Long-Term Cost-Effectiveness of Metro Networks Exploiting Point-to-Multipoint Transceivers

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***Abstract*—A comprehensive analysis of the long-term benefits of deploying point-to-multipoint transceivers in metro networks, taking into account the expected evolution of transceiver technology, is reported. Simulation results obtained over a reference network show that the savings over point-to-point transceivers can be maintained at approximately 35% for a wide range of traffic loads, highlighting the long-term cost-effectiveness of adopting point-to-multipoint transceivers.**

***Index Terms*—Point-to-multipoint, network optimization, metro-aggregation networks, coherent technology.**

I. INTRODUCTION

The design of optical networks requires optimizing several technological solutions concurrently with cost and power concerns. Communication service providers (CSPs) are evaluating long-term, sustainable, and profitable solutions across a broad range of network segments, from access to metro and core. This is required to meet the demands generated by the widespread adoption of 5G services, the advent of the Internet of Things (IoT), the rapid growth of video streaming, and several other emerging applications. The diverse traffic patterns and data rates of distinct network segments require that transmission technology and network architecture be adapted to the unique conditions in each segment [1].

Adopting technologies that enable cost-effective capacity expansion while maintaining high flexibility and low operational expenses (OPEX)is crucial, particularly in metro networks, which account for a significant amount of telecom infrastructure capital expenditures (CAPEX). Traffic to and from a large number of end nodes (*leaf nodes*) is transmitted and received by an aggregate node (*hub node*) centrally located in metro-aggregation networks; a significant imbalance in the amount of traffic handled by the hub and leaf nodes results [2]. Typically, point-to-point (P2P) optical transceivers are used to connect hub and leaf nodes in aggregation networks. They transmit and receive data at the same rate on both ends of the link and the number of transceivers at the hub node equals the total number of transceivers at the leaf nodes. Alternatively, as described in [3], point-to-multipoint (P2MP) optical transceivers have the potential of effectively supporting the capacity imbalance between leaf and hub nodes by replacing a large number of low-capacity transceivers with a small number of high-capacity ones. In this case, each high-capacity transceiver at the hub node communicates with multiple low-capacity transceivers at the leaf nodes.

P2MP optical transceivers were first studied in [4] for metro and core network applications, where data from one or more clients are mapped to several optical channels, with the resultant flows being co-routed and/or individually routed according to the number and location of the end nodes. For instance, the study reported in [5] indicates that using a P2MP solution may result in cost savings during a five-phase planning period with 400 Gb/s and 1 Tb/s transponders in backbone networks. On the other hand, the traffic pattern in core and metro-core network segments tends to be more distributed and balanced and, as a result, more naturally supported with P2P transceivers. Additionally, the high capacity needed between node pairs suggests that an entire optical channel (i.e., transceiver pair) is usually needed [6].

A novel P2MP coherent transceiver has recently been proposed for metro-aggregation networks [3]. It employs digital subcarrier multiplexing (DSCM), a technique that allows for effective sharing of the capacity of a single optical channel [7], [8]. DSCM allows fine granularity while maintaining a similar level of complexity and cost as a P2P transceiver, with the same total data throughput (e.g., a 400 Gb/s transceiver can be realized via 16 subcarriers with dual-polarization and 16QAM at $\sim$ 4GBd). Lower-capacity transceivers receiving/transmitting a subset of subcarriers can be used at the leaf nodes, better matching traffic requirements and provisioned hardware. By using fewer high-capacity transceivers at the hub node, it is also possible to decrease the footprint and power consumption of the router/switch. Moreover, DSCM also facilitates the adoption of simpler filterless node designs instead of reconfigurable optical add/drop multiplexers (ROADMs), reducing the cost of the line system [3]. According to Monte Carlo calculations using network and traffic data from a CSP, the new P2MP solution can save up to 76% in CAPEX over the course of five years, assuming an annual traffic growth rate of 30% [9].

As described above, a key feature of the DSCM-based

This work has received funding from EU Horizon 2020 program under the Marie Sklodowska-Curie grant agreement No. 813144 (REAL-NET). SKT acknowledges the support of the EPSRC project TRANSNET. JP, AN, NC acknowledge the support of the European Union's Horizon 2020 research and innovation program B5G-OPEN Project, grant agreement No. 101016663.

