Dynamic Asymmetric SC Allocation and Reconfiguration in Drop-and-Continue Optical Networks based on P2MP-TRXs

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Abstract: We study the dynamic service provisioning in drop-and-continue optical networks based on point-to-multipoint transceivers (P2MP-TRXs), and leverage asymmetric subcarrier (SC) allocation and SC-level reconfiguration to optimize resource utilization with low operational complexity.

OCIS codes: (060.1155) Software-defined optical networks; (060.4251) Networks, assignment and routing algorithms.

1. Introduction

Recent advances on coherent point-to-multipoint transceivers (P2MP-TRXs) [1] have offered a promising alternative for aggregating and carrying dynamic hub-and-spoke (H&S) traffic in metro-aggregation networks with better cost-effectiveness. Enabled by digital subcarrier multiplexing (DSCM), these P2MP-TRXs achieve more refine-grained bandwidth allocation (*e.g.*, in 4 GBaud) by operating on low-rate Nyquist subcarriers (SCs), each of which can be transmitted and managed independently, while keeping their complexity and cost similar to the point-to-point (P2P) counterparts [1]. Therefore, H&S traffic can be supported by deploying a high-speed hub P2MP-TRX to communicate with multiple low-speed leaf P2MP-TRXs, where each leaf P2MP-TRX is allocated an independent set of SCs from the hub P2MP-TRX to satisfy its bandwidth demand, reducing capital expenditures (CAPEX) and operational expenses (OPEX) significantly. Meanwhile, driven by the rising of emerging network services, the traffic in metro-aggregation networks is becoming increasingly bursty and dynamic, making the capability of achieving frequent and agile bandwidth reconfiguration capability a must-have feature. This further justifies the need of P2MP-TRXs, as their real-time reconfigurability at the SC level has recently been experimentally validated [1]. Hence, the network control and management (NC&M) schemes of P2MP-TRXs have just started to attract research interests. In [2, 3], real-time NC&M frameworks were proposed to arrange SCs of the leaf P2MP-TRXs of a single hub P2MP-TRX, for adapting to dynamic traffic. Nevertheless, these approaches did not try to optimize the SC assignments of multiple hub P2MP-TRXs jointly, and the consideration of the spectrum allocations on fiber links was absent. Moreover, all the existing studies in this area assumed that the upstream and downstream communications of a leaf P2MP-TRX use the same SC assignment, while to the best of our knowledge, asymmetric SC assignment has not been explored in the literature.

Note that, considering the fact that asymmetric traffic condition is usually common in metro-aggregation networks [4], asymmetric SC/spectrum assignment can further explore the flexibility of P2MP-TRXs to save CAPEX and OPEX, especially when we need to optimize the operation of multiple sets of hub/leaf P2MP-TRXs jointly. Therefore, in this work, we study how to readjust the asymmetric SC/spectrum assignment of P2MP-TRXs in a drop-and-continue (D&C) optical network to adapt to dynamic traffic. We first explain the operation principle of asymmetric SC/spectrum assignment and readjustment in such an optical network. Then, a reactive SC-level defragmentation algorithm is proposed to re-optimize the TRX, routing and spectrum assignment (TRSA) for coordinating the reconfiguration of leaf P2MP-TRXs, such that the provisioning performance can be further enhanced through consolidating spectra on fiber links with the minimum reconfiguration cost. Extensive simulations verify the effectiveness of our proposal.

2. Asymmetric SC Allocation and Reactive SC-Level Reconfiguration

An illustrative example on the asymmetric SC allocation in a P2MP-TRX-based D&C optical network is shown in Fig. 1, where each node can be architected either with (*e.g.*, using an optical switch) or without (*e.g.*, using passive combiners/splitters) optical filtering capability. The hub P2MP-TRX at 400 Gbps broadcasts all of its SCs to the leaf P2MP-TRXs in downstream, and receives the aggregated SCs from the leaf P2MP-TRXs in upstream. In downstream, each leaf P2MP-TRX at 100 Gbps only receives the SCs designated to it and drops the others. Note that, although a

