Evaluating Metro-Access Optical Networks as-a-Service for Flexible RAN X-haul

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***Abstract*—This article examines the feasibility of employing converged core-metro-access optical networks to support Radio Access Network (RAN) fronthaul and mid-haul transport under realistic performance constraints. The analysis focuses on the profile of the bit error rate (BER) and the latency evaluation in the context of 5G functional splits. We used a commercially available Nokia ICE-X 400G multi-carrier coherent transceiver, leveraging its digital subcarrier multiplexing (DSCM) capability: Supporting DP-16QAM modulation at 4 GHz channel spacing and 64 GBaud symbol rate per subcarrier. The study is carried out on a representative metro-access topology, where all Radio Unit (RU)- Distributed Unit (DU) - Central Unit (CU) paths are evaluated against BER thresholds and latency bounds for front-haul and mid-haul segments, respectively. The results reveal critical trade-offs between optical reach, modulation format robustness, and latency compliance and demonstrate how mid-haul link distances and routing diversity significantly impact overall transport feasibility for disaggregated RAN deployments. This work emphasizes the potential of transparent optical metro-access infrastructures to serve as an efficient and scalable transport layer for 5G and beyond.**

***Index Terms*—Metro-access networks, radio access networks, 5G, capacity analysis, ONaaS, X-haul.**

I. Introduction

The transition to fifth-generation (5G) mobile networks represents a pivotal shift in the telecommunications landscape, driven by the need to support a wide range of advanced services, including enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and massive Machine-Type Communications (mMTC) [1]. These services introduce stringent requirements for end-to-end network performance, notably in terms of latency, jitter, bandwidth capacity, and availability [2]. Meeting these performance targets requires not only radio access evolution but also significant upgrades in the transport and optical infrastructure underpinning mobile networks.

One of the key architectural innovations in 5G is the functional split of the Radio Access Network (RAN). The traditional base station is disaggregated into Radio Unit (RU), Distributed Unit (DU) and Central Unit (CU) – allowing scalable, cloud-based deployment models such as cloud-RAN and centralized RAN [3, 4]. This disaggregation imposes strict latency and bandwidth restrictions on the front-haul (RU-DU) and mid-haul (DU-CU) segments. Although the wireless domain has received significant attention, the transport segment – particularly across the converged access-metro optical network – must also evolve to support these RAN configurations efficiently and flexibly.

According to 3GPP specifications [5], splits in the range of Option 8 to Option 6 require end-to-end latency below $250\,\mu s$, whereas Option 2 can tolerate latencies between $1.5\,ms$ and $10\,ms$. Furthermore, the required travel bandwidth is not only a function of the split configuration but is also influenced by the radio bandwidth, OFDM symbols, the number of Multiple Input Multiple Output (MIMO) layers, antenna ports, modulation and coding schemes, bandwidth of the in-phase and quadrature components, and peak air interface data rates [6].

Historically, the Common Public Radio Interface (CPRI) has served as the primary standard for front-haul connectivity between Radio Equipment Control (REC) and Radio Equipment

