Channel Frequency Optimization in Optical Networks Based on Gaussian Noise Model

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***Abstract*—To make the most of limited spectrum resources in optical fibers, we propose to improve the quality of transmission leveraging the optimization of channel center frequencies in optical networks with flex-grid. For point-to-point communication, we first compute the optimal transmit power that minimizes the physical layer impairment (PLI) by using the Gaussian Noise (GN) model. We then derive the theoretical PLI-aware provisioning capacity in fixed-grid optical networks and further formulate an optimization model that can estimate the maximum number of requests that can be provisioned in flex-grid optical networks. Numerical simulation results reveal that with the help of channel center frequency optimization, 8.7% capacity improvement can be achieved in flex-grid optical networks. The SNR margin improvement is also demonstrated in both point-to-point optical communication and optical rings.**

***Index terms*—** Flexible Optical Networks; Physical Layer Impairment, Frequency Optimization; Fixed-Grid; Flex-Grid;

I. Introduction

The capacity demand for optical fiber communication continues to grow exponentially. Multi-core or multi-mode fibers enable to achieve a higher transmission capacity than conventional fibers [1]. However, as the fiber spectrum resource becomes filled, it is urgent to make the spectrum usage as effective as possible [2, 3]. In the past two decades, the evolution from wavelength division multiplexing to dense wavelength division multiplexing is accompanied by the upgrade of fine spectral grid. With the advantage of waveshaper, optical tunable filter, and bandwidth variable transponder, it is possible to operate on a fine grid with small granularity slot or even on continuous spectrum domain [4, 5]. Besides, a channel on the fine grid can utilize various modulation formats, such as BPSK, 4QAM, or 16QAM. With high order modulation formats, more traffic can be transported. As using fine spectrum grid and multiple modulation formats enables to accommodate more services of distinct granularity, we can make the spectrum usage more efficient.

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However, a dominating limitation of high-order modulation format and dense channels is physical layer impairment (PLI). In order to successfully decode the received light signal, the signal to noise ratio (SNR) of each channel should be higher than a certain threshold. A bigger SNR margin signifies a higher reliability and resilience against system aging and other transient events. Channels with different bandwidth and modulation formats will experience a different amount of PLI. The non-linear interference between channels can be also influenced by their center frequencies [6, 7]. Motivated by the fact that current spectral grid is evenly distributed (i.e. fixed-grid) and the center channel experiences the most PLI, we propose a spectrum allocation model to balance the nonlinear interference among channels. Our objective is to improve the quality of transmission leveraging channel frequency optimization so as to maximize the PLI-aware service provisioning capacity. The main contributions of this paper can be summarized as follows,

- For point-to-point communication, we first present the PLI model using the Gaussian Noise(GN) model and give the optimal transmitting power that minimizes the PLI among channels through simulations. We then further derive mathematically the upper bound of the PLI-aware service provisioning capacity.
- We propose a spectrum allocation method leveraging the optimization of channel center frequency optimization and flex-grid. Simulation results demonstrate that our method outperforms the solution with only fixed-grid in terms of transmission capacity and SNR margin.

The rest of this paper is organized as follows. In Sec. II, we present a brief related work. Sec. III gives the PLI model and problem formulation. The spectrum allocation based on fixed-grid and flex-grid are presented in Sec. IV. We then give the performance evaluation for point-to-point communication and optical rings in Sec. V and Sec. VI respectively. Finally, Sec. VII concludes this paper.

II. Related Work

The resource provisioning in optical networks generally includes routing and wavelength assignment (RWA). With the emergence of flexible optical network, RWA has been evolved into routing and spectrum assignment (RSA). Solving RSA is NP-hard. To solve it more efficiently, most works deal with the routing and spectrum assignment separately [3, 8]–[12].

