Optimal Design of Filterless Horseshoe Networks Supporting Point-to-Multipoint Transceivers

Mohammad M. Hosseini[1,*], João Pedro[2,3], Nelson Costa[2], Antonio Napoli[4], Jaroslaw E. Prilepsky,[1] and Sergei K. Turitsyn [1]

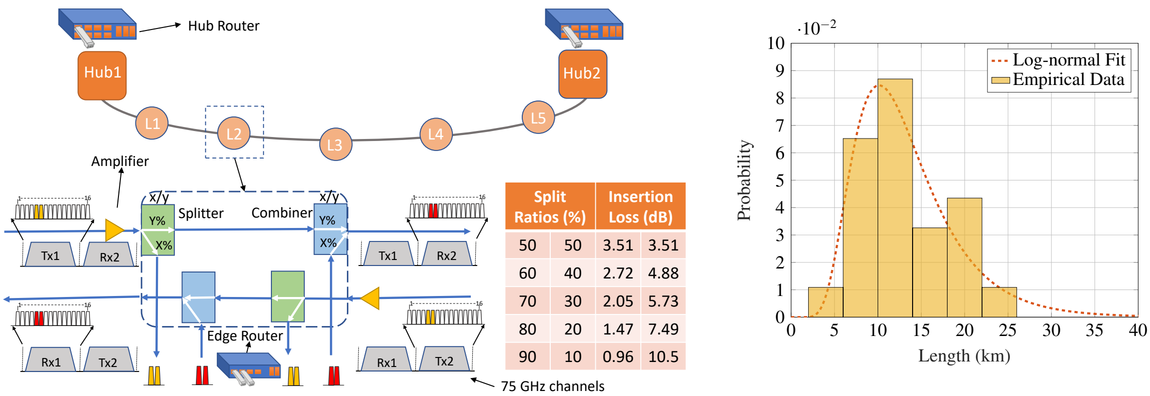
[1] *Aston Institute of Photonics, Aston University, Birmingham, United Kingdom*
[2] *Infinera, Lisbon, Portugal* [3] *Instituto de Telecomunicações, IST, Lisboa, Portugal* [4] *Infinera, Munich, Germany*

[*] *m.hosseini@aston.ac.uk*

Abstract: This paper proposes an ILP framework to optimize metro-aggregation filterless horseshoe networks for digital subcarrier multiplexing point-to-multipoint (P2MP) transceiver deployment. The results show that this significantly reduces amplifier requirements while ensuring end-to-end performance.

1. Introduction

High-speed, low-latency, and reliable Internet are fundamental for emerging applications, such as the Internet of Things (IoT) and cloud services, to increase their adoption rate. Access and metro-aggregation networks are crucial but highly cost-sensitive network segments. Metro-aggregation networks comprise regular topologies, such as rings [1] and chains/horseshoes [2], mesh topologies [3] or a combination of these [4]. Shared resources allow cost-efficient designs by avoiding under-utilization or over-provisioning. For example, in the access segment, passive optical networks (PONs) reduce the amount of fiber and central office equipment needed compared to P2P architectures by using a single wavelength to serve multiple endpoints [5]. Similarly, P2MP coherent pluggable transceivers enabled by digital subcarrier multiplexing (DSCM) have shown the potential to better match the hub-and-spoke traffic pattern that prevails in metro-aggregation networks [6]. Because the spectra of the subcarriers (SCs) do not overlap in DSCM signals, unlike in orthogonal frequency-division multiplexing (OFDM), the SCs of the Nyquist DSCM signal can be isolated and processed independently [7]. P2MP DSCM-based solutions can use a single high-capacity device at the hub node, improving key parameters such as cost, power consumption, and footprint, while typical P2P solutions rely on pairing transceivers at the hub and leaf nodes, which requires a larger number of devices at the hub node. Our previous research examined P2MP DSCM-based cost savings in filterless meshed metro-aggregation networks, but without considering how savings in the line system can be realized [8]. This work considers the deployment of P2MP DSCM-based transceivers in a filterless horseshoe topology, which is a robust architecture guaranteeing survivability to a single link and hub failures commonly used in metro-aggregation networks. It proposes an optimization framework that integrates optimal placement of amplifiers with tuneable gain and selection of splitter/combiner types (when devices with multiple splitting ratios are available) so that the total number of amplifiers is minimized while ensuring that key optical performance metrics, such as receiver sensitivity and potential limits on the power unbalance between SCs are fulfilled. The simulation results on different problem instances highlight the proposed framework's effectiveness.



