Statistical Route Feasibility in Metro-Access Optical Networks for Next-Generation RAN X-Haul

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***Abstract*—This paper investigates the statistical feasibility of routes in converged metro-access optical networks for next-generation RAN x-haul. Two network topologies are considered: N_1 with longer metro spans and N_2 with shorter, denser connectivity. Route feasibility is evaluated via Bit Error Rate (BER) profiling under two thresholds (10^{-3} and 10^{-2}), using two commercially available coherent transceivers: Cassini DCO (DP-QPSK, DP-8QAM, DP-16QAM) and Phoenix DCO (DP-QPSK, DP-16QAM). A Python-based physical-layer simulator models attenuation, ASE, and NLI to derive GSNR and end-to-end SNR per route; BER is then computed via modulation-dependent closed forms. Results show that DP-QPSK provides near-universal feasibility in both networks, while higher-order formats, especially DP-16QAM, are strongly topology and threshold dependent. N_2 enables significantly broader applicability of high-order modulation than N_1, and Cassini's intermediate DP-8QAM offers a robust capacity–reliability trade-off absent in Phoenix. These findings highlight the importance of network-aware planning and transceiver flexibility to ensure route viability for RAN transport over converged optical infrastructures.**

***Index Terms*—metro-access networks, x-haul, 5G/6G, RAN transport, Capacity Analysis, BER Analysis**

I. Introduction

The evolution of mobile networks towards 5G and beyond has intensified the demand for transport infrastructures capable of delivering services such as ultra-reliable low latency communication (URLLC), massive machine-type communications (mMTC), and enhanced mobile broadband (eMBB). These emerging services require a transport layer that can sustain both extremely high capacity and stringent quality-of-service guarantees. In metropolitan areas, the proliferation of small cells and Remote Radio Units (RRUs) has driven unprecedented traffic growth across both access and metro segments. Supporting such traffic requires scalable fronthaul and midhaul solutions, which must efficiently exploit the underlying optical infrastructure while remaining cost-efficient and accommodating heterogeneous service requirements from advanced wireless applications such as massive IoT, cloud-native services, and future 6G use cases [1, 2].

Although alternatives such as millimeter-wave, THz, and free-space optics offer advantages, their limited reach, environmental sensitivity, and restricted throughput hinder their ability to consistently meet 5G/6G performance targets. For RAN x-haul, optical fiber remains the most viable solution, providing high bandwidth, predictable latency, and robustness required for service-level agreements [3, 4]. However, deploying dedicated fibers for RAN fronthaul is cost-prohibitive, particularly in dense metro environments. A more practical approach is to leverage existing converged metro-access infrastructures through Optical Network-as-a-Service (ONaaS), primarily supported by Dense Wavelength Division Multiplexing (DWDM) backbones. While this strategy provides substantial cost and scalability benefits, the ability of such infrastructures to sustain high-capacity optical channels ultimately depends on the physical-layer feasibility of the routes across the network. A fundamental challenge in this context lies in evaluating the performance of commercially available transceivers over realistic metro-access paths, where link lengths, cascaded optical amplifiers, topological and equipment diversity strongly influence transmission quality. o quantify these combined effects, a widely adopted performance metric is the Bit Error Rate (BER), which serves as a decisive indicator of feasibility. BER captures the cumulative impact of linear and nonlinear impairments and directly relates to service-level requirements. Accordingly, higher-order modulation formats offer increased throughput but at the cost of reduced resilience to impairments, which limits their applicability in metro-access scenarios. Hence, assessing feasibility across different modulation formats and network conditions is essential to understand the trade-offs between capacity and robustness.

