes of the ambient temperature or vibrations. PMD is a statistical effect, which is broadening of the input pulse due to a phase delay between input polarization states. As the channel bit rate increases to 10 Gbps and beyond, PMD becomes one of the most critical limiting problems for data transmission in high-speed EONs [22].

In the linear regime, the power of a pulse with random polarization is split into both principle states of polarization, which leads to dual imaging at the receiver [21]. The linear degradation due to PMD can be assessed by an EOP_{PMD}. The statistics of PMD is completely described by the mean differential group delay (DGD), which is denoted as $\langle \Delta\tau \rangle$ [23]. DGD accumulates by a square law along the spans. The EOP_{PMD} of first-order PMD can be computed as given in (12), if all fibers have the same D_{PMD} [24]–[26].

$$EOP_{\mathrm{PMD}} = 10.2 \cdot \langle \Delta\tau \rangle^2 \cdot B^2, \tag{12}$$

where

$$\langle \Delta\tau \rangle = \sqrt{L(\lambda)} \cdot D_{\mathrm{PMD}} \tag{13}$$

In the following, it is shown how PMD can be included in the QoT calculation.

The routing policy has to ensure that the desired path needs to guarantee the demand of QoT for receiving requests at the destination node within an acceptable bit error rate.

As spans lose and dispersion in optical fiber degrades the QoT, a relationship between OSNR, EOP, and QoT can be defined in (14) [21], [27].

$$Q_{\text{withoutPMD}} = \sqrt{\frac{OSNR}{EOP} \cdot \frac{\Delta f_{\text{opt}}}{\Delta f_{\text{el}}} \cdot EXTP}, \tag{14}$$

where

$$OSNR = P_{\text{in}} + 58 - P_s - NF - 10\log_{10} N \tag{15}$$

In (14)-(15), Δf_{opt} and Δf_{el} represent optical and electrical bandwidth, respectively. $EXTP$ represents the extinction ratio penalty, P_{in} represents the amplifier input power, P_s represents the total span loss, NF is the Erbium doped fiber amplifier noise factor, N represents the total number of spans of a lightpath request.

In (14), PMD effect has been neglected. If the PMD effect is further considered in a lightpath, the Q-factor of a lightpath is estimated as given in (16) [21].

$$Q_{\text{withPMD}} = \frac{Q_{\text{withoutPMD}}}{EOP_{\text{PMD}}} \tag{16}$$

If the value of Q_{withPMD} is more than the threshold of QoT, denoted by $Q_{\text{threshold}}$, a lightpath request is considered as a successful transmission. Note that (16) depends on system parameters. The relationship between Q_{withPMD}, λ, $L(\lambda)$ and B can be obtained by the integration of all equations above. When $Q_{\text{threshold}}$ and B are given, the relationship between the transmission reach and the occupied wavelength of a lightpath request is expressed in (17); a polynomial is used to fit the relationship for the sake of clarity.

$$L(\lambda) = \sum_{i=0}^{\infty} \alpha_i \cdot (\lambda - \gamma)^i, \tag{17}$$

where α and γ can be determined by ensuring that the variance between the actual and fitting for each λ is not more than 0.01. It should be noticed that the maximum transmission reach of a lightpath request decreases as the occupying wavelength increases through multiple fitting tests and derivation verification.

C. SPECTRUM RESOURCES ALLOCATION BASED ON DISTANCE-ADAPTIVE MODULATION

To efficiently utilize the spectrum resources, we consider a spectrum resource allocation based on distance-adaptive modulation in EONs, where minimum spectrum resources are adaptively allocated to each link in lightpaths according to the physical condition. In the distance-adaptive transmission, a more spectrally efficient (or higher-level) modulation implies fewer spectrum resources for serving an incoming request, but it is associated with a shorter transmission distance. This paper considers the following assumptions. Each C_{slot} carries 12.5 GHz capacity for BPSK ($m = 1$) modulation and hence 25 and 37.5 GHz capacity for QPSK ($m = 2$) and 8-QAM ($m = 3$), respectively; m represents the modulation level. The maximum transmission reach for different modulation levels follow the half-distance law [28]. In other words, the modulation level can be increased by one bit by reducing the transmission distance by 50%. The relationship between the maximum transmission reach, denoted by $\mathcal{R}_{\text{max}}$, of different modulation levels is expressed in (18).

$$\mathcal{R}_{\text{max}}(\lambda, m) = \frac{L(\lambda)}{2^{m-1}} \tag{18}$$

The required contiguous slots, denoted by F, for each lightpath request is calculated according to (19).

$$F = \lceil \frac{R}{C_{\text{slot}} \cdot m} \rceil + B_{\text{GB}}, \tag{19}$$

where R indicates the requested bit rate and B_{GB} represents the guardband.

