Calcolo dell'ombreggiamento sull'involucro dell'edificio

Capacity Assessment in Converged Metro-Access Optical Networks for end-to-end RAN Fronthaul

Ahtisham Ali
Consorzio Top-IX
DET, Politecnico di Torino
Torino, Italy
ahtisham.ali@top-ix.org

Andrea Rosso
Dept. of Electronics and Telecommunications
Politecnico di Torino
Torino, Italy
andrea.rosso@polito.it

Muhammad Umar Masood
Dept. of Electronics and Telecommunications
Politecnico di Torino
Torino, Italy
muhammad.masood@polito.it

Michela Pollone
Consorzio Top-IX
Torino, Italy
michela.pollone@top-ix.org

Alessandro Galardini
Consorzio Top-IX
Torino, Italy
alessandro.galardini@top-ix.org

Vittorio Curri
Dept. of Electronics and Telecommunications
Politecnico di Torino, Torino, Italy
vittorio.curri@polito.it

***Abstract*—In this paper, we present a capacity and feasibility analysis of converged metro-access optical networks for supporting Radio Access Network (RAN) fronthauling, based on Bit Error Rate (BER) profiling. Using two commercially available transceivers—Cassini DCO and Phoenix—we assess the performance of various modulation formats (DP-QPSK and DP-16QAM) and symbol rates (32 Gbaud and 64 Gbaud) across all routes in a metro-access topology. The study evaluates route feasibility under two BER thresholds (10^{-3} and 10^{-2}), offering detailed insights into the trade-offs between capacity, symbol rate, and transmission robustness. Our results demonstrate that while higher-order modulations and higher symbol rates enable greater throughput, they exhibit lower tolerance to transmission impairments, significantly reducing the number of feasible routes. Conversely, lower-order modulations and reduced symbol rates provide more resilient performance over a wider range of network conditions. These findings support the potential of utilizing existing metro-access infrastructure to efficiently and reliably support high-bandwidth, low-latency RAN connectivity for 5G and 6G networks.**

***Index Terms*—metro-access networks, RAN, Capacity Analysis, BER Analysis**

I. Introduction

As demand for high-speed, reliable data services escalates in metropolitan areas, the transition towards 5G and the forthcoming 6G networks becomes increasingly critical. These advanced networks necessitate robust, high-capacity connectivity solutions to handle the surge in data traffic and the complexity of emerging technologies such as the Internet of Things (IoT) and cloud computing services. To meet these needs, there is a rapid deployment of numerous Remote Radio Units (RRUs) in dense urban environments for efficient data transmission [1, 2].

These RRUs are essential for enhancing network coverage and capacity but demand an equally capable transport network to manage the data load effectively. Current transport technologies, such as microwave, millimeter waves, terahertz (THz), and free-space optics, each offer unique advantages. However, these technologies typically struggle to provide the consistent bandwidth and low-latency communication required for seamless service delivery [3, 4].

In this scenario, optical fiber has emerged as the best transport technology for fronthauling and backhauling. It not only provides the high bandwidth necessary but also ensures reliable and low-latency communication with minimal signal losses, crucial for supporting the high data rates, ultra-low latency, and enhanced reliability required by 5G and 6G applications [1]. However, the use of dedicated fibers, while advantageous, is not always scalable or cost-effective, especially in urban environments characterized by dynamic and heterogeneous traffic patterns. A more viable alternative is to utilize the existing optical infrastructure to support access networks. Typically, this includes a metropolitan area network that employs traditional Dense Wavelength Division Multiplexing (DWDM) channels, alongside an access segment that operates using a Passive Optical Network (PON), which collectively form the backbone of the urban fiber infrastructure.

The integration of Radio Access Networks (RAN) with these metro-access networks can be significant in this case, as it plays a crucial role in achieving high bandwidth and low latency communications essential for modern applications. This paper explores the potential of converged metro-access networks, traditionally used for broadband service delivery, as a scalable and efficient solution for RAN fronthauling [5]. In this study, we perform a detailed statistical analysis of all the routes in the network. For this investigation, we do not consider any blocking events, focusing solely on the capacity and performance characteristics under different scenarios. Despite their capabilities, these networks often operate below their maximum capacity, presenting an opportunity to leverage their available bandwidth for additional functionalities. This study assesses the capacity of converged metro-access networks for RAN end-to-end connection on the basis of the statistical behavior of Bit Error Rate (BER) across all feasible routes in a converged metro-access network, as shown in fig 1. These findings aim to guide network operators in making informed decisions about future deployments and optimizations.

