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Impairment-Aware Integrated VONE Scheme Based on Routing, Bit Loading, and Spectrum Allocation in EONs

Xueqi Ren[1,2], Min Zhu[1,2,*], Jiahua Gu[1,2], Tianyu Shen[1,2], Chenglin Shi[2,3]

1. National Mobile Communication Research Laboratory, Southeast University, Nanjing, 210096, China
*2. Purple Mountain Laboratories, Nanjing, 211111, China, * minzhu@seu.edu.cn*
3. School of Integrated Circuits, Southeast University, Nanjing, 210096, China

Abstract: We propose a novel integer linear program formulation and impairment-aware iVONE heuristic based on routing, bit loading and spectrum allocation in OFDM-based EONs. Results indicate over 10% resources savings compared with the benchmark heuristic.

1. Introduction

For more effective use of optical network resources, elastic optical networks (EONs) in conjunction with optical orthogonal frequency-division multiplexing (OFDM) has recently been proposed as a promising technology to support network services [1-2]. Generally, these emerging network services with specific quality of transmission (QoT) requirements are provisioned in form of virtual optical network (VON) slice, consisting of virtual nodes (VNs) and virtual links (VLs). To construct the VONs, virtual optical network embedding (VONE), as a key technology of optical network virtualization, allocates necessary network resources in the physical infrastructure through node mapping and link mapping. In our previous work [3], we proposed an integrated VONE (iVONE) scheme, where the node mapping and link mapping are performed in an integrated way. Note that various physical-layer nonlinear impairments (NLIs) such as self-channel interference (SCI), and cross-channel interference (XCI) would degrade the QoT of the VLs and limit their transmission reach. Most existing related works VONE in EONs are just based on predefined transmission-reach (TR) limits in the VL mapping, where each modulation format has a TR limit [3-5], and ignore the effect of the NLI on the VL mapping. Hence, the VL mapping based on the TR may overestimate or underestimate the VL connection impairments. Moreover, there are few studies on VL mapping that independently select the modulation format for each subcarrier (SC) depending upon actual impairments such as in-band crosstalk and NLIs, although these impairments affect each SC of a VL independently. This allows each SC to be loaded with different bits and is commonly called as *bit loading* (*BL*) in OFDM-EONs, which can greatly improve the spectral efficiency and data rate, compared with uniform modulation (UM) formats scheme for all SCs [6]. This paper, to the best of our knowledge, is the first attempt to address an impairment-aware iVONE scheme based on BL technology (BL-iVONE) in OFDM-EONs.

In this paper, we propose a novel impairment-aware ILP model based on BL (BL-ILP), and then design an offline nonlinear impairment-aware iVONE heuristic based on routing, bit loading, and spectrum allocation (RBLSA). We further compare our approach with the benchmark heuristic based on the NLI-based UM scheme through simulation studies over both small-scale five-node topology and large-scale fourteen-node network topology.

2. Model and Problem Statement

We adopt the nonlinear impairment model in [6]. The signal-to-noise ratio (SNR) for SC k on a VL(u,w) of the VON-i is $\mathrm{SNR}_{i,(u,w),k} = G_{i,(u,w),k} / (G^{\mathrm{ASE}}_{i,(u,w),k} + G^{\mathrm{NLI}}_{i,(u,w),k})$, where $G_{i,(u,w),k}$ is signal power spectral density (PSD) for the SC k. The PSD of amplified spontaneous emission (ASE) noise for the SC k is $G^{\mathrm{ASE}}_{i,(u,w),k} = \Sigma_{l\in(u,w)} N_l G^{\mathrm{ASE},0}_{i,(u,w),k}$, where $G^{\mathrm{ASE},0}_{i,(u,w),k} = 10^{NF/10} \times h\nu \times (10^{\alpha L/10}-1)$. And the PSD of the NLI noise for SC k is $G^{\mathrm{NLI}}_{i,(u,w),k} = \Sigma_{l\in(u,w)} N_l G^{\mathrm{NLI},l}_{i,(u,w),k}$, where $G^{\mathrm{NLI},l}_{i,(u,w),k} = \mu(\ln(\rho B_{SC}^2) + \Sigma_q \ln((\Delta f_{k,q} + B_{SC}/2)/(\Delta f_{k,q} - B_{SC}/2)))$ is calculated for a single span of link l. In these expressions, $\mu = (3\gamma^2 G^3)/(2\pi\alpha|\beta_2|)$; $\rho = (\pi^2|\beta_2|)/(2\alpha)$; q is another occupied SC on link l; B_{SC} is the bandwidth (BW) for each SC; $\Delta f_{k,q}$ is the center frequency spacing between SC k and q. In addition, N_l, NF, h, ν, α, L, γ, β_2 denote number of spans on link l, noise figure, Planck's constant, optical carrier frequency, power attenuation, the length of each span, fiber nonlinearity coefficient, fiber dispersion respectively.