The spectrum assignment that takes account of nonlinear interference needs to determine optical transmitting power, channel order, and guard band. To find the optimal transmitting power, a simple method is to search the power value in a finite range [13]. An iterative approach is also introduced to optimize the power of different transceivers [14]. One can also refer to [3] for another method in which channel power is optimized by convex optimization. Besides power optimization, channel order has also been considered to reduce the non-linear interference. Since it is difficult to determine the best relative order of different spectrum channels, a random spectrum swapping method is introduced in [14]. As an improvement of the foregoing method, a new method presented in [15] assigns the channel with a larger SNR margin close to the spectrum range center, while the channel with a smaller SNR margin to the boundary of the spectrum range. Finally, setting guard band is also a useful and convenient way to overcome the PLIs [8, 16]. Most current researches on spectrum assignment are based on fixed-grid, which can bring more convenience on the calculation of interference and network planning. But the fixed-grid method can not fully exploit the fiber spectrum resource efficiently. In previous work, we have investigated the relationship between even guard band and request blocking [16]. In this paper, we extend it by using flex-grid to improve the transmission capacity and SNR margin.

III. Physical Layer Impairment and Problem Statement

A. PLI

The PLI of a signal in optical fibers can be calculated by the GN model. The advantage of GN model that can calculate the signal degradation by center frequencies, bandwidth, and transmit power independently, makes it more suitable for the optimization of spectrum allocation [7]. For example, when transmit power spectral density (PSD) G_i (unit: dBm/GHz), bandwidth Δf_i (unit: GHz), and center frequency f_i (unit: GHz) are determined, the SNR after N_i spans can be denoted by the following equation,

$$\text{SNR}_i = \frac{G_i}{G_i^{\text{ASE}} + G_i^{\text{NLI}}} \tag{1}$$

where the parameter G_i^{ASE} is PSD of amplifier spontaneous emission (ASE) from optical amplifiers, G_i^{NLI} is PSD of nonlinear interference noise caused by the Kerr effect of fiber. In general, if we neglect the minor impact of multi-channel interference, the nonlinear interference noise can be expressed as the sum of *self-channel interference* (SCI), G_i^{SCI}, and *cross-channel interference* (XCI), G_i^{XCI}, $G_i^{\text{NLI}} = G_i^{\text{SCI}} + G_i^{\text{XCI}}$. According to GN model, these interference G_i^{ASE}, G_i^{SCI}, and G_i^{XCI} can be written as,

$$\begin{cases} t_i^{\text{ASE}} = \dfrac{G_i^{\text{ASE}}}{G_i} = N_i G^{\text{ASE}}/G_i \\ t_i^{\text{SCI}} = \dfrac{G_i^{\text{SCI}}}{G_i} = N_i \mu G_i^2 \text{asinh}(\rho \Delta f_i^2) \\ t_i^{\text{XCI}} = \dfrac{G_i^{\text{XCI}}}{G_i} = \displaystyle\sum_{j:j\neq i} \mu N_{ij} G_j^2 \ln\left(\frac{|f_i - f_j| + \Delta f_j/2}{|f_i - f_j| - \Delta f_j/2}\right) \end{cases} \tag{2}$$

where N_i denotes the number of spans for channel i, N_{ij} denotes the number of common spans for channel i and j. The fiber attenuation factor $\alpha = 0.22$ dB/km, length per span $L_{\text{span}} = 100$ km, EDFA noise figure $n_{\text{sp}} = 7$ dB, non-linear coefficient $\gamma = 1.3$ W $\cdot$ Km^{-1}, second-order dispersion of 1550 nm $|\beta_2| = 21.7$ ps^2/km, and the coefficient $\mu = \frac{3\gamma^2}{2\pi\alpha\beta_2}$, $\rho = \pi^2 \beta_2 \alpha$. The ASE noise $G^{\text{ASE}} = 10^{\alpha L_{\text{span}}/10} h\nu n_{\text{sp}}$, where h is the Planck constant and ν is the optical carrier frequency of 193.5 THz [7, 14].