Building on our previous work [5] on BER-based feasibility analysis in metro-access networks, this paper extends the investigation by comparing two distinct network scenarios. The first, referred to as Network N_1, represents a topology with longer metro links, averaging 37 km in span, and a moderate number of nodes. The second, Network N_2, features

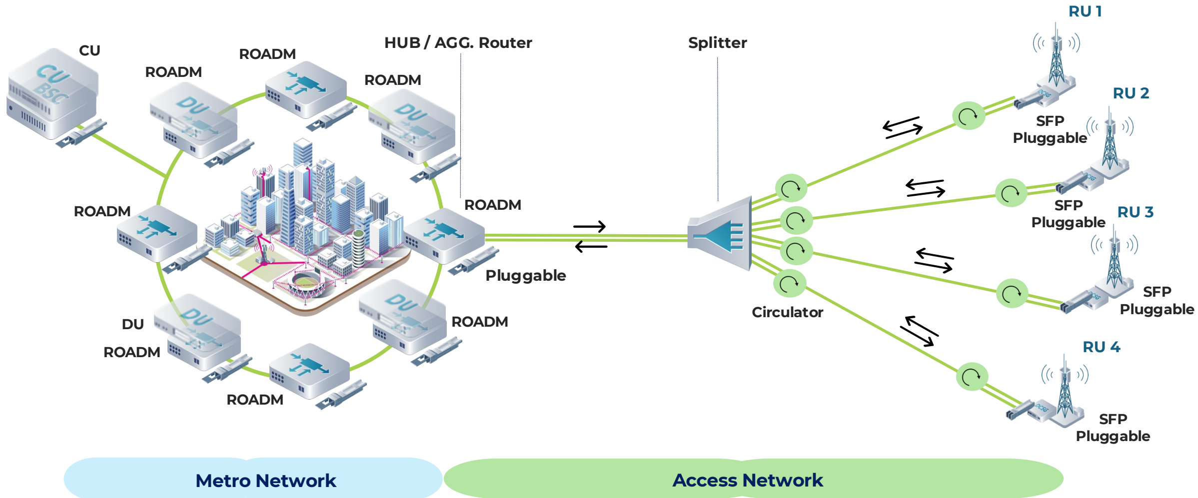

Fig. 1: Converged Metro-Access Network Scenario

shorter metro-access segments with denser node connectivity, reflecting urban deployments where traffic aggregation points are more closely spaced. By analyzing both cases, we highlight how structural differences in the underlying topology influence the set of feasible routes and their suitability for RAN transport. The analysis is conducted using two commercially available coherent transceivers: the Cassini DCO, which supports QPSK, 8QAM, and 16QAM modulation formats, and the Phoenix DCO, which supports QPSK and 16QAM. These transceivers are representative of open and disaggregated architectures increasingly adopted in metro and access networks. Their evaluation provides realistic insights into the performance boundaries of current-generation hardware when deployed over heterogeneous metro-access infrastructures. By statistically profiling BER distributions across all possible routes in N_1 and N_2, we provide a detailed characterization of the feasibility region for each modulation format and transceiver type.

The results presented in this work emphasize the interplay between topology, modulation format, and hardware capabilities in determining feasible capacity. They also underline the necessity of topology-aware transceiver selection and adaptive modulation strategies for efficiently integrating RAN traffic into existing metro-access infrastructures. Further, this study provides a framework for quantifying physical-layer feasibility and guiding the deployment of converged optical infrastructures that balance cost, scalability, and service reliability to meet the growing demands of next-generation wireless networks.

II. Simulation Scenario

Considering fully transparent converged metro-access networks (N_1 and N_2), all possible routes were evaluated for the physical layer characteristics within a Python-based simulator. The physical-layer modeling incorporates key transmission impairments, including fiber attenuation and amplified spontaneous emission (ASE) noise introduced by optical line systems. For each route, the cumulative effect of these impairments is quantified to derive performance metrics such as the received optical power (ROP), the generalized signal-to-noise ratio (GSNR), and the end-to-end signal-to-noise ratio (SNR).