978-3-903176-44-7

P2MP transceivers is that the leaf nodes' lower-capacity transceivers may receive/transmit one or several subcarriers (asymmetric allocation of downstream and upstream subcarriers is also possible). This allows broadcasting all subcarriers to the leaf nodes (downstream direction) and to optically merge subcarriers from these nodes (upstream direction). Therefore, it is possible to operate this solution over a filterless architecture, where simple and passive power splitter/combiner devices are used instead of active filters. This feature can be exploited to adopt a lower cost and more resilient (i.e., less failure-prone) optical infrastructure [9]. A critical characteristic when planning filterless networks is that closed loops must be avoided, to prevent the same optical signal from traversing the same link twice. Having this in mind, the authors of [10] examined the use of passive components in wide area networks (WANs), which in general can have a meshed physical topology, and how to establish a set of physical optical connections between all nodes without generating closed loops. The work in [11] presented the optimization of optical tree construction, routing, and wavelength assignment. However, all these works assumed the deployment of P2P transceivers and did not consider the specific constraints associated with using DSCM-based P2MP transceivers.

Early research based on DSCM-based P2MP optical transceivers considered basic network topologies such as star, chain, and ring networks [3], [9]. Although these topologies represent the majority of aggregation and access networks, the principle may also be used in more meshed (and generic) metro-aggregation networks. In previous papers, we have described an integer linear programming (ILP) model for optimizing routing, modulation format, and subcarrier assignment in mesh networks to minimize the total transceiver cost [12], [13]. Furthermore, we have recently proposed a more comprehensive optimization model that addresses the crucial restriction imposed by a filterless design: the necessity of eliminating optical signal loops [14]. We have shown that using this architecture and specific P2MP transceivers, the total transceiver cost decreases by a figure between 18% and 38%. However, all these works focused on a specific generation of coherent transceivers and a limited traffic load variation. This current work models the expected evolution in transceiver technology, describes an appropriate optimization framework, and uses both to assess the long-term cost-effectiveness of P2MP transceivers. Results obtained over a broad range of traffic loads, mimicking long-term network evolution, provide evidence that this solution can preserve its benefits over traditional P2P transceivers.

II. DIGITAL SUBCARRIER COHERENT MULTIPLEXING POINT-TO-MULTIPOINT TRANSCEIVER

The first commercial utilization of DSCM was in high-end P2P coherent transceivers, to improve optical performance (i.e., increase capacity/reach) [7], [15]. The technology has also been shown to be effective for optimizing spectrum usage (i.e., by customizing the optical channel in view of the impact of filter cascade) [16]. By exploiting the ability to slice spectrum efficiently in the digital domain, DSCM has been recently identified as a critical enabler for the realization of coherent transceivers that natively support P2MP connections in the optical domain [9]. A high-capacity DSCM-based transceiver generates multiple subcarriers (SCs) using a single optical source and transmits them to the leaf nodes. This embodies a major difference from preceding approaches, such as the sliceable bandwidth variable transponder proposed in [17], and it can be accomplished with a broadcast node architecture, where simple optical splitters are used. Each leaf node's low-capacity transceiver processes just the SCs destined to it. In the reverse direction, each leaf node sends its subset of SCs, and all SCs from different leaf nodes are optically groomed (via optical combiners) on their way to the receiver at the hub node.

Our previous work assumed that high-capacity P2MP transceivers transmit/receive up to 16 SCs, being able to communicate with up to 16 separate leaf nodes [14]. The optical channel formed by the 16 SCs occupies $\sim$ 64 GHz, which translates into a frequency slot of at least 75 GHz, assuming a grid granularity of 12.5 GHz. It is assumed dual-polarization 16-quadrature amplitude modulation (DP-16QAM) SCs are feasible up to a given maximum reach, while DP quadrature phase-shift keying (DP-QPSK) is considered for longer lightpaths (halving the SC capacity to 12.5G, but requiring the same bandwidth). It is worth noting that the practicality of DSCM-based P2MP has been shown both in the laboratory [18] and in field experiments [3], [19].

