Multi-period Planning in Metro-aggregation Networks Exploiting Point-to-multipoint Coherent Transceivers

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This paper proposes a novel Integer Linear Programming (ILP) framework to optimize the multi-period planning of metro-aggregation networks exploiting point-to-multipoint (P2MP) coherent pluggable transceivers and a filterless line system architecture. We investigate several planning strategies to minimize capital expenditure (CapEx) caused by transceivers cost based on the predictability horizon of traffic and availability of transceivers during planning while considering operational expenses (OpEx) as well. The results obtained by evaluating a deployed reference network provide evidence of reductions in transceiver cost between 20% and 32% compared to that in the point-to-point (P2P) approach, and the OpEx can be reduced by around 30% in the expense of a 10% increase in transceiver cost over a five-year planning period.

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1. INTRODUCTION

Service providers must carefully evaluate their technology, architecture, and design alternatives, given the high costs involved in upgrading and managing metro-aggregation networks. On the one hand, they target reliable network performance and minimal capacity expansions for a long time, saving operational costs. On the other hand, they typically favor deployments that have low initial capital expenditures and/or pay-as-you-grow models. This might lead to conflicting objectives, forcing them to choose between sustaining long-term traffic growth and making a lower initial expenditure. This trade-off also depends on the predictability of traffic over the network's life cycle. Various solutions may be implemented to handle this issue, for example, by considering essential aspects such as budget constraints and the degree of predictability of traffic increase. In other words, it is usually challenging to match resources deployed with the actual demands over a long period of time when traffic demands are dynamic. A comprehensive set of planning approaches is described in [1]. An efficient long-term network planning may depend on the level of certainty in traffic prediction. In [2], different uncertainty scenarios regarding the traffic requirements evolution have been analyzed. It is shown that forecast-based planning can be more cost-efficient than no pre-planning, even if the actual demand pattern deviates from the initial forecast.

Hub-and-spoke architectures are generally suitable for most small- to medium-sized networks since it is not cost-effective to deploy a direct link between each pair of nodes given the low data rates (or absence of traffic exchange) between many of them. Besides, in access and metro-aggregation networks, most of the traffic load is destined outside the network (i.e., these networks fundamentally collect traffic and send it to the next hierarchical domain and distribute traffic in the reverse direction). Therefore, there is a large imbalance between the capacity needed in one or a few central nodes (the hub nodes) and that required in a larger number of distributed nodes (the leaf nodes), where the latter type of nodes communicate only with the former one, but not with each other. In metro-aggregation networks, point-to-multipoint (P2MP) coherent pluggable transceivers – enabled by digital subcarrier multiplexing (DSCM) – show promise for more precisely matching the hub-and-spoke architecture compared to point-to-point (P2P) transceivers [3]. While conventional P2P solutions rely on pairing transceivers at the hub and leaf nodes, which demands a large number of devices at the hub node, DSCM-based P2MP solutions can use a single high-capacity device at the hub node, enhancing key metrics such as cost, power consumption, and footprint. Recent works have: (i) experimentally verified the feasibility of this technology [4] and (ii) reported that the cumulative CapEx savings, which accounted for reductions in transceiver cost and further node simplifications, could reach 76% over a five-year period when compared to the traditional P2P solution [5].

The filterless node design complements the use of DSCM-based P2MP transceivers effectively. The utilization of a filterless architecture enables to replace expensive filters (e.g., wavelength selective switches) by simpler and passive optical splitters and combiners. However, it also leads to spectrum waste and potentially higher losses. Therefore, this architecture is only suitable for some network segments, such as metro-aggregation[6], where traffic is not meshed and transmission distances are relatively short. Closed loops must be avoided when designing filterless networks to prevent the same optical signal from crossing the same connection again [7]. Additionally, filterless topologies may not offer dedicated path protection for all node pairs [8], and Inter-Tree Transceivers (ITTs), Colored Passive Filters (CPFs), and red and blue filters (i.e., which block half of the spectrum) may be required at some nodes. In [9], we studied the savings of P2MP transceivers when deployed in filterless architectures over meshed topologies in contrast to simple rings or chain ones analyzed in [5].