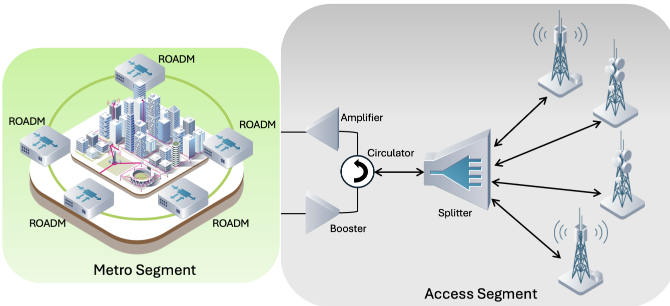

Fig. 1: Converged Metro-Access Network Scenario

II. Simulation Scenario

To evaluate the characteristics of the physical layer for all possible routes within a converged metro-access network, the overall network has been modeled in a Python simulator. The physical-layer modeling accounts for key impairments such as fiber attenuation and amplifier noise introduced by optical line systems. For each route, the cumulative effect of these impairments is used to compute metrics such as the received optical power (ROP), generalized signal-to-noise ratio (GSNR), and end-to-end signal-to-noise ratio (SNR).

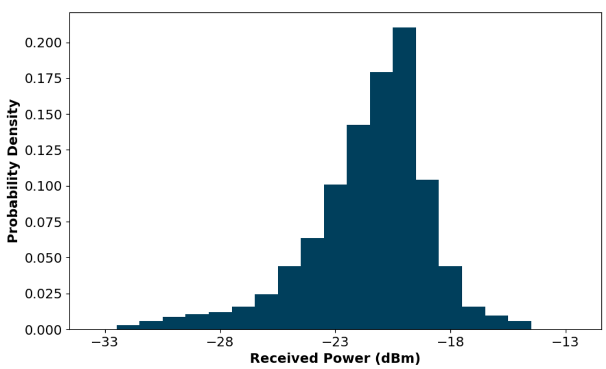

Fig. 2: Power loss distribution

For the physical layer abstraction, each network element is assumed to cause a signal gain (or loss) and introduce Gaussian noise. In particular, It has been considered the joint effect of the Amplified Spontaneous Emission (ASE) of optical amplifiers and the non-linear interference (NLI) from fiber propagation. The GSNR for i^{th} channel can be defined as:

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

where $P_{\mathrm{S},i}$ is the signal launch power, $P_{\mathrm{ASE}}(f_i)$ is ASE, and $P_{\mathrm{NLI},i}$ is the fiber NLI.

Considering a random power loss distribution on the access segment to determine the feasibility of each route within the converged metro-access network, as shown in Fig. 2 and calculated in [6]. Considering a transceiver model for both transceivers (Cassini DCO and Phoenix) as in [7], the bit error rate (BER) for each route has been computed using eq. 2 while the SNR contribution is given by eq. 3.

$$\mathrm{BER} = k_1 \cdot \mathrm{erfc}\left(\sqrt{k_2 \cdot \mathrm{SNR}}\right) \tag{2}$$

where k_1 and k_2 are constants whose values depend upon the type of modulation format [8] and are given as:

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

TABLE I: k_1 and k_2 values at different modulation formats

$$\mathrm{SNR}^{-1} = \mathrm{GSNR}^{-1} + \mathrm{SNR}_{\mathrm{TRX}}^{-1} \tag{3}$$

In this investigation, we have considered the metro-access network topology depicted in Fig. 3 with a limited subset of available leafs, exchanging antenna-to-antenna traffic. It consists of 37 optical nodes for a converged metro-access network for add-drop traffic requests. The M-nodes and A-nodes represent the metro and access segments, respectively. Metro nodes are interconnected by 19 edges representing optical line systems, each consisting of fiber pairs and in-line amplifiers. The network features an average node degree of 3.42 and an average link length of 37 km, with a maximum link length of 50 km. Access network segments are connected to the metro network via five edge links. The access segment consists of short-reach fiber links ranging from 2 km to 5 km. This access segment is based on the passive optical network (PON) configurations, having an average splitting ratio of 1:4.