In this work, we envisage that coherent technology evolution will gradually make available 800G (with 32 SCs in P2MP mode) and 1.2T (with 48 SCs in P2MP mode) transceivers, in addition to the 100G (4 SCs) and 400G (16 SCs) considered in past studies, and which are reaching commercial availability. For fairness of comparison, it is assumed that P2P transceivers operating at these rates are also made available. By modeling the introduction of next-generation coherent transceivers, it is possible to assess the expected network performance over a much wider range of traffic loads, which are representative of the traffic requirements over an extended period of time.

It is well known that the cost increases when the transceiver data rate increases (e.g., between consecutive transceiver generations), but not in direct proportion to the capacity increase [3], [20]. This means that the cost per bit/s decreases when opting for a higher capacity transceiver, so deploying fewer high-capacity transceivers for the same total aggregate capacity is usually more cost-effective. We assume that the cost of the transceivers can be determined from Eq. 1:

$$C = As^{B}, \tag{1}$$

where C is the cost of the transceiver supporting s number of subcarriers, A is a normalization factor, and B is a constant less than one, determining the cost profile. If B is greater than one, high capacity transceivers have a more expensive per bit capacity, whereas if B is one, the cost of transceivers is exactly proportional to the capacity they offer. In line with the observed evolution of transceivers capacity and cost, it is realistic to expect $0 < B < 1$. In this article, we assume $B = 0.5$ and $A = 0.25$, so that a 400G transceiver has a unitary cost. The resulting transceiver cost is presented in Table I. Since the complexity of DSCM-based P2MP transceivers is not significantly different from P2P transceivers [3], for a given data rate, the same cost is assumed for both P2MP and P2P devices.

TABLE I
TRANSCEIVER COST PER DATA RATE TYPE

Data Rate	1.2T	800G	400G	100G
Number of SCs	48	32	16	4
Cost	1.73	1.41	1	0.5

III. NETWORK ARCHITECTURE

Metro-aggregation networks are a critical segment of the telecommunications infrastructure, which gathers, combines, and routes traffic to other segments. As discussed above, to implement a filterless network architecture, one can construct a spanning tree on top of a meshed topology by selectively using splitter/combiner devices to broadcast downstream signals and merge upstream signals and wavelength blockers to prevent optical loop creation. Figure 1 shows the reference mesh network considered in this work [21]. For illustration purposes, two sets of P2P (brown) and P2MP (green) transceivers are shown in two branches of the tree. In this example, one 400G transceiver serves four 100G transceivers in the P2MP scenario, while four 100G transceivers are deployed at the hub to establish connections with a similar number of transceivers deployed at leaf nodes. Therefore, five transceivers are deployed in P2MP versus eight transceivers in the P2P method. Importantly, if leaf nodes require less traffic (e.g., 25G, 50G) it becomes possible to share the capacity of the 400G P2MP transceiver with a larger number of leaf nodes.

When using a filterless architecture, the choice of tree overlay can impact the overall cost of the P2MP solution. For example, the paths of a tree may determine which modulation format can be used for SCs being transmitted over that tree, and so impact the number and type of transceivers required at both the hub and leaf nodes. This observation encourages jointly solving the problems of setting up the spanning tree and deploying P2MP transceivers, to obtain the solution with minimum possible transceiver cost.

IV. OPTIMIZATION FRAMEWORK

The P2MP optimization framework tries to identify the most cost-effective P2MP transceiver configuration for a particular traffic distribution and metro-aggregation network topology, assuming nodes based on optical splitter/combiner devices and wavelength blockers. In order to achieve this, we developed an integer linear programming (ILP) model. Below are laid out the model's input parameters and decision variables.

Input Parameters

- $G(V, E)$: network graph with nodes $u, i, j \in V$ and links $l = (i, j) \in E$.

