Optimized Physical Design of Metro Aggregation Networks using Point to Multipoint Transceivers

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Abstract: We present an ILP-based optimization for deploying transceivers exploiting digital subcarrier multiplexing while fulfilling filterless node conditions. Applying this method to a reference mesh network reduces transceiver cost by a figure between 18% and 38%. © 2022 The Author(s)

1. Introduction

The cost of optical transceivers is one of the main capital expenditures faced by communication service providers as they upgrade their infrastructure to support the extensive deployment of 5G services, the advance of the Internet of Things (IoT), fast-growing video streaming, and other various applications.

Recently, a novel type of optical transceiver, which supports point-to-multipoint (P2MP) connectivity, has been proposed in [1]. The key difference – compared to previous P2MP solutions [2, 3] – is that it uses digital subcarrier multiplexing (DSCM), effectively slicing an optical channel's capacity and enabling that a single higher-rate transceiver communicates directly with multiple lower-rate devices. This enables to operate with fine granularity (e.g., 25 Gb/s per subcarrier) while keeping transceiver complexity and cost similar to those of a conventional point-to-point (P2P) transceiver that operates at the same maximum line rate. This also significantly enhances the network flexibility and capacity allocation over time.

In their seminal work, Bäck et al. [1] reported total cost of ownership (TCO) savings (including line system and switch/router savings) for a specific service provider network that could reach up to 76% over five years, assuming a 30% yearly traffic growth, when compared to a traditional P2P transceiver solution.

Importantly, the utilization of DSCM-based P2MP transceivers – between a hub node and multiple leaf nodes of a given network – relies on the assumption that intermediate nodes perform optical power splitting/combining in the downstream/upstream direction. This corresponds to using a filterless or drop-and-waste architecture [4, 5] at these nodes, which use simple passive optical splitter/combiner devices. Early works exploiting this novel type of transceiver, such as the one in [6], assumed aggregation networks based on passive tree topologies, which naturally fit the concept. However, DSCM-based transceivers can also be applied in meshed topologies, which are common in metro-aggregation networks, provided that optical trees can be overlaid and loops avoided [4]. This requires embedding the node design, i.e., defining where spectrum blocking needs to be enforced, in the overall optimization process. Previous works have already investigated this optimization problem but only considered traditional P2P optical transceivers [7].

This paper proposes for the first time an integer linear programming (ILP) model to jointly optimize the deployment of P2MP transceivers – i.e., routing, modulation format, and subcarrier (SC) aggregation – and the design of the nodes' architecture in a mesh metro-aggregation network topology. The ILP model is employed to assess the effectiveness of DSCM-based P2MP transceivers in a reference mesh network. The network design results highlight the potential savings that can be achieved by such a solution when compared to using traditional P2P optical transceivers.

2. Point-to-Multipoint Architecture and Optimization Framework

In the P2MP architecture, the high-capacity (e.g., 400G) transceiver located at the hub node transmits an optical signal formed by multiple SCs. The lower-capacity (e.g., 25G or 100G) transceivers at the leaf nodes receive the whole optical signal but only process the SC(s) intended for them. They transmit these SC(s) in the reverse path, which are optically merged to create the signal that reaches the hub node. Noteworthy, the feasibility of this P2MP concept has been demonstrated in both lab experiments and field trials [6].

The P2MP optimization problem aims to find the best optical tree and configuration of P2MP transceivers in terms of cost that satisfies all traffic requests. For this purpose, firstly, we calculate a set of shortest paths from every leaf node in I to the hub and store them in J. Then, we compute link-path and leaves-path incident matrices represented by $B(u,v,j)$ and $P(i,j)$, respectively. The main summary of input parameters and decision variables is tabulated in Table 1. The objective function $z = \sum_{j\in J}\sum_{o\in O_h}\Delta_{jo}\times C_o + \sum_{i\in U^-}\sum_{j\in J}\sum_{o\in O_l}\delta_{ijo}\times C_o$, models the transceivers capital expenditures that has to be minimized subject to the constraints listed in Table 2.