III. PROPOSED HIGHEST-MODULATION-FIRST LAST-FIT SPECTRUM ALLOCATION SCHEME

This section presents the proposed highest-modulation-first last-fit spectrum allocation scheme, which considers distance-adaptive modulation based transmission. The proposed scheme is intended to suppress the call blocking in the network by reducing the number of slots usages. In the proposed scheme, the highest-modulation-first determines the modulation technique and the last-fit is used for spectrum allocation of a lightpath request, which searches spectrum slot from highest-indexed to lowest-indexed. The intension of the proposed scheme is to provide higher preference of the less robust modulation technique in order to minimize the number of required slots. The last fit spectrum allocation policy is used to keep lower-indexed position slots available as much as possible, which have less dispersion effect, for incoming lightpath requests and give them the opportunity to use the less number of slots.

The procedure of spectrum allocation for each individual lightpath request in the proposed scheme is given in Algorithm 1. The time complexity to search available spectrum slots for a lightpath request considering all links and different modulation techniques is $O(|M||n|E|)$. Therefore, the time complexity of Algorithm 1 is $O(|M||n|E|)$.

We explain the proposed scheme with an example. For this purpose, we consider four lightpath requests, such as r_1, r_2, r_3 and r_4, with the same bit rate requirement of 37.5 Gbps; these requests need to be allocated in succession and their corresponding transmission distances are 1600, 1900, 1000 and 1800 km, respectively. We assume that lightpath requests r_1, r_2, r_3 and r_4 use link 1 and link 2, links 1 and 2, links 1 and 2, and link 2, respectively. We assume that each link has 11 spectrum slots with the same capability of 12.5 Gbps; the required spectrum slots using 8-QAM, QPSK and BPSK are 1, 2 and 3, respectively. The maximum transmission reach decreases with increase in the wavelength of spectrum slot; the transmission reach for different modulation level follows the half-distance law according to (18). The guardband is not considered in this example for the sake of clarity. Table 1 summarizes the considered modulation techniques that correspond to m, the allowable maximum λ, and the number of

Algorithm 1 Dispersion based highest-modulation-first last-fit spectrum allocation

Input: Lightpath request i, bit rate, routing r and its end-to-end distance.
Output: Spectrum allocation of lightpath.

1: **for** each modulation level m from high to low **do**
2: Find the maximum transmission reach, denoted by $\mathcal{R}_{\max}(\lambda, m)$, of lightpath request i using mth modulation technique.
3: **if** the lightpath distance is less than or equal to $\mathcal{R}_{\max}(\lambda, m)$ **then**
4: Estimate the required spectrum slots F for lightpath request i using (19).
5: Search available required spectrum slots F from the highest-indexed to lowest-indexed position (last-fit).
6: **if** available slots F are found **then**
7: Assign lightpath request i to the required slots F that are found in step 5.
8: **else**
9: Reject lightpath request i.
10: **end if**
11: **else**
12: Decrement m value and go to step 2.
13: **end if**
14: **end for**

spectrum slots, F, for each request. The allowable maximum λ is defined by the maximum λ that satisfies (18). We also assume that FLF follows FF if the distance of the request exceeds 1700 km, and otherwise follows LF. The spectrum allocation of lightpath requests is presented in Fig. 1, which indicates that the number of required spectrum slots after spectrum allocation using the proposed scheme is less than that of other schemes. In Fig. 1, horizontal and vertical directions present the wavelength in nm for each spectrum slot and used links for each request, respectively. The occupied wavelength, number of required slots and used modulation technique for each request using different spectrum allocation schemes are summarized in Table 2. In the following, each spectrum allocation scheme is explained considering the above example.

In FF shown in Fig. 1(a), each request searches from the lowest-indexed slot or the shortest wavelength slot and the request is allocated in accordance with the first available spectrum slots. We observe that the number of available slots after spectrum allocation using FF is 5. As FLF assigns longer lightpath requests from the lowest-indexed spectrum slot and shorter lightpath requests from the largest-indexed spectrum slot, among four requests, r_2 and r_4 are assigned according to FF and r_1 and r_3 are assigned according to LF policies based on the lightpath threshold limit, as shown in Fig. 1(b). The number of available slots after spectrum allocation using FLF is 6. In both FF and FLF,

TABLE 1. Number of required slots for each request considering different modulation techniques.

