Practical Network Design for Micro Edge Data Centers: an Italian Case

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Abstract

The growing demand for low-latency applications, IoT processing, and 5G services has accelerated the deployment of edge data centers in geographically distributed and resource-constrained environments. In such scenarios, network infrastructure must be carefully designed to meet stringent limitations in rack space, power availability, and cost, while ensuring sufficient performance and resilience.

This report investigates the trade-offs between performance and infrastructure constraints in the design of Clos-based network topologies for edge-scale deployments. A parametric exploration of five different topology variants, including full bisection and oversubscribed configurations, is conducted, with each evaluated under realistic constraints such as limited rack space (e.g. 42U), power budget (e.g. 5kW), and cost (e.g. €20,000).

A specific focus is given to the Italian context, where regulatory and infrastructural challenges further complicate the deployment of distributed data center infrastructure. By modeling and analyzing these topologies across various metrics—total cost, energy consumption, bisection bandwidth, and space usage, this study identifies feasible and efficient solutions for edge network design. The results provide actionable insights for practitioners and designers seeking to balance cost-effectiveness and performance in constrained environments.

1 Background and Related Work

Clos-based network topologies, such as Fat-Tree and Leaf-Spine, are widely adopted in cloud-scale data centers due to their scalability, path redundancy, and non-blocking bandwidth properties. In a typical three-tier Clos architecture, edge (leaf) switches connect to aggregation (spine) switches, enabling full bisection bandwidth and uniform latency across the system.

Clos-based topologies were originally introduced by Charles Clos in his seminal 1953 paper "*A Study of Non-Blocking Switching Networks*" [1], in the context of circuit-switching telephone systems. The structure, based on a multi-stage interconnection of smaller crossbar switches, was designed to achieve scalability and fault isolation while minimizing blocking. In modern data centers, Clos architectures have been adapted to packet-switched networks, enabling **scalable, high-bandwidth, and cost-efficient topologies**. Their flexibility and modularity make them a natural fit for edge-scale deployments.

Fat-Tree architecture was introduced by Al-Fares et al. [2] as a scalable design using commodity switches, demonstrating its ability to support high-throughput workloads. However, implementing a fully provisioned topology implies high costs in terms of switch count, cabling, rack space, and energy consumption.

Edge Computing arised as a new computing model that processes data at the edge of the network. The core idea is to make computing closer to the source of the data [3]. Cao et al. [4] provide a comprehensive overview of current state and recent advances in edge computing, highlighting main challenges and future research directions.

While large cloud providers can afford overprovisioned Clos networks in hyperscale data centers, small-to-medium-sized cloud and Edge Data Center operators must balance **cost-efficiency** with **network performance** and **resilience**. Data center networking implies several cost challenges, including capital expenses and operational constraints, as highlighted in works like [5] by Greenberg et al. Subsequent works such as ElasticTree [6] explored dynamic energy savings by selectively disabling network components, but primarily at runtime rather than during initial design.

Related work includes different efforts like F10 [7] focusing on fault tolerance in Clos-like networks by modifying topologies or routing schemes. Meanwhile, other recent studies underline the unique challenges in **decentralized cloud and edge computing** infrastructures, such as non-uniform workloads, resource constraints, and geographic distribution.

In a comprehensive survey, Hammadi and Mhamdi [8] analyzed how different data center network architectures, including Clos-based, VL2, and server-centric models, impact both scalability and **energy efficiency**. They emphasize that energy consumption is not only a runtime issue but also a design-level concern affected by topology, link density, and device provisioning. These insights support the need to consider power-related factors in network planning, especially in resource-constrained edge environments. However, their analysis concentrates mainly on the **type of topology** and their impact on cost and performance in practical deployment, rather than the **internal configuration or scale**.

Oversubscription was first explicitly introduced by Al-Fares et al. [2] and refers to the ratio between the total downlink bandwidth provisioned to servers and the total uplink bandwidth available at the access (leaf) layer of a data center network. An oversubscription ratio greater than 1 indicates that the aggregate demand from servers exceeds the available uplink capacity, potentially leading to **congestion and performance degradation** during peak loads [9] [8].