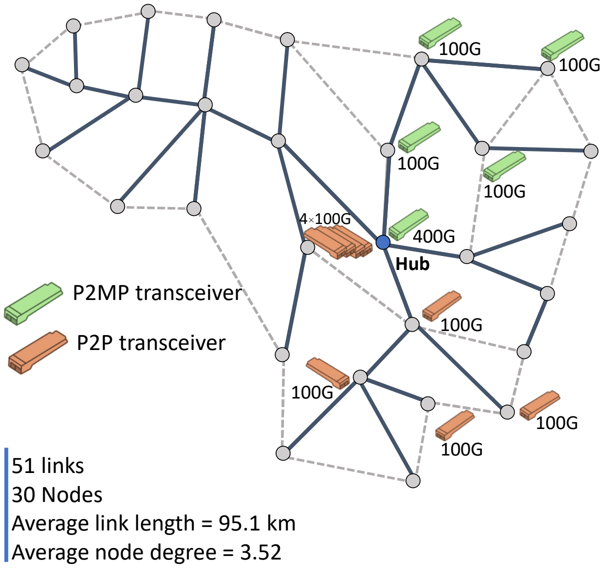


Fig. 1. Reference network topology and examples of P2P and P2MP transceivers deployment for supporting 4×100G traffic loads using a filterless tree architecture.

- V^-: a subset of V defining leaf nodes.
- W_{ij}: length of link $(i, j) \in E$.
- $T(u)$: number of 25 Gb/s data rate required by leaf node u. This is assumed to be the maximum required traffic of downstream and upstream directions.
- L_r: maximum reach with highest order modulation format (16QAM).
- O_h: set of transceivers used at the hub node.
- O_l: set of transceivers used at the leaf nodes.
- C_o: cost of transceiver type o.
- D_o: maximum data rate in terms of number of 25G (with the highest modulation format) of transceiver type o.
- B: very large positive number.

Decision Variables

- f_{ij}: positive integer variable indicating flow from node i to j.
- x_{ij}: 1 if link $(i, j) \in E$ is selected for tree, 0 otherwise.
- y_{ij}^u: 1 if edge $(i, j) \in E$ is in the path from leaf u to the hub, 0 otherwise.
- M_{1u}: 1 if path from leaf u to the hub is longer than L_r (QPSK), 0 otherwise.
- M_{2u}: 1 if path from leaf u to the hub is shorter than L_r (16QAM), 0 otherwise.
- Δ_{1o}: number of transceivers of type o used at the hub with QPSK modulation format.

- Δ_{2o}: number of transceivers of type o used at the hub with 16QAM modulation format.
- δ_{ou}: number of transceivers of type o used at leaf node u.

The objective of the ILP model is to minimize the total transceivers' cost:

$$z = \sum_{o \in O_h} \Delta_{1o} \times C_o + \sum_{o \in O_h} \Delta_{2o} \times C_o + \sum_{u \in V^-} \sum_{o \in O_l} \delta_{ou} \times C_o \,, \quad (2)$$

subject to

$$\sum_{(i,j) \in E} x_{ij} = N, \quad (3)$$

$$\sum_j f_{ij}^t - \sum_j f_{ji}^t = \begin{cases} N & i = Hub, \\ -1 & \forall i \in V^-, \end{cases} \quad (4)$$

$$f_{ij} \leq N x_{ij} \qquad \forall (i,j) \in E, \quad (5)$$

$$f_{ji} \leq N x_{ij} \qquad \forall (i,j) \in E, \quad (6)$$

$$BM_{1u} \geq \sum_{(i,j) \in E} W_{ij} y_{ij}^u - L_r \qquad \forall u \in V^-, \quad (7)$$

$$M_{1u} + M_{2_u} = 1 \qquad \forall u \in V^-, \quad (8)$$

$$\sum_{o \in O_l} \delta_{ou} D_o \leq T(u)[M_{1u} + 1] \quad \forall u \in V^-, \quad (9)$$

$$\sum_{o \in O_h} \Delta_{1o} D_o \geq \sum_u 2T(u) M_{1u}, \quad (10)$$

$$\sum_{o \in O_h} \Delta_{2o} D_o \geq \sum_u T(u) M_{2u}. \quad (11)$$

Constraint (3) guarantees that the size of the tree is equal to the number of leaf nodes (assuming all leaf nodes have to be connected to the hub). According to constraint (4), N units of flow are distributed by the hub node, and all N leaf nodes receive precisely one unit of flow. Flows can only be on trees not surpassing the total amount of flows by constraints (5–6). These constraints create spanning trees, by fulfilling the tree criteria via a single commodity approach [22]. For the sake of simplicity, but without loss of generality, we assume that the QPSK modulation format is feasible for paths longer than $L_r = 500\ km$; for paths shorter than that, 16QAM can be used. Constraints (7) and (8) determine if a QPSK or 16QAM modulation format is used. M_{1u} (M_{2u}) 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 the SCs transmitted/received by a transceiver must use the same modulation format. Constraints (9-11) count the number of required transceivers per type at the leaf and hub nodes according to the modulation format selected.