Requests	Modulation, m	Allowable maximum wavelength, λ [nm]	No. of required spectrum slots, F
r_1	8-QAM ($m = 3$)	1400	1
	QPSK ($m = 2$)	1560	2
	BPSK ($m = 1$)	1640	3
r_2	8-QAM ($m = 3$)	1340	1
	QPSK ($m = 2$)	1530	2
	BPSK ($m = 1$)	1625	3
r_3	8-QAM ($m = 3$)	1520	1
	QPSK ($m = 2$)	1620	2
	BPSK ($m = 1$)	1670	3
r_4	8-QAM ($m = 3$)	1360	1
	QPSK ($m = 2$)	1540	2
	BPSK ($m = 1$)	1625	3

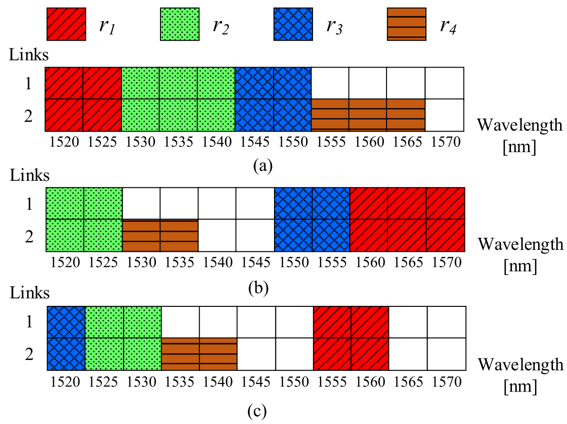

FIGURE 1. Comparison of spectrum allocation schemes using (a) FF, (b) FLF and (c) proposed HMF-LF schemes.

modulation techniques for each request are determined after searching the spectrum slot position. The proposed HMF-LF scheme, see Fig. 1(c), always gives priority to the highest-level modulation technique for spectrum allocation as it requires less number of spectrum slots and each request is allocated from the available highest-indexed spectrum slot within its allowable wavelength range. The number of available slots after spectrum allocation using the proposed HMF-LF is 10.

In summary, the proposed HMF-LF spectrum allocation scheme requires less number of spectrum slots compared to FF and FLF for assigning a lightpath request and keeps more available slots for future requests.

IV. PERFORMANCE EVALUATIONS AND RESULT ANALYSES

This section evaluates the performance of the proposed HMF-LF scheme in terms of blocking probability, modulation usage ratio and average number of required spectrum slots for each successful request. We compare its performance with the conventional non-distance-adaptive FF (NDA-FF), FF [27], FLF [16] spectrum allocation schemes.

TABLE 2. Summaries of spectrum allocation of each request.

Spectrum allocation schemes	Requests	Distance [km]	Slot wavelength, λ [nm]	Modulation, m	No. of required slots, F	No. of required total slots
FF	r_1	1600	1525	QPSK ($m = 2$)	2	10
	r_2	1900	1540	BPSK ($m = 1$)	3	
	r_3	1000	1550	QPSK ($m = 2$)	2	
	r_4	1800	1565	BPSK ($m = 1$)	3	
FLF	r_1	1600	1570	BPSK ($m = 1$)	3	9
	r_2	1900	1525	QPSK ($m = 2$)	2	
	r_3	1000	1555	QPSK ($m = 2$)	2	
	r_4	1800	1535	QPSK ($m = 2$)	2	
HMF-LF	r_1	1600	1560	QPSK ($m = 2$)	2	7
	r_2	1900	1530	QPSK ($m = 2$)	2	
	r_3	1000	1520	8-QAM ($m = 3$)	1	
	r_4	1800	1540	QPSK ($m = 2$)	2	

TABLE 3. Fitted sellmeier coefficients for light guide glasses.