The substrate EON was modeled as an undirected graph, denoted as $G^s = (N^s, L^s)$, where N^s is the set of substrate nodes (SNs) and L^s represents the set of substrate fiber links (SFLs). Each VON request can be modeled as an undirected virtual graph $vg(n^{vi}, l^{vi}) \in VG(N^v, L^v)$, where N^v is the set of VNs and L^v is the set of VLs between nodes of the set N^v. In addition, b^i is noted as the bit rate requirement (BRR) of VON-i respectively. We assume that each VL in a VON occupy the same SC resources on SFLs, which is the so-called "the spectral continuity constraint". To ensure the QoT of all VLs, the NLIs are considered by measuring the SNR of all used SCs and different modulation formats can be used for different SCs based on the BL technology.

3. ILP model and Proposed Heuristic

An ILP model is formulated to solve the impairment-aware iVONE issue based on BL. The ILP goal is to minimize the overall sum of highest indexed SCs of all the link, which tries to improve the spectral efficiency. Eq. (2-3) ensure that each VN in VON-*i* is mapped onto a unique SN. Eq. (4) ensures that all embedded VLs in VON-*i* are link-disjoint in G^s. In addition, we consider the flow conservation constraint and undirected VLs for any VON request. Eq. (5-7) are responsible for selecting the highest indexed SC for any VON request. Eq. (8) makes sure that any embedded VL satisfies overall data rate demanded by VON-*i*. Eq. (9) ensures that the selected SC *k* of any VL can only have one modulation format *m*. Eq. (10) ensures that the SC *k* with modulation format *m* on the mapped SFL (u^s,w^s) can only be used by one VL(u^{vi},w^{vi}). Eq. (11) indicates that if a specific SC *k* is selected, contiguous SCs *k*+1 and *k*+2 will also be selected for all *k* depending upon the request. Eq. (12) represent any SFL(u^s,w^s) embedded into a specific VL(u^{vi},w^{vi}). We invert SNR to convert nonlinear into linear, and finally get Eq. (13). Eq. (13) represent any SFL(u^s,w^s) embedded into a specific VL(u^{vi},w^{vi}).

Notations:

$vg(n^{vi},l^{vi})$:	*i*-th VON request.
$b(i)$:	bit-rate requirement of the *i*-th VON request.
$L^s(U^s,W^s)$:	set of SFLs on substrate EON infrastructure.
$NL\ (u^s,w^s)$:	number of spans (with one amplifier per span) on link $(u^s,w^s)\in L^s$.
G:	signal power spectral density.
F:	A very large value.
N:	total number of SC on each SFL.
$RSNR_{th}(m)$:	inverse of SNR threshold (SNR_{th}) for modulation index '*m*'.
B_{SC}:	BW of each SC (e.g., 12.5GHz).
G^0_{ASE}:	PSD of ASE of a single span on link *l*.
H_{NLI}:	$H_{NLI}=\mu ln(\rho B^2_{SC})$, means the partial NLI of each SC for request *i*.