Based on the computed BER for each route, the feasibility of the route has been decided by comparing it with BER threshold. It reflects the bitrate and capacity of the network.

III. Results and Discussions

We analyzed the route feasibility for both Cassini DCO and Phoenix transceivers based on predefined BER thresholds, shown in Fig. 4, Fig. 5, and Fig. 6. The purple and green dashed lines represent the BER thresholds of 10^{-3} and 10^{-2}, respectively. Using the cumulative frequency distribution, the feasible and non-feasible regions were defined. The green and yellow shaded regions indicate the feasible zones for BER thresholds of 10^{-3} and 10^{-2}, respectively, while the pink region corresponds to non-feasible routes (BER $> 10^{-2}$). A detailed discussion of the results is as follows:

A. *Cassini Transceiver*

Fig. 4 shows the comparison between 200G DP-QPSK and 400G DP-16QAM for the Cassini DCO transceiver. Here, we have considered a spectrum of 1 THz, 100 GHz channel spacing, and 64 Gbaud symbol rate.

For the BER threshold of 10^{-3}, DP-QPSK demonstrates exceptional resilience with 97.64% of routes (3976 out of 4072) being feasible, while DP-16QAM fails entirely under this

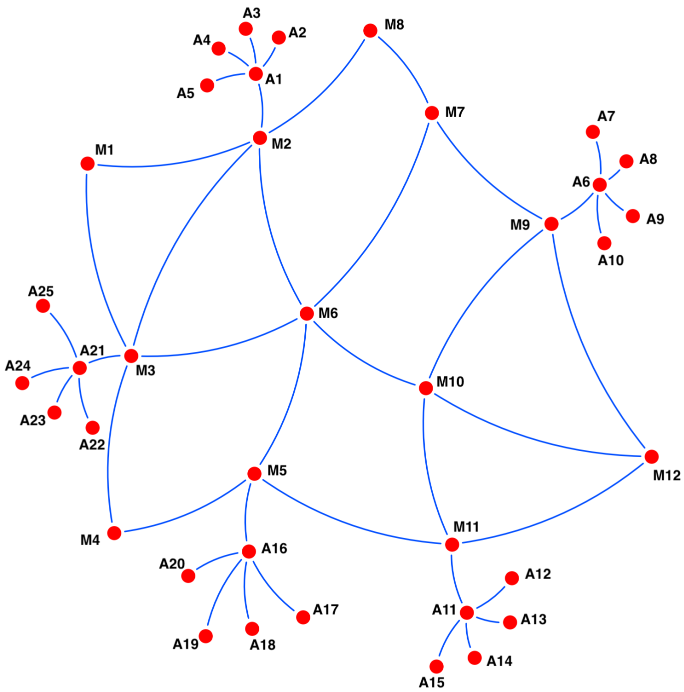

Fig. 3: Converged Metro-Access Network Topology

constraint, resulting in 0% feasible routes. For BER threshold of 10^{-2}, feasibility improves for both formats: QPSK achieves 99.73% (4061 feasible paths), and 16-QAM rises to 94.40% (3844 feasible paths). This clearly highlights the impact of modulation format and BER thresholds on route feasibility, as higher-order modulations like 16-QAM are inherently more sensitive to noise, dispersion, and nonlinearities. They require cleaner, lower-loss transmission conditions to maintain low error rates, whereas QPSK—with its larger symbol spacing—is more robust under typical network impairments. There is a significant design trade-off in optical networks: although DP-16QAM offers double the capacity per channel (400 Gbps vs. 200 Gbps for DP-QPSK), it severely restricts the number of usable routes under stringent quality constraints. In contrast, DP-QPSK enables broader path availability and higher transmission reliability, especially in metro-access or long-reach segments. Therefore, modulation format selection must be driven not only by capacity goals but also by BER tolerance and network topology.

