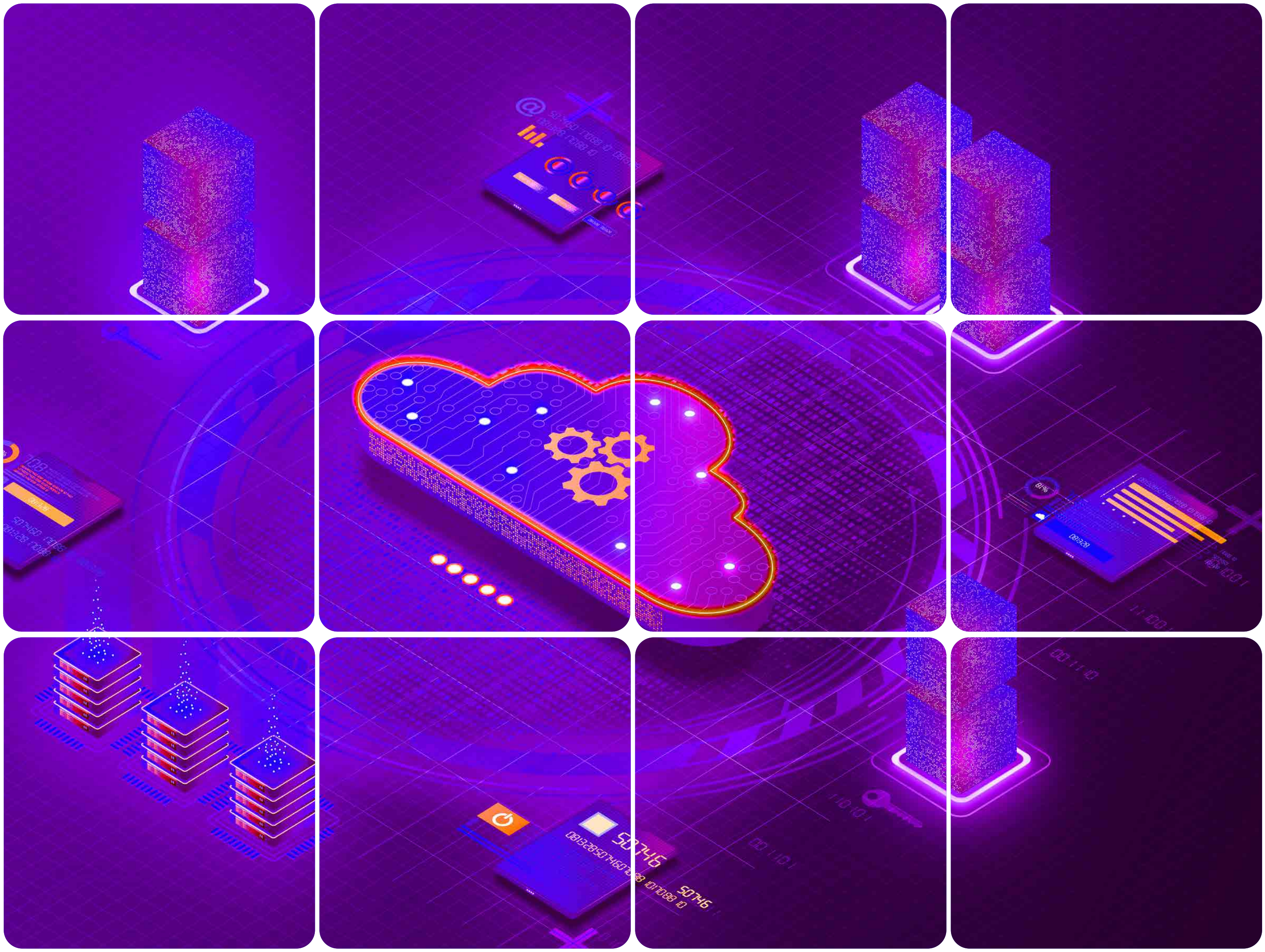

Comparing Total Cost of Ownership for Dark Fiber, Carrier Ethernet, and Wavelength Services for Data Center Interconnect at 100G and Beyond

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ACG RESEARCH

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Executive Summary

As enterprise data demands surge—fueled by artificial intelligence (AI) and cloud computing—the need for scalable, cost-effective Data Center Interconnect (DCI) infrastructure has never been greater. This paper evaluates the total cost of ownership (TCO) of three primary transport service models for DCI at 100G and beyond: Carrier Ethernet, Wavelength Services, and Dark Fiber.

Using a three-node network model over a three-year period, we analyzed costs across metro, short-haul, and long-haul use cases. Our TCO model included transport service expenses, switch/router and optical equipment investments, and operational support costs. We found that Carrier Ethernet, while simple and low in upfront capital expenditure (CapEx), becomes prohibitively expensive at higher bandwidths due to its linear cost structure per 100G circuit. Wavelength Services offer improved efficiency over Carrier Ethernet by enabling point-to-point 100G or 400G connections, but they still scale in discrete steps.

Dark Fiber, in contrast, provides enterprises with direct ownership of the optical layer, enabling the potential to leverage routed optical networks by deploying coherent pluggable dense wavelength division multiplexing (DWDM) optics. Though it has higher initial CapEx and operational complexity, it offers unmatched scalability and the lowest TCO at high bandwidth levels—especially when link distances are under 500 km. In addition, Dark Fiber networks provide lower latency and reduced jitter[1] compared to Carrier Ethernet packet networks by providing dedicated bandwidth that eliminates congestion-related packet delay variations. For metro and short-haul networks in areas where fiber is abundant, Dark Fiber emerges as the most financially efficient model once bandwidth requirements exceed 200G. In long-haul networks, while Dark Fiber maintains a TCO advantage, Wavelength Services can be competitive depending on local fiber availability and distance-related infrastructure costs.