Variables:

$bw(i,(u^{vi},w^{vi}))$:	bandwidth requirement of each VL on the i-th VON request.
$vnsn\ (n^{vi},n^s)$:	$\in\{0,1\}$,1 if VN n^{vi} of the *i*-th VON request is mapped into SN n^s.
$vlsfl\ ((u^{vi},w^{vi}), (u^s,w^s))$:	$\in\{0,1\}$,1 if VL(u^{vi},w^{vi}) of the *i*-th VON request is mapped into SFL (u^s,w^s).
$X\ ((u^s,w^s),k)$:	$\in\{0,1\}$,1 if the *k*-th SC of SFL (u^s,w^s) is occupied.
$W\ ((u^s,w^s),k)$:	$\in\{0,1\}$,1 if the occupied *k*-th SC of SFL (u^s,w^s) is the highest indexed.
$X^m\ ((u^{vi},w^{vi}),k,m)$:	$\in\{0,1\}$,1 if *m* is the modulation format used in the occupied *k*-th SC of SFL (u^s,w^s).
$I\ ((u^{vi},w^{vi}),(u^s,w^s),k)$:	$\in\{0,1\}$,1 if the *i*-th VON request is mapped into the *k*-th SC of SFL (u^s,w^s).
$PNLI((u^{vi},w^{vi}),(u^s,w^s))$:	PSD of NLI on the *k*-th SC of SFL (u^s,w^s) mapped into VL(u^{vi},w^{vi}) of the *i*-th VON.
$XCI\ ((u^{vi},w^{vi}),(u^s,w^s),k)$:	partial NLI of the *k*-th SC generated by other occupied SC in SFL (u^s,w^s).

Objective:

$$\text{Minimize: } \sum_{(u^{vi},w^{vi})}\sum_{(u^s,w^s)}\sum_{k} k\times W\left(\left(u^s,w^s\right),k\right) \tag{1}$$

Constraints:

a) Node Mapping Constraints

$$\sum_{n\in N^s} vnsn\left(n^{vi},n^s\right)=\mathbf{1},\ \ \forall n^{vi}\in N^{vi} \tag{2}$$

$$\sum_{n^{vi}\in N^{vi}} vnsn\left(n^{vi},n^s\right)\le\mathbf{1},\ \ \forall n^s\in N^s \tag{3}$$

b) Link Mapping Constraints

$$\sum_{(u^{vi},w^{vi})\in L^{vi}} vlsfl\left(\left(u^{vi},w^{vi}\right),\left(u^s,w^s\right)\right)=\mathbf{1},\ \ \forall\left(u^s,w^s\right)\in L^s \tag{4}$$

$$W\left(\left(u^s,w^s\right),k'\right)\le\mathbf{1}-\frac{\sum_{k=k'+\mathbf{1}}^{N} X\left(\left(u^s,w^s\right),k\right)}{N},\ \ \forall\left(u^s,w^s\right)\in L^s,\ \ \forall k'\in\{\mathbf{1},...,N-\mathbf{1}\} \tag{5}$$

$$W\left(\left(u^s,w^s\right),k'\right)\le X\left(\left(u^s,w^s\right),k'\right),\ \ \forall\left(u^s,w^s\right)\in L^s,\ \ \forall k'\in\{\mathbf{1},...,N\} \tag{6}$$

$$\sum_{k'=\mathbf{1}}^{N} W\left(\left(u^s,w^s\right),k'\right)\ge\frac{\sum_{k'=\mathbf{1}}^{N} X\left(\left(u^s,w^s\right),k'\right)}{N},\ \ \forall\left(u^s,w^s\right)\in L^s \tag{7}$$

$$\sum_{k=\mathbf{1}}^{N}\sum_{m=\mathbf{1}}^{M} X^m\left(\left(u^{vi},w^{vi}\right),k,m\right)\times B_{slot}\times m\ge b\left(i\right),\ \ \forall\left(u^{vi},w^{vi}\right)\in L^{vi} \tag{8}$$

$$\sum_{m=\mathbf{1}}^{M} X^m\left(\left(u^{vi},w^{vi}\right),k,m\right)\le\mathbf{1},\ \ \forall\left(u^{vi},w^{vi}\right)\in L^{vi},\ \ \forall k\in\{\mathbf{1},...,N\} \tag{9}$$

c) Spectrum Continuity and Non-Overlapping Constraint

$$\sum_{(u^{vi},w^{vi})\in L^{vi}}\sum_{m=\mathbf{1}}^{M} vlsfl\left(\left(u^{vi},w^{vi}\right),\left(u^s,w^s\right)\right)\times X^m\left(\left(u^{vi},w^{vi}\right),k,m\right)\le X\left(\left(u^s,w^s\right),k\right)$$
$$\forall\left(u^s,w^s\right)\in L^s,\ \ \forall k\in\{\mathbf{1},...,N\} \tag{10}$$