B. Phoenix Transceiver

We evaluated the feasibility of routes for DP-QPSK signals using the Phoenix transceiver at two symbol rates: 32 Gbaud and 64 Gbaud. The analysis was performed over 4072 total routes, with BER thresholds of 10^{-3} and 10^{-2}. The results are visualized in Fig. 5, where the cumulative distribution functions (solid lines) and corresponding BER probability densities (dashed lines) are shown for both symbol rates. At 32 Gbaud, the Phoenix transceiver exhibits excellent performance, with 100% of routes remaining feasible under both BER thresholds. This reflects the robustness of lower

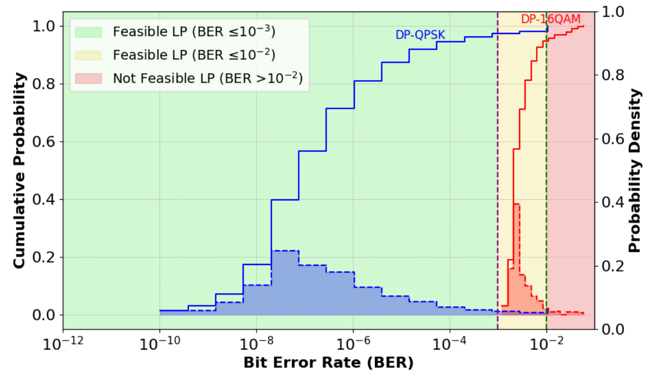

Fig. 4: Comparison between DP-QPSK and DP-16QAM for Cassini DCO

baudrate transmission, which benefits from greater tolerance to dispersion and nonlinear impairments. At 64 Gbaud, a slight degradation is observed under threshold 10^{-3}, where feasibility drops to 99%. However, under the relaxed 10^{-2} threshold, all routes remain feasible (100%).

This highlights the trade-off between symbol rate and transmission robustness: increasing the baudrate enhances spectral efficiency and reduces latency, but at the cost of reduced tolerance to impairments. Hence, symbol rate selection must balance throughput demands with physical layer limitations to ensure high-quality transmission over diverse path conditions.

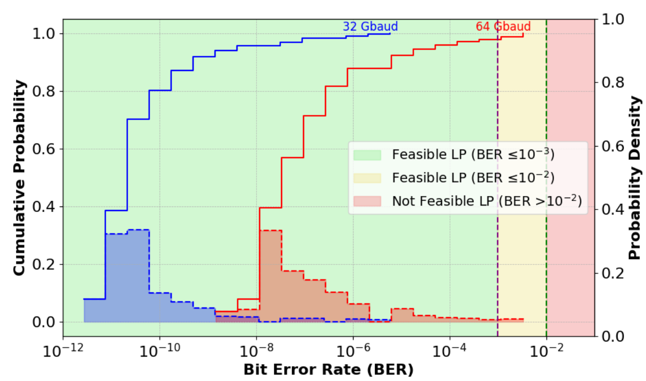

Fig. 5: Comparison between 32Gbaud and 64Gbaud for Phoenix DP-QPSK

We further evaluated the impact of symbol rate on DP-16QAM signal feasibility using the Phoenix transceiver, considering symbol rates of 32 Gbaud and 64 Gbaud over a total of 4072 routes as shown in Fig. 6.

At 32 Gbaud, DP-16QAM achieves a reasonable trade-off between capacity and signal integrity, with 87.48% of routes remaining feasible under the strict BER (10^{-3}) threshold, and 98.21% under the 10^{-2} threshold. In contrast, increasing the symbol rate to 64 Gbaud introduces significant performance degradation: only 0.54% of routes are feasible under the 10^{-3} threshold, and 80.77% under 10^{-2}. This significant drop in