Despite these risks, oversubscription is a **common and intentional design strategy** in modern data center networks, particularly in cost-sensitive or space-constrained environments, because it allows for significant savings in hardware, cabling, and power consumption. By reducing the number of high-bandwidth uplinks and spine switches, network ar-

chitects can lower both **capital expenditures (CAPEX)** and **operational costs (OPEX)**, at the cost of limiting network performance.
The choice of an appropriate oversubscription ratio is therefore a **key trade-off** in network design, requiring careful evaluation of expected workloads, traffic patterns, and quality-of-service requirements. In edge environments, where budgets and physical space are often limited, oversubscription becomes not only acceptable but necessary, provided that it is carefully balanced to avoid critical bottlenecks.
Studies has also been conducted beyond network-level considerations, for example Jin et al. [10] reviewed various **power consumption models for servers**, underscoring the importance of **accurate energy consumption estimation** when evaluating data center design trade-offs.
Despite extensive research on data center topologies, a quantitative framework to guide initial network sizing could be useful, specifically tailored to **resource-constrained environments**. This project aims to address this scope by analyzing the design trade-offs in Clos-based topologies for small and edge cloud data centers, with a focus on bandwidth, fault tolerance, and particularly **infrastructure costs**.

2 Problem Statement and Motivation

In edge and decentralized cloud environments, infrastructure constraints, such as limited rack space, power, and budget, make traditional data center design approaches suboptimal. These facilities are increasingly expected to handle large volumes of local traffic due to the proximity of data sources, latency-sensitive applications, and real-time processing demands. In fact, the global edge computing market size is expected to grow at a notable growth rate in the next years [11] [12] [13].
While edge computing reduces the volume of data sent to centralized cloud data centers, it **increases intra-facility bandwidth requirements** at the edge. As noted in recent analyses, this trend creates significant pressure on edge LAN infrastructures, which must now support high-throughput local communication between compute and storage nodes. In fact, in edge computing, communication between edge data centers and central data centers is minimized, in order to provide the best results in terms of latency and responsiveness. To sustain performance, network topologies must be carefully engineered with **sufficient internal bandwidth, fault tolerance, and efficiency**, but without the **overspending** tolerated in hyperscale facilities. Cost is a metric that must be taken into account.
This problem is especially acute for **small to medium-scale operators**, such as regional cloud providers, academic institutions, or telecommunication operators deploying micro data centers. They often adopt **Clos-like topologies** for their scalability and structured redundancy, but could improve their configuration decision, such as appropriate number of spine switches, oversubscription levels, or fault-tolerant design variants.

The motivation behind this project is further enriched by the intention to examine a specific real-world context: the state of **network infrastructure in Italy**, my home country. Italy represents a particularly interesting scenario for analyzing the adoption of network topologies in edge environments, due to the combination of a **strong push for digital transformation** and significant **infrastructural and regulatory constraints** [14] [15].
In recent years, Italy has seen growing demand for edge services driven by the adoption of 5G, IoT, and AI, especially in public and industrial sectors. However, this expansion is limited by two major technical and logistical issues:

- **Uneven electrical infrastructure**: Many regions, particularly in southern and rural areas, lack the power capacity required to sustain high-density data centers.
- **Regulatory and administrative bottlenecks**: The absence of a dedicated regulatory framework for data centers complicates the authorization process, as facilities are often treated as standard industrial buildings.

As shown in Figure 1, the **Italian power grid** is characterized by a significant geographical imbalance. While the northern regions benefit from a dense network of high-voltage lines and substations, the southern areas, particularly inland and rural zones, exhibit lower grid density and fewer interconnections. This structural disparity reinforces the need for edge data center solutions that are power-aware and adapted to **localized infrastructure constraints**.
Bureaucratic and regulatory constraints play a crucial role when it comes to constructing and deploying data center infrastructure on Italian territory.
Obtaining permits and authorizations for new installations is often a lengthy and costly process, due to complications related to taxation, building classification, and energy usage requirements.