For enterprises building connected AI infrastructures and high-density data center footprints, Dark Fiber represents the most strategic long-term investment for scalable, high-capacity DCI.

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[1] Jitter refers to the variation of packet delays due to network queuing. Networks with high jitter or delay variation can negatively impact certain applications like video streaming and private line emulation.

Introduction

In today's digital economy, data is the lifeblood of innovation, especially with the rapid evolution of AI, cloud computing, and digital services. At the heart of this transformation are data centers and their interconnection infrastructure. As demand for data processing and movement intensifies, especially for bandwidth-intensive and latency-sensitive applications, the TCO of different DCI transport options becomes a critical consideration for enterprise IT and network architects.

This paper explores and compares the TCO of three primary DCI transport options—Carrier Ethernet, Wavelength Services, and Dark Fiber—for enterprises requiring 100G and beyond of interconnect bandwidth. These comparisons are based on a three-node DCI network model and consider capital expenditures (CapEx), operational expenditures (OpEx), scalability, and architectural implications. The three-node network provides an example of an enterprise connecting three data centers.

Data Center Interconnect Bandwidth Growth

Data Center Interconnect bandwidth requirements are growing at an unprecedented pace. This growth is largely driven by the following trends:

- **Enterprise AI Adoption:** Enterprise adoption of AI workloads is accelerating. As organizations deploy their own AI-capable data centers or leverage co-location, cloud, or hyperscale AI providers, they face the challenge of ultra-high bandwidth DCI requirements. The Cisco AI Readiness Index shows that 65% of organizations are already adopting GenAI for business[2] functions.
- **AI Workloads:** AI workloads require massive bandwidth between Graphics Processing Units (GPUs) for training and inference AI models, pushing interconnect bandwidth requirements to 400G and beyond.
- **Data Center Power Growth:** As data centers increase in compute density and energy consumption, their bandwidth requirements follow suit, which may require data interconnection to additional sites due to single-site power constraints. Power and network demand are closely

[2] Cisco AI Readiness Index - Cisco

linked in modern AI data centers. According to McKinsey, global data center demand is expected to more than triple by 2030[3], exceeding 179 Gigawatts.

- **Disaster Recovery/Resilience:** Increase need for Disaster Recovery and Business continuity as DCI technology enables seamless backup and replication across geographically distributed data centers[4].
- **Advancements in Optical Networking and SDN Technologies:** Innovations in optical fiber technology, DWDM, and Software-Defined Networking (SDN) are enhancing DCI efficiency[5].

Given this landscape, enterprises need to carefully evaluate their DCI transport strategy, balancing performance, cost, and operational complexity.

Transport Alternatives & Network Architecture

Enterprises planning for DCI at 100G and above have three primary transport options to consider: Carrier Ethernet, Wavelength Services, and Dark Fiber. Each of these architectures presents a different set of trade-offs in terms of operational complexity, scalability, and cost structure.

Carrier Ethernet is typically delivered in increments of 100G or less and provides a simple, scalable, and service provider-managed transport model. As illustrated in Figure 1, routers at each site (A, B, and C) connect to the provider's Ethernet cloud using 100G grey optics. The service provider abstracts the underlying transport, and the enterprise only needs to manage its routers and Ethernet service interfaces. This model appeals to enterprises seeking minimal operational burden and predictable monthly recurring charges (MRCs). However, the cost structure scales linearly with bandwidth, meaning that each additional 100G circuit incurs its own transport fee. While the upfront CapEx is relatively low, recurring OpEx can become significant as bandwidth needs grow. Another potential challenge with Carrier Ethernet is that it is a packet service using virtual circuits, which have unpredictable latency and jitter. This could cause problems with AI connectivity, which is latency and performance sensitive.

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[3] Telco operators' growth lies in AI infrastructure | McKinsey

[4] https://linkewire.com/2025/02/03/data-center-interconnect-market/

[5] https://linkewire.com/2025/02/03/data-center-interconnect-market/

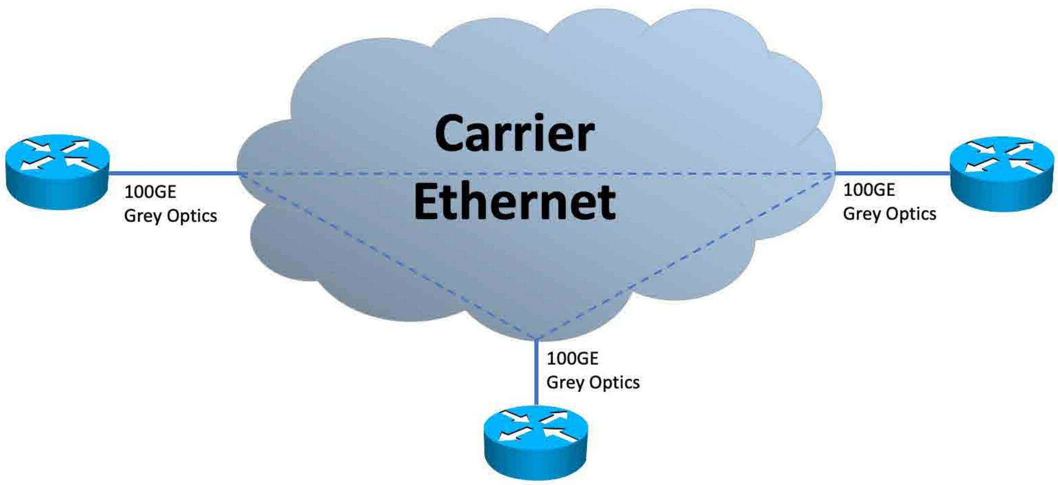

Figure 1: Three-node Carrier Ethernet network

Wavelength Services offer point-to-point, full-duplex connectivity at either 100G or 400G increments. Like Carrier Ethernet, Wavelength Services are managed by the service provider who is responsible for the optical layer. The enterprise connects to the service provider's optical termination equipment using 100G or 400G gray optics at the router end, but unlike Carrier Ethernet, the optical path between endpoints is fully dedicated, resulting in better performance and isolation. As shown in Figure 2, the architecture forms a direct optical triangle between Routers A, B, and C. This architecture provides lower latency and potentially lower costs at high bandwidths compared to Carrier Ethernet. However, like Carrier Ethernet, Wavelength Services costs scale linearly—this time in 100G or 400G blocks—making it more cost effective than Carrier Ethernet at higher capacities but still relatively inflexible in scaling beyond 400G.