Table 1: ILP model parameters and variables

Input Parameters	
$G(U,E)$	Network graph with nodes $u \in U$ and links $l=(u,v)\in E$.
U^-	A subset of U defining leaf nodes.
$P(i,j)$	Leaves-path incident matrix; p_{ij} ∈[0,1] and equal to one if path j contains leaf i.
$B(u,v,j)$	Link-path incident matrix; b_{uvj} ∈[0,1] and equal to one if path j contains link (u,v).
$T(i)$	Traffic expressed by number of $25Gb/s$ SCs for leaf i.
O_l,O_h	Transceiver types for leaf and hub nodes.
M_j	Modulation factor for path j.
C_o, G_o	Cost and capacity of transceiver type o.
W	Very large positive number.
Decision Variables	
λ_{ij}	Binary variable equal to 1 if leaf i communicates with the hub through path j.
Δ_{jo}	Number of transceivers of type o used at hub communicating via path j.
δ_{ijo}	Number of transceivers of type o used at leaf node i communicating via path j.
β_{uv}	Integer variable indicating flow on link (u,v).
π_j	Binary variable equals to 1 if path j is used.
θ_{uv}	Binary variable equals to 1 if link (u,v) is used.

Table 2: ILP model constraints

$$\sum_{j\in J}\lambda_{ij}=1, \quad \forall i\in U^-. \tag{1}$$

$$\lambda_{ij}\le P(i,j), \quad \forall i\in U^-, \forall j\in J. \tag{2}$$

$$\sum_{i\in I}\sum_{o\in O_l} G_o\delta_{ijo} \le \sum_{o\in O_h} G_o\Delta_{jo}, \quad \forall j\in J. \tag{3}$$

$$T(i)\lambda_{ij}\le \sum_{o\in O_l} G_o M_j\delta_{ijo}, \quad \forall i\in U^-, j\in J. \tag{4}$$

$$W\pi_j \ge \sum_{o\in O_h}\Delta_{jo}, \quad \forall j\in J. \tag{5}$$

$$W\theta_{uv}\ge \sum_{j}\pi_j B(u,v,j), \quad \forall (u,v)\in E. \tag{6}$$

$$\sum_{(u,v)\in E}\theta_{uv}=N. \tag{7}$$

$$\sum_{v\in U^-}\beta_{rv} - \sum_{v\in U^-}\beta_{vr} = N. \tag{8}$$

$$\sum_{v\in U^-}\beta_{vu} - \sum_{v\in U^-}\beta_{uv} = 1, \quad \forall u\in U^-. \tag{9}$$

$$0\le \beta_{uv},\beta_{vu}\le N\theta_{uv}, \quad \forall (u,v)\in E\cup E'. \tag{10}$$

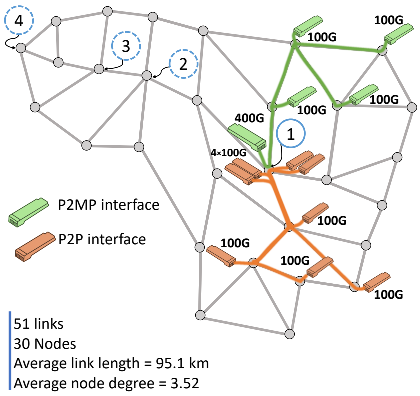

Fig. 1: Reference network and examples of P2P and P2MP transceivers deployment (8 P2P vs 5 P2MP interfaces).

Constraints (1) and (2) enforce all leaf nodes communicate with the hub node only once and via a path that includes those nodes, respectively. Constraints (3) and (4) count the number of transceivers at the hub and leaf nodes. Constraint (5) finds chosen paths for the P2MP deployment, while constraint (6) finds the links of those paths. A single commodity approach is used for tree construction [8]. The first condition is that the size of the tree must be N, where N is the number of leaf nodes (constraint (7)). N units of flow are sent from the hub node to all leaf nodes in (8), and every leaf node consumes only one unit of flow by constraint (9). Finally, condition (10) guarantees that flows exist only in both directions of those links selected for the tree construction and do not exceed the size of the tree.

3. Results and Discussion

Figure 1 depicts the reference mesh network considered in this work. Moreover, two instances of P2P (brown) and P2MP (green) transceiver deployment are illustrated. To study the impact of hub location on the effectiveness of P2MP, we consider four nodes from the center towards the edge of the network as potential hubs. A set of eight candidate shortest paths is considered for every leaf-hub pair. We assume dual-polarization QPSK and 16QAM as the available modulation formats with 4 GBaud per SC in the P2MP transceivers. This results in 12.5G (QSPK) and 25G (16QAM) capacity per SC. The parameter M_j models the impact of the modulation format on the SC capacity. For simplicity, considering 16QAM as the highest modulation format, M_j takes "1" for paths shorter than or equal to 500 km, whereas QPSK is assigned for routes longer than 500 km by choosing $M_j = 0.5$. 400G and 100G transceivers are available at the hub nodes, whereas 100G and 25G can be used at leaf nodes. For comparison purposes, the scenario using P2P 100G transceivers is also considered by performing a set of modifications to the ILP model. A non-uniform traffic pattern is defined in which the number of SCs required for each leaf node is

