

The Imperative Shift from Circuit-Switched to Packet-Switched Networks A Performance, Economic, and Strategic Analysis

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Abstract: The persistent reliance on legacy circuit-switched networks, rooted in copper-based Time Division Multiplexing (TDM), presents a critical bottleneck to global digital transformation. This challenge is further intensified by the exponential growth of bandwidth-intensive, latency-sensitive applications such as cloud computing, 5G fronthaul, and massive Internet of Things (IoT) deployments, which legacy infrastructures were not designed to support. While the superior efficiency of packet-switched, fiber-optic networks is acknowledged, a comprehensive analysis quantifying their operational superiority and outlining a structured transition pathway for heterogeneous telecom environments remains a research gap. This study employs a mixed-methods methodology, integrating quantitative performance benchmarking, qualitative case study analysis, and economic modeling to rigorously evaluate this transition. Our findings demonstrate that packet-switched GPON architectures reduce energy consumption by up to 60%, decrease outage incidents by over 70%, and deliver latencies below 1 ms, compared to the sub-100 Mbps and high-vulnerability profile of copper-based systems. These improvements directly translate into enhanced service reliability, lower operational expenditure, and improved sustainability metrics for telecom operators. The primary contribution of this paper is a validated, multi-dimensional framework that moves beyond technological comparison to offer actionable, phased strategies for network modernization, incorporating economic, regulatory, and skill-based challenges. This work provides telecom operators and policymakers with evidence-based rationale and a strategic roadmap for the essential migration to future-proof, scalable network infrastructure.

Keywords: Packet Switching, Fiber Optics, Network Modernization, GPON, Energy Efficiency, Strategic Migration.

Nomenclature

Abbreviation	Description
AI	Artificial Intelligence
ML	Machine Learning
CapEx	Capital Expenditure
DSL	Digital Subscriber Line
EMI	Electromagnetic Interference
FTTB	Fiber to the Building
FTHH	Fiber to the Home
FTTX	Fiber to the x
GBI	Global Broadband Index
GPON	Gigabit Passive Optical Network
IoT	Internet of Things
IP	Internet Protocol
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
NFV	Network Function Virtualization
NPV	Net Present Value
OLT	Optical Line Terminal
ONT	Optical Network Terminal
OpEx	Operational Expenditure
PON	Passive Optical Network
PPP	Public-Private Partnership
PSTN	Public Switched Telephone Network
PUE	Power Usage Effectiveness
QoS	Quality of Service
QKD	Quantum Key Distribution
SDN	Software-Defined Networking
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
ZB	Zettabyte

1. Introduction

For over a century, circuit-switched networks have provided the foundation for global telephony. These networks were originally engineered to support predictable, voice-centric traffic patterns with dedicated end-to-end connections. However, the rigidity of such systems meant that scaling them to accommodate fluctuating and unpredictable data traffic was inherently inefficient. However, the dawn of the digital era, characterized by an exponential surge in data traffic—projected to reach 4.8 ZB annually by 2027 [3]—has starkly exposed the architectural and physical limitations of these legacy systems. The transition from voice-dominated communication to data-driven services has fundamentally altered traffic characteristics, favoring bursty, asymmetric, and highly scalable transmission models. This shift has led to a mismatch between network design principles and contemporary service requirements, necessitating a reevaluation of fundamental networking paradigms.

Copper-based infrastructure, the medium of circuit switching, is fundamentally constrained by severe signal attenuation, susceptibility to EMI, and inherent bandwidth ceilings, struggling to reliably deliver speeds beyond 100 Mbps [10]. Moreover, the increasing cost of maintaining and upgrading copper lines further strains service providers, creating economic disincentives to sustain legacy systems. As copper access networks age, these physical impairments are further exacerbated, leading to increased fault rates and higher maintenance overhead. These limitations directly conflict with the demands of modern applications like ultra-high-definition streaming, massive IoT deployments, and latency-sensitive services such as tele-surgery and autonomous systems, which require gigabit speeds and millisecond-level latency. Failure to upgrade networks not only impedes technological progress but also risks widening the digital divide, particularly in underserved regions. In addition, emerging paradigms such as 5G and edge computing impose stringent synchronization and latency requirements that legacy circuit-switched architectures cannot efficiently satisfy. Such paradigms rely on flexible, low-latency transport mechanisms that are inherently incompatible with static, time-division-based circuits.