Sample	ω_1	ω_2	ω_3	φ_1	φ_2	φ_3
$13.5GeO_2 : 86.5SiO_2$	0.711040	0.451885	0.704048	0.064270	0.129408	9.425478
Quenched SiO_2	0.696750	0.408218	0.890815	0.069066	0.115662	9.900559

A. SIMULATION ENVIRONMENTS

We set up the experiments for 14 nodes with 21 bi-direction physical links of National Science Foundation Network (NSFNET) [29] and 14 nodes with 24 bi-direction physical links of Indian network [30], as shown in Figs. 2(a) and 2(b) respectively. In the conventional FLF spectrum allocation scheme, the distance threshold to distinguish longer and shorter lightpaths is considered 3500 km in NSFNET and 3000 km in Indian network [16].

The following assumptions are considered for simulation purpose. Measurements can be performed on materials contemplated for core $13.5GeO_2 : 86.5SiO_2$ compositions and for claddings Quenched SiO_2, respectively [31], as shown in Table 3. Wavelength range is considered from 1520 nm to 1590 nm due to lower propagation loss in the optical fiber link. The relationship between optical bandwidth and electric bandwidth is $\Delta f_{\mathrm{opt}}/\Delta f_{\mathrm{el}} = 1.25/0.7$ [25]. The spacing between two wavelengths is 0.1 nm for 12.5 GHz frequency spacing. The bandwidth of each lightpath request is uniformly distributed within a range from 10 Gbps to 200 Gbps [11]. We consider the channel bit rate candidates in the network are 10, 40 and 100 Gbps [27]. The threshold of QoT, $Q_{\mathrm{threshold}}$, is assumed by 3.4 without dispersion compensation [32]. The other used system parameters are summarized in Table 4 [27]. We have simulated the proposed algorithm with 200000 lightpath requests, distributed randomly among all the possible source-destination node pairs in each network. The lightpath requests are generated based on a Poisson process and their holding times follow negative exponential distribution [15]. Three modulation techniques are considered in this paper, namely, BPSK, QPSK and 8-QAM. The route between a source-destination pair is found by Dijkstra's algorithm [33] for each lightpath request. The guardband is assumed by two spectrum slots to avoid interference effects between adjacent optical lightpaths [15].

TABLE 4. System parameters and their values in physical layer models.

Parameters	Values
$EXTP$, P_{in}, P_s	20 dB, 25 dB and 23 dB
σ_λ, σ_0	70 nm and 50 ps
NF, D_{PMD}	5 dB and 0.05 ps/$\sqrt{\mathrm{km}}$

B. PERFORMANCE COMPARISON OF BLOCKING PROBABILITY

This subsection presents the performance of the proposed HMF-LF scheme in terms of blocking probability. Figs. 3(a) and 3(b) compare the blocking probabilities using the conventional NDA-FF, FF, FLF and the proposed HMF-LF spectrum allocation schemes in NSFNET and Indian network, respectively, and Fig. 4 shows the volume of admissible traffic among different schemes when the satisfied blocking probability is considered 0.01.

The blocking probability for all schemes increases with increase in traffic load both in NSFNET and Indian network. This is because the number of lightpath requests in unit time increases with increase in the traffic load. When the occupied spectrum resources in each optical link tend to be saturated, the next incoming lightpath requests will be faced with the shortage of available spectrum resources. The blocking probability for each scheme in NSFNET is greater than that of the Indian network. This is because the average link length of the Indian network is shorter than that of NSFNET, and hence a less number of spectrum slots are required for establishing lightpath requests with a higher-level modulation