In the physical layer abstraction, each network element is modeled as introducing a signal gain (or loss) together with Gaussian noise contributions. Both ASE noise from optical amplifiers and non-linear interference (NLI) from fiber propagation are considered. The GSNR for the i^{th} is expressed as

$$\mathrm{GSNR}_i = \frac{P_{\mathrm{S},i}}{P_{\mathrm{ASE}}(f_i) + P_{\mathrm{NLI},i}(f_i)} \tag{1}$$

where $P_{\mathrm{S},i}$ is the signal launch power, $P_{\mathrm{ASE}}(f_i)$ represents ASE contribution and $P_{\mathrm{NLI},i}$ corresponds to the fiber nonlinear interference. The total SNR is obtained by combining GSNR with transceiver limitations as

$$\mathrm{SNR}^{-1} = \mathrm{GSNR}^{-1} + \mathrm{SNR}_{\mathrm{TRX}}^{-1} \tag{2}$$

Based on a random power loss distribution on the access segment as discussed in [5, 6], the feasibility of each route within the converged metro-access network was determined, as shown in Fig. 3. BER estimation was done by considering transceiver models for both Cassini DCO and Phoenix DCO, as in [7]. The BER is computed as

$$\mathrm{BER} = k_1 \cdot \mathrm{erfc}\left(\sqrt{k_2 \cdot \mathrm{SNR}}\right) \tag{3}$$

where k_1 and k_2 are constants whose values depend upon the type of modulation format [8]. These values are listed in Table I.

In this analysis, we have considered two converged metro-access network topologies referred to as network N_1 and network N_2 as shown in Fig. 2. Each network features both