The ILP model can also be adapted to model the case of P2P transceivers. In this case, transceiver pairs (operating at the same data rate) must be installed at the leaf and hub nodes. This scenario can be modeled by removing constraints (10), (11) and the first two terms of objective function (2) and multiplying the third term, which corresponds to leaf node transceivers cost, by a factor of two.

V. RESULTS AND DISCUSSION

In this section, we provide a detailed analysis of the performance of DSCM-based P2MP transceivers with varying data rates in a metro-aggregation mesh network. Table II presents four different scenarios in terms of the types of P2MP transceivers that can be used at the leaf and hub nodes, which are used to model the possible evolution of consecutive transceiver generations.

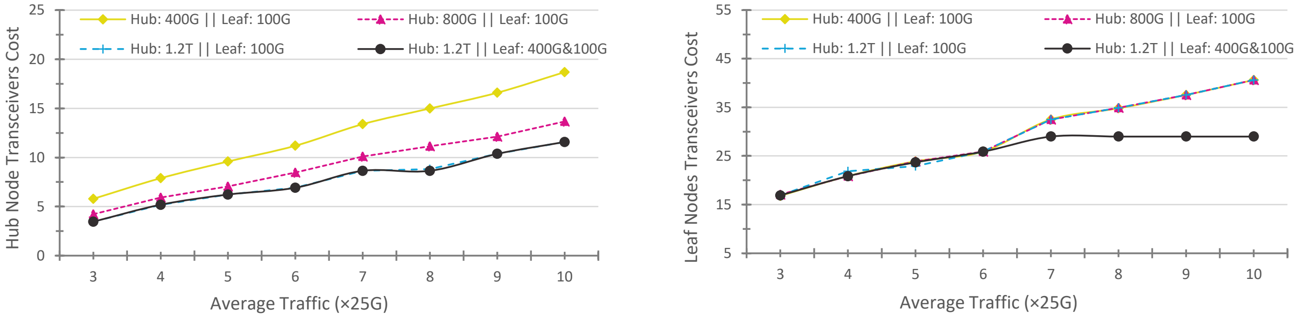
TABLE II
TRANSCEIVER DATA RATE SCENARIOS

Scenario	**1**	**2**	**3**	**4**
Hub	400G	800G	1.2T	1.2T
Leaf	100G	100G	100G	400G, 100G

A non-uniform traffic pattern is assumed: the number of 25G data rate each leaf node requires is randomly selected from the set of $[x, x+4]$, where x takes the value of $\{1,2,3,4,5,6,7,8\}$ to cover a broad range of traffic load conditions. In the following, we use the average number of needed SCs per leaf node to ease the display of results. The results shown in this section are the average value of 10 independent Monte-Carlo simulations. In other words, the process of generating traffic and solving the problem is done ten times, and then an average figure of the costs is reported.

Figure 2(a) shows the cost of transceivers deployed at the hub. As expected, when traffic increases from 3 SCs to 10 SCs, the hub node transceivers' cost increases almost linearly. However, Scenario 1 (yellow), which utilizes 400G transceivers at the hub, leads to the highest cost, while the other scenarios benefit from the higher capacity 800G and 1.2T transceivers, to reduce the cost at the hub. Particularly, at higher traffic loads, Scenarios 3 (blue) and 4 (black) clearly provide the lowest cost by exploiting the decrease in cost per bit enabled by 1.2T transceivers. The cost of transceivers at the leaf nodes is presented in Fig. 2(b). At low to moderate traffic loads, and because only 100G transceivers are used at the leaf nodes, all four scenarios result in a similar cost. Importantly, the advantage of also making 400G transceivers available for deployment at these nodes (Scenario 4) becomes evident for traffic loads larger than 6 SCs. According to the model used to generate traffic, an average traffic load above 6 SCs implies that the traffic load will go beyond 8 SCs (i.e., $>$ 200G when using 16QAM) for some leaf nodes. This is a threshold above which a 400G transceiver becomes less costly than using (three or more) 100G transceivers, according to the transceiver cost model employed in this work.