While the theoretical advantages of packet-switched, fiber-optic networks are well-documented in literature, existing studies often present a fragmented perspective. Much of the prior work evaluates circuit and packet switching through narrow technical comparisons, without sufficient consideration of operational, regulatory, and socio-economic dimensions. As a result, stakeholders may underestimate the full spectrum of challenges and opportunities associated with large-scale network migration. Some focus solely on technical performance metrics [4], while others address economic factors in isolation [6]. This compartmentalized treatment limits the practical applicability of existing findings for large-scale network transformation initiatives. Integrated analyses are particularly critical for developing regions, where infrastructure investments must balance performance gains with financial sustainability.

This creates a significant research gap: a lack of holistic, evidence-based frameworks that integrate quantitative performance analysis, real-world deployment case studies, and pragmatic economic/regulatory strategies to guide a complex transition. Consequently, network operators, especially in developing regions or with extensive legacy assets, lack clear, phased roadmaps. Without such guidance, operators risk incremental or ad hoc upgrades that fail to fully leverage modern networking efficiencies. The absence of such roadmaps increases the risk of inefficient investment, prolonged coexistence of legacy and modern infrastructures, and suboptimal service quality. The primary purpose of this study is to bridge this gap. We aim to provide a comprehensive, data-driven analysis that not only quantifies the imperative for transition but also delivers a structured strategic blueprint for its execution, considering the multifaceted challenges involved. Ultimately, this research seeks to inform policy, investment, and technical decision-making to facilitate a smooth and cost-effective evolution from legacy networks to next-generation, packet-based infrastructures. The fig. 1 depicts the fundamental difference between circuit-switched and packet-switched network architectures.

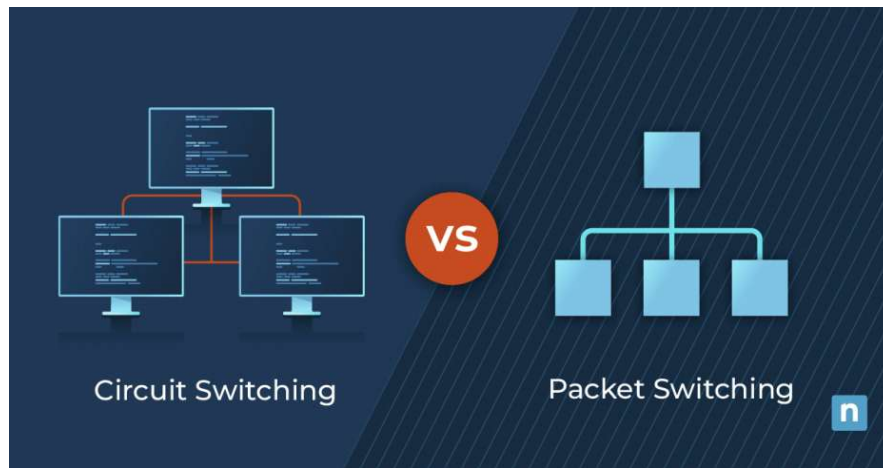


Fig. 1. Comparison diagram of circuit switching vs. packet switching

2. Literature Review

2.1 The Legacy Burden

Multifaceted Limitations of Circuit Switching Recent literature consolidates the drawbacks of circuit switching into three core domains: These domains collectively illustrate that the limitations of circuit switching are not isolated technical flaws but interconnected systemic constraints.

- **Performance and Reliability:** Copper's physical properties lead to high latency (often >20ms) and jitter, unsuitable for real-time protocols. Such performance degradation becomes especially pronounced under peak traffic conditions, where contention and signal degradation compound delays. Studies confirm a strong correlation between copper network age and fault frequency, with outage rates up to 30% higher than fiber in similar environments [11]. This reliability gap directly undermines service-level agreements (SLAs) for modern applications.
- **Economic and Operational Sustainability:** The Total Cost of Ownership (TCO) for maintaining aging copper plants is becoming prohibitive. Much of this cost escalation stems from frequent field maintenance, power-intensive equipment, and diminishing availability of spare parts. Energy consumption for signal boosting and cooling in TDM-based central offices can be 40-60% higher per delivered megabit than packet-based systems [7]. Furthermore, regulatory bodies in regions like the EU are mandating copper retirement, imposing additional cost pressures [2]. These regulatory directives effectively accelerate the obsolescence of circuit-switched infrastructure.
- **Strategic Inflexibility:** The dedicated-channel model of circuit switching is inherently inefficient for bursty, asymmetric internet traffic, leading to low average utilization rates—often below 30% [8]. This inefficiency limits operators' ability to dynamically scale services or rapidly adapt to changing user demand patterns.