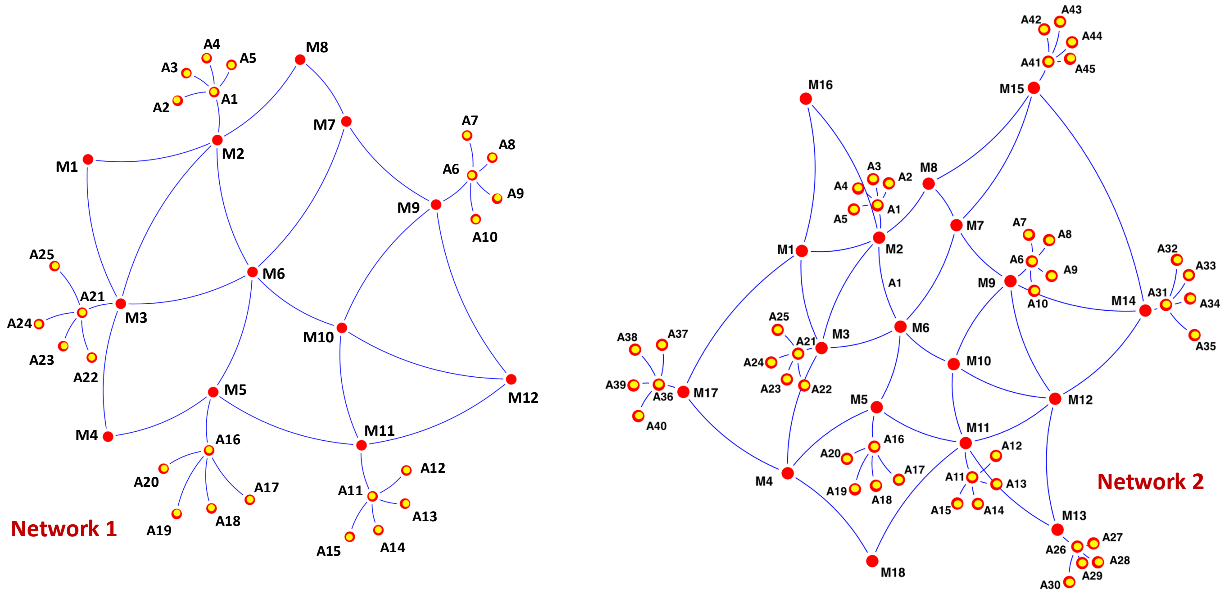

Fig. 2: Converged Metro-Access Network Topology

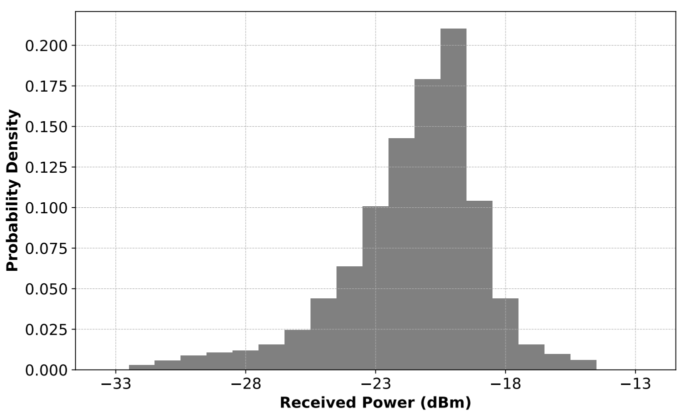

Fig. 3: Power loss distribution

Modulation Format	bit/symbol	k_1	k_2
DP-QPSK	4	$1/2$	$1/2$
DP-8QAM	6	$2/3$	$3/14$
DP-16-QAM	8	$3/8$	$1/10$

TABLE I: k_1 and k_2 values for different modulation formats

metro (M) and access (A) segments with a cluster of four access nodes exchanging end-to-end traffic. The access segment is connected to a metro network through a ROADM and a circulator, allowing BiDi transmission in the access segment and paired fibers in the metro segment. Both networks reflect a realistic metro-access deployment and provide a representative framework for assessing route feasibility in support of RAN transport. To limit computational complexity, a maximum of 10 hops was imposed on each evaluated path.

Network N_1 consists of 37 nodes in total, including 12 metro nodes and 25 access nodes serving RUs. It features an average node degree of 3.42, with fiber spans averaging 37 km and a maximum link length of 50 km. Network N_2 represents a denser configuration, comprising 63 optical nodes, of which 18 belong to the metro segment and 45 to the access segment. Here, the metro segment exhibits an average node degree of 4.06, with the longest fiber link extending to 12 km.

For both networks, the feasibility of each route was determined by comparing the computed BER against two thresholds (10^{-3} and 10^{-2}). A route is considered feasible if the BER requirement is satisfied. This evaluation provides a comprehensive indication of route viability for supporting RAN transport over the converged optical network, thereby reflecting the bitrate and capacity achievable under realistic physical-layer conditions.

III. Results and Discussions

The feasibility analysis was conducted using Cassini and Phoenix DCO transceivers across the two converged metro-access network topologies, N_1 and N_2. Figures 4–7 show the cumulative probability and probability density of BER distributions for each transceiver and network. Feasible and non-feasible regions were defined based on the cumulative frequency distribution. The green and yellow shaded regions correspond to feasible zones at BER thresholds of 10^{-3} and 10^{-2}, respectively, whereas the pink region indicates non-feasible routes with BER values greater than 10^{-2}. While Figures 8–9 summarize the overall fraction of feasible and non-feasible routes under the BER thresholds. The results are analyzed in detail in the following discussion.

A. Cassini Transceiver

Fig. 4 and 5 present the BER distributions for DP-QPSK, DP-8QAM, and DP-16QAM in networks N_1 and N_2. At the strict BER threshold of 10^{-3}, DP-QPSK achieves almost complete feasibility in both topologies, with 99.2% of routes

