# Dynamic Subcarrier Allocation for Multipoint-to-Point Optical Connectivity

H. Shakespear-Miles[1], M. Ruiz[1], A. Napoli[2], and L. Velasco[1*]
[1]Optical Communications Group (GCO), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
[2]Infinera, Munich, Germany
e-mail: luis.velasco@upc.edu

***Abstract:*** *A mathematical programming model is proposed to dynamically allocate subcarriers in the upstream direction of point-to-multipoint connections based on Digital Subcarrier Multiplexing. Numerical results show significant capital and energy cost reduction.*
***Keywords:*** *Digital Subcarrier Multiplexing, Point-to-multipoint connections.*

## I. INTRODUCTION

Digital Subcarrier Multiplexing (DSCM) systems bring large efficiency and cost reduction for access/metro applications, as they use multiple subcarriers (SC), e.g., 4, 8 or more, instead of a single one [1][3]. In typical point-to-point (P2P) systems, the DSCM is realized at the transmitter (Tx) side and each SC is individually detected and post-processed at the coherent receivers (Rx). However, point-to-multipoint (P2MP) connectivity is also possible, which would be beneficial to support of advanced 5G and 6G infrastructure [2]. In the architecture proposed by the authors in [2], a number of edge nodes communicate with a single hub; in the upstream direction, the SCs generated by the edge nodes were all aggregated at the hub, whereas in the downstream direction, the SCs generated by the hub were received by the edge nodes. In such architecture, each edge node had assigned a subset of SCs, thus creating P2P pipes inside a P2MP optical connection.

A P2MP approach can result into large capital cost reduction coming from the reduction in the number of devices in the hub node. Cost reduction can be made even larger in dynamic traffic scenarios, where not all the SCs need to be active, i.e., during some time intervals when the traffic decreases. Such dynamic spectrum allocation can result in an increment on the number of edge nodes that can be supported in the P2MP connection. In addition, the authors in [3] showed that important energy savings can be obtained by activating only the SCs needed to support the current traffic.

In this paper, we focus on proving dynamic spectrum allocation to the edge nodes for more efficient P2MP connectivity. Owing to the fact that several Txs can request allocating new SCs for the incoming traffic, in this paper we solve this problem assuming a centralized network controller. A simple and efficient Integer Linear Programming (ILP) model is proposed to find the optimal spectrum allocation for the edge nodes. In this regard, we focus on the upstream direction, that we call multipoint-to-point (MP2P), where the edge nodes (Tx) demand a variable number of SCs as a function of the local traffic being conveyed to the hub node (Rx). Note that this problem is more complex than that for the downstream direction, where only the hub node manages the spectrum allocation.

## II. DYNAMIC SC ALLOCATION FOR MP2P CONNECTIVITY

Fig. 1a illustrates a MP2P optical connection based on DSCM, where $n$ Txs at the edge nodes communicate with a single Rx at the hub node. Every Tx has a portion of the spectrum, i.e. *wavelengths*, assigned (dotted lines), where its SCs are allocated. The SCs of every Tx are aggregated using, e.g., an optical coupler. It is worth noting that Rx needs to support the aggregated number of SCs. A possible example would be 4 Tx supporting 4 SCs each, and one Rx supporting 16 SCs in total. Although it would be possible that the Tx could allocate every SC in a different part of the optical spectrum, we assume that this is not possible, to reduce the cost of the Tx, and all the SCs need to be allocated in a small portion of the spectrum, named *channel*, with minimum width to support the required SCs.

Fig. 1b summarizes our approach, where the channel assigned to every Tx might overlap with that of other Tx; we name this *spectrum oversubscription*. The objective is to increase the number of Txs participating in the MP2P connection.

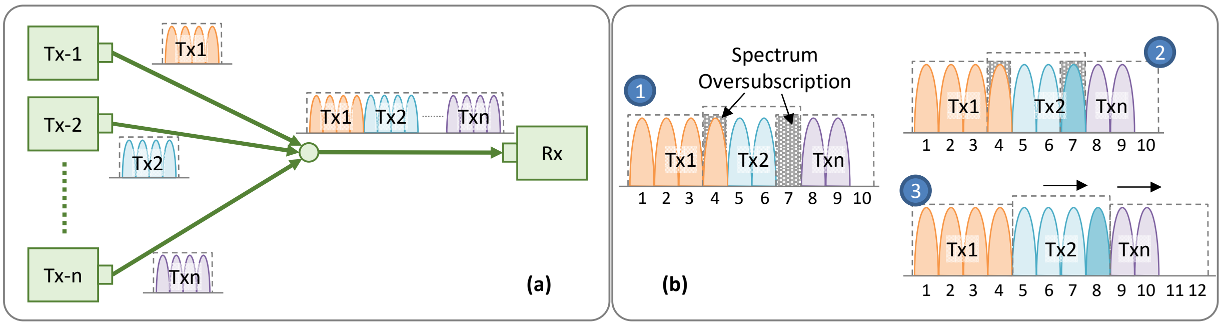


Fig. 1. MP2P connectivity based on DSCM (a) and dynamic SC allocation and reconfiguration.

