Architecting Wavelength-Switched Optical Networks with Coherent P2MP Transceivers

(*Invited Paper*)

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***Abstract*—The recently presented coherent point-to-multipoint transceivers (P2MP-TRXs), which are enabled by digital subcarrier modulation, have been viewed as a promising substitute for the point-to-point transceivers, especially for the network segments with hub-and-spoke traffic patterns. This paper studies the network planning of wavelength-switched optical networks with P2MP-TRXs, which includes correlated routing and spectrum assignment, placement of P2MP-TRXs in groups and corresponding subcarrier assignments. We design an efficient heuristic to find near-optimal solutions in polynomial time.**

I. Introduction

Over the past decade, fiber-optic networks have undergone dramatic changes for better adaptivity and higher cost-efficiency [1–5]. While the development of flexible-grid elastic optical networking (EON) has significantly improved the agility of the optical layer and made data transmissions in it much more spectrum-efficient and cost-effective [6–10], communication service providers (CSPs) have to search for new optical networking technologies continuously, especially for reducing the cost per bit (CpB) of their networks [11, 12].

While state-of-art coherent point-to-point transceivers (P2P-TRXs) continue to reduce CpB of serving bandwidth-intensive unicast flows in core networks, deploying them in the network segments such as metro-aggregation networks could be less desirable [13]. Specifically, the traffic demands in such segments exhibit a distinct pattern of hub-and-spoke (H&S) [14], *i.e.*, a hub node communicates with multiple leaf nodes simultaneously. To cope with such traffic pattern, CSPs need to deploy a large number of P2P-TRXs in pairs at hub and leaf nodes. However, this entails sub-optimal utilization of equipment capacities and hinders further optimization of capital expenditures (CAPEX) and operating expenses (OPEX).

The recent advances on point-to-multipoint transceivers (P2MP-TRXs) have provided a promising alternative to handle such H&S traffic more cost-efficiently [15]. Enabled by digital subcarrier modulation (DSCM), a P2MP-TRX provides a finer spectrum assignment granularity by generating a set of low-speed Nyquist sub-carriers (SCs) to fulfill the bandwidth of a wavelength channel, and can maintain its complexity and cost similar to those of a conventional P2P-TRX that operates at the same maximum line-rate [13]. Besides, the activation status of the SCs of such P2MP-TRXs can be flexibly adjusted so as to operate directly in the existing networks with legacy fixed-grid optical line systems, or single-fiber-based duplex lines [16].

In this work, we consider how to plan P2MP-TRX-based wavelength-switched optical networks (WSONs) for better scalability and spectrum-efficiency, which is different from the filterless optical network (FON) based solutions that were commonly addressed in previous studies on P2MP-TRX-based network planning [14]. Here, each hub node and all of its leaf nodes are covered by a light-tree [17], where the spectrum assignment on each branch of the light-tree is tailored to only deliver the SCs required by the leaf node that terminates the branch. As the SCs on all the branches are from the same hub P2MP-TRX, their spectrum usages are thus tightly correlated. Obviously, such a correlated routing and spectrum assignment (RSA) for light-trees is much more complex than that for the conventional WSONs based on P2P-TRXs. To the best of our knowledge, the correlated RSA cannot be solved with any of the existing algorithms in the literature.

In this paper, we study the aforementioned network planning problem, such that the capital expenditures (CAPEX) of the planned P2MP-TRX-based WSON is minimized. An effective polynomial-time heuristic based on layered auxiliary graph (LAG) is designed, to solve the correlated RSA for light-trees without introducing excessive spectrum fragmentation. Finally, simulations are carried out to evaluate our proposal, and the results confirm its performance and effectiveness.

II. Network Model and Algorithm Design

A. Network Model

We denote the optical network as a graph $G\left(V, E\right)$, where V and E are the sets of nodes and fiber links, respectively. For each node $v \in V$ there is an optical switch with broadcast-and-select capability [15]. To satisfy the pending traffic demands, each node v can be either a hub node, a leaf node, or both.