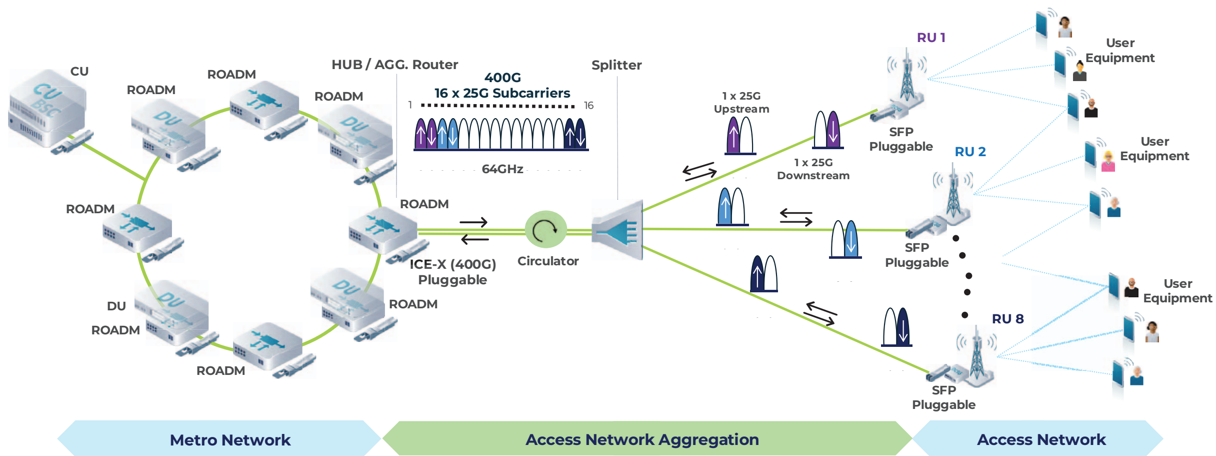

Fig. 1: P2P and P2MP Converged Metro Access Network Architecture using DSCM Pluggable TRx

(RE), typically mapping to DU and RU components in modern 5G RAN. According to the CPRI specification v6.1 [7], CPRI defines both the physical specifications (layer 1) and the data link layer (layer 2) to transport digitized radio signals. While CPRI has been widely adopted, its reliance on constant bit rate and time-division multiplexing made it bandwidth-intensive and inflexible, especially under the dynamic requirements of 5G. To address these limitations, the enhanced CPRI (eCPRI) standard [8] was introduced, offering Ethernet-based encapsulation and packet-based transport. This shift enables more efficient and scalable front-haul architectures that better align with the 5G performance and deployment models [9].

This paper explores the potential of using converged metro-access optical networks to support latency-sensitive RAN front-haul and mid-haul transport. We investigated route feasibility under strict BER and latency constraints, leveraging advanced NOKIA ICE-X transceiver supporting 400G transport and physical-layer modeling for practical urban topologies to enable Optical Network as-a-service (ONaaS). Our scenario reflects a representative urban topology in which RUs are connected through access nodes to metro nodes hosting DUs, which in turn interface with centralized CUs in the data center, forming a complete RU–DU–CU transport chain. The enabling technologies, including digital subcarrier multiplexing optics, standardized QoT estimation tools, and open orchestration frameworks, are introduced in the next section to contextualize the proposed system design and performance analysis.

II. Enabling technologies for Optical Network-as-a-Service

A. DWDM as an Enabler for 5G Transport

At the physical layer, Dense Wavelength Division Multiplexing (DWDM) technologies standardized by ITU-T G.694.1 [10] provide the spectral efficiency and channel scalability necessary to accommodate multiple RAN flows over existing fiber infrastructures. DWDM, with its ability to assign dedicated wavelengths to different services or endpoints, plays a key role in implementing scalable front-haul (FH) and mid-haul (MH) over access and metro segments.

DWDM is widely used in national long-haul backbone networks, regional networks, and core/aggregation layers of metro networks to deliver high-speed connectivity for multiple high-capacity and low-latency applications. With the growing demand for end-user bandwidth, there is an increasing trend towards adopting cost effective DWDM solutions in converged metro-access networks. This shift allows operators to optimize the use of existing infrastructure while reducing both capital (CAPEX) and operational (OPEX) expenditures [11].

With the rapid densification of 5G and increasing bandwidth demands, coherent DWDM systems have been proven to be both technically feasible and cost-efficient for 5G small cell front-haul, mid-haul and back-haul. These systems support high-capacity aggregation ranging from 10 Gb/s to Tb/s over distances of 10-22 km with minimal performance degradation. Dense urban small cell networks operating in sub-6 GHz bands require the evaluation of key performance metrics, including latency, jitter, scalability, and cost considerations (CAPEX / OPEX). This can be achieved through a comparative analysis of various transport technologies that balance technical performance with economic viability, enabling telecom network operators to implement high capacity, low latency 5G connectivity solutions in an urban environment [12].