In the first case in Fig. 1b (labeled 1), spectrum oversubscription is observed between the channel assigned to Tx1 and Tx2 (wavelength 4), as well between Tx2 and Txn (wavelength 7). Note that Tx1 has a SC active in wavelength 4, whereas wavelength 7 is not in use. Let us imagine that Tx2 needs to allocate a new SC to cope with some increment of traffic. Such SC must be allocated inside the assigned channel, which in this case is possible as wavelength 7 was available (2). At this time, Tx2 cannot allocate new SCs since all the wavelengths in the assigned channel are being used. Therefore, a reconfiguration in the neighboring assigned channel (that for Tx1 or Txn) can be tried. In (3), the channel assigned to Txn has been reconfigured, as well as the allocated SCs (SC in wavelength 8 has been deactivated and SC in wavelength 10 activated). In consequence, wavelength 8 has been released and a SC Tx2 can allocate the needed SC.

## III. **ILP MODEL**

This section proposes an ILP model to dynamically solve SC allocation and reconfiguration. The problem statement is:
Given:

- the total spectrum available for the MP2P connection, represented by ordered set $W = \{w_1, w_2, \ldots, w_{|W|}\}$, where $|W|$ is the maximum number of wavelengths supported by the Rx.
- the set of candidate channels described by set $C = \{c_0, c_1, c_2, \ldots c_{|C|-1}\}$, where $c_0$ is the empty set and every $c_i$ ($i$:1..|C|-1) is a subset of contiguous wavelengths of size 1..$m$, being $m$ the maximum number of wavelengths supported by each Tx. We assume all Tx with the same characteristics.
- a set of Txs $T=\{t_i, t_2, .., t_n\}$, where every Tx $t$ has an associated capacity requirement $k_t$.

Output: the configuration of every wavelength and its assignment to every Tx, and the channel assigned to every Tx.
Objective: 1) minimize the amount of lost traffic; 2) to minimize the number of used SC, thus minimizing energy cost; and 3) minimize the number of SCs that are reconfigured.

The parameters and decision variables of the problem are:

| | | | |
|---|---|---|---|
| $\alpha_i$ | Weights of the multi-objective function | $c_t$ | Current channel selected for transponder $t$. |
| $k_c$ | Capacity of channel $c$ | $u_{tc}$ | Whole number describing the difference between $k_t$ and $k_c$. |
| $\delta_{tc}$ | Equal to 1 if channel $c$ is a candidate for transponder $t$, 0 otherwise. | $\delta_{cw}$ | Equal to 1 if wavelength $w$ is in use for candidate channel $c$, 0 otherwise. |
| $v_{tc}$ | Total number of active wavelengths $w$ in channel $c$ for transponder $t$. | $s_{tw}$ | Equal to 1 if Tx $t$ current occupies wavelength $w$; 0 otherwise. |
| $r_{tc}$ | Whole number describing the number of wavelengths $w$, that were modified with respect to $c_t$. | $x_{tc}$ | Binary decision variable, equal to 1 if channel $c$ is assigned to Tx $t$; 0 otherwise. |

In order to ensure fast computation time, the number of possible solutions was limited through a pre-calculation following a similar approach than in [4], where the set of channels $C$ is calculated as $\delta_{tc} = 1, \forall t \in T, c \in C \mid overlap(s_{tw}, c_t) \mid\mid c == c_0$ and $\delta_{cw}$ can be easily calculated for the channels. Additionally, we compute $u_{tc} = \max(k_t - k_c, 0), \forall t \in T, c \in C \mid \delta_{tc} = 1$ to calculate the traffic that could be lost, $v_{tc} = |c|, \forall t \in T, c \in C$ to track the number of wavelengths in use, and $r_{tc} = |\, index(c_t) - index(c)|, \forall t \in T, c \in C$ to measure the number of SC reconfigurations made for a potential new channel.