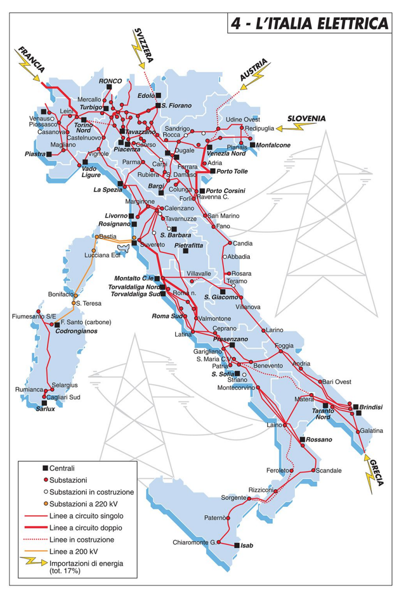

Fig. 1. Italian electric power grid

As a result, many data center operators choose to **initially**

deploy their infrastructure within existing buildings, postponing expansion until the necessary approvals are granted. This reality further emphasizes the importance of designing systems that can operate effectively within tight energy and space constraints, while still maintaining adequate network performance.

In such a scenario, local operators face a critical question: **How can resilient, high-performance network infrastructures be built under energy, space, and budget constraints?**

Although several network architectures have been proposed to address performance, scalability, and energy efficiency, including those reviewed in [8], most studies focus on **topology type**, not on how **specific design choices within the same topology** affect key outcomes. For example, decisions about the **number of spine switches, oversubscription ratios**, or **redundancy levels** in a Clos network are often left as default sizing.

This project aims to explore the **design space of Clos topologies for edge-scale deployments**, quantifying the trade-offs between **performance (e.g., bandwidth, resilience)** and **infrastructure costs** (e.g., switch count, cabling, power), designed to address the specific challenges of **regional edge data centers**. The goal is to provide a lightweight modeling approach to support network decisions in constrained environments, ensuring technical viability and financial sustainability in edge facilities.

3 Methodology and Solution Outline

This project proposes a modeling-based approach to explore the design space of **Clos-based interconnection networks** for **regional edge data centers**, focusing on balancing **cost**, **performance**, and **fault tolerance** under resource constraints.

The core idea is to **quantitatively analyze multiple Clos topology configurations**, varying parameters such as the number of spine switches, oversubscription ratios, and redundancy levels, considering edge deployments in the range of micro-scale edge data centers (128-1024 servers), where Clos topologies are viable but must be cost-optimized. These infrastructures lie between small on-premise nodes and hyperscale facilities, and require careful engineering to meet increasing local bandwidth demands while remaining cost-efficient [16].

A high-level sketch of the proposed methodology is as follows:

1. **Topology Definition**: Define a set of Clos network configurations, from full bisection bandwidth designs, oversubscribed variants, fault-tolerant schemes (N+1 spine redundancy), according to [17].

2. <u>**Performance**</u> **Modeling**: For each configuration, estimate key performance metrics analytically, including **bisection bandwidth**, **link utilization**, **oversubscription ratio**.

3. <u>**Cost**</u> **Modeling**: In parallel, estimate **infrastructure costs** based on realistic pricing of switches (by port count and speed), cabling requirements (per port), rack space usage, and estimated power usage. Need to analyze vendor data and prior research to be used as reference points.

4. **Trade-off Analysis**: Results are summarized in tables (Google Spreadsheet) and plots (Google Colab Notebook) to compare different metrics across considered topologies.

5. **Contextualization**: Analyze the outcomes in the context of **decentralized cloud infrastructure**, to possibly provide design guidelines for operators of small/regional edge data centers that need to balance limited budgets and high reliability and throughput.

This is a **modeling-based approach** (rather than full simulation), enabling rapid evaluation and practical insights that could be later refined through implementation/simulation.

4 Design Space and Exploration

The objective of this design space exploration is to systematically analyze how different network topologies and their internal configuration parameters impact the feasibility and performance of micro edge data center deployments. The focus is placed on **Clos-based architectures**, commonly used in scalable data center networks, and their adaptation to **resource-constrained environments** typical of edge infrastructure.

The design space is explored across a range of realistic configuration parameters, reflecting actual limitations in space, power, and budget that are frequently encountered in localized deployments, particularly in **regional or semi-urban areas**, as often found in the Italian context.

4.1 Switch Model and Assumptions

The evaluation assumes a two-tier Clos architecture composed of commodity **24-port switches at the leaf layer** and **48-port switches at the spine layer**. This configuration reflects a practical and cost-effective setup commonly found in small scale data centers, particularly in edge or distributed environments.

