# A Network Dimensioning Algorithm for Exploiting the Capabilities of Subcarrier-based Point-to-Multipoint Coherent Optics

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**Abstract** *We present the first generalized dimensioning algorithm for optical networks with subcarrier-based Point-to-Multipoint (P2MP) coherent transceivers, which covers hub-spoke determination, transceiver allocation, along with light-tree routing and spectrum assignment, in arbitrary topologies. The benefits of P2MP optics in a metro-network case study are evaluated.* ©2022 The Author(s)

## Introduction

Digital-subcarrier based Point-to-Multipoint (P2MP) coherent pluggable transceivers have recently been presented, with the capability to be both Point-to-Point (P2P) and P2MP, splitting the traffic into independent subcarriers, allowing transceivers at different data rates to communicate, e.g. an optical connection using up to four 25G subcarriers can be established from a 100G transceiver to a 400G one [1]. Such technology motivates research on how the P2MP paradigm can reshape the network architecture, and the new design algorithms needed for that.

Most initial studies on the cost benefits of P2MP technology focus on simple tree, chain and ring topologies and pure hub-spoke (H&S) traffic patterns [1][2], where the majority of the traffic is exchanged between hub and spokes, and much less traffic passes between spokes. In [3], we proposed a capacity planning algorithm and studied the P2MP advantages in fault-tolerant rings for different traffic profiles. For general mesh networks, two ILP-based approaches were proposed in [4] and [5] optimizing various aspects. However, both studies assume a given set of hub and leaf nodes, and strictly H&S traffic demands. In this paper, we consider the general case, where all nodes can make use of P2MP aggregation and potentially serve as hub nodes in established light-trees, and a mixed traffic profile is assumed. In [6], we performed a preliminary approach without considering realistic wavelength blocking constraints. Here, we propose a novel network dimensioning algorithm which assigns subcarrier traffic demands to light-trees (determining transceiver allocation), and performs routing and spectrum assignment. We perform a multi-period study on the 5G metro reference scenario described in [7] using the proposed approach to evaluate potential benefits of P2MP equipment.

## Problem definition

We assume a physical mesh fiber network where optical connections are established forming a given IP topology, along with the required capacity in each IP adjacency. IP links are implemented as a set of bidirectional optical connections between the end nodes. If P2P technology is used, the resulting IP link capacities determine the transceiver rates required at each node and the problem reduces to standard routing and spectrum assignment. If P2MP transceivers are employed, end nodes of different IP links can share transceivers, forming light-trees, making transceiver allocation more complex. The key difference –when considering P2MP- is that it requires partitioning the capacity demands, expressed in terms of the number of subcarriers (i.e., subcarrier demands), into logical trees. Such a decision (i) defines the hub/spoke nature of each node in each tree, and the transceiver types, and (ii) is tightly coupled to the route and spectrum assignment of each light-tree. To ensure feasible subcarrier assignment within this allocated spectrum, we limit each tree to one “hub”, i.e., 1 shared transceiver, forming hub-spoke trees. The objective is to minimize the overall transceiver costs.

## Network Dimensioning Algorithm: SSTG

This section presents the Smart Subcarrier Tree Growth (SSTG) algorithm proposed for solving the problem of forming light-trees, routing and spectrum assignment with P2MP transceivers. The algorithm inputs are the set of network nodes, fiber links between them, and the IP link capacity demands $s_{ij,}$ expressed as the number of subcarriers to carry between each node pair ($i$,$j$), assumed as bidirectional. We use $s^*_{ij}$ to denote the subcarrier demands *pending* to be carried.

SSTG has an outer and an inner loop. Each iteration of the outer loop creates a light-tree, and assigns a route, spectrum and subcarriers to it. For that, first the node pair with highest $s^*_{ij}$ pending capacity demand is selected. Transceivers are allocated to the end nodes with the rate needed to serve the demands, or the highest available rate if the demands exceed it. The maximum possible subcarrier demands are then established via a *k*-shortest path and first fit assignment. If that is not possible, blocking occurs, and the algorithm terminates.