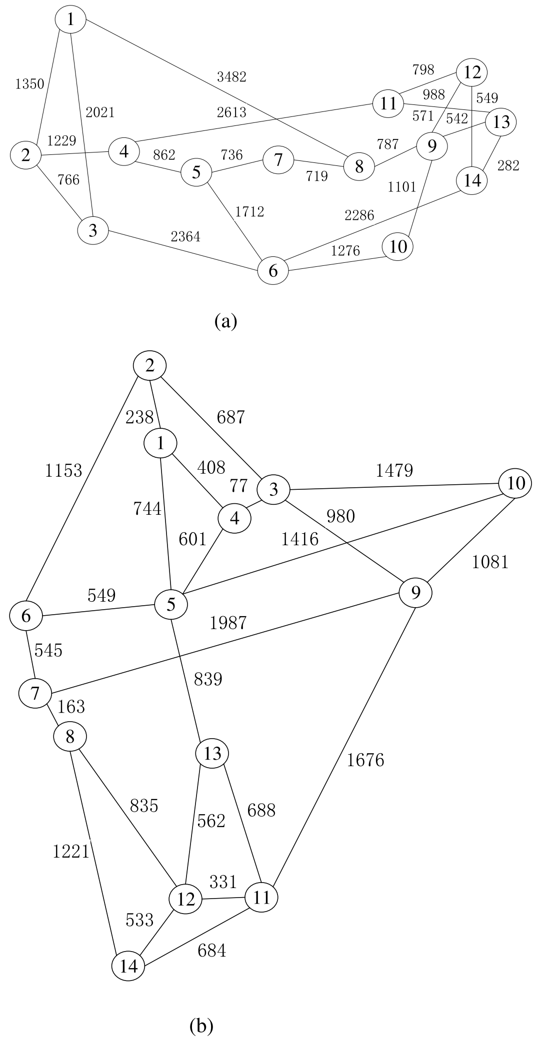

FIGURE 2. Physical topology of (a) NSFNET and (b) Indian network with optical fiber link length in kilometers.

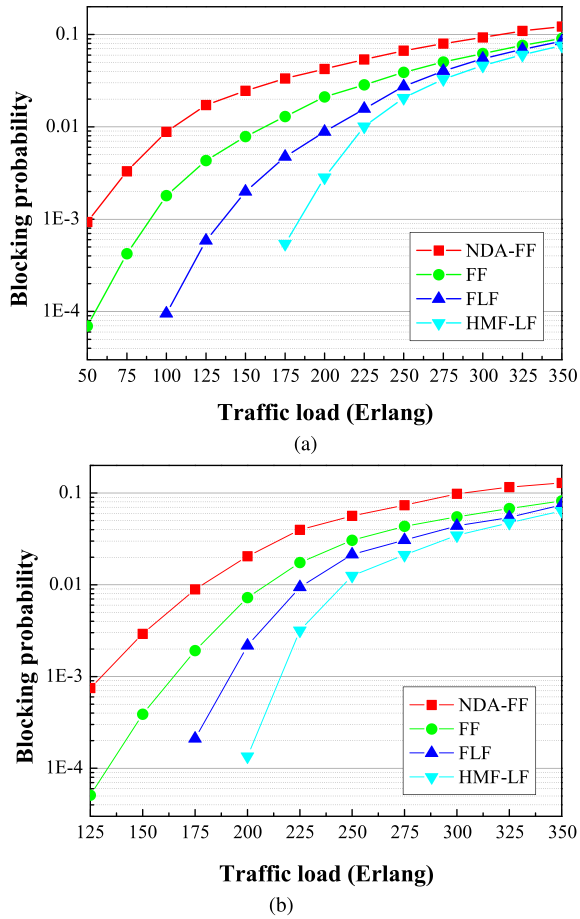

FIGURE 3. Blocking probability performance comparison among the NDA-FF, FF, FLF and HMF-LF evaluated in (a) NSFNET and (b) Indian network.

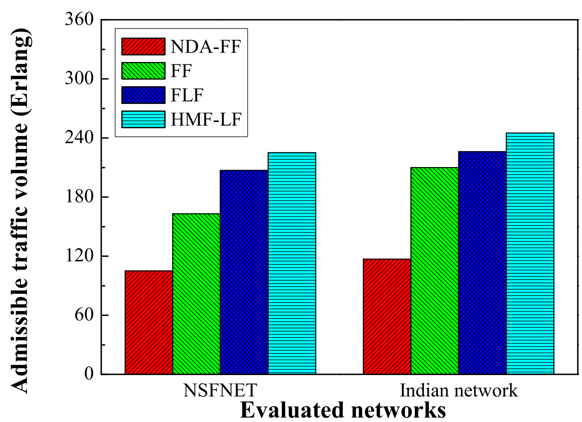

FIGURE 4. Admissible traffic volume comparison under 1% blocking of lightpath requests among the NDA-FF, FF, FLF and HMF-LF.

format. It is evident that the proposed HMF-LF scheme always provides lower blocking probability compared to the conventional NDA-FF, FF and FLF schemes. The HMF-LF scheme always attempts to allocate the lightpath requests with the least required available spectrum slots by the highest-level modulation technique and guarantees the occupied spectrum slots position is as high as possible. In this case, more requests can be transmitted by highest-level modulation and the spectrum resources can be effectively utilized. It is seen that the NDA-FF shows the highest blocking probability due to the single modulation candidate. Besides, the blocking probability of FLF is lower than that of FF. This is because the FLF scheme always allocates the shorter distance lightpath requests to the highest-indexed spectrum slots and guarantees the longer distance lightpath requests are allocated at lowest-indexed spectrum slots. By this way, the number of required slots for the longer distance lightpath requests is minimized, which increases the spectrum utilization.