d) Spectrum Contiguity Constraints

$$\left.\begin{array}{l} X\left(\left(u^{vi},w^{vi}\right),k+\mathbf{1},m\right)\ge\left(X\left(\left(u^{vi},w^{vi}\right),k+\mathbf{2},m\right)+X\left(\left(u^{vi},w^{vi}\right),k,m\right)-\mathbf{1}\right)/N \\ X\left(\left(u^{vi},w^{vi}\right),k+\mathbf{1},m\right)\le X\left(\left(u^{vi},w^{vi}\right),k+\mathbf{2},m\right)+X\left(\left(u^{vi},w^{vi}\right),k,m\right)\end{array}\right\}$$
$$\forall\left(u^{vi},w^{vi}\right)\in L^{vi},\ \ \forall k\in\{\mathbf{1},...,N-\mathbf{2}\},\ \ \forall m\in\{\mathbf{1},...,M\} \tag{11}$$

e) Bit Loading Constraints

$$PNLI\left(\left(u^{vi},w^{vi}\right),\left(u^s,w^s\right)\right)\ge\left(G^{\mathbf{0}}_{ASE}+H_{NLI}\right)\times NL\left(u^s,w^s\right)\times vlsfl\left(\left(u^{vi},w^{vi}\right),\left(u^s,w^s\right)\right)$$
$$+\sum_{k'\ne k}\mu\times NL\left(u^s,w^s\right)\times I\left(\left(u^{vi},w^{vi}\right),\left(u^s,w^s\right),k'\right)\times\ln\frac{\left|k'-k\right|\times B_{slot}+B_{slot}/\mathbf{2}}{\left|k'-k\right|\times B_{slot}-B_{slot}/\mathbf{2}}$$
$$\forall\left(u^{vi},w^{vi}\right)\in L^{vi},\ \ \forall\left(u^s,w^s\right)\in L^s,\ \ \forall k\in\{\mathbf{1},...,N\} \tag{12}$$

$$\sum_{(u^{vi},w^{vi})\in L^{vi}} PNLI\left(\left(u^{vi},w^{vi}\right),\left(u^s,w^s\right)\right)+F\times X^m\left(\left(u^{vi},w^{vi}\right),k,m\right)\le RSNRth\left(m\right)\times G+F$$
$$\forall\left(u^s,w^s\right)\in L^s,\ \ \forall k\in\{\mathbf{1},...,N\},\ \ \forall m\in\{\mathbf{1},...,M\} \tag{13}$$

A heuristic algorithm is also developed as follows. Specially, N^i_{SC} is the required number of SCs for the VON-*i*, which is computed as $N^i_{SC}=b^i/[SU(m)*B_{SC}]$, where SU(*m*) is the spectrum utilization of the modulation format *m* [7]. Then, we define $C(n^s)$ and $C(l^s)$ as the weight value of each N^s and the cost of each L^s, respectively. $C(n^s)$ is the number of links associated with N^s and $C(l^s)$ is calculated as $C(l^s)=[G^{ASE,0}_{i,(u,w),k,}+G^{NLI,l}_{i,(u,w),k}]\ /\ N^l_{SC}$, where N^l_{SC} is total used SCs on link *l*. To investigate the performance of BL-iVONE, we consider an impairment-aware iVONE scheme based on UM (UM-iVONE) as the benchmark algorithm.

Algorithm 1 integrated VONE based on BL (BL-iVONE)

Step 1: We employ a virtual auxiliary graph (VAG), which decomposes G^s into multiple layered topology by N_{SC}^{i} to assist the distribution of resources [3]. Calculate $N_{SC}^{i,max}$ and $N_{SC}^{i,min}$ for each VON by choosing different modulation formats.

Step 2:, Configure N_{SC}^{i} in ascending order from $N_{SC}^{i,min}$ to $N_{SC}^{i,max}$ and build VAG construction employed in [3] by current N_{SC}^{i}. Start node mapping(NM) and sort all the $n^s \in N^s$ in G^s in descending order based on $C(n^s)$. If $C(n^s)$ satisfy $C(n^v)$, map VN n^v into SN n^s, otherwise, try another appropriate n^s.