The inner loop *grows the tree*, adding to it in each iteration one more P2P connection with subcarriers, as long as there exist pending demands and the tree has room for them. To choose the new connection to add, the inner loop tries all available node pairs (*i*,*j*) with (1) pending SC demands $s^*_{ij}$, (2) where at least one node already has a transceiver in the tree, (3) and adding such connection would not mean that more than one transceiver in the tree would be a hub (i.e. it has connections with >1 node). The number of connections' subcarriers to add is the maximum possible, according to $s^*_{ij}$ and the maximum tree capacity according to the usable transceivers. If both nodes (*i*,*j*) of a tentative connection have transceivers, the tree route and spectrum is reused. If only one of them has, the node outside the tree *n*' is connected to it, by adding a path from *n*' to a so-called *stitch node* *n*'', already present in the tree. All potential stitch nodes are tried, and a *k*-shortest path and first-fit search of a valid stitch connection (*n*',*n*'') is evaluated, so the spectrum of all the tree is recalculated. The (*i*,*j*) connection to be added, and the stitch node *n*'', are the ones that minimize the total spectrum occupied (summing up all links in the tree), divided by the number of tree subcarriers. Ties are solved by first preferring the option with lower average cost per subcarrier, and then with lower average length in km per subcarrier. Such preferences disincentive inefficient subcarrier and tree assignments that include long paths only for adding a small number of subcarriers to the tree.

If no connections can be added to the tree, the tree is allocated, and the outer loop starts again creating a new tree. The algorithm ends when all subcarrier demands are carried, or the spectrum is exhausted so blocking occurs at the start of the outer loop.

## Numerical Results

### *Simulation Setup*

The 5G optical metro reference scenario used for this study is Telecom Italia reference fiber topology in [7]. The physical network is composed of 52 nodes and 72 bidirectional links structured into two tiers of metro-access and metro-core nodes [7]. Optical transparency is assumed within the entire regional network.

A static traffic model is considered representing the aggregated traffic of 3 types of traffic flows: (i) P2P traffic, (ii) heterogeneous server-mediated traffic and (iii) edge computing and storage services as described in [7]. The network is assumed to serve a population of 2.5M. According to [8] for 2021, the average Internet user generates 57GB/month, giving an average of 176 Kbps, with peak hours roughly 6 times busier (1 Mbps). We normalize the above mentioned traffic model to represent short (1-2 year), medium (5 years) and long-term (10 years) peak traffic per user, assuming a CAGR of roughly 31%, as shown in Table 1.

To generate different IP topologies, the percentage of IP bidirectional adjacencies established with respect to a fully connected IP topology, referred to as the IP density, is varied, ranging from 10-50% in 10% increments. The set of IP adjacencies chosen for each topology is selected in decreasing order of the highest traffic demands between node pairs. The required capacity of each IP adjacency is determined by assuming regular OSPF/ECMP IP routing.

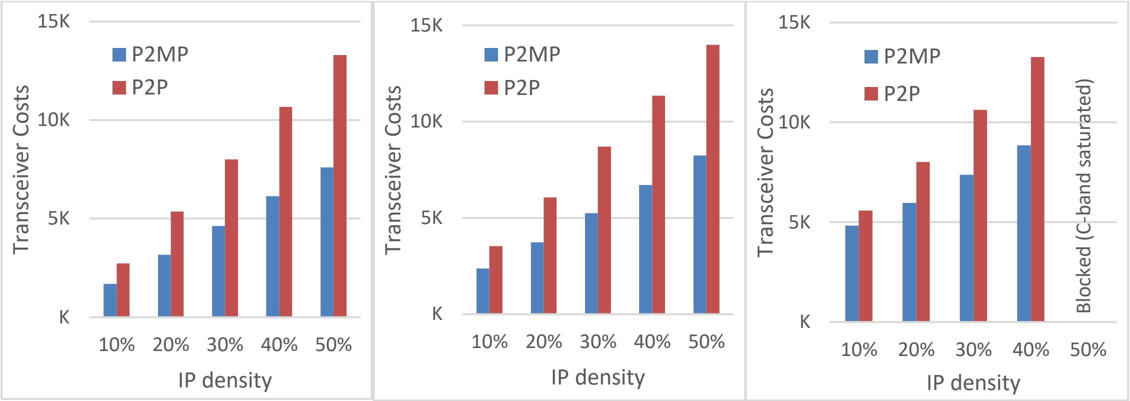
We consider transceiver rates of 100, 400 and 800 Gbps for both P2P and P2MP equipment, with 25G subcarriers for the P2MP case. The costs are assumed equal for P2P and P2MP, and proportional to the square root of capacity as shown in Table 1 [9][10]. For spectrum allocation, we assume for both P2P and P2MP, an occupation of 25 GHz for 100G, 75 GHz for 400G and 137.5 GHz for 800G. These are adaptations to the 12.5 GHz grid of the respective 16, 64 and 130 GHz occupations [10]. For the P2MP solutions, a light tree occupies the spectrum corresponding to the hub transceiver. The simulation setup is performed with the E-lighthouse Network Planner [11].