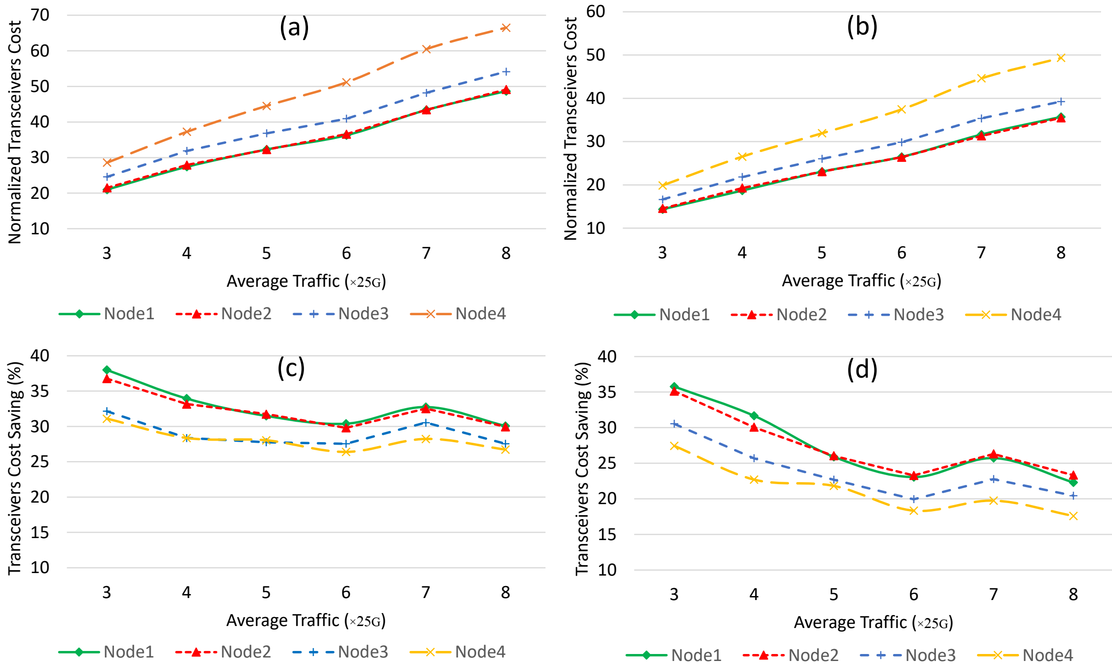

Fig. 2: Normalized P2MP transceivers cost versus average traffic for four different hub locations considering (a) optimistic and (b) conservative cost profiles and (c), (d) their corresponding savings compared to P2P approaches.

randomly selected from $[x, x+4]$, where $x = \{1,2,3,4,5,6,7,8\}$. We use $x+2$ as the average number of SCs when presenting and discussing the results. All the results presented are the average value of eight independent Monte-Carlo simulations. Conservative and optimistic profiles are studied to account for cost uncertainty regarding the transceiver cost per data rate. The optimistic cost profile assumes 100G and 25G are half and a quarter of 400G price, respectively. Those values are one-third and one-ninth of 400G price in the conservative profile.

Figure 2 (a) illustrates the normalized transceiver cost for the optimistic cost profile versus the average traffic when nodes 1, 2, 3, and 4 are selected as hubs. As expected, when the traffic load increases, the normalized transceiver cost also increases. However, this cost is higher when the hub moves from the center towards the network's edge, which is a consequence of using longer paths and consequently resorting to lower order modulation formats. Fig. 2 (c) shows the savings when using P2MP instead of P2P transceivers. As can be seen, these savings range between a minimum of 25%, when the hub is at node 4, and a maximum of 38%, when the hub is at node 1. The savings are smaller when the hub is closer to the edge of the network because of the restrictions imposed by the optical tree, which result in some longer paths when compared to the more relaxed routing with P2P transceivers. Moreover, savings tend to be higher at lower traffic loads, which is a consequence of not using 25G P2P transceivers. Overall, the transceiver cost and the P2MP vs. P2P cost savings are smaller with the conservative cost profile (Fig. 2 (b) and (d)), but they show the same trends.

4. Conclusion

We proposed a novel ILP model for optimizing P2MP transceiver deployment in a mesh network. Results obtained in a reference topology show that although the cost savings that can be obtained with these transceivers (vs. P2P transceivers) depend on the traffic load, hub location and cost profile, they are always considerable.

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