(a) (b)

Fig. 1: (a) Illustration of DSCM-based P2MP transceiver in horseshoe topology using passive optical splitters/combiners and (b) a log-normal distribution fitting the length of optical links from real networks.

2. Network Topology and Optimization Framework

Fig. 1(a) shows a filterless horseshoe architecture comprising two hubs and five leaf nodes, and six optical fiber links. Each link consists of a pair of optical fibers. Passive 1:2 optical splitters and combiners are used for the add-and-drop functions. Every leaf node communicates with both hub nodes bidirectionally using disjoint paths to provide redundancy. In the case of DSCM-based P2MP transceivers, the hub nodes broadcast SCs using high data rate transceivers to all leaf nodes, and a copy of the complete optical signal is tapped-off by a suitable splitter in every leaf node. Lower data rate transceivers are used at leaf nodes to process only the desired SCs. In the upstream direction, SCs are optically groomed by combiners and may reach the hub with different power levels. The correct operation of the receiver in the hub can impose an upper bound on the power difference between SCs.

Protection is obtained at the expense of doubling the number of transceivers and introducing more losses at leaf nodes (optical signals pass through two optical combiners/splitters when crossing each leaf node). In order to achieve an optimized network design, we aim to minimize the number of optical amplifiers while meeting the reach requirements and not exceeding the nonlinearity and SCs power difference limit (in the upstream direction) thresholds. Fig 1(b) shows a log-normal distribution fitted to the data from the real horseshoe topologies described in [2]. We use this distribution to generate horseshoes with different link lengths for statistical confidence in the results. In this scenario, the optimal design of each transmission direction is independent of the other. For clarity and without loss of generality, we only consider optimizing the fiber direction that transports SCs in the Hub 1 to Hub 2. The main input parameters and decision variables of the ILP model are described in Table 1.

Parameter	Description
$G(V,E)$	graph with leaf nodes $u,u_p,v \in V$ and links $l \in E$
$W(u)$	length of the link goes to leaf u
α	fiber attenuation (0.22 dB/km)
$G_e(g)$	EDFA gain from $(0,6,7,\ldots,20dB \in g)$
P_{sc}	launch power per SC (-12 dBm)
P_n	threshold nonlinear power per SC (-10 dBm)
P_s	sensitivity power (16QAM: -24dBm)
P_l	maximum power difference of SCs (8 dB)
$H(s,p)$	insertion loss of splitter/combiner s at port p

Var	Description
Δ_s^u	binary variable for combiner selection; 1 if combiner s is selected for leaf u, 0 otherwise
∇_s^u	binary variable for splitter selection; 1 if splitter s is selected for leaf u, 0 otherwise
γ_p^u/δ_p^u	loss of port p of combiner / splitter selected for leaf u
μ_g^u	binary variable; 1 if amplifier at leaf u takes gain g
ϕ_u^1	Hub 2 receiver (Rx) power per SC coming from leaf u
ϕ_u^2	leaf u Rx power per SC coming from Hub 1
ε_1 / ε_2	lower / upper bound of variables ϕ_u^1

Table 1: Left-hand side: input parameters (values assumed in this work are shown in parentheses); Right-hand side: decision variables of the ILP model.

The goal of the ILP model is to minimize the function $z = \sum_u \sum_{G_e(g)\neq 0} \mu_u^g + w[\varepsilon_2 - \varepsilon_1]$, which expresses the number of amplifiers and the difference between the highest and lowest SC power levels at the Rx input of the Hub 2. The weight factor w ensures that the highest priority is to minimize the number of amplifiers. The constraints are as follows:

$$\sum_s \Delta_s^u = 1 \quad \forall u \in V, \tag{1}$$

$$\sum_s \nabla_s^u = 1 \quad \forall u \in V, \tag{2}$$

$$\gamma_p^u = \sum_s \Delta_s^u H(s,p) \quad \forall u \in V, \tag{3}$$

$$\delta_p^u = \sum_s \nabla_s^u H(s,p) \quad \forall u \in V, \tag{4}$$

$$\sum_g \mu_g^u = 1 \quad \forall u \in V, \tag{5}$$

$$\varepsilon_1 \leq \phi_u^1 \quad \forall u \in V, \tag{6}$$

$$\varepsilon_2 \geq \phi_u^1 \quad \forall u \in V, \tag{7}$$

$$\varepsilon_2 - \varepsilon_1 \leq P_l, \tag{8}$$

$$\phi_u^1, \phi_u^2 \geq P_s \quad \forall u \in V, \tag{9}$$

$$\phi_u^1 = P_{sc} + \sum_{v>u} G_e(g)\mu_g^u - \alpha \sum_{v>u} W(v) - \gamma_{p_1}^u - \sum_{v>u} (\gamma_{p_2}^v + \delta_{p_2}^v) \quad \forall u \in V, \tag{10}$$

$$\phi_u^2 = P_{sc} + \sum_{v<u} G_e(g)\mu_g^u - \alpha \sum_{v\leq u} W(v) - \delta_{p_1}^u - \sum_{v<u} (\gamma_{p_2}^v + \delta_{p_2}^v) \quad \forall u \in V, \tag{11}$$

$$P_{sc} + \sum_{v\leq u} \sum_g G_e(g)\mu_v^g - \sum_{v\leq u} (\gamma_{p_2}^v + \delta_{p_2}^v) - \alpha \sum_{v\leq u} W(u) \leq P_n \quad \forall u \in V, \tag{12}$$

$$P_{sc} + \sum_{u_p<v\leq u} \sum_g G_e(g)\mu_v^g - \sum_{u_p<v\leq u} (\gamma_{p_2}^v + \delta_{p_2}^v) - \alpha \sum_{u_p<v\leq u} W(u) - \gamma_{p_1}^u \leq P_n \quad \forall u, u_p \in V. \tag{13}$$

Constraints (1) and (2) select for each leaf node the combiner and splitter types (among the ones available), respectively. Constraints (3) and (4) assign the corresponding loss of the combiners and splitters to the add and drop ports. An amplifier with gain $G_e(g)$ is placed at leaf u through constraint (5). Note that gain 0 means no amplifier is needed. The lower and upper bounds of the power level per SC received by Hub 2 are determined by constraints (6) and (7), respectively. The difference cannot exceed P_l, from constraint (8). Constraint (9) guarantees the received power meets the transceiver sensitivity (i.e., minimum input power). Constraints (10) and (11) calculate the power received by Hub 2 from leaf nodes and the power received by leaf nodes from Hub 1 (per SC), respectively. Constraints (12) and (13) ensure the power per SC does not exceed the non-linearity threshold power in downstream (Hub1 to leaf nodes) and upstream (leaf nodes to Hub 2) directions, respectively. At each leaf node, a splitter, a combiner and their add/drop port assignment, and an amplifier gain must be selected, leading to a solution search space of size $(|g| \times 2|s| \times 2|s|)^{|u|}$.

3. Results and Discussion

We consider two horseshoe networks comprising 5 and 10 leaf nodes, in which the links are randomly generated using the distribution depicted in Fig. 1(b). In the following, all the results shown were obtained from 100 independent simulation runs. Amplifiers can be placed at the leaf nodes' input (according to the ILP model). The values of the design parameters are shown in Table 1(a). Fig 2(a) shows the average maximum power difference between SCs at the input of Hub 2 Rx and the average minimum number of amplifiers placed in horseshoes with 5 leaf nodes when different sets of candidate splitter/combiner types are considered. 95% confidence intervals are also shown as error bars. When all the splitters/combiners listed in Fig. 1(a) are considered in the optimization (referred to as scenario "All"), the minimum number of required amplifiers is around 2, increasing to 3.9 when only 50/50 splitters/combiners are considered. Using only 90/10 splitters/combiners leads to fewer amplifiers being deployed, but at the expense of a higher maximum power difference between SCs. Figure. 1(b) shows the same analysis and similar trends when the number of leaf nodes is increased to 10. For instance, deploying a set of 70/30 and 90/10 amplifiers leads to an average of 4.2 amplifiers, which is slightly larger than that in the "All" scenario and still almost half of that of using 50/50 splitters/combiners.