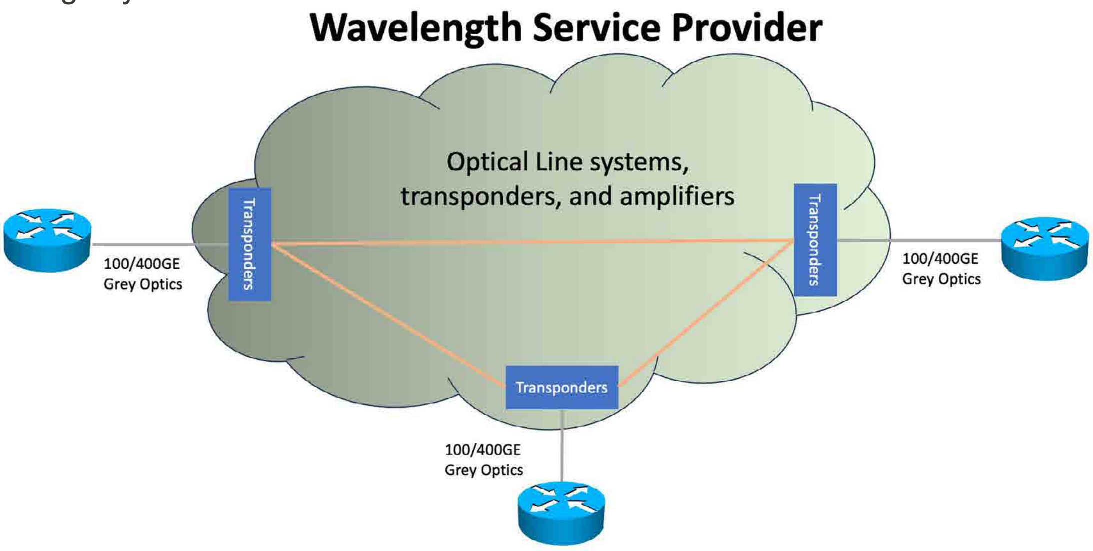

Figure 2: Three-node Wavelength Services network

Dark Fiber offers enterprises the highest level of control, scalability, and potential cost efficiency over time. Dark Fiber also provides lower latency and jitter than Carrier Ethernet. In this model, the enterprise leases fiber pairs and assumes responsibility for deploying and managing the optical transport equipment. As seen in Figure 3, this setup creates direct fiber links between switches and routers, bypassing the service provider's managed infrastructure. The network combines IP and optical layers through IP over DWDM. An example of this is the implementation of the Cisco Routed Optical Networking solution, using coherent pluggable optics in (router or switch) IP ports instead of traditional DWDM transponders, enabling high-bandwidth transmission over a single fiber pair at much lower costs. The key advantage of Dark Fiber lies in its fixed monthly cost per mile per fiber pair, which does not increase with each additional 100G or 400G circuit. This cost model results in roughly flat growth rather than linear scaling with bandwidth, meaning the cost per bit decreases dramatically as capacity increases.

This makes Dark Fiber particularly attractive for organizations with rapidly scaling bandwidth needs.

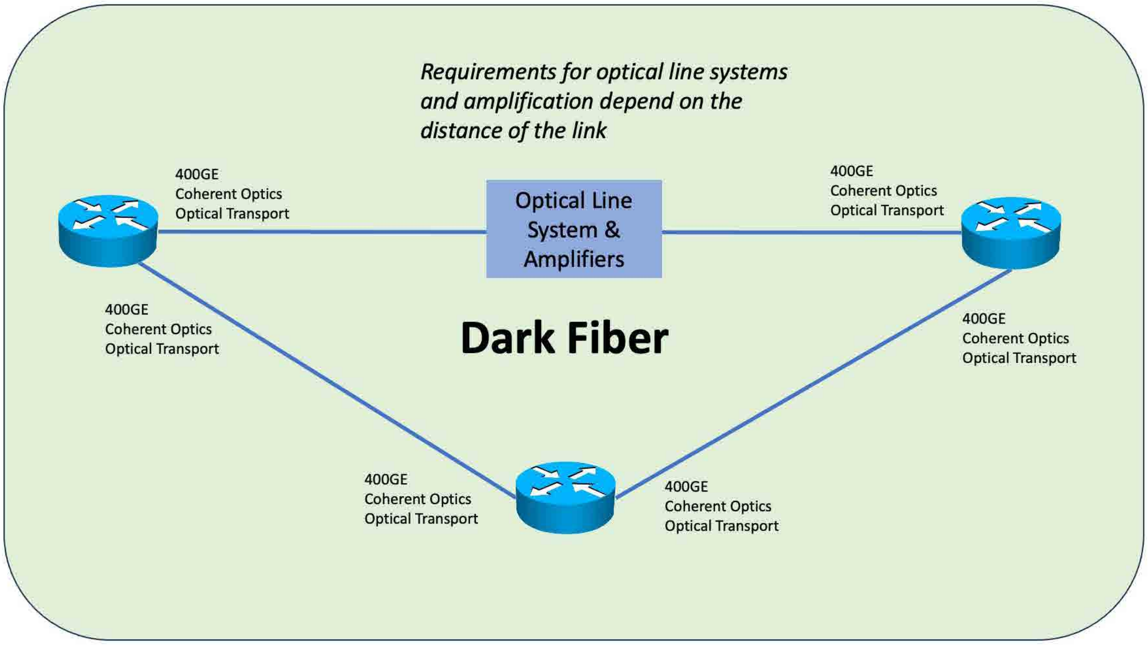

Figure 3: Three-node Dark Fiber network

When deploying Dark Fiber, the network architecture varies depending on the distance between nodes. For links shorter than 120 km, optical components with simplified line systems can be directly integrated into switches or routers without the need for in-line amplification, as illustrated in Figure 4.