The evolution of 5G RAN architecture towards eCPRI-based functional splits imposes stringent performance requirements, including ultra-low latency and dynamic bandwidth allocation. Recent studies highlight the need for transport solutions that balance these constraints with scalability and cost efficiency. A semi-active WDM architecture enables automatic eCPRI wavelength provisioning, real-time network quality-of-service (QoS) monitoring, and hybrid amplification that supports the 25 Gb/s data rate with 1 µs latency over 20 km distances that is fully compliant with eCPRI requirements and operational cost advantages, offering a scalable solution for dense DU-RU deployments in C-RAN environments [13].

B. Standardized QoT Estimation and Abstraction

Furthermore, standardized Layer 1 and Layer 2 protocols, including Optical Transport Network (OTN), Ethernet, and advanced Time-Sensitive Networking (TSN) mechanisms, provide the performance guarantees necessary to meet 5G service level agreements. However, ensuring the Quality of Transmission (QoT) along optical paths remains a critical requirement, especially for dynamic RAN transport scenarios. In this context, Gaussian Noise in Python (GNPy) [14], an open-source physical layer modeling library developed under the Telecom Infra Project (TIP), provides a modular framework for estimating optical impairments such as ASE noise and nonlinear interference. GNPy enables the creation of a digital twin of the optical network, allowing for topology-aware QoT validation, route feasibility analysis, and what-if scenario testing before provisioning services. By supporting standardized input formats (e.g., OpenROADM, JSON/YAML topologies) and multi-vendor configurations, GNPy helps abstract the complexity of the physical layer, making it a critical enabler for performance-aware and software-defined networking (SDN)-integrated transport orchestration [15]. The industry is also moving towards greater openness and programmability of transport networks through initiatives such as the Telecom Infra Project (TIP) [16], OpenROADM [17], OpenConfig, and the Optical Internetworking Forum (OIF). These initiatives aim to define open models and interfaces for optical networks, paving the way for Optical Network-as-a-Service (ONaaS). Despite significant progress, gaps remain, particularly in the standardization of protocols, models, and APIs used to dynamically allocate optical resources (e.g., wavelengths, spectrum slots, transceiver parameters) in response to service requests. Without common abstractions for resource allocation, it becomes difficult to deliver ONaaS capabilities in a truly vendor-neutral and programmable way. Finally, as RAN architectures become increasingly disaggregated, open and standardized support for connecting RUs must replace legacy proprietary front-haul implementations. An interoperable and unified transport framework is required, one that allows RUs to connect dynamically across access-metro networks and supports flexible DU placement to meet both front-haul and mid-haul latency constraints.

C. DSCM-Enabled OpenXR Optics for P2P and P2MP

Metro aggregation networks are typically built on a hub-and-spoke architecture, where a large number of spoke devices, such as cell sites, fiber nodes, or Optical Line Terminals (OLTs), connect to a smaller set of hub devices, such as routers or Evolved Packet Cores (EPC). Traditionally, optical transport in such networks is based on point-to-point links, which require dedicated transceivers at both ends. In this way, a hub that serves N spokes requires $2N$ transceivers, often resulting in underutilized hardware, inefficient use of router ports, and excessive layers of packet aggregation. These inefficiencies drive up both capital and operational costs, especially as the access network evolves to support bandwidth-intensive services like 5G, Distributed Access Architectures (DAA), and next-generation PON.

Digital SubCarrier Multiplexing (DSCM) technology offers a promising solution by improving spectral and hardware efficiency. Unlike Orthogonal Frequency-Division Multiplexing (OFDM), DSCM uses non-orthogonal subcarriers generated by a single laser source, operating at higher symbol rates [18]. This allows a single coherent wavelength to be divided into multiple independent subcarriers, each of which can be routed to different endpoints using advanced Digital Signal Processing (DSP). DSCM has already seen commercial deployment in metro and core networks, enabling transmission rates of up to 800 Gb/s per wavelength [19].