As we consider static network planning, we need to determine the placement of P2MP-TRXs on each node $v \in V$, and solve the correlated RSA for setting up lightpaths to connect the deployed P2MP-TRXs, such that all the traffic demands can be satisfied. We model the pending traffic demands as a matrix $\mathbf{D} = [D_{u,v}]_{|V|\times|V|}$, where each element $D_{u,v}$ denotes the traffic demands from u to v $(u, v \in V)$. For convenience, we treat a hub P2MP-TRX and all of its leaf P2MP-TRXs as a group. Then, based on the traffic demands in $\mathbf{D}$, we can determine the capacities of the P2MP-TRXs in a group with an leader-follower approach. Specifically, the capacity of the hub P2MP-TRX is first selected and then the capacity of

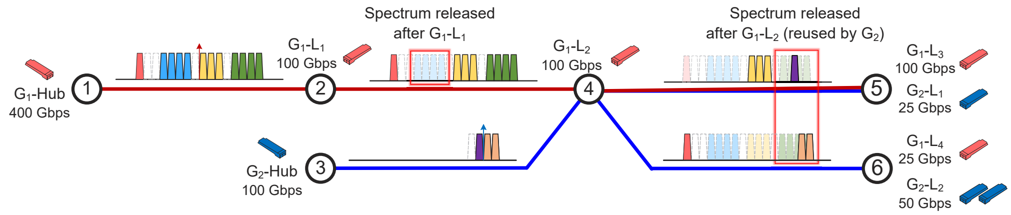


Fig. 1. Example on spectrum saving and reuse in a P2MP-TRX-based WSON.

each leaf P2MP-TRX is chosen accordingly. Each hub P2MP-TRX divides and assigns its capacity to its leaf P2MP-TRXs, in terms of non-overlapping SCs. Here, the SC contiguity constraint needs to be satisfied, *i.e.*, the SCs allocated to each leaf P2MP-TRX have to be spectrally contiguous. Since the SCs of a hub P2MP-TRX can be managed independently [13], we let the hub P2MP-TRX choose the modulation format of its SCs assigned to each leaf P2MP-TRX based on the length of the lightpath between them [14].

P2MP-TRX-based WSONs can leverage optical filtering to ensure that each leaf P2MP-TRX in a group only receives the SCs that are destined to it. Hence, unnecessary spectrum usage can be avoided, which can be seen in the illustrative example in Fig. 1. Here, G_n denotes the n-th group. Then, G_n-*Hub* is the hub P2MP-TRX of the n-th group, and G_n-L_m represents the m-th leaf P2MP-TRX in the n-th group. As shown in Fig. 1, the WSON filters out the SCs assigned to G_1-L_1 after they have been received at *Node* 2, which release the spectrum occupied by them for being used by other groups. Meanwhile, after *Node* 4, the SCs assigned to G_1-L_2 have been filtered out, and thus their spectrum can be reused by the SCs assigned to G_2-L_1 and G_2-L_2 on *Links* 4-5 and 4-6, respectively.

B. LAG-based Fragmentation Aware Planning Algorithm

We consider two aspects in the planning of P2MP-TRX-based WSON, *i.e.*, the total deployment cost of P2MP-TRXs, and the overall spectrum usage measured in the maximum index of used FS' (MIFS) [18, 19]. Here, it should be noted that different from the conventional WSON planning where P2P-TRXs are allocated in pairs, the planning of P2MP-TRX-based WSONs needs to not only deploy P2MP-TRXs in hub-leaf groups, but also decide the corresponding SC assignments and RSA schemes in the leader-follower way. Specifically, each hub-leaf group covers a light-tree, but the spectrum assignment on each of its branch can be different as each leaf P2MP-TRX only needs to receive the SCs assigned to it.

However, such correlated RSA in tree structures can fragment spectra on fiber links severely if without proper SC and FS assignment strategies. This motivates us to 1) leverage the LAG technique designed for solving RSA in EONs [10, 20] to obtain light-trees, and 2) design spectral and spatial fragmentation metrics specifically for P2MP-TRX-based planning to assist the SC assignments of leaf P2MP-TRXs, so as to improve the continuity and contiguity of available FS' on and between fiber links. We propose LAG-based fragmentation aware algorithm (LAG-FA), with the goal of improving the continuity and contiguity of available FS' on and between fiber links when solving the correlated RSA. The input to the algorithm is the physical network topology $G(V, E)$ and traffic demand matrix $\mathbf{D}$, and it leverages the following steps to provision all the demands.

Step 1: We find the node v_h with the largest pending traffic demands, select it as the hub node for the next deploying P2MP-TRX group, and initialize $k = 1$.

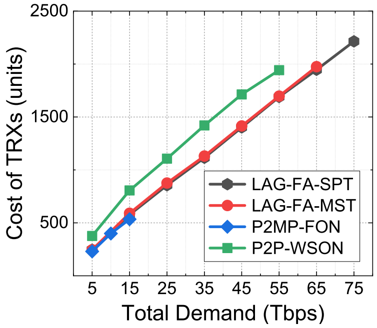
Step 2: we build the k-th LAG for the FS block (FSB) of $[k, k+\hat{F}_o-1]$ to get a light-tree to cover the hub node v_h and its potential leaf nodes. Based on the light-tree $\mathcal{T}_k$ and pending traffic of v_h, the hub P2MP-TRX can be deployed, and then its leaf P2MP-TRXs X_k can be determined, respectively.