Our prior research in [9, 10] has focused on single network design instances with static traffic sets and fixed costs. However, evaluating the long-term efficiency of P2MP systems requires modeling the effects of crucial elements, such as traffic evolution, cost erosion, and market introduction of transceivers with higher capacity. This paper considers several multi-period filterless network planning scenarios, considering both capital and operational expenditure metrics for the optimal deployment of P2MP transceivers based on a novel integer linear programming (ILP) model. To the best of our knowledge, this is the first ILP-based P2MP transceivers multiperiod planning in meshed networks. The proposed model for a reference network design shows notable savings in transceiver requirements during the entire network lifecycle.

The remainder of the paper is structured as follows. In Sec. 2, the P2MP transceiver architecture is presented, and a cost model for different data rates is provided. Several multi-period planning strategies for P2MP transceivers deployment are discussed in Sec. 3, and the optimization framework based on integer linear programming is proposed in Sec. 4. Next, Sec. 5 provides discussions and highlights the paper's key findings. Finally, Sec. 6 summarizes the study and suggests future research directions.

2. P2MP TRANSCEIVER DEPLOYMENT

A. P2MP Coherent Transceivers

P2MP transceivers are designed to communicate with multiple nodes simultaneously. DSCM-based P2MP transceivers located at the hub node encode data on optical subcarriers (SC). The entire set of SCs can reach all destination leaf nodes since each leaf node only processes those intended for it thanks to Nyquist multiplexing, encoding upstream data to the same optical SCs and transmitting them towards the hub node [11]. Although ROADM-based networks can benefit from DSCM-based P2MP transceivers [12], filterless networks might be a more cost-effective choice, as they inherently support the broadcast of SCs in the downstream direction (i.e., hub to leaf) and optical merging of SCs in the upstream direction (i.e., from leaf to hub).

This work assumes a P2MP transceiver that slices the optical spectrum into 25G SCs, each realized with dual-polarization 16-quadrature amplitude modulation (16-QAM) and a 4 GBaud symbol rate. For example, a 400G transceiver supports 16 SCs (total symbol rate of approximately 64 GBaud) that can communicate with four leaf nodes (100G each) or up to 16 leaf nodes (25G each). Other combinations can also be realized depending on the traffic pattern.

The described transceiver technology provides an upgrade path that ensures backward compatibility if the individual SC properties are preserved (e.g., same 4 GBaud symbol rate, same modulation formats supported). Therefore, as coherent transceiver technology evolves to support higher symbol rates (e.g., > 120 GBaud), it is envisioned that an 800G (1.2T) transceiver of higher capacity will manage a total of 32 (48) SCs [11].

B. P2MP Transceiver Cost Model

A key motivation to develop and commercialize higher data rate transceivers is their lower cost per bit. The cost model for transceivers with different capacities considered in this work is $Cost = \frac{\sqrt{N_s}}{4}$, where N_s denotes the number of supported SCs. According to this formula, the cost of the 400G transceiver is one unit (normalization of the cost to the price of the 400G transceiver), and the relative prices of the 100G, 800G, and 1.2T transceivers are 0.5, 1.41, and 1.73, respectively. This model generalizes the approximation that a $4\times$ increase in capacity is achieved at the expense of a $2\times$ cost increase [5]. Note that other cost profiles can be considered modeling a higher or lower cost per bit/s [9].

C. Filterless Network Architecture

When capacity requirements are not high enough to risk spectrum exhaustion, as is normally the case in metro-aggregation networks, filterless architectures offer a viable alternative. Using passive components instead of active ones provides key advantages such as lower cost and lower probability of failures [7]. In networks with a single hub and several leaf nodes, a single spanning tree per direction satisfies the requirements of the filterless design since it enables connecting every leaf node to the hub (the tree's root) while avoiding the creation of optical loops. Optical combiners and splitters connect fibers upstream and downstream, respectively. Spectrum blockers or transceivers themselves can terminate optical signals at selected fibers. In Fig. 1, a physical tree design with combiners and splitters is implemented. In this example, a 400G transceiver in the hub communicates with four 100G transceivers placed at the leaf nodes.

Note that the location of the hub can impact the cost of P2MP deployment [9]. For simplicity, but without loss of generality, in the remaining of this work, we assume that the node with the smallest total length of shortest paths to all other nodes is selected as the hub. This can help to reach leaf nodes with shortest distances from hub nodes. However, in real-case scenarios, other factors, such as the relationship of metro networks with backbone networks and geographical considerations, can determine the hub's location.

When planning a filterless architecture, the selected tree can influence the total cost of the P2MP (or P2P) solution. For instance, its size and shape can determine the feasible modulation formats between the hub and a given leaf node, which can impact the type and quantity of transceivers needed at the hub and leaf nodes. Furthermore, the tree must be constructed at the beginning of network operation, making it a critical choice for long-term planning. These insights support the simultaneous optimization of the spanning tree and the deployment of P2MP (or P2P) transceivers to achieve the best solution.