A parameter $k_{i,j}$ is introduced to define the ratio of frequency center distance between channel i and channel j as follows,

$$k_{i,j} = |f_i - f_j|/\Delta f_j \tag{3}$$

Therefore, the frequency distance $f_{ij} = |f_i - f_j| = k_{i,j}\Delta f_j = k_{j,i}\Delta f_i$. The variable f_i is replaced by $k_{i,j}$ in the following text. By substituting (2) into (1), we can get a universal QoT in (4).

$$\begin{aligned} QoT_i : & N_i \frac{G^{\text{ASE}}}{G_i} + N_i \mu G_i^2 \text{asinh}(\rho \Delta f_i^2) \\ & + \sum_{j:j\neq i} \mu N_{ij} G_j^2 \ln\left(\frac{2k_{i,j}+1}{2k_{i,j}-1}\right) \leq \frac{1}{\text{SNR}^{\text{th}}(c_i)} \end{aligned} \tag{4}$$

B. Problem Statement

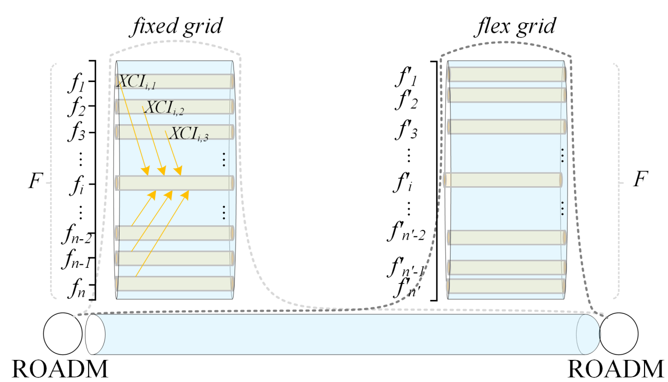


Fig. 1. Illustration of the fixed-grid and flex-grid in fiber link.

We use $G(V, E)$ to denote the optical network, where V represents the set of optical cross-connect nodes and E represents the set of links. Each link $e \in E$ represents two fibers. Due to the limited spectrum resource assumption, the available spectrum resource of each fiber is limited to F (unit: GHz). For the request i in demand set D, it requires traffic r_i (unit: Gbps) from source node s_i to destination node d_i. The required spectrum resource on the lightpath should be continuous on spectrum interval $(f_i - \frac{\Delta f}{2}, f_i + \frac{\Delta f}{2})$, where $\Delta f_i = r_i/\text{SE}(c_i)$. Thus, the spectrum continuity and spectrum contiguity constraints can be satisfied. Besides, the SNR must satisfy the QoT in (4). Therefore, the modulation format c_i, PSD G_i, and spectrum starting index or spectrum order should be carefully designed. In Table I, we have illustrated the spectral efficiency and threshold of possible modulation

TABLE I
SPECTRAL EFFICIENCY AND SNR THRESHOLD OF DIFFERENT MODULATION FORMATS [17].

Modulation Format c	Spectral efficiency (SE) (bits/s/Hz)	SNR^{th}
PM-BPSK	2	3.56
PM-4QAM	4	6.52
PM-8QAM	6	10.98
PM-16QAM	8	13.1

format [17]. Solving the above problem that consists of the routing, spectrum assignment, and power allocation is difficult. Therefore, we assume that a routing and spectrum assignment result is given.

Given a resource provisioning result with determined lightpath and starting spectrum index, we can calculate the PLI for all requests. As illustrated in Fig. 1, the nonlinear interference will deteriorate other channels. Since the non-linear interference of neighborhood channel is proportional to frequency distance f_{ij}, the channel center frequencies f_i can be further optimized. Therefore, we need to design proper frequency space for each request.

The objective of our model is to improve one or several channels' transmission quality. Since the spectrum resource is limited, the performance of optimal result can be measured by the maximum number of accepted channels, *i.e.* capacity.

IV. Fixed-grid and Flex-Grid Resource allocation model

In this section, we introduce the resource allocation model. To validate the perception of center frequency optimization, we first focus on point-to-point communication and assume that the transmit optical power $G_i = G$, bandwidth $\Delta f_i = \Delta f$, and modulation format $c_i = c$. Therefore, the span length of all requests is equal, $N_i = N_{ij} = N_s$. The QoT in (4) is updated as follows,

$$\sum_{i:i\neq j} \ln\left(\frac{2k_{i,j}+1}{2k_{i,j}-1}\right) \leq H(G) \tag{5}$$

where $H(G) = \frac{1}{\mu N_s \text{SNR}^{\text{th}}(c)}\left(\frac{1}{G^2} - \frac{N_s G^{\text{ASE}}\text{SNR}^{\text{th}}(c_0)}{G^3}\right) - \text{asinh}(\rho\Delta f^2)$.

