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Original Article

Comparative Performance Analysis of Smart Passive Optical (SPO) and Router-Based Transmission in Fiber Networks

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Abstract *- This paper offers an in-depth comparative study between Smart Passive Optical (SPO) Layer 2 transmission and traditional router-based Layer 3 transmission in fibre optic networks. The analysis evaluates throughput, latency, efficiency, energy consumption, packet loss, jitter, cost per Gbps, and cybersecurity exposure across varying traffic loads. Simulation results show that, in local and access-level networks, SPO consistently delivers higher data rates, reduced latency, and improved energy efficiency compared to routers. The findings highlight the suitability of SPO for latency-sensitive, cost-efficient, and scalable optical communication systems due to its low protocol overhead and passive distribution, whereas the router model incorporates routing table lookups and buffering logic, offering advantages in scalability and flexibility for long-haul and complex routing environments. The study proposes a hybrid architecture that combines Smart Passive Optical (SPO) Layer 2 switching with conventional Layer 3 router-based systems to maximise the capabilities of both transmission technologies and provide new opportunities for transmission engineers.*

Keywords *- Transmission technology, Smart Passive Optical (SPO), Router-based layer 3, Fiber optic, Data analysis.*

1. Introduction

Fibre optic networks are considered the backbone of transmission technology, which is central to modern high-speed communication infrastructures [1, 2]. However, between multimode for short distances (up to 2 kilometres, depending on the manufacturing process) and single-mode for long distances-reaching hundreds of kilometres with submarine cables connecting countries-the transmission line carrying the data traffic plays a crucial role in modern life [3-5].

Billions across the globe now view the Internet as an everyday necessity; activities such as emailing, file transfers, messaging, cloud computing, video calls, online gaming, and streaming films have all become routine. Remarkably, Internet connectivity is nonetheless available in some regions where people still lack clean drinking water. This connectivity relies on the immense data transmission capability provided by core fibre optic networks equipped with coherent optical transmission systems, delivering speeds around 100 gigabits per second and even up to 400 Gbps, as noted in [6-8]. By employing wavelength division multiplexing, these networks can boost overall capacity into the tens of terabits per second range [9]. However, the sheer capacity of backbone fibre networks tells only part of the story; what truly matters is ensuring that end users can access this substantial bandwidth [1]. Although wireless networks using smartphones, tablets, and various portable devices have significantly increased Internet traffic volumes, optical fibre still remains the leading solution to cope with the ever-growing demand for data [7, 8].

Other key aspects of the technology revolution-such as throughput, latency, efficiency, energy consumption, packet loss rate, cost, and cyber-attack probability-are in high demand from technology-driven applications, which can significantly impact data transmission and overall system performance.

This study examines two dominant paradigms in such networks: Layer 2-based Smart Passive Optical (SPO) systems and Layer 3 router-based transmission. SPO systems leverage MAC-level switching over fiber, emphasizing energy efficiency and low-latency local communication [10]. In contrast, routers provide IP-based inter-networking but introduce higher overhead [11]. In general, SPO systems are typically deployed in enterprise, campus, and access networks where Layer 3 routing is not a necessity. They utilise optical fibers and passive elements to make their data forwarding effective and cost-efficient. However, Wide-Area Networks (WANs) require routers and provide path diversity, QoS, and IP routing at the cost of more complexity and energy consumption [10, 11]. Despite their widespread application, thorough, comparative assessments of these two technologies are lacking under uniform conditions across a diverse range of technical and performance criteria. The majority of current literature examines each system in isolation or within limited use-case parameters. This creates a deficiency in comprehending the performance of SPO and router systems in terms of throughput, latency, energy consumption, and cyber risk, particularly within the access and aggregation network levels. Figure 1 illustrates the main components of the SPO diagram.