**Tab. 1:** Reference Scenario.

| **Topological data** | | **Peak traffic per user (Mbps)** | | **Transceiver costs** | |
|---|---|---|---|---|---|
| Nodes | 52 | Short term | 2 | 100G | 10 |
| Links | 72 | Medium term | 5 | 400G | 20 |
| Population | 2.5M | Long term | 20 | 800G | 20.8 |

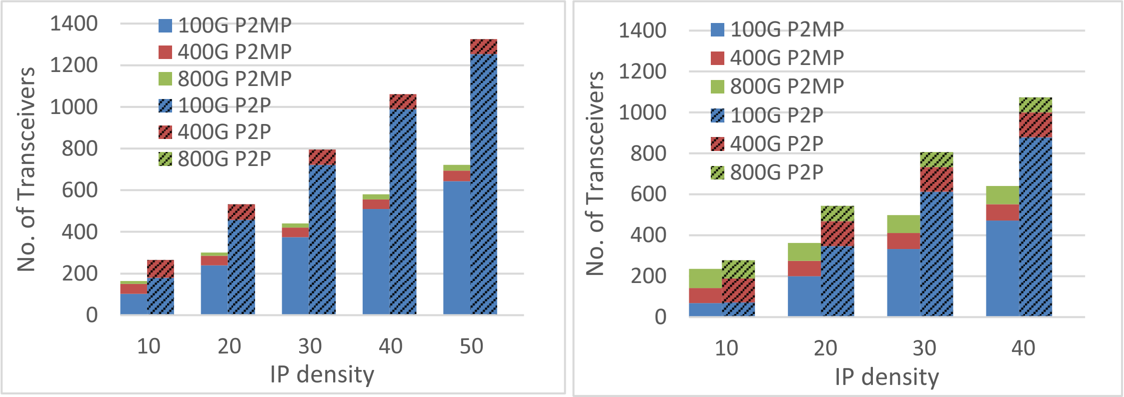
### *Results*

Figure 1 shows transceiver costs of the capacity planning solutions using P2P vs. P2MP transceivers for varying IP densities for short, medium and long-term traffic. We can see that costs are reduced with P2MP equipment in all



(a) (b) (c)

Fig. 1: Transceiver costs for (a) short (b) medium and (c) long-term traffic



(a) (b)

Fig. 2: Number of transceivers for (a) medium and (c) long-term traffic

cases (ranging from 13% to 43%), but benefits increase for denser IP topologies. This accords with the fact that denser topologies imply more lower-capacity IP links allowing for more advantages of aggregation at subcarrier granularity of P2MP. Note that while overall transceiver costs increase with IP density, higher IP densities imply fewer IP hops reducing IP layer costs and latency. Cost benefits decrease for longer-term traffic, but are still significant (33%) at higher IP densities before blocking occurs, which happens when the C-band (4 THz in our tests) is exhausted.

To provide more insight into the obtained solutions, Figure 2 plots the number of transceivers used in the medium and long term time frames, along with the transceiver rate distribution. We can see that the P2MP solutions use fewer transceivers in all cases, with savings ranging from 15% to 47%, following the same trends as transceiver costs. For a fixed traffic load, as the IP density increases, more lower rate transceivers are needed, particularly for P2P solutions which do not allow for aggregation. Short term traffic is omitted for lack of space, but follows similar trends.

## Conclusions

In this paper, we propose the first network dimensioning algorithm for P2MP optics in general mesh topologies, solving demand partitioning into hub/spoke trees, transceiver allocation, and routing and spectrum assignment. We use this algorithm to perform a multi-period cost analysis exploring the benefits of P2MP coherent optics on a reference metro aggregation use case. In all algorithm results, P2MP optics compared to P2P could bring significant cost savings and employ fewer transceivers, although advantages decrease as traffic increases, particularly for sparser IP topologies. However, even for long term traffic, P2MP optics can still bring high savings for dense low latency IP topologies.

## Acknowledgements

The research leading to these results has received funding from the European Commission through the H2020 B5G-OPEN (G.A. 101016663), and by the Spanish national projects ONOFRE-3 (ref. PID2020-112675RB-C41) and Go2Edge (ref. RED2018-102585-T).

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