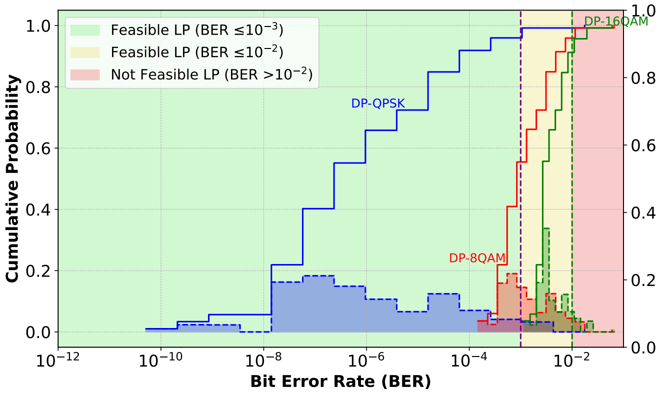

Fig. 4: Comparison between DP-QPSK, DP-8QAM, and DP-16QAM for Cassini DCO in N_1

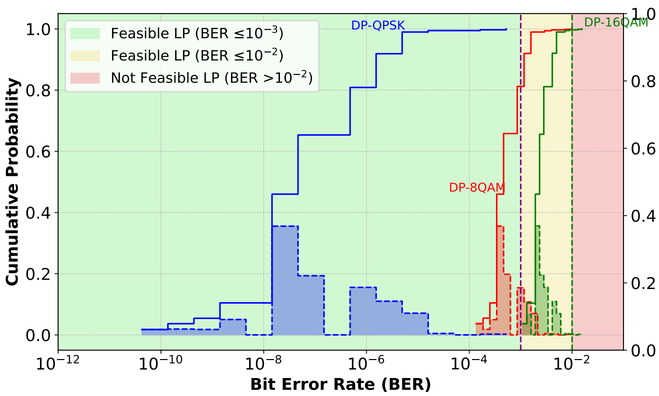

Fig. 5: Comparison between DP-QPSK, DP-8QAM, and DP-16QAM for Cassini DCO in N_2

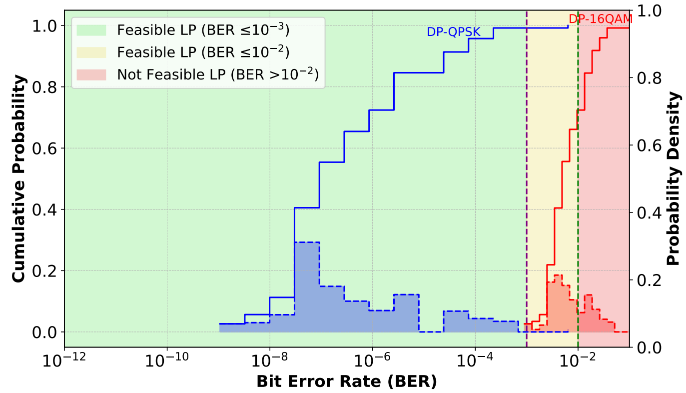

Fig. 6: Comparison between DP-QPSK and DP-16QAM for Phoenix DCO in N_1

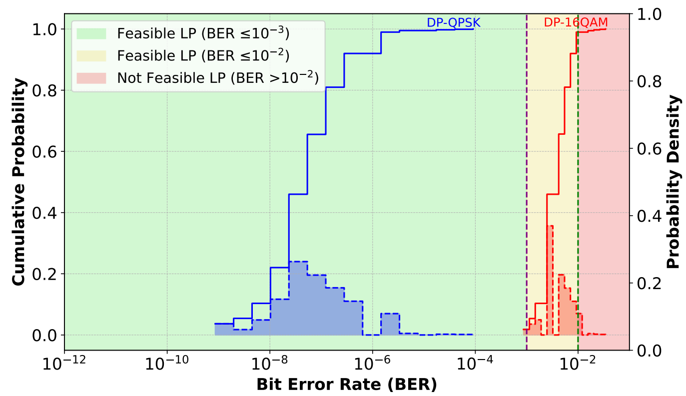

Fig. 7: Comparison between DP-QPSK and DP-16QAM for Phoenix DCO in N_2

feasible in N_1 and full feasibility in N_2. DP-8QAM provides moderate coverage, with 55.5% feasible in N_1 and 81.2% in N_2. In contrast, DP-16QAM exhibits poor resilience under this constraint, leaving nearly all routes above the feasibility limit in N_1 and only marginal feasibility in N_2.