We observe that the proposed HMF-LF scheme accommodates 8.7% and 8.4% more admissible traffic volume than that of using the conventional FLF scheme, as shown in Fig. 4, when the satisfied blocking probability is considered 0.01 in NSFNET and Indian network, respectively.

Note that NDA-FF and FF will not be included in the next two performance comparisons as the blocking probability of NDA-FF and FF is adequately higher than that of FLF and HMF-LF. The work in [16] already confirmed that FLF provides better performance compared to NDA-FF and FF.

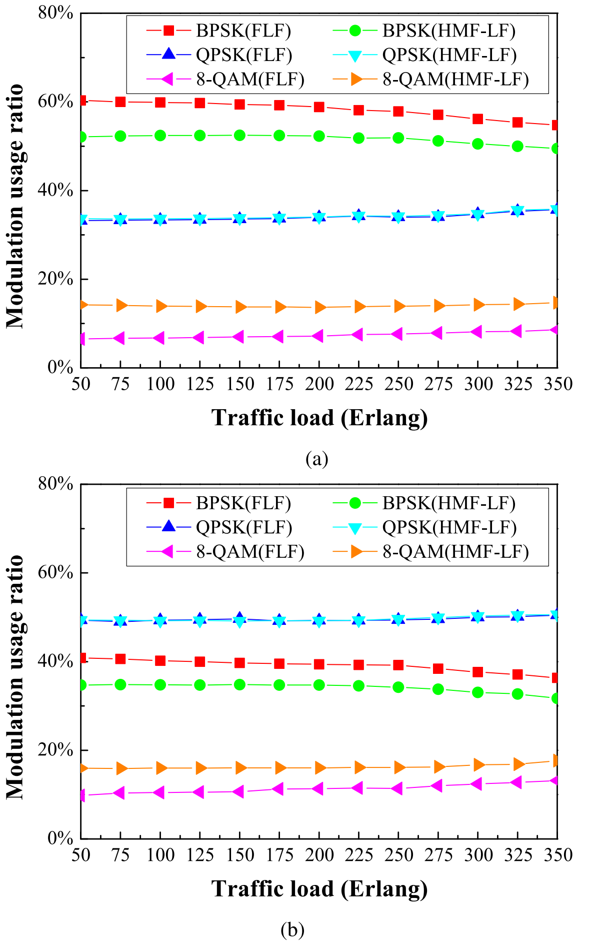

FIGURE 5. Modulation usage ratio versus traffic load, obtained by using conventional FLF and proposed HMF-LF spectrum allocation schemes in (a) NSFNET and (b) Indian network.

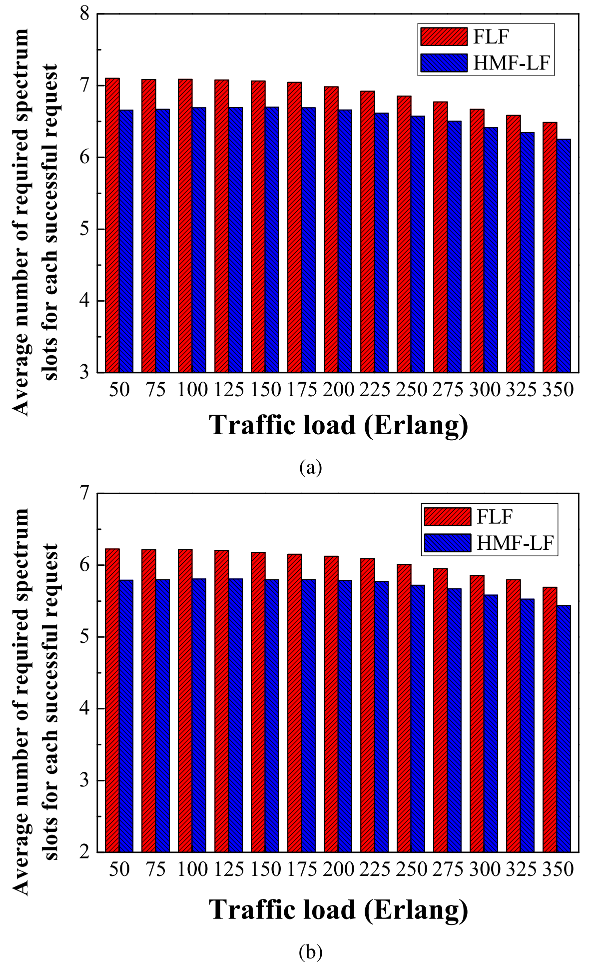

FIGURE 6. Average number of required spectrum slots versus traffic load, obtained by using conventional FLF and proposed HMF-LF spectrum allocation schemes in (a) NSFNET and (b) Indian network.