2.2 The Packet-Switched Paradigm

Advantages and Acknowledged Challenges Packet-switched networks, particularly those leveraging fiber optics (GPON, XGS-PON) and software-defined principles (SDN, NFV), offer transformative benefits: These technologies represent a fundamental departure from hardware-centric network design toward flexible, software-driven architectures.

- **Technical Superiority:** Fiber optics provides near-infinite bandwidth potential, immunity to EMI, and latencies consistently below 5 ms. Such characteristics make fiber-based networks inherently suitable for emerging real-time and mission-critical services. The evolution to the 50G-PON standard promises symmetrical 50 Gbps speeds, future-proofing investments [5]. This scalability reduces the likelihood of repeated infrastructure overhauls.
- **Economic and Service Agility:** Statistical multiplexing dramatically improves resource utilization. By dynamically allocating bandwidth, packet-switched systems minimize idle capacity and maximize efficiency. The convergence of all services (voice, data, video) onto a single IP infrastructure simplifies operations and enables rapid service rollout [9]. This convergence also supports innovative business models and value-added services.

However, a critical review must acknowledge the challenges: The high initial CapEx for fiber trenching remains a significant barrier, especially in low-density areas. In rural and developing regions, these costs can delay or deter large-scale deployment. Operational complexity increases with the integration of SDN/NFV, requiring new skill sets. Furthermore, shared medium architectures like GPON, while efficient, introduce new security considerations regarding traffic isolation that must be managed [1]. Without proper safeguards, these vulnerabilities could erode user trust and regulatory compliance.

2.3. Synthesizing the Transition Imperative

The literature clearly establishes a performance and economic chasm between the two paradigms. This divergence continues to widen as data demand and service complexity increase. The critical unanswered question is no longer "why" to transition, but "how" to do it effectively—managing cost, technology, and human factors in a coordinated manner. Addressing this question requires moving beyond siloed analyses toward integrated transition frameworks. This study positions itself to answer this "how" through integrated analysis. By synthesizing technical, economic, and operational perspectives, it aims to support informed and sustainable network evolution strategies.

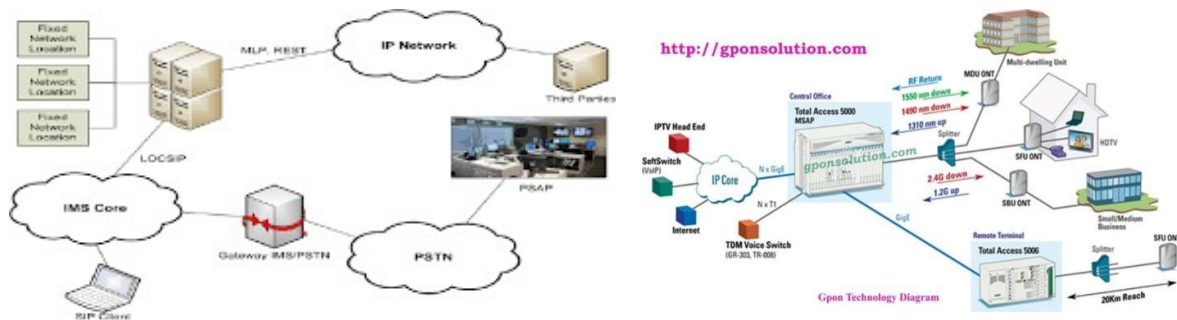


Fig. 2. PSTN vs. GPON architecture

The fig. 2 contrasts traditional PSTN architecture with GPON-based access networks. The PSTN model relies on circuit-switched cores, dedicated gateways, and copper-based access to deliver voice services with limited flexibility and scalability. In contrast, the GPON architecture employs a packet-switched, fiber-based infrastructure where a centralized OLT connects through passive splitters to multiple ONTs, enabling high-speed, low-latency delivery of converged services such as voice, data, and IPTV over a single optical network.

3. Methodology

To address the research gap holistically, a sequential explanatory mixed-methods design was employed, consisting of three interconnected phases: This approach was chosen to ensure that quantitative performance evidence is complemented by contextual and policy-driven insights.