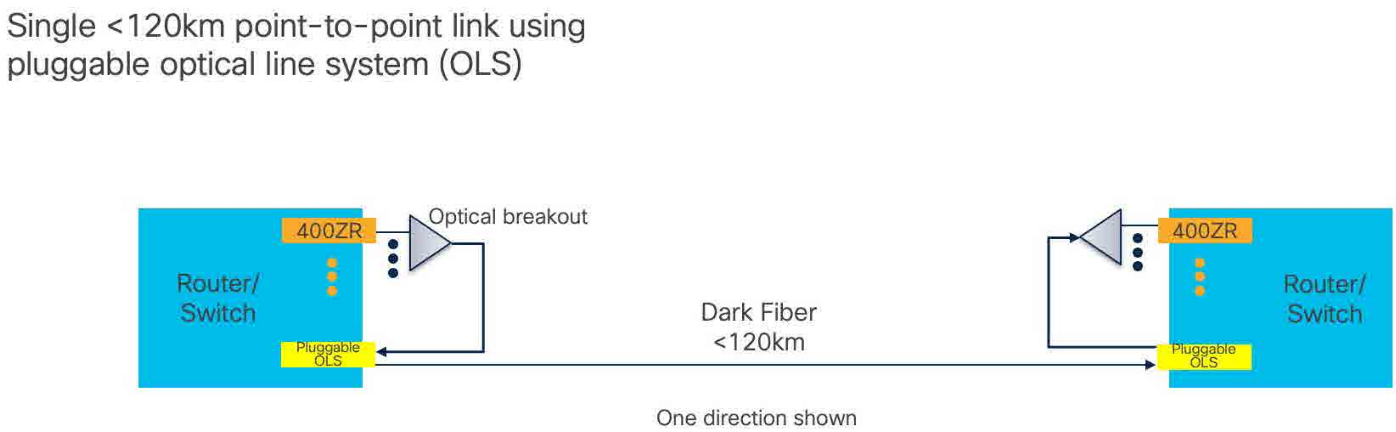

Figure 4: Optical network connection for links less than 120 km

For longer links—between 120 km and 500 km—a traditional optical line system (without transponders) is used alongside the routers with coherent optics, as shown in Figure 5. Cisco Routed Optical Networking with coherent optics provides a cost-optimized solution as opposed to a traditional optical transport network with transponders[6]. In this scenario, routers utilize in-line amplifiers, which are required approximately every 100 km, to maintain signal strength across the fiber.

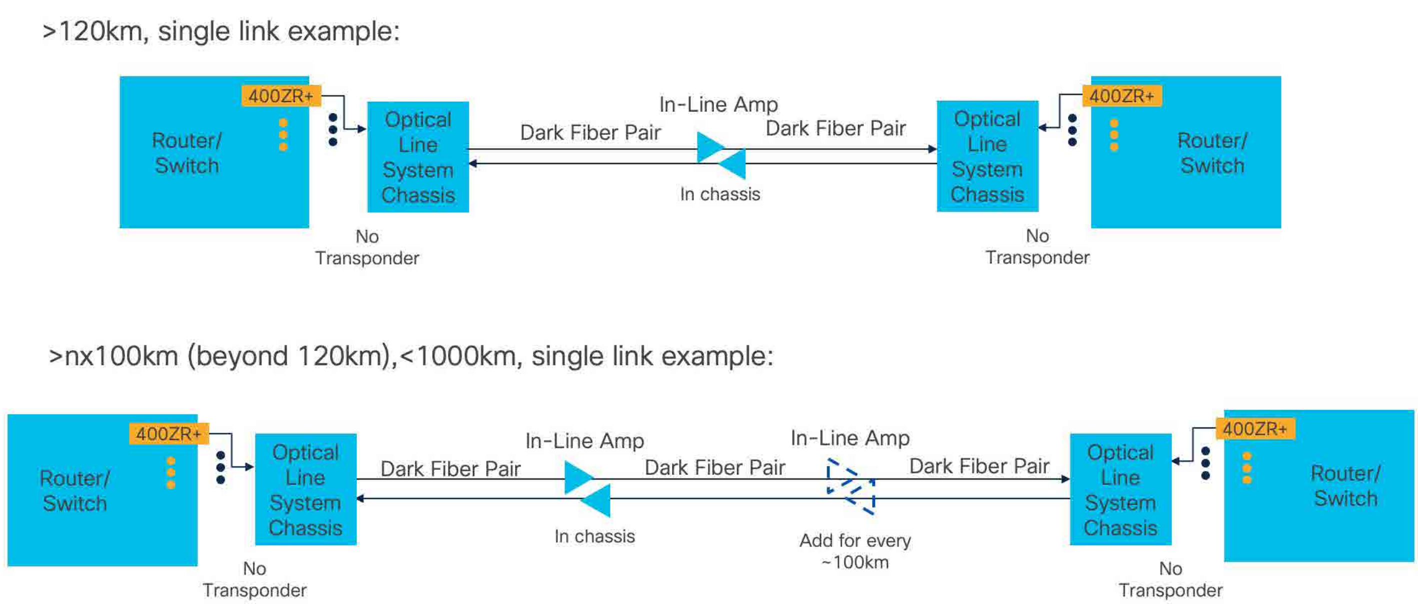

Figure 5: Optical network connection for links between 120 km and 500 km

[6] https://www.acgcc.com/reports/the-economic-benefits-of-routed-optical-networks-f/