Each leaf switch is connected to both **server nodes (downlinks)** and **spine switches (uplinks)**. The number of available ports for each direction is determined based on the chosen oversubscription ratio or topology variant. For example, in oversubscribed configurations, a portion of the 24 ports is allocated to uplinks, while the remaining ports are used to connect servers.

Spine switches are used solely to aggregate uplinks from all leaf switches, as defined by the Clos-architecture structure.

The number of leaf switches k and spine switches S are the **only independent parameters** in the model; all other quantities and metrics are **derived accordingly**, based on the selected topology and its constraints.

While k can be chosen arbitrarily to define the scale of the deployment, the value of S is determined in order to satisfy the required bisection bandwidth and oversubscription ratio for each configuration.

All switch ports are assumed to operate at 1 Gbps, both for simplicity and plot visualization. However, this value can be modified if needed. Cabling is considered **passive** (copper or fiber). Assuming equal link speeds for both downlinks (server connections) and uplinks (spine connections) is a strong assumption. In practice, architectures like Fat-Tree allow for heterogeneous link speeds, enabling alternative topological designs that support a greater number of spine switches or servers, while maintaining desired oversubscription ratios and bandwidth guarantees.

4.2 Explored Topologies

Five topological variants within the Clos family are analyzed:

Full Bisection

This topology represents the **performance upper bound** among the configurations studied. Each leaf switch connects to all spine switches, providing full bisection bandwidth with no oversubscription. While this ensures maximum throughput and path diversity, it also results in **high infrastructure cost**, both in terms of switch count and cabling complexity.

Oversubscription 2:1

This topology reduces the number of uplinks per leaf switch while maintaining a reasonable performance level. The ratio of available uplink bandwidth is half the one available for downlink, for each leaf switch. This **2:1 ratio** is commonly used in enterprise data centers to **balance performance with infrastructure cost**, making it well suited for edge deployments with moderate bandwidth requirements.

Oversubscription 4:3

This intermediate topology sits between full bisection and 2:1 oversubscription. It offers better performance than 2:1 while reducing the uplink count compared to full bisection. The **4:3 ratio** provides a good trade-off when slightly higher internal bandwidth is needed, at a marginally increased cost and power consumption.

Oversubscription 4:1

This highly oversubscribed configuration aims to **maximize cost and space efficiency**. By reducing uplinks to a minimum, it enables the connection of more servers per switch. While it delivers **limited bisection bandwidth**, it may be acceptable in edge workloads with low east-west traffic or low concurrency. It is particularly suitable in rural or semi-industrial edge deployments where power and rack space are severely constrained.

N+1 Redundant Topology

Excluded from final plots

A fifth topology, **N+1 Clos**, was also modeled but excluded from most plots to reduce redundancy. It mirrors the full bisection topology in terms of connectivity and performance, with the addition of **one extra spine** switch to improve fault tolerance. This design can be relevant in critical edge environments that require **high availability**, though it introduces slightly higher cost and rack usage with no improvement in nominal bandwidth.

4.3 Parameters and Evaluation metrics

For each topology, the following parameters are varied (Figure 2:

- **Number of leaf switches k**
- **Number of server per leaf s**, based on port availability
- **Number of uplinks per leaf**, derived from oversubscription ratio
- **Number of spine switches S**, defined as needed to support total uplinks
- **Total servers $N = k*s$**

All configurations are stored in a shared Google Sheet, which serves as the reference dataset for analysis (available here).

The impact of these configurations is assessed in terms of the following metrics:

- **Total Cost (€)**

  Includes the cost of all switches (leaf and spine), network cabling.

- **Power Consumption (W)**

  Derived from the number and type of switches and estimated based on typical power usage per unit (references here [18]).

- **Rack Space Usage (U)**

  Total rack units occupied by all switches, assuming **1U per leaf/spine switch**. 1 rack is assumed to be composed by a total number of 42 rack units.

- **Bisection Bandwidth (Gbps)**

  Measures the maximum theoretical throughput across the network core.

- **Relative Performance (%)**

  Normalized bandwidth performance relative to the configuration offering the highest bisection bandwidth.