The cost savings of using P2MP instead of P2P transceivers is defined as $\frac{Cost(P2P) - Cost(P2MP)}{Cost(P2P)} \times 100$. Figure 3(a) illustrates the savings achieved when compared to the case where only 100G P2P transceivers are used. In general, using higher data rate transceivers at the hub leads to more impressive savings. Moreover, transceiver savings for Scenarios 1–3 (yellow, magenta, blue) are fairly constant while traffic increases, whereas the savings of Scenario 4 (black) become more pronounced from 6 to 10 SCs. As discussed above, this



(a)

(b)

Fig. 2. Cost of transceivers deployed at (a) the hub and (b) the leaf nodes versus average traffic loads.

is a consequence of being able to exploit 400G transceivers at leaf nodes with very high traffic requirements (larger than 6 SCs). To have a fair comparison with traditional P2P approaches, we present in Fig. 3(b) the savings of the P2MP scenarios when compared to the P2P case where 400G and 100G transceivers are available simultaneously. These results highlight that if in both cases (P2MP and P2P) 100G and 400G transceivers can be used at the leaf nodes (Scenario 4), P2MP enables considerable savings (i.e., between 30% and 40%) up to very high traffic loads. This provides evidence that, in the long-term, P2MP transceivers will continue to hold their advantage over traditional P2P transceivers in metro-aggregation networks.

VI. CONCLUSIONS

We described an ILP model for optimizing the deployment of DSCM-based P2MP transceivers. The cost of meeting all traffic requirements using P2MP transceivers was compared to that of utilizing traditional P2P transceivers in a reference network topology for a wide range of traffic loads and considering different generations of coherent transceivers. The results show that significant cost savings can be achieved, ranging from 30% up to nearly 40%, when the appropriate set of P2MP transceivers is utilized. Future work will include extending the analysis to more detailed modeling of physical impairments and exploring multi-period and brownfield planning.

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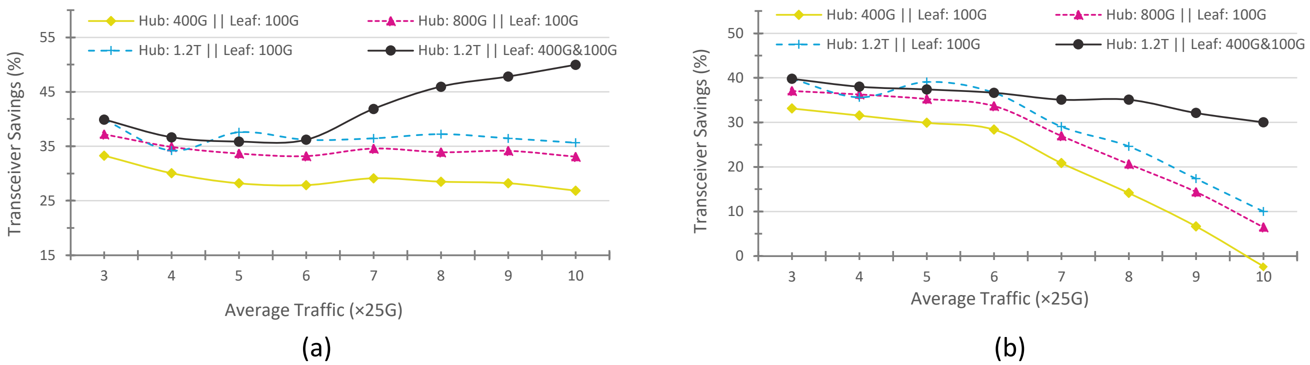

(a) (b)

Fig. 3. Transceiver savings of P2MP compared to the P2P approach with (a) 100G only and (b) combination of 100G and 400G transceivers versus average traffic loads.

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