Step 3: We leverages the fragmentation-aware (FA) approach in [9] to assign SCs to leaf P2MP-TRXs. Specifically, we extend the FA approach in [9] to evaluate the SC assignments to leaf P2MP-TRXs in both the spectral and spatial domains. We start with setting the start SC index as $j = 1$, and terminates the search until all the candidate P2MP-TRXs in X_k have been taken care of or all the SCs of the hub P2MP-TRX have been checked (*i.e.*, $j > S_{o_h}$). Specifically, If there exists a unique leaf P2MP-TRX whose cut is the smallest, we just insert the P2MP-TRX and its SC assignment in a set Y_k. Otherwise, we check the misalignments caused by the P2MP-TRXs whose cuts are the smallest, and insert the one with the smallest misalignment and its SC assignment in Y_k.

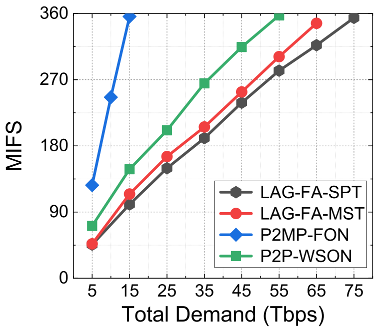
Step 4: After getting Y_k for all the possible FSBs, we select the optimal set of SC assignments for the current group led by the hub P2MP-TRX on node v_h, and update the network status. Note that, ties are taken care of by preferring first the scheme that utilizes more SCs of the hub P2MP-TRX and then the one that can provision more demands. If there are still unprovisioned demands, we go back to **Step 1**.

III. Performance Evaluations

Our simulations use the 14-node Germany topology in [21], with the assumption that the WSON uses the flexible-grid with each FS at 12.5 GHz, and each fiber link accommodates 358 FS' in C-band. Traffic demands in $\mathbf{D}$ are randomly generated according to a total traffic amount. We have considered two benchmarks: 1) the deployment of P2MP-TRXs in FONs, and 2) the deployment of P2P-TRXs in WSONs. We consider transceiver rates of $\{25, 100, 400\}$ Gbps, while the capacity of 25 Gbps can only be considered by leaf P2MP-TRXs or P2P-TRXs. For a P2MP-TRX at $\{25, 100, 400\}$ Gbps, it occupies at most $\{1, 2, 6\}$ FS', respectively, and provides/utilizes $\{1, 4, 16\}$ SCs, each of which occupies 4



(a) Total deployment cost of transceivers.



(b) Maximum index of used FS' (MIFS).

Fig. 2. Total cost and MIFS of the deployed TRXs.

GHz, while bandwidth occupied by P2P-TRXs is proportional to their respective rates. One FS is reserved as the guard-band on each side of a lightpath. If the length of the lightpath between a hub-leaf/P2P pair is within 500 km, dual-polarization 16 quadrature amplitude modulation (DP-16QAM) is adopted, and dual-polarization quadrature phase shift keying (DP-QPSK) otherwise [22]. The capacity of an SC is 25 Gbps and 12.5 Gbps with DP-16QAM and DP-QPSK, respectively. The cost of a 25-Gbps and 100-Gbps TRX is $\frac{1}{4}$ and $\frac{1}{2}$ of that of a 400-Gbps TRX, respectively, and the cost of P2MP-TRXs are in line with P2P-TRXs [14].

Simulations at different scales are then performed to evaluate the solutions. The transceiver cost and spectrum consumption of the solutions are compared in Figs. 2(a) and 2(b), respectively. The P2MP-TRX-based solution can significantly reduce the transceiver cost and spectrum consumption in both topologies compared to its P2P-TRX based counterpart, since the capacity of P2MP-TRXs can be better utilized through sensible SC allocation. Meanwhile, optical switching capabilities provided by WSON is necessary for exploiting the potential of deploying P2MP-TRXs in more demanding network segments, as several times the traffic demand can be provisioned compared to their deployment in FONs. As for the proposed LAG-FA, the one that calculates light-trees with the minimum spanning tree (MST) algorithm induces more CAPEX in most cases. This is mainly because the shortest-path tree (SPT) algorithm can ensure a shorter length for lightpaths between hub-leaf pairs in each light-tree.

IV. Conclusion

We studied the network planning of WSONs with DSCM-enabled P2MP-TRXs, aiming to minimize the CAPEX of planned networks, and proposed an efficient polynomial-time heuristic LAG-FA to find near-optimal solutions. Simulation results confirmed the performance of the proposed algorithm.

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