Many enterprises do not have the capabilities in house or the economies of scale to effectively manage their own fiber network. To overcome operational complexity, fiber network operations can be outsourced to either managed operations providers who can manage the Dark Fiber leased transport acquired from a Dark Fiber provider, or to managed optical fiber network (MOFN) providers who can offer a complete package of dedicated Dark Fiber with its associated maintenance and operation. MOFN providers have both expertise and economies of scale to allow enterprises to use Dark Fiber services with lower risk. To reduce operational complexity in Dark Fiber deployments, industry standardization efforts have increased to streamline monitoring and management of the optical layer within data center interconnect (DCI) architectures using IP network management software.

In summary, Carrier Ethernet and Wavelength services provide managed, incremental options for DCI, suitable for enterprises that prefer predictable OpEx and lower operational complexity. Dark Fiber, while requiring greater network management expertise, offers superior scalability and cost efficiency for high-capacity use cases. For enterprises expecting sustained bandwidth growth—especially in AI or cloud—Dark Fiber becomes increasingly compelling as a long-term strategic investment. The pros and cons of each service are summarized in Table 1.

Transport	Pros	Cons
Carrier Ethernet	• Ethernet services are widely available. • Services at bandwidths ranging from 1G to 100G are cost effective. • The network is fully managed by the service provider.	• For bandwidth greater than 100G costs increase linearly and can be very expensive. • Ethernet is a packet network with variable latency and jitter.
Wavelength Services	• Dedicated point-to-point circuits. • Low latency and jitter. • More cost effective than Carrier Ethernet at bandwidths greater than 100G. • Service provider manages optical network.	• As bandwidth increases expenses scale linearly. • Wavelength services are not as widely available as Carrier Ethernet. • Scaling bandwidth can be limited by the service provider’s service-level agreements (SLAs) and costs.

Transport	Pros	Cons
Dark Fiber	• Flat expense for virtually unlimited bandwidth. • Low latency and jitter. • Routed Optical Networking provides cost-effective solution. • Scaling and flexibility are controlled by the enterprise, not the service provider.	• Dark Fiber expenses scale with distance. • Prices depend on fiber availability in metro areas. • Dark Fiber does incur a greater operational challenge than Carrier Ethernet or Wavelength services, but some of this burden could be shared with the Dark Fiber provider or third-party partner.

Table 1: Pros and cons of each transport service

TCO Model Assumptions

To compare the financial implications of various DCI architectures supporting 100G and above, we developed a TCO model based on the above three distinct network transport scenarios: Carrier Ethernet, Wavelength Services, and Dark Fiber. Each model assumes a three-node DCI network and includes a comprehensive evaluation of capital and operational expenses over time. We also assume the maximum bandwidth per wavelength is 400G[7] in the Dark Fiber and Wavelength Services scenario.

The TCO analysis is structured around three primary categories of expenditure: Transport Service Expenses, Router and Optical Equipment Expenses, and Network Operations Expenses. This holistic view ensures that both upfront investment and ongoing costs are considered when evaluating each option.

TCO Model Results

Our total cost of ownership (TCO) analysis evaluates three DCI transport models—Carrier Ethernet, Wavelength Services, and Dark Fiber—across three distinct use cases:

[7] When the bandwidth goes above 400G we add an additional 400G link.

- **Metro networks** (average 50 km between data centers)
- **Short-haul networks** (average 200 km between data centers)
- **Long-haul networks** (average 500 km between data centers)

Each scenario is modeled as a three-node network over a three-year period, with bandwidth requirements scaling from 10 Gbps to 1.6 Tbps. The cost model integrates transport service fees, router and optical hardware, and ongoing operations and support expenses.

The results, visualized in the TCO curve charts, show a clear trend: Carrier Ethernet becomes the most expensive option as bandwidth scales beyond 200 Gbps, due to its strictly linear pricing per 100G circuit. In contrast, Dark Fiber and Wavelength Services offer superior cost efficiency at higher capacities, with distinct cost dynamics driven by distance, transport scalability, and operational complexity.

Cost Sensitivity by Distance

When comparing Dark Fiber and Wavelength Services, it's important to note that Dark Fiber scales linearly with distance, while Wavelength Services costs rise in step increments, not always proportionally with bandwidth. This makes Dark Fiber particularly cost effective in metro and short-haul deployments, especially where competition among fiber providers drives down leasing costs.

However, in long-haul deployments, the balance can shift—Wavelength Services may become more viable due to the higher cost of long-distance fiber construction, limited availability, and more complex amplifier and optical line system requirements for the enterprise. For this reason, it's important to get estimates of expenses for each service based on the locations of data centers.

Summary of Results

The key results of our analysis are:

- Dark Fiber shows TCO savings compared to managed Carrier Ethernet services across metro, short-haul, and long-haul networks above 100G and scaling up to 67% savings above 800G.
- For metro distances: utilizing a Dark Fiber network shows TCO savings compared to both Carrier Ethernet and Wavelength Services above 100G.

- For short-haul distances: utilizing a Dark Fiber network shows better TCO vs. Carrier Ethernet (above 100G), and offers TCO advantages vs. Wavelength Services starting at 200G.
- For long-haul distances: utilizing a Dark Fiber network shows better TCO vs. Carrier Ethernet (above 200G) and offers TCO advantages vs. Wavelength Services at bandwidths above 800G.