In this work, we consider the use of the NOKIA ICE-X 400G coherent pluggable transceiver to demonstrate a point-to-multipoint (P2MP) deployment enabled by DSCM as depicted in Fig. 1. The ICE-X transceiver can divide a 64 GHz 400G channel into 16 subcarriers, each carrying 25 Gb/s using 16-QAM modulation at a 4 GBaud symbol rate [20]. These subcarriers can be independently assigned to different access nodes, allowing a single hub transceiver to serve multiple endpoints with variable data rate demands [21, 22]. This level of flexibility and granularity reduces the number of required optical interfaces and simplifies the aggregation architecture, making DSCM-based XR optics potentially suitable for scalable and cost-effective converged metro-access architectures, especially in the context of 5G and beyond network deployments. Its ability to dynamically allocate subcarriers to different endpoints enables flexible provisioning across the front-haul segments (connecting RUs to DUs), mid-haul segments (aggregating DUs to CUs), and even back-haul segments (connecting to the mobile core). This aligns well with the architectural demands of disaggregated RAN deployments, where high-capacity, latency-sensitive links must be served efficiently over a shared optical infrastructure.

Motivated by these capabilities, we performed a statistical analysis of route-level performance, taking into account BER thresholds, FH and MH latency constraints, and QoT considerations derived from realistic optical impairments. Ultimately, this study aims to identify both the potential and the current limitations of using such converged optical infrastructures for 5G and 6G RAN transport while highlighting the importance of ongoing standardization efforts toward open, interoperable and service-oriented network architectures.

III. Simulation Scenario

We performed a statistical analysis considering a fully transparent converged metro-access scenario using a NOKIA ICE-X multi-carrier transceiver (TRx). To proceed with the statistical analysis, we initially performed an experimental characterization of the transceiver, which allowed us to derive the key performance model of the transceiver, specifically the relationship between Signal-to-Noise Ratio (SNR) and Received Optical Power (ROP).

The overall simulated network topology includes two metropolitan areas, referred to as City A and City B, as