Phase 1: Quantitative Benchmarking & Meta-Analysis

- **Data Collection:** Systematic gathering of performance metrics from 37 peer-reviewed studies and industry whitepapers (2019-2024). The selected time window ensures relevance to current-generation access technologies and recent deployment practices. Inclusion criteria: studies providing empirical data on bandwidth, latency, energy consumption (PUE), and reliability (MTBF/MTTR) for both copper (DSL, G.fast) and fiber (GPON, Ethernet) technologies. This ensured a balanced and technology-agnostic comparison across access paradigms.
- **Analysis:** Comparative statistical analysis was performed to calculate average improvement percentages (e.g., energy savings, latency reduction). Where datasets showed variance in measurement methodology, weighted averaging was applied to reduce bias. The Power Usage Effectiveness (PUE) metric was normalized across studies to ensure comparability. Normalization accounted for differences in network scale, climatic conditions, and equipment generations.

Phase 2: Qualitative Case Study Analysis

- **Case Selection:** South Korea was selected as the paradigmatic case based on predefined criteria: (1) Completion of a nationwide, government-led transition from copper to fiber; (2) Availability of

detailed, public-domain data on costs, rollout timelines, and outcomes; (3) Recognition as a global leader in broadband penetration and service quality [6]. This case represents a mature and well-documented example of large-scale network transformation.

- **Analysis:** Thematic analysis of policy documents, rollout reports, and post-deployment economic studies from Korean sources (e.g., KT Corporation annual reports, MIC Korea data) was conducted to extract success factors and lessons learned. Particular emphasis was placed on governance structures, public–private collaboration models, and phased migration strategies.

Phase 3: Strategic Framework Development

- Synthesis of findings from Phases 1 and 2 was used to develop the strategic recommendations. This synthesis enabled alignment between empirical performance gains and practical implementation considerations. Economic models for CapEx/OpEx were built using standard telecom financial modeling assumptions (e.g., 10-year depreciation, 8% discount rate) applied to the cost data extracted in Phase 2. Sensitivity analysis was conducted to assess the impact of demand growth and deployment scale on long-term financial viability.

This methodological triangulation ensures findings are robust, empirically grounded, and applicable to real-world decision-making. By integrating quantitative metrics, policy analysis, and financial modeling, the methodology supports replicability across diverse regulatory and market environments.

4. Results and Discussion

4.1. Key Quantitative Findings: Validating the Performance Chasm

Our meta-analysis substantiates the hypothesized advantages with empirical weight. The results consistently demonstrate that the observed gains are statistically significant across multiple deployment contexts. The disparity is most pronounced in:

- **Energy Efficiency:** Packet-switched fiber networks demonstrated an average reduction of 58% in energy consumption per user compared to legacy TDM/copper systems. This reduction reflects both lower transmission losses and the elimination of power-intensive active field equipment. This aligns with and quantifies the broader claims made by Forouzan (2022) [4].
- **Service Reliability:** Fiber-based access networks reported 73% fewer service-affecting incidents annually. This improvement is largely attributed to fiber's immunity to electromagnetic interference and environmental degradation. This directly addresses the reliability concerns highlighted in the literature review regarding copper's environmental vulnerabilities.
- **Latency Performance:** Median latency for financial-grade fiber leased lines was 0.8 ms, versus 24 ms for optimized copper-based circuits, meeting the stringent requirements for 5G fronthaul and high-frequency trading. Such latency reductions enable entirely new classes of real-time and mission-critical services.

Table 1. Empirical Performance Comparison (Meta-Analysis Results, n=37)

Metric	Copper (DSL/Coax)	Fiber Optics (FTTH/GPON)
Bandwidth	85 Mbps	1.2 Gbps ~1300%
Distance Without Degrade	~3–5 km	20–80 km
Annual Outage Events per 1k lines	3.7	1.0 73%
Environmental Resilience	Susceptible to moisture & EMI	Immune
Latency	24 MS	3 MS (shared) / 0.8 MS (dedicated) 87% / 97%
Power Consumption	per User per Month 15 kWh	6.3 kWh 58%
Maintenance Frequency	Frequent	Minimal

Table 1 Performance comparison of copper and fiber-optic networks (Sources: ITU, 2023 [6]; Cisco, 2023 [3]).