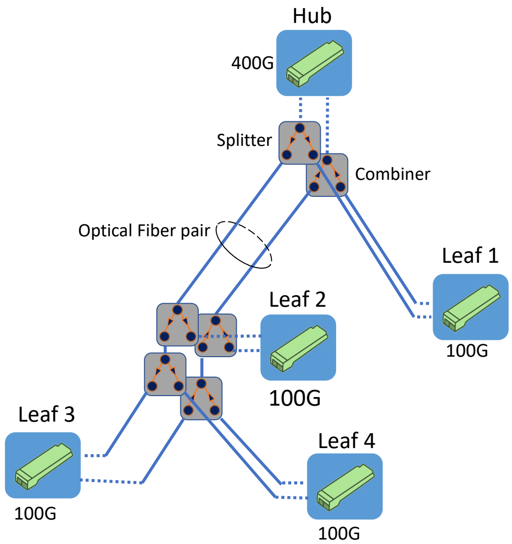

Fig. 1. A 400G transceiver deployment at the root of a tree for communicating with four 100G transceivers located at four leaf nodes using combiners and splitters.

3. MULTI-PERIOD PLANNING SCENARIOS

To meet the growing demand for traffic, network operators must continuously plan to establish resources. However, planning can be affected by several variables, such as uncertainty in traffic forecasting, technology evolution, and financial constraints. For example, higher data rate transceivers are cheaper considering the cost per transported bit but become available later. Additionally, each generation of transceivers has a finite lifespan, and their deployment is halted after some time as their competitive edge deteriorates. Due to this fact and volume discounts, the price of a particular transceiver generation usually drops steadily during its lifespan. These findings motivate operators to delay capacity upgrades. However, implementing this strategy requires more frequent capacity increases, resulting in higher operating costs and increased risks of degrading service quality. This work considers a five-year planning scenario in which 800G and 1.2T transceivers come to the market in the second and fourth years, respectively.

All-period planning, incremental or single-period planning, and extended-period planning are the three different multi-period planning scenarios that are considered in this work [1]. The all period planning method [13] and single-period planning [14, 15] are two extreme choices based on considering the demand forecast for all periods or only for the next period, respectively. The optimal situation for all-period planning, which takes into account the traffic forecast for all periods, is when there is high confidence in the prediction. In contrast, single-period planning is used when there is little confidence in traffic projections and/or when minimal near-term investments are required. If traffic projections are reasonably accurate for the first three years, extended-period planning falls in the middle of these two extremes.

Leaf node transceivers can be managed in one of two ways; Once a transceiver is placed in a leaf node, one method is to keep it there for the remaining of the planning period; we refer to this method as the "unmovable transceiver strategy" in this article. The alternative is to relocate a transceiver to a different leaf node later if doing so allows for a decrease in CapEx ("movable transceiver strategy"). It should be noted that visiting the leaf site is required each time a leaf node is upgraded, either by removing and/or deploying a transceiver. Moving transceivers might have impacts on things other than cost, such as interruption in the services. However, the actual impact depends on several factors, such as the size of the network, the speed of configuration, and whether there is redundancy (protection) or not. As a result, the chosen strategy can impact both CapEx and OpEx (the latter hereafter measured as the number of site visits). CapEx, OpEx, and traffic uncertainty are the main tie-in elements that need to be considered in multi-period planning.

Given a meshed network topology, which includes a hub node and a set of leaf nodes and where the nodes' architecture is based on passive splitters/combiners, the main problem to be solved is to determine the optimal P2MP transceiver deployment configuration over multiple periods and under the different above-discussed planning scenarios when the traffic demands and set of available transceivers are changing/evolving over time.

4. OPTIMIZATION FRAMEWORK

In order to determine the most economical P2MP transceiver configuration – under filterless architecture restrictions for a specific planning scenario, network topology, and traffic load – this section provides a novel and comprehensive optimization framework. Below is a description of the primary input parameters and decision variables of the ILP model devised for this purpose.