A. Optimal PSD

In (5), $H(G)$ is the upper boundary of XCI term. To increase more margin on XCI term, we should choose the PSD G_{opt},

$$G_{opt} := \arg max(H(G)) \tag{6}$$

By solving the first and second derivative order of $H(G)$, we can get $G_{opt} = \frac{3}{2}N_s G^{\text{ASE}}\text{SNR}^{\text{th}}$, $H_{max} = \frac{4G^{\text{ASE}}}{27\mu\left(N_s G^{\text{ASE}}\text{SNR}^{\text{th}}\right)^3} - \text{asinh}(\rho\Delta f^2)$. It is marked as circle in Fig. 2. Related work on power optimization can refer to [3, 15], in which resource allocation with flat power has the similar benefit as optimal solution with independent power. Therefore, we can confirm that not much difference is made if we take the assumption of equal power G.

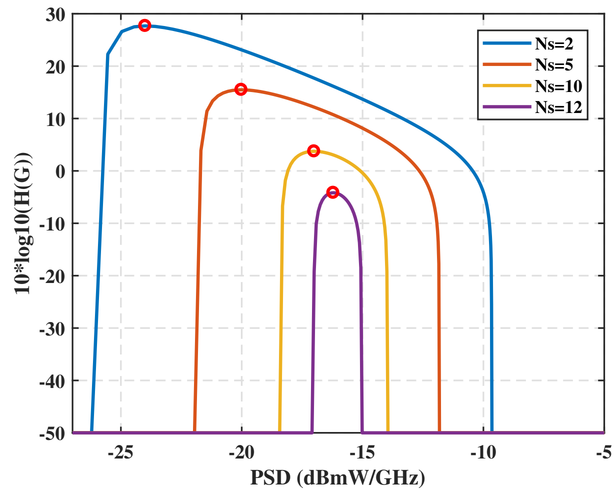


Fig. 2. The function $H(G)$ as G varies.

On the left hand of (5), we use $L^i(f_1, f_2, ..., f_n)$ to denote XCI term, which is the function of variable $k_{i,j}$. Two kinds of frequency grid mode is compared, (a) fixed-grid, and (b) flex-grid (no frequency grid assumption). Since the spectrum resource of point-to-point communication is limited, we choose the number of accepted channels as the metric.

B. Fixed-grid

An even frequency grid with space f_Δ, and the unit guard band ratio $k_0 = f_\Delta/\Delta f$ is assumed. We get the expression of $k_{i,j}$ in (7).

$$k_{i,j} = |i-j|k_0. \tag{7}$$

We use $L_1^i(f_1, f_2, ..., f_n)$ to denote XCI term in the left side of (5). In such case, $L_1^i(f_1, f_2, ..., f_n)$ is a function of sole variable k_0. As the frequency space f_Δ increases, the XCI term L_1^i will reduce so that more channels can be accepted. When all spectrum resources on interval $(0, F)$ run out, the number of channels can reach its maximum.

Due to the same bandwidth Δf and even frequency space f_Δ, the center channel must experience the most interference. In other word, we just need to focus on the center channel to determine whole channels' quality. Thus, we discuss two scenarios with odd and even number of accepted channels.