When the threshold is relaxed to 10^{-2}, feasibility improves substantially for higher-order formats. In N_1, 95.9% of routes are feasible with DP-8QAM and 91.2% with DP-16QAM. In N_2, feasibility rises to nearly 100% for both 8QAM and 16QAM, with less than 1% of routes remaining infeasible. These results confirm that while QPSK is universally robust, the practical adoption of higher-order formats strongly depends on both network topology and the tolerated BER margin.

B. Phoenix Transceiver

Figures 6 and 7 illustrate the BER distributions for DP-QPSK and DP-16QAM in networks N_1 and N_2. At the strict BER threshold of 10^{-3}, DP-QPSK maintains strong robustness in both topologies, with 99.2% of routes feasible in N_1 and full feasibility in N_2. In contrast, DP-16QAM shows very limited applicability under this condition. In N_1, nearly all routes exceed the feasibility limit, leaving 16QAM practically unusable. In N_2, the shorter spans enable better performance, but feasibility remains constrained to a minority of routes.

When the threshold is relaxed to 10^{-2}, feasibility improves substantially for DP-16QAM. In N_1, 65.2% of routes become feasible, although 33.9% remain non-feasible. In N_2, performance improves further, with 90.2% of routes feasible and only 8% infeasible. These results indicate that while Phoenix ensures robust connectivity with QPSK, its lack of an intermediate modulation option such as 8QAM limits flexibility. Consequently, 16QAM adoption with Phoenix remains highly topology-dependent, requiring either shorter links or tolerance to higher BER margins.

C. Overall Feasibility Comparison

The aggregated results in Figs. 8 and 9 illustrate the feasibility percentages for both networks and transceivers under the two BER thresholds.

At 10^{-3}, QPSK ensures nearly universal feasibility in both N_1 and N_2. Cassini's intermediate 8QAM format provides additional flexibility, with 55.5% feasibility in N_1 and 81.2% in N_2, whereas Phoenix offers no intermediate option between QPSK and 16QAM. Under this strict threshold, 16QAM remains severely limited in N_1 and only marginally feasible in N_2.