Metro Networks (50 km)

Metro networks—such as deployments within New York City or the San Francisco Bay Area—are characterized by relatively short distances between facilities. At this range, Dark Fiber proves to be the most cost-effective solution at bandwidths exceeding 100G, primarily because the cost of Dark Fiber transport is distance based, not bandwidth based.

A summary of three-year cumulative Dark Fiber savings over Carrier Ethernet and Wavelength Services is presented in Table 2. The savings in the table are presented for the cases where bandwidth requirements grow past 100G, 400G, and 800G. In metro networks Dark Fiber is more cost effective than Carrier Ethernet and Wavelength Services at bandwidth greater than 100G. Above 400G, Dark Fiber presents a three-year TCO savings of 48% vs. Carrier Ethernet and 55% vs. Wavelength Services.

	Dark Fiber Savings	
Bandwidth	Carrier Ethernet	Wavelength
>100G	4%	15%
>400G	48%	55%
>800G	67%	67%

Table 2: Metro network three-year cumulative Dark Fiber Savings over Carrier Ethernet and Wavelength Services

Figure 6 illustrates the three-year TCO of Dark Fiber, Carrier Ethernet, and Wavelength Services. Dark Fiber maintains a flat cost curve while Carrier Ethernet and Wavelength Services scale upward in clear step functions. This flattening of Dark Fiber costs results from the fact that a single fiber pair can support multiple terabits with coherent pluggable DWDM optics, while Carrier Ethernet and Wavelength Services incur incremental MRCs per circuit or wave.

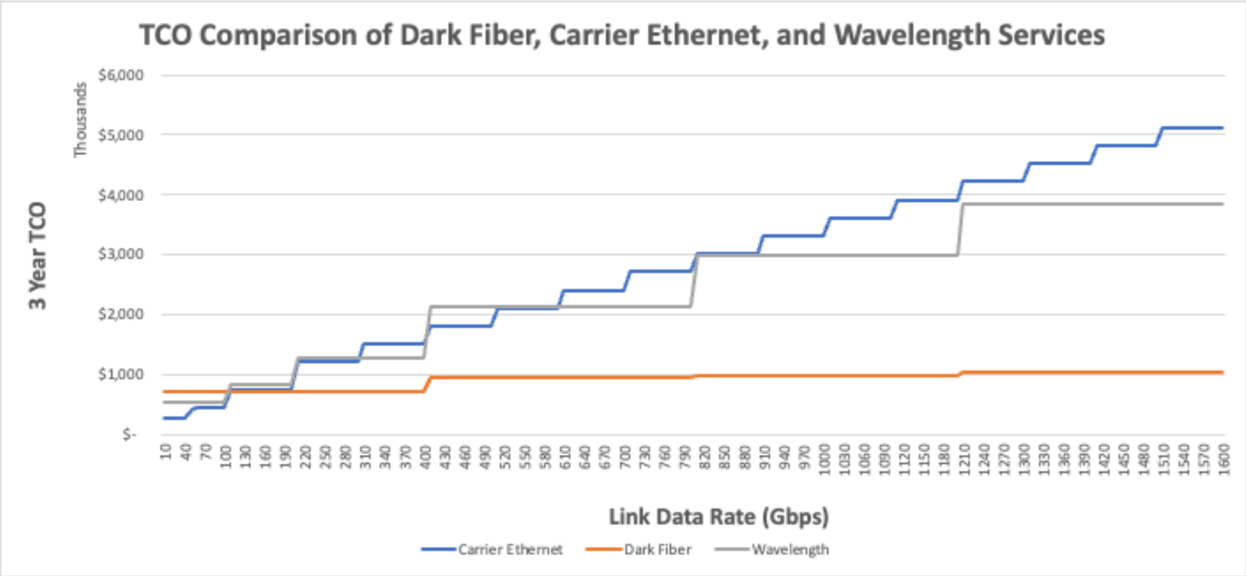

Figure 6: Comparison of Dark Fiber, Carrier Ethernet, and Wavelength Services for metro networks

Short-haul Networks (200 km)

Short-haul networks connect data centers across regional geographies, such as between nearby cities or across a broader metropolitan region. For this use case, we assume an average link distance of 200 km. In these scenarios, the cost comparison becomes more sensitive to distance-based pricing, particularly for Dark Fiber.

A summary of three-year cumulative Dark Fiber savings over Carrier Ethernet and Wavelength services is presented in Table 3. The savings in the table are presented for the cases where bandwidth requirements grow past 100G, 400G, and 800G. In short-haul networks Dark Fiber is more cost effective than Carrier Ethernet at bandwidths greater than 100G. It is more cost effective than Wavelength Services at bandwidths greater than 400G. Above 400G, Dark Fiber presents a three-year TCO savings of 61% vs. Carrier Ethernet and 30% vs. Wavelength Services.

	Dark Fiber Savings	
Bandwidth	Carrier Ethernet	Wavelength
>100G	20%	-48%
>400G	61%	30%
>800G	77%	48%

Table 3: Short-haul network three-year cumulative Dark Fiber Savings over Carrier Ethernet and Wavelength Services

As shown in Figure 7, the three-year TCO for Carrier Ethernet increases steeply with bandwidth, quickly surpassing both Dark Fiber and Wavelength Services. While Dark Fiber initially carries a higher entry cost, it becomes more favorable than Wavelength Services beyond the 400G mark. Dark Fiber continues to offer the lowest TCO beyond 400G, driven by its flat transport costs despite increasing bandwidth.