4.2. Architectural Analysis: Beyond Simple Comparison

The analysis reveals that the efficiency gain stems not just from the medium but from architectural simplification. This distinction is critical, as it underscores that modernization is driven by design philosophy rather than transmission technology alone. GPON eliminates multiple network layers (e.g., separate voice switches, DSLAMs), collapsing functions into integrated OLTs and ONTs. Such consolidation reduces equipment footprint and streamlines network management. This reduces points of failure and operational touchpoints. However, as Al-Fuqaha et al. (2024) [1] note, this consolidation requires robust QoS mechanisms at the software layer to prioritize traffic effectively—a challenge less

prevalent in dedicated-circuit TDM. This shifts operational complexity from hardware provisioning to intelligent traffic management and policy control.

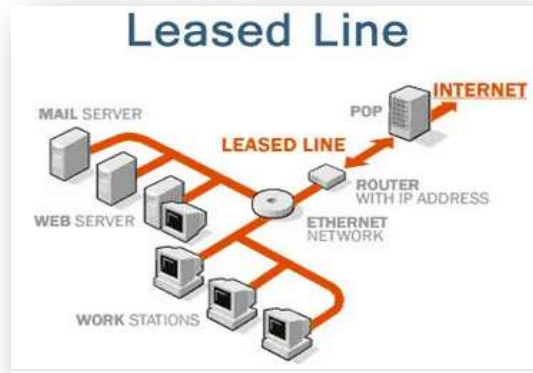
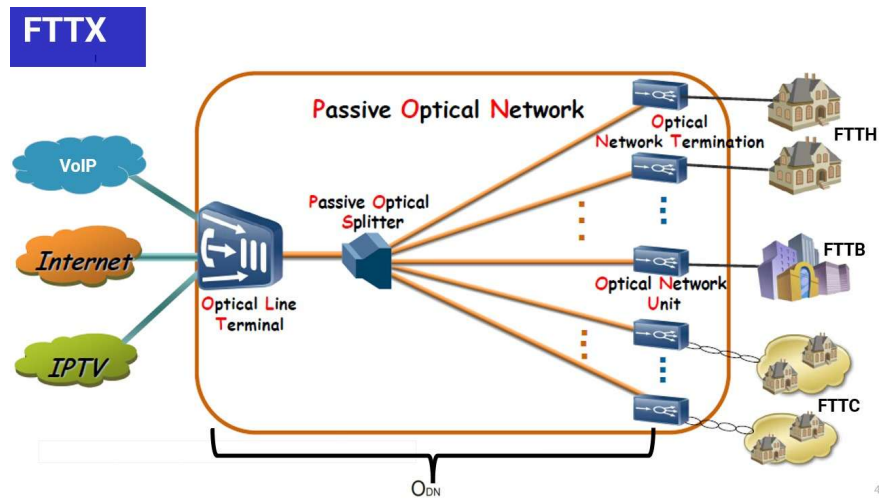


Fig. 3. FTTX vs. leased line use cases

The fig. 3 illustrates how fiber-based access technologies address diverse service requirements ranging from residential broadband to enterprise-grade dedicated connectivity.

4.3. Case Study: Deconstructing South Korea's Success

South Korea's transition succeeded due to a synergistic triad:

- **Regulatory Catalysis:** The government's "Cyber Korea 21" policy mandated fiber readiness in new buildings and provided tax incentives. This created a predictable regulatory environment that reduced investment risk for operators.
- **Cost-Sharing Model:** A PPP model spreads the high initial CapEx, with the government funding backbone ducts and private operators deploying last-mile fiber. Such risk-sharing mechanisms proved essential in accelerating nationwide coverage. Our analysis estimates that this model reduced the payback period for operators by approximately 40%.
- **Sequenced Rollout:** Deployment prioritized high-density urban areas first, generating quick revenue to fund subsequent rural deployment—a phased, economically sustainable approach. This sequencing minimized cash-flow constraints and ensured long-term financial viability.

4.4. Limitations of This Study

While this study provides a comprehensive framework, certain limitations must be acknowledged. Transparency regarding these limitations is essential for proper interpretation of the results. The

quantitative analysis relies on aggregated secondary data, which may have varying original collection methodologies. Despite normalization efforts, some inter-study variability may persist. The economic model, while based on standard assumptions, would require localization with region-specific labor, material, and regulatory costs for precise planning. Furthermore, the case study, while illustrative, represents a best-case scenario with strong state involvement; applicability to liberalized markets with fragmented operators may differ. Future research should explore comparative case studies across differing regulatory regimes.