Input Parameters

- $G(V, E)$: network graph with nodes $u, i, j \in V$ and links $e = (i, j) \in E$.
- V^-: a subset of V that defines leaf nodes.
- h: index of the Hub node.
- N: the number of leaf nodes.
- W_{ij}: length of the link $(i, j) \in E$.
- S: set of planning periods.
- T_u^s: number of 25 Gb/s data rates required by leaf node u in period s. This is assumed to be the maximum traffic required in the downstream and upstream directions.
- LR: maximum reach with highest-order modulation format (16QAM).
- O_h, O_l: sets of transceivers that can be used at the hub and leaf nodes.
- C_o^s: relative cost of transceiver type o in period s.
- D_o: maximum data rate in terms of the 25G slot (with the highest modulation format) of the transceiver type o.
- B: very large positive number.
- $J(s)$: weighting factor of period s determining the importance of each period.
- $Q(s)$: cost decline parameter for period s.

Decision Variables

- f_{ij}: positive integer variable that indicates the flow from node i to j.
- x_{ij}: 1 if the link $(i,j) \in E$ is selected for the tree, 0 otherwise.
- y^u_{ij}: 1 if the link $(i,j) \in E$ is in the path from leaf u to the hub, 0 otherwise.
- M_{QPSK}: 1 if the path from leaf u to the hub is longer than LR (only quadrature phase-shift keying (QPSK) modulation format can be used), 0 otherwise.
- M_{16QAM}: 1 if the path from leaf u to the hub is shorter than LR (16QAM modulation format can be used), 0 otherwise.
- Δ^s_{1o}: cumulative number of transceivers of type o used in period s at the hub with the QPSK modulation format.
- Δ'^s_{1o}: integer number indicating the number of transceivers of type o added in period s in the hub with the QPSK modulation format.
- Δ^s_{2o}: cumulative number of transceivers of type o used in period s at the hub with 16QAM modulation format.
- Δ'^s_{2o}: integer number indicating the number of transceivers of type o added in period s in the hub with the 16QAM modulation format.
- δ^s_{ou}: cumulative number of transceivers of type o used in period s at the leaf node u.
- δ'^s_{ou}: integer number indicating the number of transceivers of type o added in period s in leaf u.

The objective of the ILP model is to minimize the total transceivers' cost (transceivers at hub and leaf nodes) as presented in Eq. 1. The weighting factor $J(s)$ is introduced in the objective function to model the relative importance of each planning period in the optimization. This helps to optimize multiple periods with a single run of the ILP model. Given pricing policies such as price skimming, customer-driven pricing, premium pricing, improvement in silicon technology, transceivers' cost usually decreases after market introduction. Because of these factors, parameter $Q(s)$ is used to model changes in cost of transceivers over time.

$$z = \sum_{s\in S} Q(s)J(s)[\sum_{o\in O_h}(\Delta'^s_{1o} + \Delta'^s_{2o}) \times C^s_o + \sum_{u\in V^-}\sum_{o\in O_l} \delta'^s_{ou} \times C^s_o], \tag{1}$$

subject to

$$\sum_{(i,j)\in E} x_{ij} = N, \tag{2}$$

$$\sum_j f_{ij} - \sum_j f_{ji} = \begin{cases} N & i = h, \\ -1 & \forall i \in V^-, \end{cases} \tag{3}$$

$$f_{ij} \le N x_{ij} \qquad \forall (i,j) \in E, \tag{4}$$

$$f_{ji} \le N x_{ij} \qquad \forall (i,j) \in E, \tag{5}$$

$$\sum_j y^u_{ij} - \sum_j y^u_{ji} = \begin{cases} 1 & \forall u \in V^-, i = u, \\ 0 & \forall u \in V^-, i \ne u, h, \\ -1 & \forall u \in V^-, i = h, \end{cases} \tag{6}$$

$$y^u_{ij} \le x_{ij}, \qquad \forall u \in V^-, \forall (i,j) \in E, \tag{7}$$

$$BM_{1u} \ge \sum_{(i,j)\in E} W_{ij} y^u_{ij} - LR \qquad \forall u \in V^-, \tag{8}$$

$$M_{QPSK} + M_{16QAM} = 1 \qquad \forall u \in V^-, \tag{9}$$

$$\sum_{o\in O_l} \delta^s_{ou} D_o \le T^s_u [M_{QPSK} + 1] \quad \forall u \in V^-, \forall s \in S, \tag{10}$$

$$\sum_{o\in O_h} \Delta^s_{1o} D_o \ge \sum_{u\in V^-} 2T^s_u M_{QPSK} \qquad \forall s \in S, \tag{11}$$