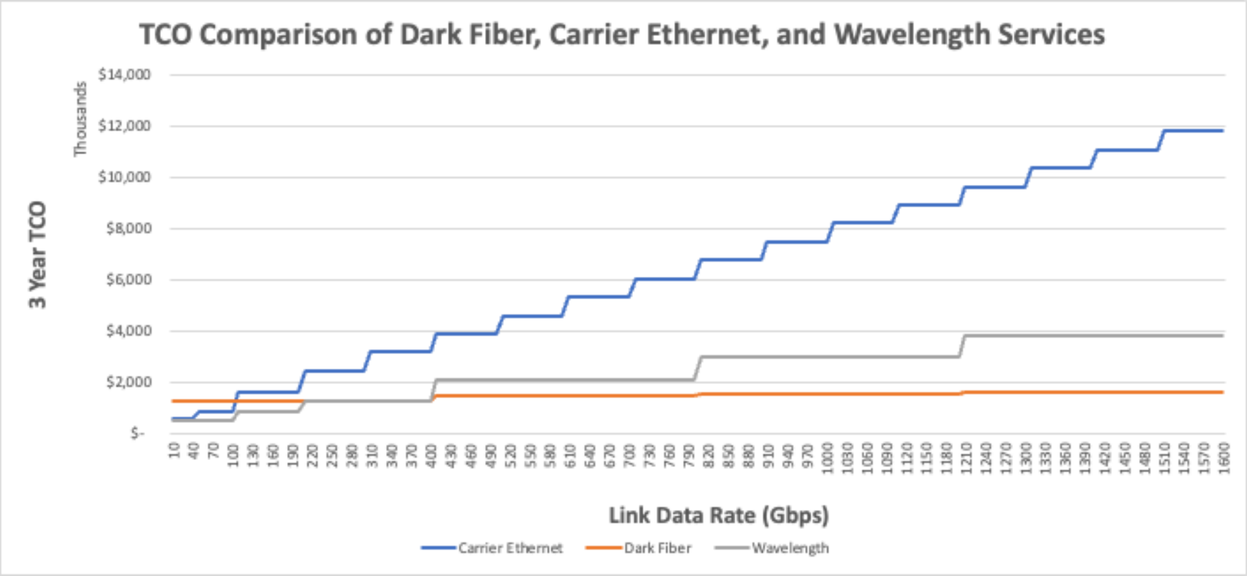

Figure 7: Comparison of Dark Fiber, Carrier Ethernet, and Wavelength Services for short-haul networks

Long-haul Networks (500 km)

Long-haul networks span broader geographic areas, such as inter-regional links or cross-country backbones. These deployments introduce new challenges related to signal regeneration, amplifier placement, and fiber availability. For this scenario, we model a typical long-haul DCI network with an average link length of 500 km.

A summary of three-year cumulative Dark Fiber savings over Carrier Ethernet and Wavelength Services is presented in Table 4. The savings in the table are presented for the cases where bandwidth requirements grow past 100G, 400G, and 800G. In long-haul networks Dark Fiber is more cost effective than Carrier Ethernet at bandwidths greater than 400G, presenting a 46% TCO savings over three years. It is more cost effective than Wavelength Services at bandwidths greater than 800G, presenting a 14% TCO savings over three years.

	Dark Fiber Savings	
Bandwidth	Carrier Ethernet	Wavelength
>100G	-21%	-156%
>400G	46%	-19%
>800G	68%	14%

Table 4: Long-haul network three-year cumulative Dark Fiber Savings over Carrier Ethernet and Wavelength Services

As depicted in Figure 8, Carrier Ethernet again shows the steepest TCO curve, rapidly escalating beyond 400G and making it the least cost-effective choice for long-haul deployments. While Wavelength Services initially present a better alternative, Dark Fiber becomes the clear winner at higher speeds, particularly for enterprises anticipating bandwidth requirements of 800G or more.

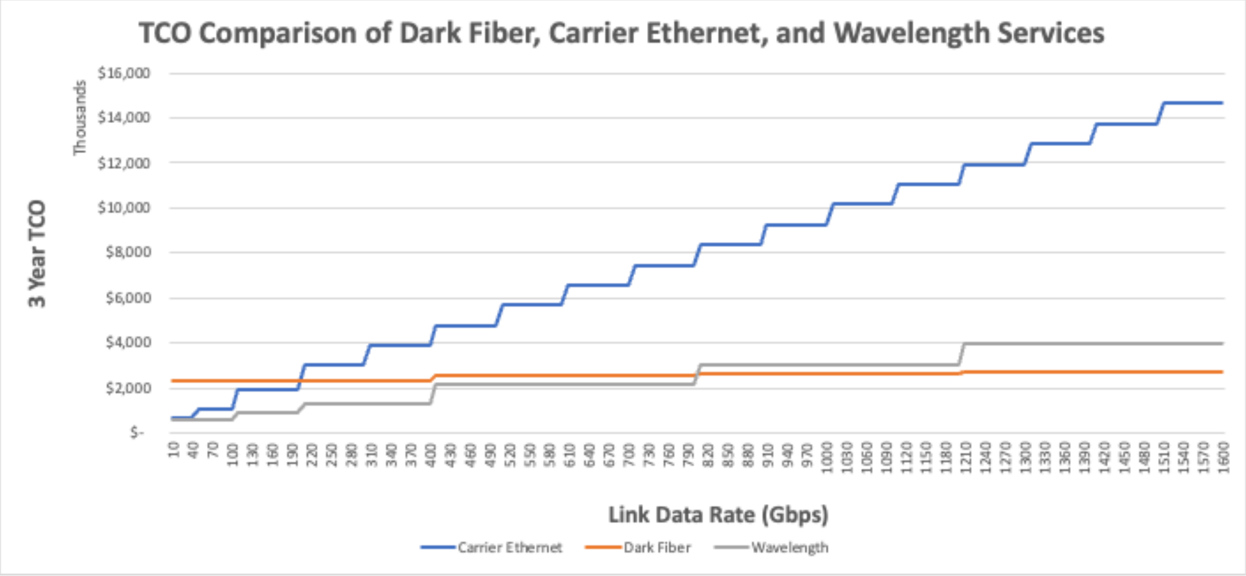

Figure 8: Comparison of Dark Fiber, Carrier Ethernet, and Wavelength Services for long-haul networks

Conclusion

This study demonstrates that as bandwidth requirements scale beyond 100G, traditional transport models like Carrier Ethernet become cost prohibitive. While Carrier Ethernet offers the lowest upfront costs, predictable OpEx, and ease of use, its cost per bit quickly outpaces other solutions.