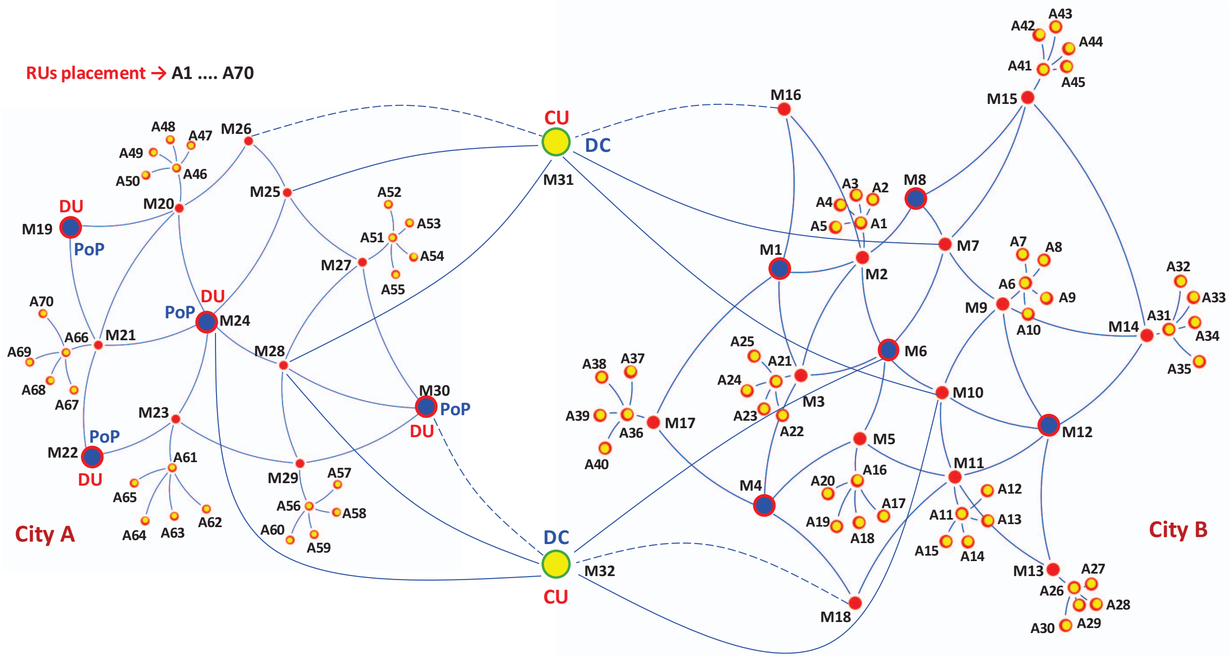

Fig. 2: Converged Metro Access Network Topology

shown in Fig. 2. Each city comprises a combination of metro (M) and access (A) segments. Metro and Access segments are represented by M and A nodes, respectively. Access segments are structured with four access nodes per cluster, each connected to two RUs. In both cities, each access segment consists of four access nodes per cluster that are connected to two RUs responsible for antenna-to-DU-CU traffic. These access nodes are connected to the metro network through a ROADM and a circulator, allowing to go seamless from single-fiber BiDi transmission on the access segment to the metro fiber pairs. The network is designed to emulate realistic urban fiber deployments, making it suitable for assessing route-level feasibility for RAN transport. To limit computational complexity in the feasibility analysis, a maximum hop count of 12 was imposed on each RU-CU path evaluated.

- City A: Comprises 44 optical nodes, including 12 metro nodes and 25 access nodes connected to RUs. The network has an average node degree of 3.42 and an average fiber link length of 6.9 km, with a maximum link length of 10 km.
- City B: Comprises 63 optical nodes, with 18 belonging to the metro segment and 45 to the access segment. The average degree of the metro node is 4.06, and the maximum fiber length is 12 km.

To determine the feasibility of each route within the converged metro-access network, we considered two factors: BER and latency constraints for FH and MH, as described earlier. The total SNR is computed by combining GSNR and $\mathrm{SNR}_{\mathrm{TRX}}$ as shown in Eq. 1. The BER is computed on the basis of the total SNR for each path using Eq. 2, which includes contributions from both the optical channel (GSNR) and the TRx noise that determines the feasibility of the end-to-end route based on the BER thresholds.

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

$$\mathrm{BER} = \frac{3}{8}\,\mathrm{erfc}\left(\sqrt{\frac{\mathrm{SNR}}{10}}\right) \tag{2}$$

The latency is computed independently for the FH and MH segments. Physical distances from RU-DU and DU-CU are converted to latency values assuming a propagation delay of $5\,\mu\mathrm{s\,km}^{-1}$.

A route is considered feasible if both the computed BER remains below the threshold required for the DP-16QAM modulation format, and the total latency is within the acceptable limits defined by the functional split constraints of RAN (e.g. $250\,\mu\mathrm{s}$ for Option 7.2 FH and $1000\,\mu\mathrm{s}$ ($1\,\mathrm{ms}$) for MH) [23, 24]. This dual-criteria assessment provides a comprehensive indication of route viability to support RAN transport over the converged optical network.

IV. Results and Discussion

To evaluate the impact of mid-haul distance on overall RAN transport feasibility, we analyzed the complete end-to-end routes from each RU to the CU by combining the paths from RU to DU (FH) and from the DU to the CU (MH). The analysis considers only selected variable-length mid-haul routes, specifically those involving the dotted paths shown in the network topology (Fig. 2): M26–M31–M16 and M30–M32–M18. These links represent variable inter-city connections between the DUs, located at Points of Presence (PoPs), and the CUs hosted in Data Centers (DCs).