- **Cost per Gbps (€/Gbps)**

  Efficiency metric calculated as total cost divided by bisection bandwidth

- **Performance-to-Cost Ratio**

  Ratio between relative performance and total cost, used to identify configurations offering high performance per euro spent.

- **Total number of servers (N)**

  Computed as the number of leaf switches multiplied by the number of servers connected to each leaf switch

Figure 3 shows other configuration parameters defined to analyze the different topologies.

Topology	# Leaf k	# Spine S	Uplink per leaf	Total uplink BW per leaf (Gbps)	Total BW (Gbps)	Bisection BW (Gbps)	Oversubscription Ratio
Full-Bisection	k	S	S	S * link_speed	k * S * link_speed	k/2 * S	1:1
Oversubscribed 2:1	k	S	S	S * link_speed	k * S * link_speed	k/2 * S	2:1
Oversubscribed 4:3	k	S	S	S * link_speed	k * S * link_speed	k/2 * S	4:3
Oversubscribed 4:1	k	S	S	S * link_speed	k * S * link_speed	k/2 * S	4:1

Fig. 2. Topology definition table preview

Type	Value
BW for uplink link (Gbps)	1
BW for downlink link (Gbps)	1
SWITCH SPINE 48 ports uplink PRICE	1800
Switch Spine 48 ports uplink POWER USAGE (W)	100
Switch Spine 48 ports uplink SPACE USAGE (U)	1
SWITCH LEAF 24 ports server + uplink PRICE	1000
Switch leaf 24 ports server + uplink POWER USAGE (W)	70
Switch leaf 24 ports server + uplink SPACE USAGE (U)	1
Link fiber (LC-LC, OM3)	12€
Link copper (CAT6)	3€
Spine <-> Leaf link type	Optical fiber

Fig. 3. Configuration parameters

5 Results and Analysis

This section presents and analyzes the results obtained from the systematic evaluation of the selected network topologies across multiple metrics and constraint scenarios. The analysis focuses on showing the differences in terms of network performance, cost and energy efficiency.
Finally, it proposes a method to identify feasible topology configurations, given determined constrained, to simulate a realistic edge data center scenario.
A series of comparative plots are used to highlight how each topology behaves as the system scales, and how it performs when subjected to real-world constraints such as power, rack space, and budget.

5.1 Cost, Power, Rack Usage, and Bandwidth VS Number of Servers

The first set of plots examines how each topology scales across four fundamental dimensions: **total cost, power consumption, rack space** and **bisection bandwidth**, as a function of the total number of servers.
The plot shows how Cost, Power Consumption and Rack Space grows similarly with the varying of the number of servers, while Bisection Bandwidth presents more linearity and how the oversubscription ratio highly influences it.
Full Bisection shows the highest cost and power usage, as expected, due to the increasing number of spine switches required to maintain full bandwidth.

Fig. 4. Cost, Power VS Number of Servers

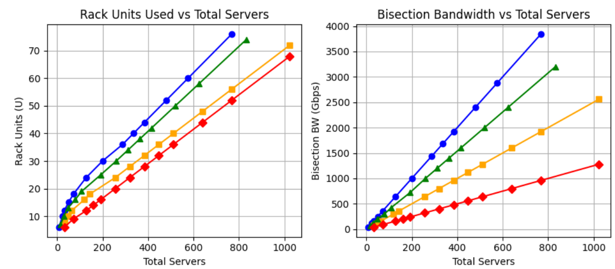

Fig. 5. Rack Usage, Bandwidth VS Number of Servers

Oversubscription 4:1 is the most compact and cost-effective solution, but suffers from poor scalability in terms of bandwidth.
Oversubscription 2:1 and **4:3** presents intermediate characteristics, making them ideal for medium-scale edge deployments.

5.2 Bisection Bandwidth VS Cost

This plot visualizes the performance-cost-trade-off for each topology across different system sizes.