1) odd number channels: With an odd number of accepted channels n, we focus on channel $\frac{n+1}{2}$th in the center. The XCI term $L_1^{\frac{n+1}{2}}$ can be expressed as follows,

$$\begin{aligned} L_1^{\frac{n+1}{2}} &= \sum_{j:j\neq i} \ln\left(\frac{2k_{i,j}+1}{2k_{i,j}-1}\right) \\ &= 2\left(\ln\frac{2k_0+1}{2k_0-1} + \ln\frac{4k_0+1}{4k_0-1} + \cdot + \ln\frac{2k_0\frac{n-1}{2}+1}{2k_0\frac{n-1}{2}-1}\right) \\ &= 2\left(\ln\frac{\Gamma(\frac{n+1}{2}+\frac{1}{2k_0})}{\Gamma(\frac{n+1}{2}-\frac{1}{2k_0})} - \ln\frac{\Gamma(1+\frac{1}{2k_0})}{\Gamma(1-\frac{1}{2k_0})}\right) = F_{\text{odd}}(n) \end{aligned} \tag{8}$$

By substituting (8) into (5), we can get $n_{\text{odd}} \leq F_{\text{odd}}^{-1}(H_{max})$.

2) even number channels: In the second scenario where the maximum number of accepted channels n is even, we focus on center channel $\frac{n}{2}$th. The XCI term can be written as follows,

$$\begin{aligned} L_1^{\frac{n}{2}} &= \sum_{j:j\neq i} \ln\left(\frac{2k_{i,j}+1}{2k_{i,j}-1}\right) \\ &= 2\left(\ln\frac{2k_0+1}{2k_0-1}+\cdots+\ln\frac{2k_0\frac{n}{2}-1+1}{2k_0\frac{n}{2}-1-1}\right)+\ln\frac{k_0 n+1}{k_0 n-1} \\ &= 2\left(\ln\frac{\Gamma(\frac{n}{2}+\frac{1}{2k_0})}{\Gamma(\frac{n}{2}-\frac{1}{2k_0})}-\ln\frac{\Gamma(1+\frac{1}{2k_0})}{\Gamma(1-\frac{1}{2k_0})}\right)+\ln\frac{k_0 n+1}{k_0 n-1}=F_{\text{even}}(n) \end{aligned} \tag{9}$$

Similarly, by substituting (9) into (5), we can also get $F_{\text{even}}(n) \leq H_{max} \Rightarrow n_{\text{even}} \leq F_{\text{even}}^{-1}(H_{max})$.

Without PLI limitation, the maximum number of requests is restricted by the spectrum resource. The maximum number of requests is $\frac{F-\Delta f}{f_\Delta}+1$. Finally, we conclude that the maximum number of channels in fixed-grid should equal n_{I}, which is presented in (10).

$$n_{\text{I}} = \min\left(\frac{F-\Delta f}{k_0\Delta f}+1, F_{\text{odd}}(H_{max}), F_{\text{even}}(H_{max})\right) \tag{10}$$

C. Flex-grid

No frequency grid is assumed on the center frequency. Compared to fixed-grid, the frequency center variable f_i in (5) are changed from one-dimensional optimization to n-dimensional optimization. We use $L_2^i(f_1, f_2, ..., f_n)$ to denote the XCI term in left side of (5). These n channels can be totally accepted if $\max_{1\leq i\leq n}(L_2^i) \leq H_{max}$. The model that we use to solve the upper bound of $L_2^i(f_1, f_2, ..., f_n)$ is presented as a non-linear programming model in (11).

$$\begin{aligned} \min \quad & L_2^{max} \qquad \boldsymbol{(flexG)} && (11a) \\ s.t. \quad & L_2^i(f_1, f_2, ..., f_n) \leq L_2^{max} \quad \forall i && (11b) \\ & f_i + \Delta f \leq f_{i+1} \quad \forall i && (11c) \\ & f_1 - \frac{\Delta f}{2} \geq 0, f_n + \frac{\Delta f}{2} \leq F && (11d) \end{aligned}$$

The objective of flexG is to minimize the maximum XCI term L_2^{max}. Constraints (11b) define the upper bound of all nonlinear interference term $L_2^i(f_1, f_2, \cdots, f_n)$. Constraints (11c) assure the spectrum non-conflict requirement. Constraint (11d) ensures only the spectrum resource on interval $(0, F)$ can be used. It can be proved that the feasible sets of model flexG is convex [18]. In the simulation, we solve the model with the Optimization Toolbox of MATLAB™ [19]. Therefore, the number of channels n_{II} in flex-grid should be tested by the fact: the maximal interference term of all n_{II} channels should be less than H_{max}, while all $n_{\text{II}}+1$ channels should not be less than H_{max}.