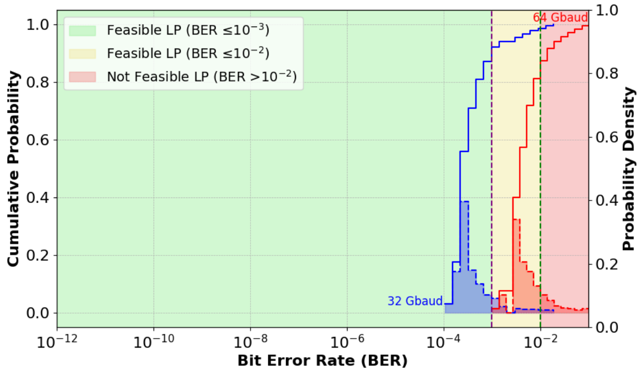

Fig. 6: Comparison between 32Gbaud and 64Gbaud for Phoenix DP-16QAM

feasibility can be attributed to the increased sensitivity of higher baudrate 16QAM signals to transmission impairments such as chromatic dispersion and nonlinearities. As the symbol rate increases, each symbol occupies a shorter time window, reducing the signal's tolerance to distortions, especially for higher-order modulations.

These results highlight a key limitation when combining high-order modulation with high symbol rates because such configurations promise high spectral efficiency and throughput, they impose stringent physical-layer requirements that significantly reduce the set of usable routes. Therefore, practical deployments must carefully balance modulation format and symbol rate based on path quality, potentially leveraging adaptive modulation schemes to maintain high performance without compromising transmission reliability.

IV. Concluding Remarks

This study presented a statistical feasibility analysis of routes in a converged metro-access optical network, focusing on their potential to support fronthaul requirements for 5G and future 6G Radio Access Networks (RAN). We evaluated route performance using BER-based thresholds across different modulation formats (DP-QPSK and DP-16QAM) and symbol rates (32 Gbaud and 64 Gbaud) for Cassini and Phoenix transceivers. The results highlight trade-offs between data capacity, symbol rate, and transmission robustness. While DP-16QAM and higher symbol rates offer greater throughput, their feasibility is significantly constrained under strict BER requirements. In contrast, lower-order modulations and lower symbol rates deliver more resilient performance across a broader range of optical paths.

These findings are particularly relevant for urban network operators aiming to scale RAN deployments efficiently. Metro-access networks can be strategically used to provide reliable, high bandwidth transport for dense RAN environments. This study emphasizes the necessity of considering physical layer constraints to ensure effective end-to-end service delivery. By understanding the performance limitations of various transceiver configurations under realistic BER constraints, network planners can make informed decisions on modulation and symbol rate adaptation to optimize end-to-end connectivity. Ultimately, this work supports the case for integrating RAN traffic into existing fiber-based metro-access infrastructures, offering a scalable and cost-effective approach to meet the evolving demands of next-generation wireless networks.

Acknowledgments: Ahtisham Ali's work is fully funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie project EWOC under grant agreement No. 101073265. This work has also received support from the EU Horizon Project ALLEGRO grant agreement No. 101092766 and the EU Next Generation EU partnership on 'Telecommunications of the Future' (PE00000001 – program 'RESTART').

References

[1] C. Ranaweera, C. Lim, Y. Tao, S. Edirisinghe, T. Song, L. Wosinska, and A. Nirmalathas, "Design and deployment of optical x-haul for 5g, 6g, and beyond: progress and challenges," *Journal of Optical Communications and Networking*, vol. 15, no. 9, pp. D56–D66, 2023.

[2] Z. Vujicic, M. C. Santos, R. Méndez, B. Klaiqi, J. Rodriguez, X. Gelabert, M. A. Rahman, and R. Gaudino, "Towards virtualized optical-wireless heterogeneous networks," *IEEE access*, 2024.

[3] 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.

[4] T. Sharma, A. Chehri, and P. Fortier, "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.

[5] J.-i. Kani, T. Suzuki, Y. Kimura, S. Kaneko, S.-Y. Kim, and T. Yoshida, "Disaggregation and virtualization for future access and metro networks [invited tutorial]," *Journal of Optical Communications and Networking*, vol. 17, no. 1, pp. A1–A12, 2024.

[6] G. Simon, P. Chanclou, F. Saliou, J. Potet, and M. Wang, "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, Y.-K. Huang, G. Borraccini, E. Ip, A. D'Amico, Z. Wang, H. Nishizawa, G. Zussman, T. Chen, T. Wang *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.