The mathematical programming formulation for the problem is as follows, where the objective function (eq. (1)) minimizes the three defined objectives, which are weighted by the $\alpha_i$ parameters, where $\alpha_1 > \alpha_2 > \alpha_3$ to maintain the priority of the objectives. Constraint (2) ensures that only one Tx can be assigned to one eligible channel, and constraint (3) ensures that every wavelength can be occupied with, at most, one and only one SC from one single Tx.

$$\min \sum_{t\in T} \sum_{c\in C} [\propto_1 \cdot u_{tc} + \propto_2 \cdot v_{tc} + \propto_3 \cdot r_{tc}] \cdot x_{tc} \tag{1}$$

subject to:

$$\sum_{c\epsilon C} \delta_{tc} \cdot x_{tc} = 1 \quad \forall t \epsilon T \tag{2}$$

$$\sum_{t\epsilon T} \sum_{c\epsilon C} \delta_{tc} \cdot \delta_{cw} \cdot x_{tc} \leq 1 \quad \forall w \epsilon W \tag{3}$$

## IV. **RESULTS**

A simulation scenario was set up following a similar architecture that that outlined in Fig. 1, with up to 8 Txs and 1 Rx; Txs can support up to 4 SCs and the Rx up to 16 SCs. For simulation purposes we assumed that every SC is configured with 16QAM, 11 Gbaud, and 60 Gb/s capacity. The simulator was developed in Python using the PuLP package for solving the ILP problem. To simplify the discussion, we consider two extreme scenarios with Txs with traffic following similar daily patterns (see Fig. 2); in Fig. 2(a) the traffics are almost in-phase, whereas in Fig. 2(b) they are in opposite phase. To study the effects, we define *traffic multiplexing ratio* as a way to quantify the phase synchronization of the traffics generated by the Tx (0≡*in-phase* and 1≡*opposite-phase*). Note that the traffic volume in the peak entails that Txs will require allocating 4 SCs.

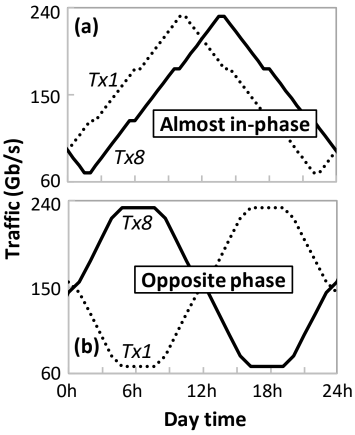
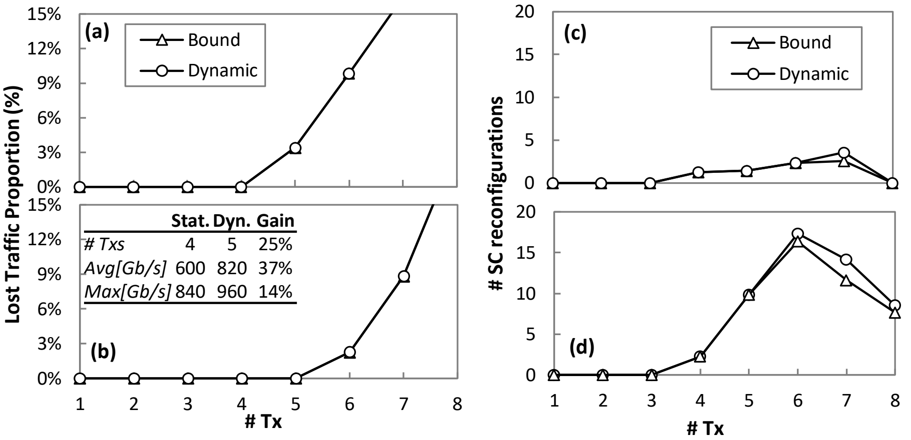


Fig. 2. Traffic Scenarios



| | Stat. | Dyn. | Gain |
|---|---|---|---|
| *# Txs* | 4 | 5 | 25% |
| *Avg[Gb/s]* | 600 | 820 | 37% |
| *Max[Gb/s]* | 840 | 960 | 14% |