V. Evaluation in Point-to-Point Communication

A. Capacity Improvement

By setting each channel with PM-16QAM and traffic rate of 250 Gbps, fiber spans with 10 and F=2000 GHz, we calculate the maximum accepted number of channels based on fixed-grid and flex-grid. The result is shown in Fig. 3. For fixed frequency grid, with no knowledge of optimal frequency grid, we vary the even frequency channel grid from 40 GHz to 150 GHz. The number of accepted channels reaches the maximum 23 when frequency grid is 87 GHz.

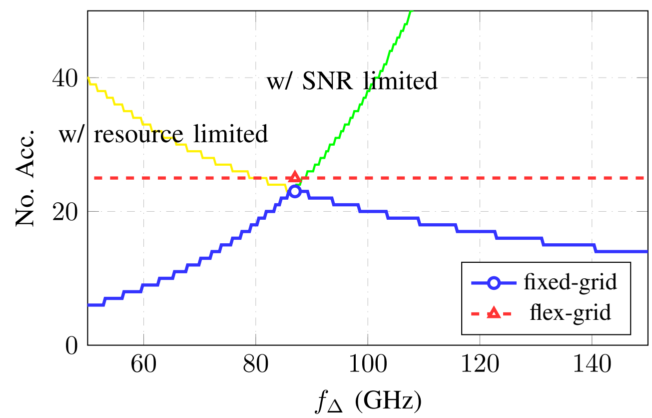


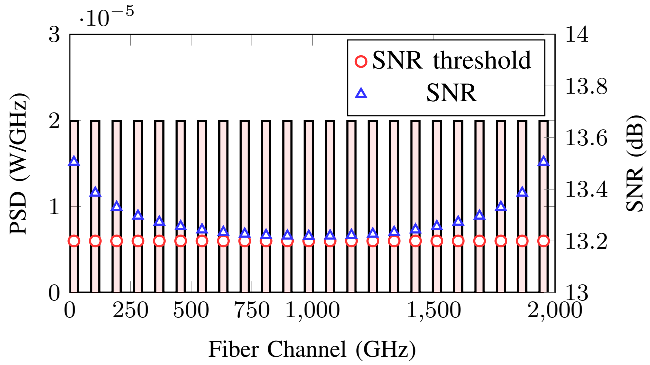
Fig. 3. Number of accepted channels with example of 16QAM at 10 spans as frequency grid increases.

In Fig. 3, as the frequency grid increases, the number of channels increases before it reaches to its maximum. It can be explained that only SNR is considered and large frequency space will reduce the interference on all channels. As the frequency grid continues to grow, the number of channels decreases, because some channels are outside the fiber. However, for the flex-grid that optimizes the channel frequencies, we observe that the number of channels can further increase to 25. The capacity improvement percentage is about 8.7%.

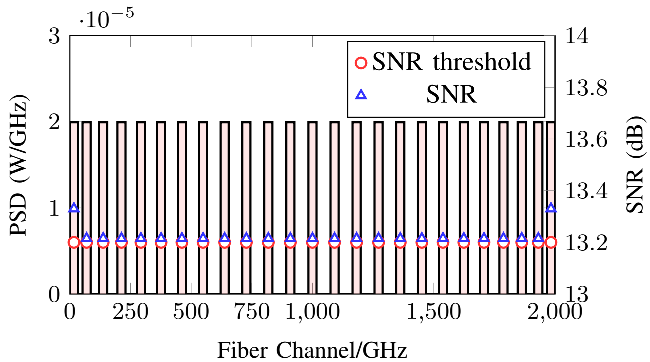
The channel distribution of these two examples are plotted in Fig. 4. In the fixed-grid example, the extreme edge channels' SNR is larger than the center channel. Besides, the center channel's SNR gets to the threshold more closely than other channels. In flex-grid example, the SNR distributes uniformly on fiber links. In other words, by optimizing the frequency space, model flexG can balance all channels' SNR. It can be seen in Fig. 4(b), the channel in the center needs more space than the extreme edge to reduce XCI interference. Compared to the fixed-grid example with even space, model flexG uses the frequency space from 50 to 90 GHz, rather than the even frequency space of fixed-grid 87 GHz.