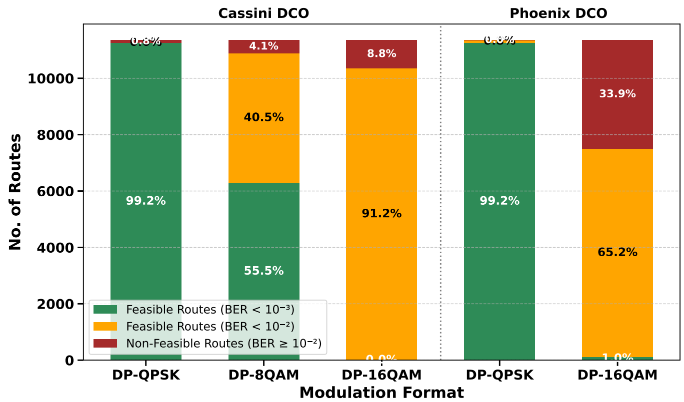

Fig. 8: Route Feasibility Analysis in N_1

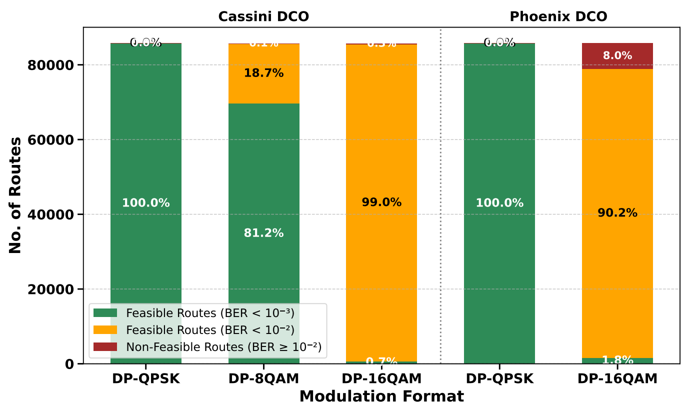

Fig. 9: Route Feasibility Analysis in N_2

At 10^{-2}, the feasibility of higher-order formats improves considerably. In N_1, Cassini achieves 95.9% with 8QAM and 91.2% with 16QAM, while Phoenix 16QAM lags behind at 65.2%. In N_2, feasibility exceeds 99% for Cassini 8QAM and 16QAM, and 90.2% for Phoenix 16QAM. These comparisons demonstrate that network topology and transceiver design jointly determine the practical viability of higher-order modulation in metro-access networks.

IV. Concluding Remarks

This paper presented a feasibility analysis of converged metro-access networks for RAN transport using two commercially available coherent transceivers, Cassini and Phoenix DCO. The study evaluated all possible routes in two representative topologies, N_1 with longer metro spans and N_2 with shorter and denser connectivity, under two BER thresholds (10^{-3} and 10^{-2}).

The results demonstrated that DP-QPSK provides nearly universal feasibility in both networks and with both transceivers, confirming its robustness to physical-layer impairments. Higher-order modulation formats, particularly DP-16QAM, offer greater per-channel capacity, but their feasibility is strongly constrained by network topology and BER margin. In N_1, longer spans severely limited 16QAM applicability, whereas in N_2 the denser connectivity enabled feasibility above 90% when the relaxed threshold was considered. Cassini's support for an intermediate format, DP-8QAM, provided a useful trade-off between capacity and robustness, a flexibility not available with Phoenix.

Overall, the findings highlight two key insights: (i) network topology decisively impacts the practical viability of advanced modulation formats, and (ii) transceiver design, particularly the availability of intermediate formats, can significantly enhance route feasibility. These results emphasize the need for topology-aware planning and adaptive modulation strategies to ensure route viability for RAN transport over converged optical infrastructures.

In practice, these insights support operator decisions on transceiver selection and modulation policies that balance cost, scalability, and service reliability in metro-access RAN deployments. Future work will extend this analysis by incorporating dynamic traffic patterns, spectrum allocation policies, and adaptive modulation schemes to provide a more comprehensive evaluation of metro-access networks as enablers for next-generation RAN deployments.

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References

[1] C. Ranaweera *et al.*, "Design and deployment of optical x-haul for 5g, 6g, and beyond: progress and challenges," vol. 15, no. 9, pp. D56–D66, 2023.

[2] Z. Vujicic *et al.*, "Towards virtualized optical-wireless heterogeneous networks," *IEEE access*, 2024.

[3] T. Sharma *et al.*, "Review of optical and wireless backhaul networks and emerging trends of next generation 5g and 6g technologies," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 3, p. e4155, 2021.

[4] J. Costa-Requena, A. Afriyie, C. P. Konstantinos, K. Eleni, K. Dimitrios, N. Carapellese, and E. Y. Padilla, "Sdn-enabled thz wireless x-haul for b5g," in *2021 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. IEEE, 2021, pp. 211–216.

[5] A. Ali *et al.*, "Statistical evaluation of lightpath feasibility in converged optical metro-access networks," in *2025 IEEE Photonics Society Summer Topicals Meeting Series (SUM)*, 2025, pp. 1–2.

[6] G. Simon *et al.*, "Clustering g-pon field data to improve flexibility in next generation pon systems," in *2021 European Conference on Optical Communication (ECOC)*. IEEE, 2021, pp. 1–4.

[7] T. Mano *et al.*, "Modeling the input power dependency of transceiver ber-onsr for qot estimation," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2024, pp. M1H–4.

[8] A. Rosso, "Modeling and controlling optical transponder whiteboxes based on the physical layer digital twin," Master's thesis, Politecnico di Torino, 2024.