$$\sum_{o\in O_h} \Delta^s_{2o} D_o \ge \sum_{u\in V^-} T^s_u M_{16QAM} \qquad \forall s \in S, \tag{12}$$

$$\delta'^s_{ou} = \delta^s_{ou} - \delta^{s-1}_{ou} \qquad \forall u \in V^-, \forall o \in O_l, \forall s \in S, \tag{13}$$

$$\Delta'^s_{1o} = \Delta^s_{1o} - \Delta^{s-1}_{1o} \qquad \forall o \in O_h, \forall s \in S, \tag{14}$$

$$\Delta'^s_{2o} = \Delta^s_{2o} - \Delta^{s-1}_{2o} \qquad \forall o \in O_h, \forall s \in S. \tag{15}$$

Constraint (2) guarantees that the size of the tree is equal to the number of leaf nodes N (assuming that all leaf nodes have to be connected to the hub). According to constraint (3), N auxiliary flow units are distributed by the hub node, and all N leaf nodes receive precisely one flow unit. Flows can only be on trees and do not exceed total flows by constraints (4–5). These necessities construct a spanning tree by fulfilling the criteria of the spanning tree (no loop and containing all nodes) using a single commodity approach [16]. Note that the network must be connected since in the case of isolated nodes, finding a spanning tree is not possible. For simplicity, in the remaining of this work, we consider that the QPSK modulation format is attainable for paths longer than $LR = 500$ km, while for paths shorter than that, 16QAM can be used. Note that using QPSK instead of 16QAM halves the capacity per SC. Paths between leaf nodes and the hub on the constructed tree are calculated by the constraint (6), where one unit of auxiliary flow is generated by node u and passing through other nodes; only the hub receives it. Constraint (7) confirms that the paths are contained in the trees. Constraints (8) and (9) specify if QPSK or 16QAM modulation format can be used. M_{QPSK} (M_{16QAM}) takes the value of 1 if the path to the leaf node requires the QPSK (16QAM) modulation format. Note that it is assumed that all SCs transmitted/received by a transceiver must use the same modulation format. Constraints (10-12) measure the cumulative number of required transceivers while constraints (13-15) count the number of transceivers added in period s per type at the leaf and hub nodes according to the modulation format selected.

The scenario of movable transceivers can be executed by adding Eq. (16) to the previous set of constraints and allowing δ'^s_{ou} to take both positive and negative integer values, therefore enabling to increase/decrease the number of units of a given transceiver type at each leaf node.

$$\sum_{u\in V^-} \delta'^s_{ou} = [\sum_{u\in V^-} (\delta^s_{ou} - \delta^{s-1}_{ou})] \ge 0 \qquad \forall o \in O_l, \forall s, \tag{16}$$

The ILP framework can also be adapted to design a network using P2P transceivers. In this situation, the leaf and hub nodes must have transceiver pairs that operate at the same data rate. As a result, we can model it by removing the first term of objective function (1) and doubling the second.

5. RESULTS AND DISCUSSION

This section investigates the performance of DSCM-based P2MP transceivers during a five-year planning span under different scenarios and compares the outcome with that of employing traditional P2P transceivers instead operating the metro-aggregation reference network depicted in Fig. 2.

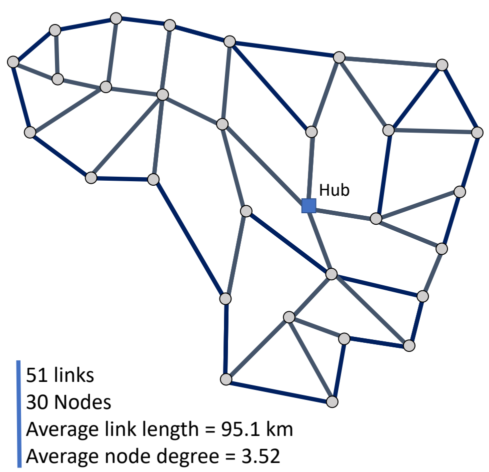

Fig. 2. Considered reference network with 30 nodes and 51 links [17].

If $J(s)$ takes a much larger number for a given year compared to that for the other years (e.g., first year), the model will prefer to minimize CapEx in that specific year first. Similarly, if $J(s)$ takes equal values for all years, the objective will be modelling all-period planning. We also assume a 10% cost reduction per year after transceivers became available on the market by setting the cost decline parameter to $Q(s) = 0.9^{s-1}$ in Eq. 1, where s varies from 1 to 5.