B. Minimum Margin Improvement

As mentioned previously, flexG can balance SNR margin for the channels. Therefore, we compare the SNR margin improvement of two grid modes using the same number of channels, *e.g.* 23. The result is shown in Fig. 5. The SNR distribution of flex-grid is flat in all channels, while the fixed-grid is of bowl shape. The minimum SNR margin improvement of flex-grid is 0.094 dB. Compared to the optimized power allocation with 0.043 dB margin improvement, the frequency optimization is also small [3].



(a) fixed-grid



(b) flex-grid

Fig. 4. Channel distribution and SNR of the example in fixed-grid and flex-grid. (a) blue circle in Fig. 3; (b) red triangle in Fig. 3.

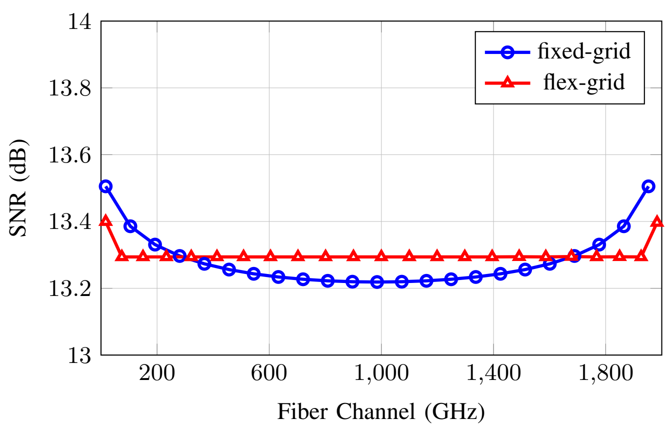


Fig. 5. SNR margin of different channels (modulation format PM-16QAM).

VI. Evaluation in Optical Rings

In last section, we have observed the performance enhancement by optimizing channel's center frequencies in point-to-point communication, including the capacity improvement and margin improvement. The flex-grid's benefit in optical networks will be stated in this section.

Flexible optical networks are typically structured into three main tiers, namely access networks, metropolitan area networks, and backbone networks [20]. The ring topology of metropolitan area networks has less connectivity. In order

TABLE II
Parameters In the simulation of optical ring

Network sets & Parameters	
$T_{i\lambda}$	Link spectrum table of routing and spectrum results. $T_{i\lambda} = i$ means request i uses both link l and slot λ.
$x_{il} \in 0, 1$	Equals 1 if request i uses link l.
N_i	Traversing span numbers of request i.
N_{ij}	Common traversing span numbers of request i and j.
N_{tr}	Maximum transmission reach.
λ_i	Frequency slot of request i.
Variables	
f_i	Frequency center of request i.

to focus on the issue of spectrum assignment and limit the complexity of resource provisioning problem, we study the frequency optimization of ring network in this paper. No interference exists for any opposite traffic. Therefore, we just need to concentrate on the traffic in one direction (*e.g.* counterclockwise) and one route will be provisioned for each request.

Our frequency optimization is based on a specified routing and spectrum assignment result, in which the traversing path and spectrum order have been determined. Besides, as the problem's scale expands, an optimal assignment method that brings a specified benefit could be solved intractably [8]. Therefore, we optimize the frequency with enumerating all possible results in a small amount of requests.