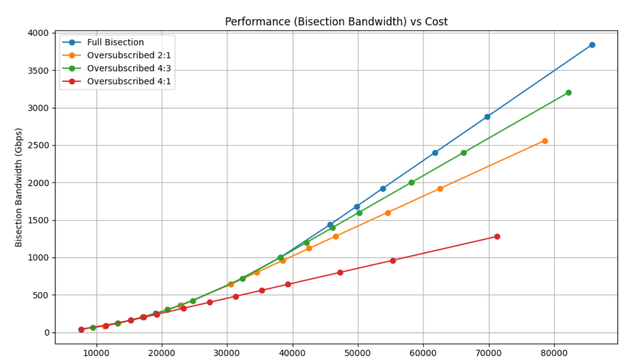

Fig. 6. Bisection Bandwidth VS Cost

Full Bisection achieves the highest bandwidth, but at the cost of increasingly expensive infrastructure.
Oversub 2:1 and 4:3 dominate the Pareto frontier, delivering reasonable bandwidth at significantly lower cost.
Oversub 4:1 appears in the low-cost/low-performance corner, suitable for constrained use cases.

5.3 Performance-to-Cost Ratio vs Number of Servers

This metric provides a normalized measure of efficiency, showing how relative performance scales per unit cost.

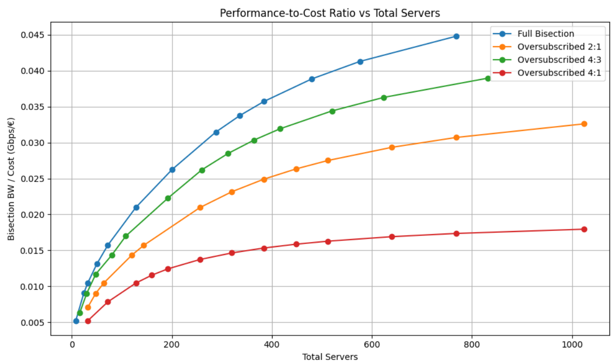

Fig. 7. Performance-to-Cost Ratio vs Number of Servers

This analysis suggests that while oversubscription is essential for cost savings, the 4:3 and 2:1 configurations offer the best trade-off, with Full Bisection outperforming all others only when budget and rack space are not limiting factors.

5.4 Relative Performance vs Effective Cost (Fixed N)

At fixed server counts (e.g., N = 64, 128), this plot compares normalized performance against total effective cost. Each topology is assigned a unique score that is shown in the plot.

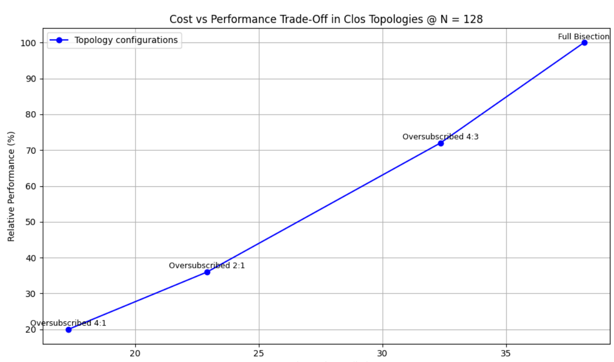

Fig. 8. Performance-to-Cost Ratio vs Number of Servers

The plot shows a relatively linear pattern, highlighting how oversubscription levels highly influence the relative performance value.

Oversubscription 4:3 emerges as a good trade-off configuration.

5.5 Feasible Configurations Under Realistic Constraints

Finally, a scatter plot is used to display only those configurations that satisfy all practical constraints:

- Power <= 5kW
- Rack Space <= 42 U (1 Rack)
- Budget <= 15000 €
- OPZ. Server >= n

Most **full bisection configurations are excluded** due to exceeding budget constraints. The **oversubscribed topologies**,

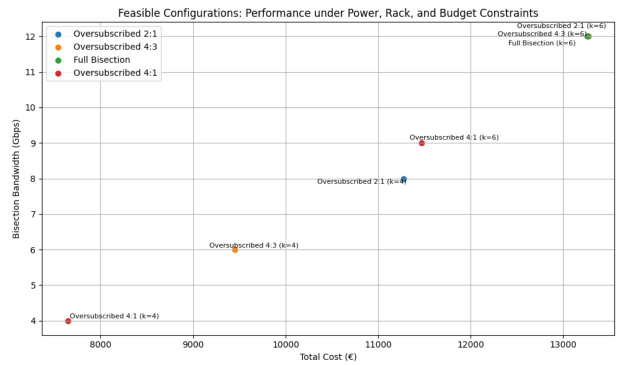

Fig. 9. Feasible configurations under constraints

particularly **2:1** and **4:3**, dominate this feasible region, reinforcing their practical relevance.