The baseline relative cost obtained by the formula provide in section 2.B (costs are normalized to the cost of 400G transceiver) for all transceivers investigated in this study is shown in Table 1. Note that an extremely high-cost value (e.g., 1000) is utilized in the ILP formulation to model the unavailability of a transceiver type in a given year. From a technological point of view, the main difference between DSCM-based P2MP and conventional P2P transceivers is their digital signal processing (DSP) units where SCs are created or processed [11]. However, their transmit & receive optical subassembly (TROSA) might be similar.

A Poisson distribution with a mean value of 100G is used to construct the first traffic pattern. For each leaf node, the annual growth rate is set at a random number between 35% and 45% for different periods. This way of traffic definition, along with the use of Monte Carlo simulations, gives confidence to the results against uncertainty in the traffic load definition, as it covers up to 10% traffic variations in different years and in different leaf nodes. There are other ways to deal with traffic uncertainty, such as analyzing unexpected traffic changes [2] or predicting traffic using machine learning methods [18]. To facilitate the interpretation of the data from the reader, we express the average traffic load per leaf node in terms of multiples of 25G.

Table 1. Relative transceiver cost per data rate by year without considering cost discount

	100G	400G	800G	1.2T
Year 1	0.5	1	Unavailable	Unavailable
Year 2	0.5	1	1.41	Unavailable
Year 3	0.5	1	1.41	Unavailable
Year 4	0.5	1	1.41	1.73
Year 5	0.5	1	1.41	1.73

Figure 3(a) depicts the total cost of transceivers for the three scenarios outlined in Section 3 while considering the unmovable strategy. The starting cost is higher with all-period planning, but the cost growth is slower, resulting in the lowest cost in the final periods. This is expected because this method prioritizes minimizing the final CapEx, even if it means settling for a less optimum solution in the early stages due to capacity over-provisioning (i.e., higher capacity transceivers deployed to satisfy low/moderate initial traffic requirements). The costs of extended and single-period planning in the first two years are comparable. However, because of decisions that are not optimal in the long run, single-period planning becomes less cost-effective over time. Interestingly, extended-period planning outperforms all-period planning until the third period, resulting in a greater cumulative cost than all-period planning afterward.

Figure 3(b) illustrates the cost reductions achieved using P2MP transceivers against P2P transceivers. It should be noted that the traffic requirements between the hub and a single leaf node only justify adopting 100G and 400G data rates in the P2P scenario. At a glance, the amount of savings is between 20% and 32% in different planning strategies. All-period P2P planning initially deploys a greater number of 400G transceivers, reducing the need to replace the transceivers in subsequent years. This clarifies why the savings are higher at the start and lower at the end of the planning cycle. The amount of CapEx saved with the other two planning options is less dependent on the planning years. Focusing on the final period, it can be seen that P2MP transceivers grant the highest cost savings when adopting single-period planning.

The effects of being able to relocate transceivers across leaf nodes throughout various planning periods are evaluated in the following set of results. Figure 4(a) shows the advantage of the movable P2MP transceiver approach compared to the non-movable one in terms of cost reduction. Additionally, an OpEx-related metric, the number of site visits to deploy/swap transceivers – is depicted in Fig. 4(b). The possibility of moving transceivers between leaf nodes reduces the cost of all-period planning by roughly 13% at first (reduced over-provisioning compared to the unmovable transceivers strategy), but there are no meaningful benefits for the next four years. However, in order to have this early CapEx decrease, site visits increase from 44 to 78 (77% increase). In the last planning periods, there are significant improvements in both extended-period and single-period planning methods. Compared to the unmovable transceiver strategy, CapEx is cut by ∼12% at the end of the planning cycle,