C. PERFORMANCE COMPARISON OF MODULATION USAGE RATIO

This subsection presents the performance of the proposed HMF-LF scheme in terms of modulation usage ratio in the network, which is as a ratio of the number of lightpath requests with each modulation to the number of total successful requests [11]. Figs. 5(a) and 5(b) show the modulation usage ratio versus traffic load in NSFNET and Indian network, respectively, obtained by using the conventional FLF and proposed HMF-LF spectrum allocation schemes.

We observe that the QPSK usage ratios for the FLF and proposed HMF-LF schemes in NSFNET both are greater than that in Indian network. This is because the average optical path length of NSFNET is longer than that of Indian network. Lightpath requests obtain more opportunities to use QPSK modulation technique for transmission due to the shorter transparent distance in Indian network. Furthermore, the BPSK usage ratios for the FLF and proposed HMF-LF schemes decrease with traffic load increase both in NSFNET and Indian network. The higher-level, namely QPSK and 8-QAM, usage ratio increases with increase in traffic load. This is because the long transparent distance lightpath requests are easy to be blocked when the available spectrum resources are less, and the average lightpath distance of successful requests reduces with increase in traffic load. On the other hand, we observe that the 8-QAM usage ratios using the proposed HMF-LF scheme are always higher than that of using FLF, and the BPSK usage ratios are lower in addition. This is because the FLF always attempts to allocate shorter distance lightpath requests at the highest-indexed spectrum slots which has shorter maximum transmission reach. In this case, the shorter distance lightpath requests have a lower opportunity to select highest-level modulation, even if there are available spectrum slots in lowest-indexed spectrum slots.

D. PERFORMANCE COMPARISON OF AVERAGE NUMBER OF REQUIRED SPECTRUM SLOTS FOR EACH SUCCESSFUL REQUEST

We also evaluate the performance of the proposed HMF-LF scheme in terms of average number of required spectrum slots for each successful request in the network. Figs. 6(a) and 6(b) show that the number of average required slots for each successful request versus traffic load in NSFNET and Indian network, respectively, obtained by using the conventional FLF and proposed HMF-LF schemes.

We observe that when the traffic load increases, the average number of required spectrum slots for each successful request decreases both in NSFNET and Indian network. This is because the average lightpath distance of successful requests reduces and the higher-level modulation usage ratio increases with increase in traffic load. We further notice that the average number of required spectrum slots using the proposed HMF-LF scheme is less than that of using the conventional FLF scheme. This is because the higher-level modulation usage ratio of the proposed HMF-LF scheme is greater than that of using the conventional FLF scheme. As a result, the proposed HMF-LF scheme can use the least required spectrum slots for transmission demand and provide more available spectrum slots for the next incoming lightpath requests. This observation implies that the proposed HMF-LF scheme utilizes the spectrum resources more effectively than the conventional FLF scheme.

V. CONCLUSION

This paper proposed a spectrum allocation scheme based on highest-modulation-first last-fit (HMF-LF) for elastic optical networks (EONs) in order to suppress the call blocking in the network. The proposed scheme searches the available spectrum slots from the highest-indexed spectrum slots and selects the slot position with the modulation level as high as possible, which guarantees the least spectrum slots consumption. We introduced a dispersion based highest-modulation-first last-fit algorithm for allocation lightpath requests. The performance of the proposed scheme was evaluated through simulation study in NSFNET and Indian network. From the numerical results, it was observed that the proposed scheme reduces the blocking probability compared to conventional schemes. We also observed that the proposed scheme accommodates approximately 8.7% and 8.4% more admissible traffic volume than that of using the convention first-last fit spectrum allocation scheme, when the satisfied blocking probability is considered 0.01 in NSFNET and Indian network, respectively.

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