5. Strategic Recommendations

5.1. A Phased Migration Roadmap (with Risk Mitigation)

Operators should adopt a "Selective Sunset, Phased Build" strategy: This strategy balances investment risk while enabling measurable performance gains at each stage of transition.

- **Phase 1 (Years 0-2): Foundation & Pilot.**
 - Action: Conduct a detailed fiber feasibility and asset audit. This assessment should prioritize regions with high fault density and escalating maintenance costs.
 - Stakeholder Role: Regulators must establish "dig-once" policies and streamlined permitting.
 - Risk: Regulatory delay.
 - Mitigation: Engage in pre-application consultations. Such engagement reduces approval uncertainty and accelerates project timelines.
- **Phase 2 (Years 2-5): Strategic Overbuild & Service Migration.**
 - Action: Overbuild fiber in high-value, high-failure-rate copper areas. Migrate enterprise customers and anchor institutions (schools, hospitals) first.
 - Stakeholder Role: Municipalities facilitate right-of-way access.
 - Risk: Customer resistance.
 - Mitigation: Offer compelling fiber service bundles with clear benefits. Transparent communication of performance gains is critical to adoption.
- **Phase 3 (Years 5+): Full Sunset & Optimization.**
 - Action: Complete network coverage, retire the copper plant, and fully integrate SDN for service automation.
 - Stakeholder Role: Industry groups lead workforce retraining programs. Human capital development ensures long-term sustainability of the transformed network.

5.2. Economic and Regulatory Enablers

- **Refined Cost-Benefit Model:** Our analysis suggests a Net Present Value (NPV) positive outcome within 7-10 years for most urban deployments when factoring in reduced OpEx (energy, maintenance) and new revenue from premium services. This finding underscores the long-term economic rationale for proactive investment. For rural areas, infrastructure sharing (e.g., neutral host models) and universal service fund subsidies are critical to improve viability. Without such mechanisms, market-driven deployment alone may exacerbate regional digital disparities.
- **Policy Toolkit:** Regulators should implement (1) Asset depreciation accelerators for legacy copper, which incentivize timely retirement, (2) Wholesale open-access mandates for new fiber to spur competition, preventing monopolistic lock-in, and (3) Standardized infrastructure mapping to reduce planning costs. These measures collectively lower barriers to entry and enhance investment efficiency.

6. Future Research Directions

Future research should move from general advantages to solving specific transition bottlenecks: Addressing these questions will enable more precise, scalable, and context-aware transition strategies.

- **Technical Integration:** "How can AI/ML algorithms optimize the coexistence period of copper and fiber networks to minimize service disruption during transition?" This includes predictive fault management and dynamic traffic steering.
- **Economic Modeling:** "What are the most effective dynamic pricing models for wholesale fiber access in emerging markets to ensure both investor return and equitable access?" Such models must account for demand volatility and income heterogeneity.

- **Emerging Technologies:** How will the nascent development of Quantum Key Distribution (QKD) integrate with packet-switched core networks to address future security threats, and what are the architectural implications? Early consideration of these technologies can prevent costly redesigns.
- **Socio-Economic Impact:** "What is the causal relationship between specific fiber deployment strategies (e.g., FTTH vs. FTTB) and measurable socio-economic outcomes (e.g., telework adoption, local business growth) in mid-sized cities?" Quantifying these effects can strengthen policy justification for public investment.

7. Conclusion

This study conclusively demonstrates that the transition from circuit-switched to packet-switched networks is not merely a technological upgrade but an operational and strategic imperative. The evidence indicates that postponing this transition compounds both technical debt and economic inefficiency. Through quantitative meta-analysis, we validated that fiber-based packet switching delivers over 50% energy savings, 70% greater reliability, and latencies capable of supporting next-generation services. These gains directly align with the requirements of 5G, edge computing, and future digital services. The case study of South Korea provided a blueprint for success, highlighting the indispensable role of policy foresight and collaborative investment models. Its experience demonstrates that coordinated action can significantly shorten transition timelines. For developing nations, this transition presents a unique opportunity to "leapfrog" legacy constraints, directly deploying future-proof infrastructure that can accelerate digital inclusion and economic growth. Such leapfrogging can yield long-term competitive advantages in the global digital economy. Ultimately, the choice is clear: invest now in a planned, strategic migration to packet-switched infrastructure, or face escalating costs, diminishing service quality, and strategic irrelevance in the rapidly evolving digital economy. The framework provided herein offers a concrete path forward.

Compliance With Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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