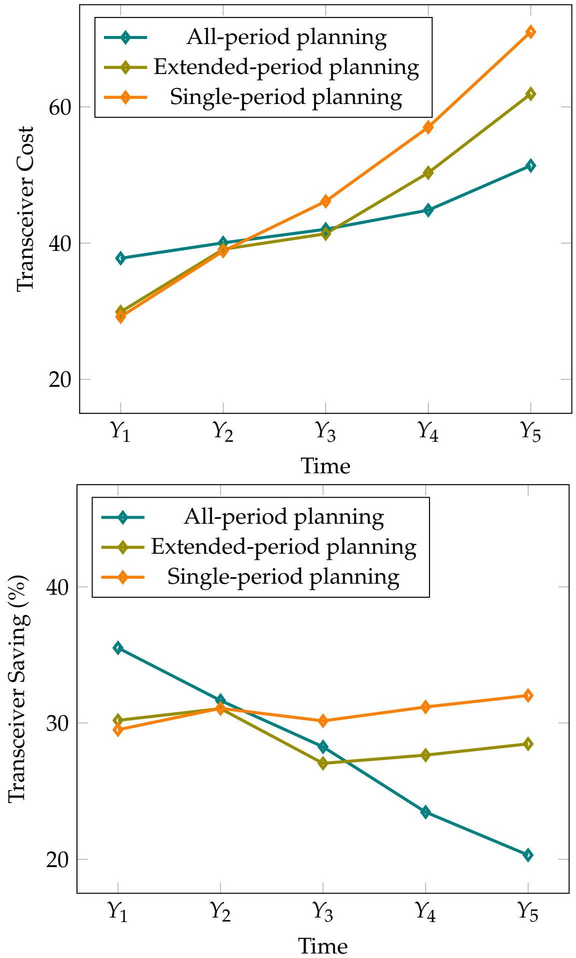

Fig. 3. (a) P2MP transceiver cost for all-period, extended-period and single-period planning, and (b) the amount of savings compared to the corresponding P2P transceiver approaches.

whereas OpEx increases by ∼8% for extended-period planning. The single-period planning strategy results in a nearly 14% reduction in CapEx and a marginal reduction in OpEx. Single-period planning always necessitates more site visits, followed by extended-period planning, whereas all-period planning requires a lower number of visits (benefit from adopting higher data rate transceivers early on).

To gain further insight into how movable and unmovable strategies affect the final solutions, Table 2 provides information on the number of transceivers deployed of each type for one of the traffic load sets in the single-period planning strategy. Both unmovable and movable transceivers' strategies deploy the same number of transceivers in the first and second years. Yet, due to rising traffic, the unmovable transceiver approach continues to add additional 100G transceivers in the following years. The movable transceiver strategy, in contrast, moves existing transceivers, particularly 100G transceivers, between leaf nodes (the number of displaced transceivers is specified in parentheses). As a result, even if only traffic for the next year is planned, the low data rate transceiver count can be reduced by facilitating transceiver reuse. In summary, all-period planning can result in the lowest transceiver cost and the fewest leaf site visits at the end of the five-year planning period in situations where the traffic forecast is available for all five years. On the other hand, the movable transceiver strategy enables a significant reduction in transceiver cost in the event that extended-period or single-period planning is selected based on specific circumstances (e.g., traffic uncertainty and initial budget constraints).

It is necessary to investigate all aspects of the scenarios carefully, as the cost of visits can be considerable. However, the exact contribution to the total cost compared to transceivers is not well known. Therefore, they cannot be added to form a single accurate cost in the objective function. One way is by running a Pareto analysis [19] on different possibilities of the OpEx and the CapEx. Eq. 1 in the ILP model can be replaced by Eq. 17:

$$z = CapEx + w \times OpEx \tag{17}$$

where $CapEx$ is the total CapEx in Eq. 1 and $OpEx$ is the number of visits. By varying weight w, different pairs of OpEx-CapEx can be calculated since the importance of OpEx and CapEx is changed in the objective function. In a decision-making process, one can select the most suitable solution based on predefined criteria. Fig. 5 shows the OpEx (in terms of the number of visits) against normalized CapEx in all-period planning when the approach of unmovable transceivers is used for four different sets of traffic demands. As can be seen, there is a trade-off between CapEx and OpEx. The results confirm that minimizing CapEx and OpEx can be conflicting. In these cases, the OpEx