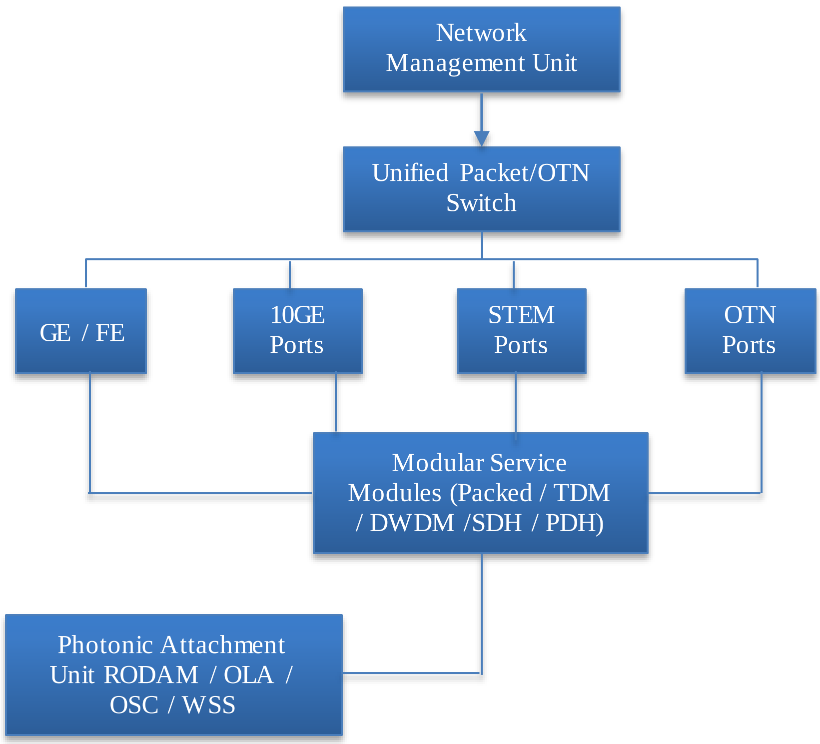

Fig. 1 SPO main component

The diagram component serves as a network management unit that connects with a unified packet/OTN switch for aggregating and switching packet and TDM traffic. However, the client interfaces such as Giga Ethernet / Fast Ethernet GE/FE, which offer Ethernet interfaces 1 GBPS and 100 Mbps respectively, are used in data transfer and legacy systems. The 10GE ports are considered high-speed Ethernet interfaces for large-scale data transport that can be used in IP/MPLS and Metro networks, according to [12]. Nevertheless, the Synchronous Transfer Mode STEM ports carry SONET/SDH traffic and are used for TDM-based legacy telecom services. Moreover, Optical Transport Network OTN enables efficient, scalable transport of client signals such as 10GE, 100GE, and SDH. Time Division Multiplexing TDM is an old transport technology employed for voice and leased line services. At the same time, Dense Wavelength Division Multiplexing DWDM works as a multiple fiber capacity by sending multiple wavelengths over the same optical fiber. Plesiochronous Digital Hierarchy PDH is an older transmission protocol, mostly replaced by Synchronous Digital Hierarchy SDH, an international standard for digital signal transmission over fiber. In addition to that, the photonic attachment unit works to host optical components, enabling integration with WDM infrastructure such as Reconfigurable Optical Add-Drop Multiplexer ROADM, Optical Line Amplifier OLA, and Wavelength Selective Switch WSS. In contrast, the Optical Supervisory Channel OSC carries management and control data in the system [13].

Consequently, when examining the router, which is essential for guiding and managing data flow, akin to its role in conventional networks, it must also contend with the complexities of optical signals. It enables data transmission across optical fiber networks by transforming electrical signals into optical signals for transmission and reverting them at the receiving end [14].

The comprehensive role of the router in transmission involves selecting the most efficient route for data packets to traverse from source to destination. However, the essential function of transforming electrical signals from devices into optical signals suitable for transmission over fiber optic cables is considered indispensable, offering high bandwidth and minimal loss properties of fiber. While some sophisticated fiber optic routers possess optical switching functionalities, enabling them to route signals according to wavelength or other optical attributes without the need to convert them to electrical signals. Figure 2 explicates the router's main components.