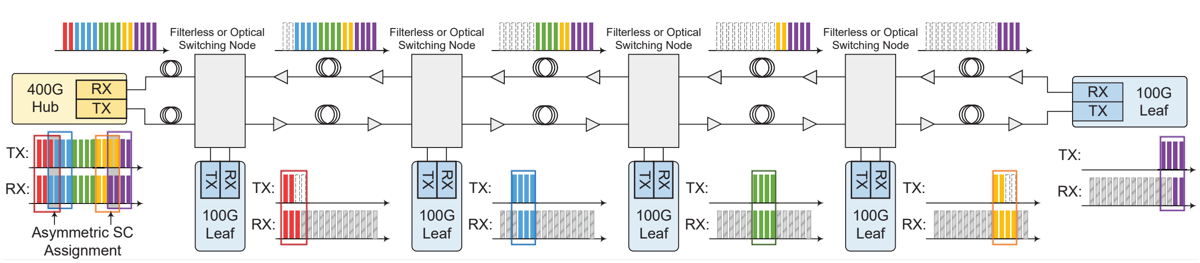


Fig. 1. Asymmetric SC allocation for DSCM-based P2MP-TRXs in a D&C optical network.

leaf P2MP-TRXs at 100 Gbps can receive/transmit an optical signal that occupies up to 4 contiguous SCs (as marked with rectangles in Fig. 1), they may only use part of these SCs in the upstream/downstream directions. Then, as shown in Fig. 1, we allocate different numbers of SCs to a leaf P2MP-TRX in upstream and downstream, respectively, saving a hub P2MP-TRX and spectra on fiber links. Specifically, if symmetric SC allocation is used, the 5 leaf P2MP-TRXs will need 19 SCs in total and thus cannot be served with a single hub P2MP-TRX that can only provide 16 SCs, while with asymmetric SC allocation, the demands of all the leaf P2MP-TRXs can be satisfied with one hub P2MP-TRX.

Fig. 2(a) shows the NC&M framework based on software-defined networking (SDN) to realize SC management in real-time. The centralized SDN controller collects the traffic status between node pairs and uses the traffic estimator to predict future traffic. The predicted traffic is then forwarded to the real-time SC management module, which leverages the basic TRSA and reactive SC-level reconfiguration modules to determine the SC-level reconfiguration scheme for serving future traffic well. Finally, the new provisioning scheme is forwarded to the network orchestrator to be implemented in the data plane. As the SC/spectrum assignment in filterless D&C optical networks is pretty straightforward, we, in the following, consider how to optimize the SC-level reconfiguration scheme in a D&C optical network $G(V,E)$ with optical filtering capability, where V and E are the sets of nodes and fiber links, respectively. Each node $v \in V$ equips a broadcast-and-select-capable wavelength switch that possesses sub-wavelength switching capability in 12.5-GHz frequency slots (FS') [5]. A traffic demand from s to d is denoted as a tuple $r(s,d,b_{s,d},b_{d,s},\tau)$, where $b_{s,d}$, $b_{d,s}$, and τ are the bandwidth demands in Gbps for $s \rightarrow d$ and $d \rightarrow s$ and the service duration, respectively. The basic TRSA module tries to serve r first with the remaining capacity of active hub P2MP-TRXs, and if no active hub P2MP-TRX is available, it then seeks to activate a new hub P2MP-TRX. The demand r is served with the found scheme with the least spectrum usage, and will be blocked if a provisioning scheme is unavailable due to the resource constraints.

Next, we propose an asymmetric reactive SC-level reconfiguration scheme, namely, aR-SC-Recfg, and use it as a supplement of the basic TRSA to better cope with the fragmented usages of SCs and FS' due to dynamic operation. Specifically, aR-SC-Recfg aims to improving provisioning performance through inter-hub coordination during reconfiguration. The bottom subplot of Fig. 2(a) gives an example, in which the demand of a new leaf P2MP-TRX (G_1-L_{new}) cannot be served by an active hub P2MP-TRX (G_1-Hub) directly or by only reconfiguring G_1-Hub and its leaf P2MP-TRXs. Specifically, as shown in Fig. 2(b), although G_1-Hub has sufficient spare SCs for the demand, the spare SCs cannot be reused because either they are fragmented and not spectrally-contiguous or their FS' are already used by G_2-Hub on the related fiber links. However, Fig. 2(c) indicates that G_1-L_{new} can be provisioned if we reconfigure G_1-Hub, G_2-Hub and their leaf P2MP-TRXs coordinately, which is exactly what aR-SC-Recfg is capable of.