This filtered view is useful to distinguish theoretically efficient configurations from those that are actually deployable in constrained environments.

A table is then generated, containing all the feasible configurations and their parameters, like the example in Figure 10.

	Topology	k = # leaf	N = # server	Total Cost (€)	Total Watt (W)	Rack Space (U)	Bisection BW (Gbps)
1	Full Bisection	6.0	24	13260.0	820.0	10.0	120.0
40	Oversubscribed 4:3	6.0	30	13263.0	820.0	10.0	120.0
27	Oversubscribed 2:1	6.0	48	13272.0	820.0	10.0	120.0
53	Oversubscribed 4:1	6.0	72	11472.0	720.0	9.0	90.0
26	Oversubscribed 2:1	4.0	32	11272.0	680.0	8.0	80.0
13	N+1	4.0	12	9445.0	580.0	7.0	60.0
39	Oversubscribed 4:3	4.0	16	9448.0	580.0	7.0	60.0
0	Full Bisection	4.0	8	7630.0	480.0	6.0	40.0
52	Oversubscribed 4:1	4.0	32	7648.0	480.0	6.0	40.0

Fig. 10. Feasible configurations for given constraints

This method allows for the definition of deployment constraints and the identification of both feasible and optimal configurations. It provides network operators and data center designers with a practical and immediate tool to quickly assess deployable network options.

The code to use this framework is available at this link.

5.6 Summary of Key Insights

- Oversubscription 2:1 provides the best overall balance between cost, bandwidth, and scalability.
- Oversubscription 4:3 is a strong alternative, especially when slightly higher performance is needed without significant cost increase.
- Full Bisection is ideal for maximum performance, but requires considerable resources and should be reserved for performance-critical edge cases.
- Oversubscription 4:1 is only suitable in low-bandwidth, cost-constrained environments.
- The optimal topology depends on deployment constraints and scale, not just performance objectives.

6 Discussion, Limitations and Future Work

The analysis presented in this work offers a practical framework for evaluating and selecting network topologies in resource-constrained edge data centers. By modeling multiple Clos-based configurations and quantifying their trade-offs in terms of cost, bandwidth, power, and physical footprint, this study provides actionable insights for designing efficient and scalable edge infrastructures.

The results confirm that **oversubscription** is not just a compromise, but rather a **strategic design tool** that enables cost-effective deployments while preserving acceptable levels of performance. In particular, **2:1 and 4:3 oversubscribed topologies** consistently demonstrate strong performance-to-cost ratios and high feasibility under realistic constraints, making them ideal candidates for micro data center deployments.

Full bisection, although the most performant, incurs significant overhead in terms of infrastructure and power, and should be reserved for performance-critical environments with relaxed resource constraints.

The proposed approach also includes a method for filtering configurations based on user-defined deployment constraints (e.g., power, rack space, budget), offering a practical decision-support tool that can guide network planning in diverse operational contexts. This is particularly relevant for **edge deployments in Italy**, where regulatory, infrastructural, and geographic limitations pose concrete challenges.

However, the study also has several limitations. The model assumes:

- Homogeneous link speed (1 Gbps)
- Static traffic patterns without congestion modeling
- Fixed switch models and no latency considerations

Future work may extend this framework by:

- Supporting heterogeneous link speeds and hierarchical topologies (e.g., 3-tier Clos)
- Modeling traffic flow and latency under realistic load conditions
- Applying software simulation or realistic deployment to better perform topology selection

This project explored the design space of Clos-based network topologies for micro edge data centers, with a focus on **performance-cost trade-offs** under **realistic deployment constraints**. Through parametric modeling and visual analysis, it identified the most efficient and feasible configurations for small- to medium-scale environments, especially in infrastructurally limited contexts such as Italy.

The methodology and results aim to **assist data center designers** and network engineers in making informed, constraint-aware decisions when deploying edge infrastructure. While the analysis is based on simplified assumptions, it lays the foundation for a more comprehensive design tool adaptable to a wide range of scenarios.

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