Wavelength Services provide a balance between simplicity and scalability, especially in environments where optical expertise or Dark Fiber availability is limited. However, their per-wave pricing still introduces scaling constraints, especially in metro and short-haul networks.

Dark Fiber consistently outperforms both alternatives from a TCO perspective when bandwidth requirements are high and link distances are manageable. Dark fiber is advantageous in metro networks where bandwidth scaling rapidly exceeds 100G. The ability to amortize the cost of fiber transport while supporting multi-terabit capacity on a single pair gives it a unique advantage in metro and regional DCI networks. Dark Fiber has become more cost effective in recent years due to the maturity of IP over DWDM implementations using coherent optics, such as Cisco Routed Optical Networking. Coherent optics provides the proven maturity, reliability, and interoperability to deliver low-cost optical DCI with pluggable optics deployed in routers or switches. Furthermore, the emergence of managed operations providers and managed optical fiber network providers has reduced the complexity and expense of enterprises taking on the management of Dark Fiber networks.

Organizations should assess their long-term bandwidth growth, in-house optical networking capabilities, and regional fiber availability when choosing a DCI transport architecture. As AI and cloud workloads continue to drive exponential growth in data movement, building a DCI strategy on a foundation of scalable and cost-efficient transport is critical—and in most high-capacity scenarios, Dark Fiber is the clear path forward.

Glossary

AI (Artificial Intelligence):

A field of computer science focused on developing systems that can perform tasks requiring human-like intelligence, such as learning, decision-making, and pattern recognition. AI workloads often require high bandwidth for data movement between processors.

Bandwidth:

The maximum rate of data transfer across a network path, typically measured in gigabits per second (Gbps) or terabits per second (Tbps). In DCI networks, higher bandwidth is required for AI, cloud, and enterprise workloads.

CapEx (Capital Expenditures):

Upfront investment in hardware and infrastructure, such as routers, optics, and fiber, required to build or upgrade a network.

Carrier Ethernet:

A managed packet-based transport service provided by telecom operators, typically delivered in fixed bandwidth increments (e.g., 10G, 100G). It abstracts underlying transport but introduces variability in latency and jitter.

Coherent Optics:

A class of advanced optical transceivers that use digital signal processing and the modulation of multiple properties of light to transmit high-bandwidth signals (100G and above) over long distances with improved efficiency.

Dark Fiber:

Unused (unlit) optical fiber that enterprises can lease and operate themselves. Offers control over the physical transport layer, enabling deployment of high-capacity coherent optical systems.

DCI (Data Center Interconnect):

The networking infrastructure used to connect data centers, enabling high-capacity communication between sites.

DWDM (Dense Wavelength Division Multiplexing):

An optical multiplexing technology that increases bandwidth by sending multiple signals simultaneously over a single fiber pair, using different wavelengths (colors) of light.

FTE (Full-Time Equivalent):

A unit of labor representing the workload of one full-time employee. Used in OpEx modeling to estimate operational support costs.

Grey Optics:

Typically intensity modulated direct-detect (IMDD) optical transceivers that operate over short distances and connect routers to provider equipment. Unlike DWDM optics, they are not color-tuned for multiplexing.

Jitter:

Variation in packet delay over time. Excessive jitter can disrupt real-time applications like voice and video and impact private line emulation over packet networks.

Latency:

The time it takes for data to travel from source to destination. Lower latency is crucial for real-time and AI applications.

Managed Operations Providers: A third-party specialized in operating data and optical networks on behalf of enterprises, regardless of ownership of the infrastructure to be managed

Managed Optical Fiber Network (MOFN):

A third-party service that provides and operates dedicated Dark Fiber infrastructure for enterprises, including maintenance and operations support, reducing complexity and risk.

MRC (Monthly Recurring Charge):
The ongoing cost charged by service providers for using their network services, such as Carrier Ethernet or Wavelength Services.

OpEx (Operational Expenditures):
Ongoing costs associated with running a network, including staff salaries, maintenance, utilities, and service provider fees.

Packet Network:
A communication network that transmits data in packets. Used in Carrier Ethernet but introduces variable latency and jitter compared to optical circuits.

Routed Optical Networking:
A Cisco architecture where IP routers are directly connected via coherent DWDM optics, eliminating the need for standalone transponders and simplifying optical transport.

Scalability:
The ability of a network to grow in bandwidth or capacity without significant cost or complexity increases.

TCO (Total Cost of Ownership):
A comprehensive cost model that includes both capital expenditures and operational expenditures over the lifecycle of a network deployment.

Transponder:
A device used in optical networks to convert and transmit signals over long distances, traditionally placed between routers and the optical line system. Coherent pluggables are gaining in popularity as an alternative to transponders, enabling a modern routed optical network architecture.

Wavelength Services:
A transport service providing dedicated optical connections (100G or 400G) between locations over the provider’s DWDM network. Offers predictable performance but scales in fixed bandwidth steps.

Peter Fetterolf, Ph.D. is an expert in network technology, architecture and economic analysis. He is responsible for financial modeling and whitepapers as well as software development of the ACG Research Business Analytics Engine. Dr. Fetterolf has a multidisciplinary background in the networking industry with over thirty years of experience as a management consultant, entrepreneur, executive manager, and academic. He is experienced in economic modeling, business case analysis, engineering management, product definition, market validation, network design, and enterprise, and service provider network strategy.