We conduct the channel frequency optimization as follows. When we get the routing results, we note x_{il} to determine whether request i uses link l. The spectrum assignment result that arranges request i on frequency slot λ is denoted by link spectrum table $T_{l\lambda}$ ($T_{i\lambda}$=i, means request i uses both link l and slot λ). Other parameters can refer to the Table II. Since the cross-interfering spans and optimal power rely on the routing path, we cannot use the same frequency optimization in point-to-point communication. Then, we update the channel frequency's optimization problem in networks as follows,

$$\max \quad y \quad \textbf{FLEXG}$$

$$\textbf{\textit{s.t.}} \quad N_i \frac{G^{\text{ASE}}}{G_i} + N_i \mu G_i^2 \text{asinh}(\rho \Delta f_i^2) + \sum_{j:j\neq i} \mu N_{ij} G_j^2 \ln\left(\frac{2k_{i,j}+1}{2k_{i,j}-1}\right) \leq \frac{1}{\text{SNR}^{\text{th}}(c)} - y \quad \forall i \quad (12a)$$

$$k_{i,j} = (f_j - f_i)/\Delta f, k_{i,j} = k_{j,i} \quad \forall \lambda_i < \lambda_j \quad (12b)$$

$$f_i + \Delta f \leq f_j \quad \forall N_{ij} \neq 0 \& \lambda_i < \lambda_j \quad (12c)$$

$$\Delta f + f_j - f_i \leq F \quad \forall N_{ij} \neq 0 \& \lambda_i < \lambda_j \quad (12d)$$

As we stated aforementioned, in order to validate the optimization for routing and spectrum assignment results, we design a small number of requests, *e.g.* 4 in our paper. They consume traffic 250 Gbps with modulation format 16QAM. The topology, source and destination node pair can refer to [8, Fig. 2]. But we set link length with 200 km to assure the

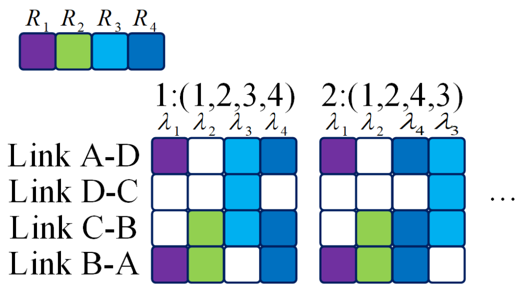


Fig. 6. Illustration of all possible routing and spectrum assignment results.

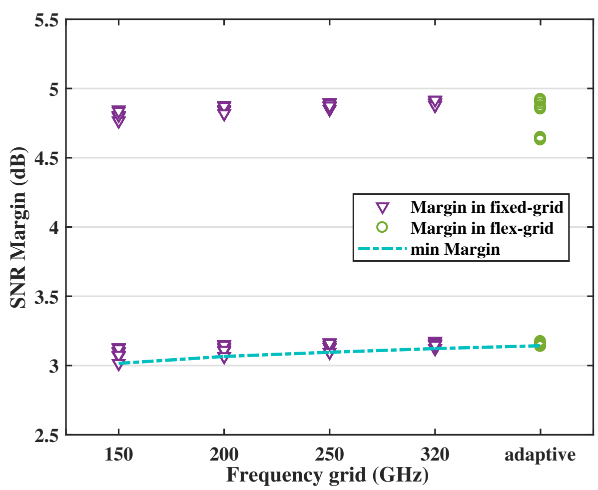


Fig. 7. Margin improvement in 4 nodes optical ring [8]. Each dot represents the request's margin improvement against its threshold.

transmission of higher order modulation format 16QAM. No guard band is forced.

The possible routing and spectrum assignment results are illustrated in Fig. 6. By solving the model in (12), we can get an optimal result with flexible center frequencies. Besides, we also design a benchmark by adding the constraint (13) that fixes each slot on grid with frequency f_Δ.

$$f_j - f_i = (j-i)f_\Delta, \forall N_{ij} \neq 0, \lambda_i < \lambda_j \qquad (13)$$

The margin result is shown in Fig. 7. Each dot represents the margin improvement of one routing and spectrum assignment result. When increasing the frequency grid, we can observe that the minimum SNR margin goes up. However, it can not achieve the same performance as adaptive method where we use flex-grid.

VII. Conclusion

In this paper, we have proposed a resource allocation model that optimizes the channel center frequencies based on GN model. Compared with the existing fix-grid with even frequency space, our scheme can improve minimum SNR margin and increase the number of accepted channels. In point-to-point communication, 8.7% capacity improvement is achieved. Moreover, the proposed resource allocation model is rigorous which can obtain the optimal solution.

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