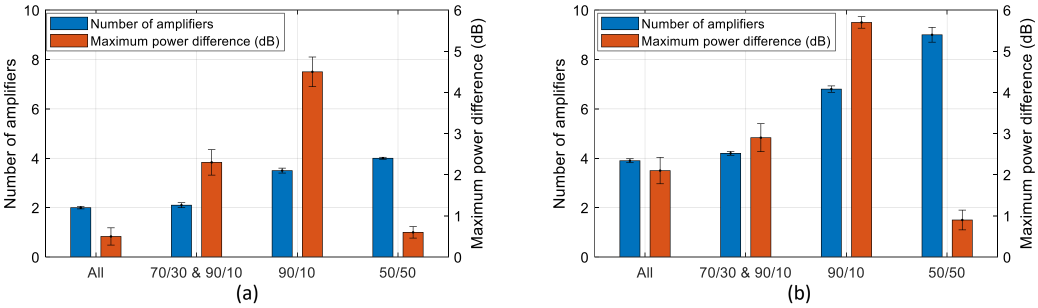


Fig. 2: Minimum number of amplifiers and maximum power difference of SCs at Hub 2 Rx versus set of candidate splitter/combiner types used in horseshoe network with (a) 5 leaf nodes and (b) 10 leaf nodes.

Figs. 3(a) and (b) show the probability of usage of different splitters/combiners in the "All" and "70/30 & 90/10" scenarios while considering topologies with 10 leaf nodes. It can be seen that 80/20 and 70/30 splitters and combiners are used more than any other types in "All" and "70/30 & 90/10" scenarios, respectively. However, 50/50 splitters and combiners have the minimum usage in the "All" scenario. This observation provides evidence that the availability of these devices with unbalanced power split/combine ratios is key to minimizing the number of amplifiers required.

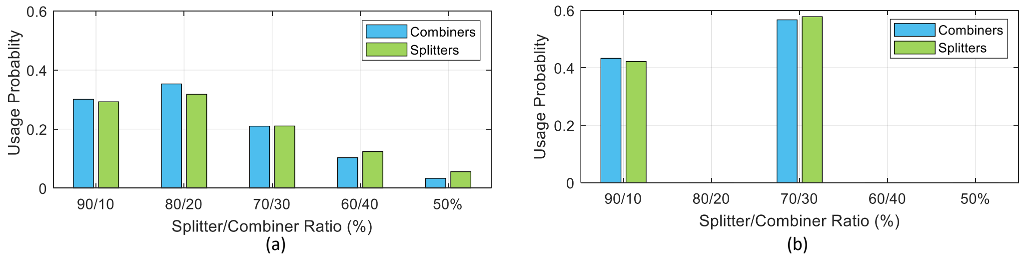


Fig. 3: Usage probability of the different splitter/combiner types in 10-leaf horseshoe networks.

4. Conclusion

We proposed a novel ILP model for the optimized design of the physical infrastructure of the horseshoe topology for P2MP DSCM-based transceiver deployment. Results obtained using statistically generated networks show that two and four amplifiers can meet the design criteria of networks with five and ten leaf nodes, respectively.

Acknowledgement

This work has received funding from the EU Horizon 2020 program under the Marie Skłodowska-Curie G.A. 813144 (REAL-NET). J. Pedro, N. Costa, and A. Napoli thank the European Commission for funding their activities through the H2020 B5G-OPEN (G.A. 101016663).

References

[1] P. Pavon-Marino et al., *J. Opt. Commun. Netw.* **2022**, *14*, B30–B44.
[2] J. Bäck et al. in 2022 International Conference on Optical Network Design and Modeling (ONDM), IEEE, **2022**, pp. 1–6.
[3] M. M. Hosseini et al. in Optical Fiber Communication Conference, Optica Publishing Group, **2022**, W3F–2.
[4] L. S. de Sousa, A. C. Drummond, *Opt. Switch. Netw.* **2022**, 100719.
[5] H. S. Abbas, M. A. Gregory, *J. network computer applications* **2016**, *67*, 53–74.
[6] D. Welch et al., *J. Light. Technol.* **2021**, *39*, 5232–5247.
[7] M. Qiu et al., *Opt. Express* **2014**, *22*, 18770–18777.
[8] M. Mohammad Hosseini et al., *J. Opt. Commun. Netw.* **2022**, *14*, 586–594.