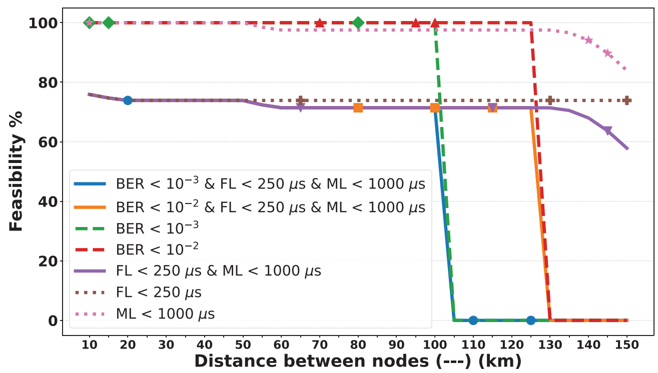

Fig. 3: Feasibility percentage versus variable mid-haul distance considering different constraint combinations: BER thresholds, front-haul and mid-haul latency bounds

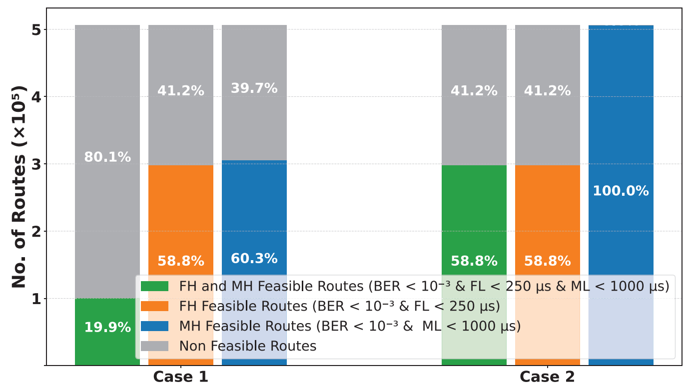

Fig. 4: Route feasibility analysis considering FH and MH constraints

The variable-length mid-haul segments are used to model different inter-city deployment scenarios, with distances ranging from 10 km to 150 km. For each value, we assessed the feasibility of the RU–CU route by checking compliance with both BER thresholds under different forward error correction (FEC) regimes in coherent optical systems (soft-decision FEC (SD-FEC) 10^{-2} and hard-decision FEC (HD-FEC) 10^{-3}) for 400G transmission using DP-16QAM as discussed in [25, 26], considering and latency constraints (Front-haul Latency (FL) $<250\,\mu s$ and mid-haul Latency (ML) $<1000\,\mu s$).

Fig. 3 shows the percentage of feasible routes as a function of the mid-haul distance. Multiple combinations of constraints are visualized to highlight their individual and combined impact. As depicted in Fig. 3, when only BER is considered (ignoring latency), the feasibility remains relatively high up to a distance of 100 km. However, when latency constraints are added, particularly for the front-haul segment, the number of feasible routes drops significantly as the mid-haul distance increases. This is expected since the longer fiber links directly contribute to propagation delay and SNR degradation, both of which affect feasibility.

The most restrictive combination, which requires both BER $< 10^{-3}$ and latency constraints (FL $< <250\,\mu s$, ML $<1000\,\mu s$, feasibility falls steeply from 60% after 100 km of distance due to SNR degradation, represented by dotted lines. On the other hand, for a more relaxed BER constraint (e.g. $< 10^{-2}$), the feasibility gradually degrades and remains above 60% even up to 125 km. This indicates the sensitivity of high-order modulation formats to optical SNR and suggests that such formats are best suited for metro or short-haul mid-haul deployments unless advanced digital signal processing (DSP) or forward error correction (FEC) techniques are applied. Interestingly, when latency alone is considered, feasibility is generally maintained up to mid-haul distances of around 130 km, beyond which the $1000\,\mu s$ threshold starts to eliminate longer DU–CU paths. This reinforces the importance of latency-aware path selection and motivates the use of topology-aware network slicing or DU reallocation for distance-sensitive services.

Overall, these results highlight that MH feasibility is highly sensitive to physical path length, especially when strict BER and latency targets are applied. Latency constraints begin to dominate feasibility beyond 100 km even if optical QoT remains acceptable. Route planning must jointly consider front-haul and mid-haul latencies, as well as physical impairments and modulation format thresholds.