The basic idea of aR-SC-Recfg is to shift the SC/FS assignments of in-service lightpaths (LPs) outward on both sides (as shown in Fig. 2(b)), to leave enough SCs and FS' to serve the ends that will be blocked otherwise. Therefore, each feasible SC-level reconfiguration scheme $y \in Y$ for a demand r needs to ensure: 1) enough available SCs/FS' can be obtained on a candidate routing path for it ($p \in P_r$), and 2) a potential hub P2MP-TRX ($h \in H_r$) has sufficient spare SCs for it. Then, aR-SC-Recfg needs to monitor: 1) the feasible free FS blocks $\{x^r_P\}$ on each candidate routing path $p \in P_r$, and 2) the feasible free SC blocks $\{x^r_H\}$ on each potential hub P2MP-TRX $h \in H_r$, and each feasible SC-level reconfiguration scheme $y \in Y$ can also be represented by a pair of FS and SC blocks (x^r_P, x^r_H). Note that, there is a special case of activating a new hub P2MP-TRX, which only cares about the feasible free FS blocks on candidate paths, and thus such a scheme is denoted as $(x^r_P, \emptyset)$. The maximum possible size of an FS or SC block can be obtained by assuming that the in-service LPs using them can be reconfigured to the lowest/highest possible spectrum locations.

After obtaining all the feasible SC-level reconfiguration schemes to store in set Y, we loop through them to find the one with the minimum reconfiguration cost to implement. Specifically, for each reconfiguration scheme $(x^r_P, x^r_H) \in Y$,

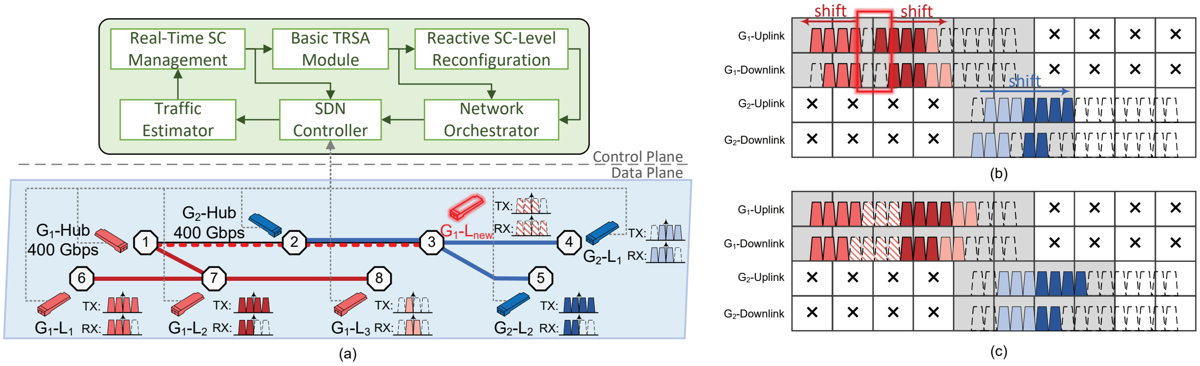
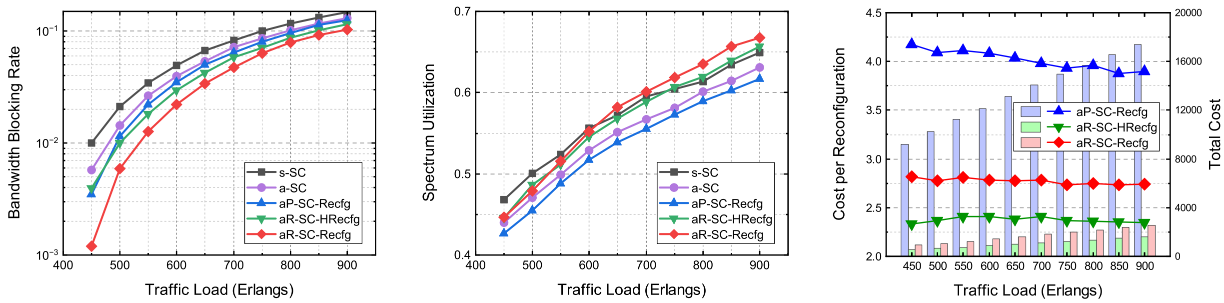


Fig. 2. (a) NC&M framework based on SDN for real-time SC allocation and reconfiguration, (b) Fragmented SC usage due to dynamic operation, and (c) Provisioning traffic demands through coordinated reactive SC-level reconfiguration.



(a) (b) (c)

Fig. 3. Results on (a) Bandwidth blocking rate, (b) Spectrum utilization, and (c) Reconfiguration cost.

its cost $C(x_P^r, x_H^r)$ is defined as the total number of SC shifts to realize it, with each FS shift on the related candidate path being converted to SC shifts in account of the mismatch between FS' and SCs [6].