Step 3: Perform the VL mapping after finishing the NM. Find 3 shortest paths based on $C(l^s)$ and calculate SNR for each current used SC. Calculate the total bitrates carried by current used SCs of the VON.

Step 4: If the total bitrates satisfy the BRR of the VON, accept VON, otherwise, go to **step 2**.

Step 5: Block the request, release all the occupied spectrum resources.

4. Numerical Results

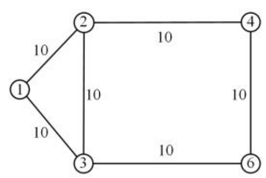

Fig. 1. Five-node Topology

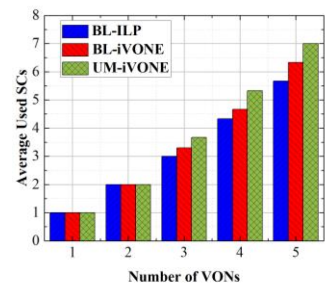

Fig. 2(a). Average Used SCs

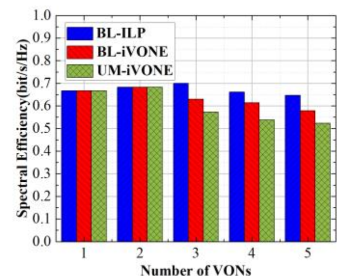

Fig. 2(b). Spectral Efficiency

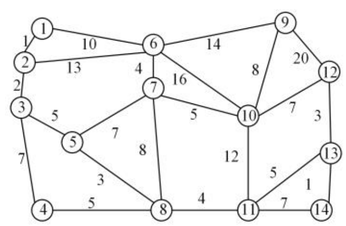

Fig. 3. Fourteen-node Topology

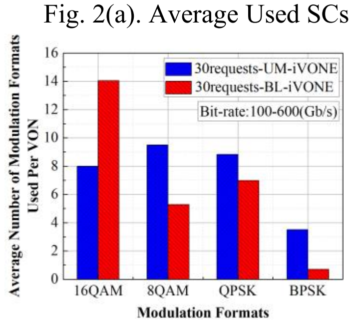

Fig. 4(a). Average Number of Modulation Formats Used Per VON

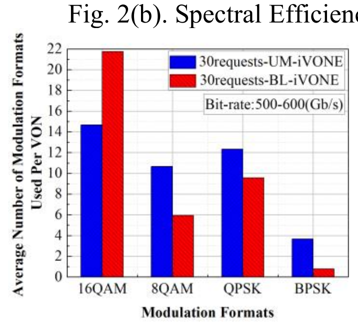

Fig.4(b). Average Number of Modulation Formats Used Per VON

In the simulation, we use a five-node and a 14-node topology shown in Fig. 1 and Fig. 3, respectively. The number on each link represent the number of spans. The simulation parameters are as follows: the BW of each SC with 12.5GHz, the sum of SCs for each link with 350, NF=4.5dB, L=100km, α=0.22dB/km, v=193THz, γ=1.32(W·km)$^{-1}$, β_2=-22.7ps^2/km, signal PSD for small-scale network set as 11mW/THz, signal PSD for large-scale network set as 15mW/THz. We have considered BPSK, 4-QAM, 8-QAM and 16-QAM modulation formats and the approximate SNR thresholds are 12.6 dB, 15.6 dB, 19.2 dB and 22.4 dB, respectively at BER 10^{-9}[8]. The BRR of VON is generated from 80 to 120 Gb/s for five-node topology. For 14-node topology, the BRR of VON is generated from the ranges of [100, 600], [500, 600] Gb/s.

Fig. 2(a) shows that BL-ILP always uses the fewest SCs and BL-iVONE is tightly close to BL-ILP due to the spectral fragments. In Fig. 2(b), BL-ILP shows the optical spectral efficiency better than other algorithms because of the optimality of ILP and BL-iVONE is superior to UM-iVONE due to BL. The effectiveness of BL is illustrated in Fig. 4 based on 30 requests. We observe that the usage of higher order modulation formats like 16-QAM are more compared to UM-iVONE. As described above, BL-iVONE presents preferably network performances.

5. Conclusion

In this paper, we proposed a nonlinear iVONE to improve the spectral efficiency and data rate. Simulations shows BL-iVONE over 10% resources savings with the benchmark heuristic.

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