Fig. 3. Dynamic vs Static Performance Analysis

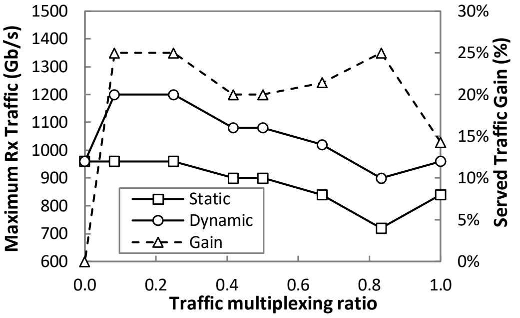


Fig. 4. Influence of traffic multiplexing ratio

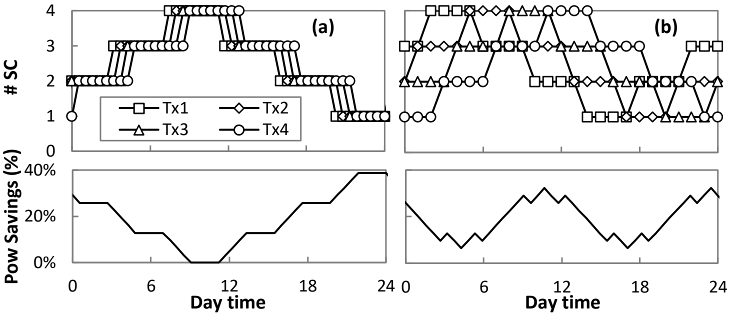


Fig. 5. Power Consumption Analysis

The *dynamic* SC allocation was compared against a *static* SC allocation in which a maximum of 4 SCs would be used by each Tx, independently of the traffic seen. Additionally, contiguity was relaxed in the ILP model for comparison purposes, representing a *bound* for the reallocation method.

The proportion of lost traffic (traffic rejected over incoming traffic) for the almost in-phase traffic scenario is presented in Fig. 3(a). As for the static method (not shown in the figure), the dynamic and bound ones are able to support 4 Txs without loss. Traffic loss appear when the number of Txs increases, since all the Tx require allocating 4 SCs simultaneously. Interestingly, the dynamic and bound methods are able to support 5 Txs without traffic loss under the opposite phase traffic scenario in Fig. 3(b). The inset in the figure summarizes the gain w.r.t. the static method in terms of number of Txs and supported traffic.

Fig. 3(c)-(d) show the average number of SC reconfigurations per Tx to avoid conflicts from spectrum oversubscription. Under the opposite phase traffic scenario, about 10 reconfigurations were necessary to support 5 Txs without traffic loss. Hence, a relatively small amount of reconfigurations translates to a large amount of gain. To further explore the influence of the traffic multiplexing ratio together with the peak traffic volume, other traffic scenarios were examined. Fig. 4 presents the maximum traffic seen without traffic loss and the gain for the static (with 4Txs) and dynamic (with 5 Txs) methods as a function of the traffic multiplexing ratio. We observe that as soon as the traffic multiplexing ratio increases, the dynamic method is able to produce sizable gains (15-25%) compared to the static one.

Finally, let us study the energy consumption for the two extreme traffic scenarios in a configuration with 4Txs. The number of SCs in use and the power savings compared to the static method are presented in Fig. 5(a) for the almost in-phase and Fig. 5(b) for the opposite phase scenarios. As expected, power savings are concentrated during off-peak periods under the almost in-phase traffic scenario, whereas they are more spread under the opposite phase one, being around 20% on average under both scenarios.

## V. CONCLUSIONS

We showed that dynamic SC allocation brings significant capital and operational cost reduction in P2MP connectivity, as compared to the static SC allocation. In addition, we observed that imposing contiguity constraints to the Tx does not affect the benefits from the dynamic SC allocation. Hence, imposing such constraint can potentially bring cost reduction from the simplification of the Tx design.

## ACKNOWLEDGMENT

The research leading to these results has received funding from the H2020 B5G-OPEN (G.A. 101016663), the MICINN IBON (PID2020-114135RB-I00), and the ICREA Institution.

## References

[1] T. Rahman *et al*., “Digital Subcarrier Multiplexed Hybrid QAM for Data-rate Flexibility and ROADM Filtering Tolerance,” in Proc. OFC, 2016.

[2] D. Welch *et al*., “Point-to-Multipoint Optical Networks Using Coherent Digital Subcarriers,” IEEE/OPTICA Journal of Lightwave Technology, vol. 39, pp. 5232 - 5247, 2021.

[3] L. Velasco *et al*., ”Autonomous and Energy Efficient Lightpath Operation based on Digital Subcarrier Multiplexing,” IEEE Journal on Selected Areas in Communications, vol. 39, pp. 2864-2877, 2021.

[4] M. Klinkowski *et al*., “Elastic Spectrum Allocation for Time-Varying Traffic in FlexGrid Optical Networks,” IEEE Journal on Selected Areas in Communications (JSAC), vol. 31, pp. 26-38, 2013.