3. Performance Evaluation

Simulations use the 14-node Germany topology [7], assuming that each fiber accommodates 358 FS' and each SC is 4 GHz. A hub P2MP-TRX delivers 400 Gbps, while a leaf P2MP-TRX can be at either 100 or 400 Gbps. DP-16QAM is adopted (the capacity of an SC is 25 Gbps) if the physical length of an LP is within 500 km, and DP-QPSK is used (an SC delivers 12.5 Gbps) otherwise. Then, depending on the modulation format of its SCs, a P2MP-TRX at $\{100, 400\}$ Gbps uses up to $\{4, 16\}$ SCs, or $\{2, 6\}$ FS' after considering the mismatch between FS' and SCs. In each simulation, dynamic demands are generated according to the Poisson traffic model, and for each demand, its source and destination are randomly selected, and its bidirectional bandwidth requirements are set within $[10, 100]$ Gbps. When setting up an LP between a hub-leaf P2MP-TRX pair, we reserve an FS as the guard-band on each side of the LP's spectrum usage. In addition to aR-SC-Recfg, we consider four benchmarks: 1) symmetric SC allocation without reconfiguration (s-SC), 2) asymmetric SC allocation without reconfiguration (a-SC), 3) asymmetric reactive SC-level reconfiguration only considering single hub P2MP-TRXs (aR-SC-HRecfg) that is modified based on the approach in [2], and 4) asymmetric proactive SC-level reconfiguration (aP-SC-Recfg) adapted from the approach in [6].

The simulation results on the bandwidth blocking probability, spectrum utilization, and reconfiguration cost are shown in Figs. 3(a)-3(c), respectively. In Fig. 3(a), we can see that the schemes without reconfiguration provide higher blocking probability than those with, justifying the necessity of SC-level reconfiguration. For those without reconfiguration, a-SC achieves lower blocking probability than s-SC, which confirms the benefit of asymmetric SC allocation. This benefit can also be seen in Fig. 3(b), which indicates that s-SC occupies more spectra than a-SC, wasting spectrum resources due to its unwise provisioning scheme. Our proposed aR-SC-Recfg provides the lowest blocking probability among all the schemes in Fig. 3(a), while Fig. 3(b) suggests that aR-SC-Recfg utilizes the most spectra when the traffic load is relatively high ($\geq$ 650 Erlangs). Therefore, by combining Figs. 3(a) and 3(b), we can conclude that aR-SC-Recfg utilizes P2MP-TRXs the best and achieves the most efficient spectrum usage to provision dynamic traffic demands. Finally, Fig. 3(c) compares the reconfiguration cost of aR-SC-Recfg, aR-SC-HRecfg and aP-SC-Recfg. As aR-SC-HRecfg only considers single hub P2MP-TRX for SC-level reconfiguration, its reconfiguration cost is the lowest. However, the reconfiguration cost of aR-SC-HRecfg is just slightly lower than that of aR-SC-Recfg (14.3% lower on average), while the blocking probability of aR-SC-Recfg is much lower than that of aR-SC-HRecfg, which is achieved by the effective inter-hub coordination during SC-level reconfiguration. Between aR-SC-Recfg and aP-SC-Recfg, aR-SC-Recfg uses significantly less reconfiguration cost to achieve lower blocking probability.

4. Conclusion

We proposed a scheme to address the dynamic service provisioning in D&C optical networks based on P2MP-TRXs, where asymmetric SC allocation and SC-level reconfiguration was introduced to optimize the utilization of spectra and P2MP-TRXs with low operational complexity. Extensive simulations confirmed the effectiveness of our proposal.

References

[1] D. Welch *et al.*, "Digital subcarrier multiplexing: Enabling software-configurable optical networks," *J. Lightw. Technol.*, Feb. 2023.
[2] H. Shakespear-Miles *et al.*, "Multi-agent-based dynamic optical subcarrier allocation for near real-time P2MP operation," *ECOC 2022*.
[3] Q. Wang *et al.*, "On real-time optical subcarrier management in P2MP networks with mixed-strategy gaming," *OFC 2023*.
[4] D. Moniz *et al.*, "Design strategies exploiting C+L-band in networks with geographically-dependent fiber upgrade expenditures," *OFC 2020*.
[5] Z. Zhu *et al.*, "Impairment- and splitting-aware cloud-ready multicast provisioning in elastic optical networks," *IEEE/ACM Trans. Netw.*, Apr. 2017.
[6] R. Li *et al.*, "Service provisioning in wavelength-switched optical networks based on P2MP transceivers," *ACP 2023*.
[7] J. Pedro *et al.*, "Cost-effective strategies to scale the capacity of regional optical transport networks," *J. Opt. Commun. Netw.*, Feb. 2022.