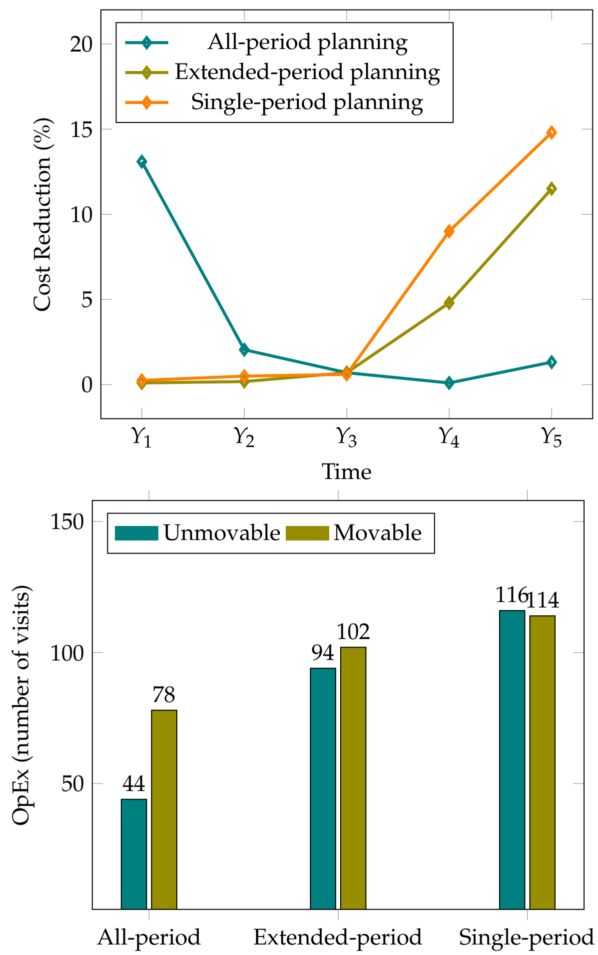

Fig. 4. (a) Cost reduction of the movable transceiver approach compared to unmovable transceivers for different planning strategies and (b) their number of visits to the leaf nodes.

Table 2. Number of transceivers added per type at leaf nodes in unmovable and movable transceivers approaches.

	Year 1	Year 2	Year 3	Year 4	Year 5
Unmovable Transceivers	44×100G	14×100G	13×100G	22×100G	34×100G
Movable Transceivers	44×100G	14×100G	5×400G (8×100G)	5×400G (2×400G+18×100G)	8×400G (5×400G+36×100G)

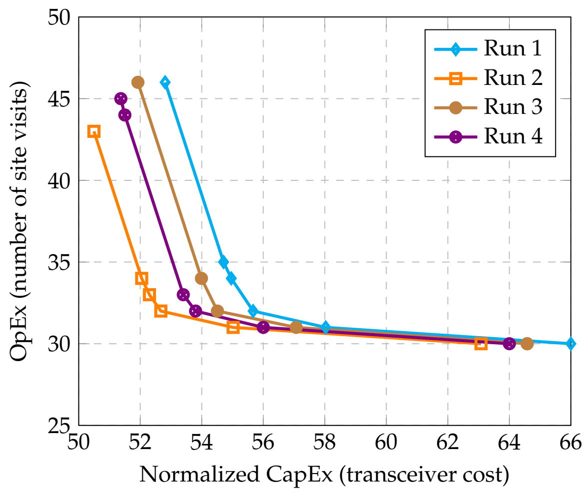

Fig. 5. OpEx vs. CapEx relation in unmovable all-period planning for four traffic sets.

ranges between 30 and 46 visits, while the CapEx changes from about 50 to 66. Reducing the OpEx (associated to the number of site visits) from 45 to around 33 is possible at the expense of a CapEx (transceiver cost) increase from about 51 to 56.

The upper bound of the complexity of an ILP can be determined by the number of decision variables and constraints. However, the actual computational complexity, and computation time highly depend on the specific problem instance. Computation time of two instances of the same problem can be significantly different because of different paths to optimal solutions. In the particular case of the instances solved in this work, most took less than approximately 3 minutes using a typical laptop (16 GB RAM, Core i7 @1.8 GHz CPU). Although, the network we considered is significantly large for its kind (metro-aggregation networks), with larger problems that might arise, developing heuristics apparently can be useful as well.

6. CONCLUSIONS

This paper described a novel ILP model for multi-period planning in metro-aggregation networks using P2MP (or P2P) transceivers and filterless node architecture and enabling or disabling the possibility of relocating transceivers between planning periods. The cost of accommodating all traffic demands using P2MP transceivers was compared with conventional P2P transceivers in a reference network topology during a five-year planning period and factoring in cost decline. The results demonstrate that significant cost savings can be obtained, ranging from 20% to nearly 32%, depending on the planning strategy. This work also provides evidence that in case of a lack of confidence on how traffic requirements will evolve, it is possible to exploit a trade-off between CapEx and OpEx. Particularly by performing transceiver relocation to minimize transceiver cost (CapEx) at the expense of increasing the number of site visits (OpEx).

Future work will include a more accurate modelling of the impact of optical performance on the feasibility of the available modulation formats in each path and it will focus on developing strategies to further optimize/simplify the nodes' architecture (e.g., minimizing the number of optical amplifiers needed).

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