We also explored how the availability of multiple redundant mid-haul paths and interconnecting distances (as summarized in Table I) affect the feasibility of RU-to-CU routes under stringent latency and BER constraints. Unlike the previous scenario, which relied on two dedicated mid-haul paths, this architecture incorporated three distinct mid-haul routes toward each CU, reflecting a more realistic and resilient deployment design. In this analysis, two configurations were compared. In Case 1, the mid-haul links connecting metro nodes to the CU were configured with relatively long fiber lengths, with some paths extending up to 100 km. In Case 2, the same set of links was included, but with significantly reduced distances, approximately half the lengths used in Case 1. The goal was to assess how reducing fiber spans and enhancing path diversity can improve the feasibility of supporting 5G RAN FH and MH transport. Fig. 4 presents the distribution of routes evaluated in terms of their feasibility. The classification distinguishes between fully feasible routes, partially feasible ones where only either FH or MH constraints are met, and completely non-feasible paths.

The comparison reveals a substantial improvement when transitioning from Case 1 to Case 2. In Case 1, only 19.9% of the total RU–CU paths were found to be feasible under the joint conditions of BER $< 10^{-3}$, FL $<250\,\mu s$, and ML $<1000\,\mu s$. The majority of the remaining routes were found non-feasible primarily due to violations of the mid-haul

links → **Cases ↓**	*M25–M31–M7* *M30–M32–M18* (km)	*M28–M31–M10* *M28–M32–M10* (km)	*M24–M32–M6* *M26–M31–M16* (km)
1	60	80	100
2	30	40	50

TABLE I: Link Distances considered for feasibility analysis latency constraint, driven by the longer fiber spans. Despite meeting the BER threshold in many cases, the physical length of the inter-city connections introduced delays that exceeded the permissible limits for option 2 functional split.

In contrast, Case 2 showed a dramatically improved outcome. By reducing the distances of the mid-haul links and maintaining the same level of redundancy, the number of feasible routes increased to 58.8%, effectively tripling the success rate. This demonstrates how sensitive mid-haul performance is to physical design choices, particularly when strict latency limits must be met.

What is especially noteworthy is that the number of available front-haul routes remained nearly unchanged between the two cases, indicating that the observed improvements were driven almost entirely by better mid-haul performance. This reinforces the notion that mid-haul design, specifically link placement and path diversity, is a decisive factor in determining end-to-end feasibility when using converged optical infrastructure to support 5G RAN services.

In general, the comparison between Case 1 and Case 2 highlights the importance of strategic CU connectivity and physical topology planning. In scenarios where mid-haul distances are high and redundancy is limited, a significant portion of otherwise viable optical paths may be ruled out due to latency violations. Conversely, even modest reductions in fiber distance, combined with multiple CU path options, can dramatically increase the viability of 5G RAN transport over existing metro-access optical networks.

V. Conclusion

This paper presented a feasibility assessment of using converged metro-access optical networks to support RAN FH and MH transport in 5G deployments. By modeling RU–DU–CU connectivity over a realistic urban topology and applying strict constraints on BER and latency, we evaluated the performance limits of such optical infrastructures in terms of feasible RU–CU routes, and analyzed their implications on supported transport capacity. For example, based on the modulation format used (DP-16QAM) and the number of subcarriers per transceiver, a single 400G coherent link could support up to 16×25 Gb/s connections from DU to CU - provided that BER and latency constraints are met throughout the route.

Our results show that while many paths satisfy BER thresholds, end-to-end feasibility is significantly impacted by latency, especially across mid-haul segments. Using only long, fixed mid-haul paths limits feasible coverage, whereas introducing multiple redundant CU connections and reducing fiber distances greatly enhances transport feasibility. In the best case, feasibility improved from below 20% to above 58%, underscoring the value of path diversity and distance-aware network planning.

These findings confirm the potential of transparent optical metro-access networks to serve as shared transport for disaggregated RAN elements. However, they also expose critical design dependencies, such as latency-sensitive path selection and the need for standardized optical service interfaces to enable dynamic on-demand provisioning. Future work will focus on integrating these feasibility models into SDN-controlled orchestrators and exploring optical virtualization techniques for service-aware RAN transport.

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