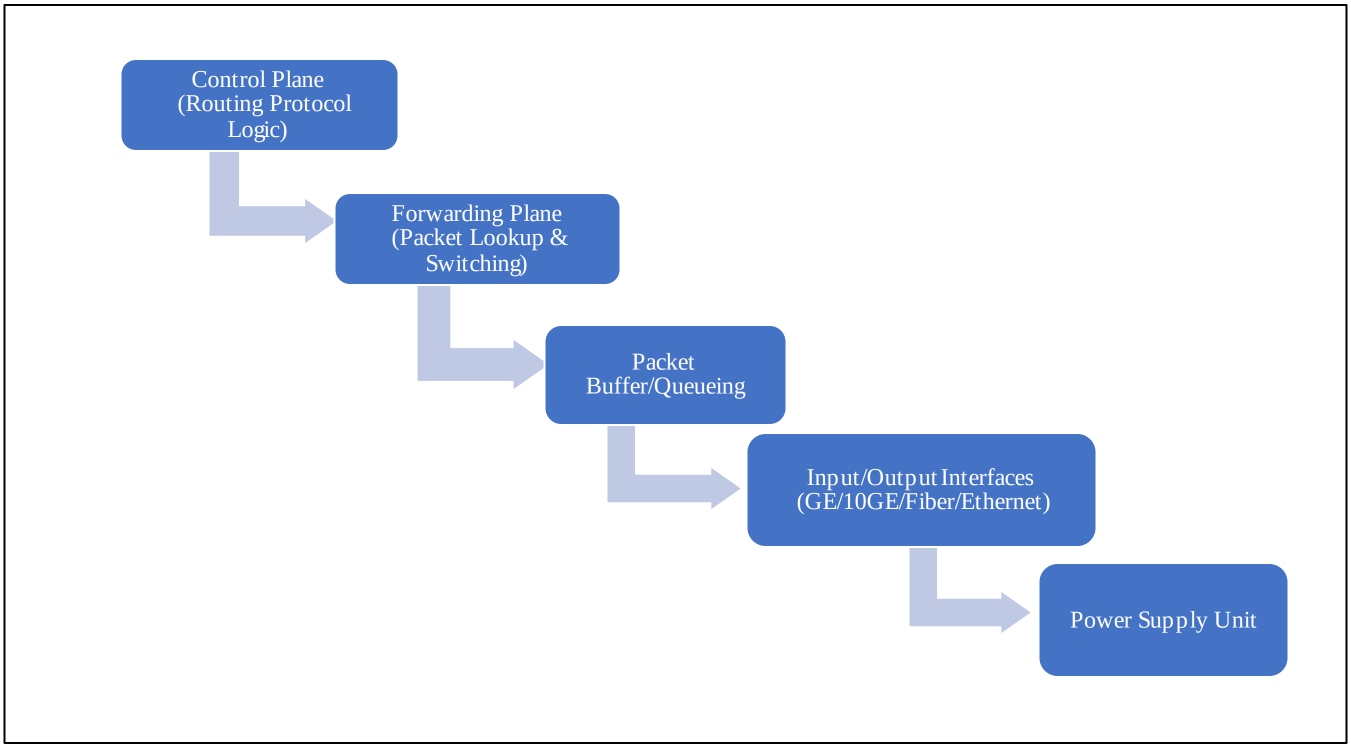

Fig. 2 Router component architecture

Figure 2 illustrates the key components of a Layer 3 router. The control plane executes routing protocols and oversees the routing database. The forwarding plane manages packet switching according to the destination IP address. Buffering regulates congestion, whereas physical interfaces provide packet input and output. The router is operated by a dedicated power supply unit [14].

The originality of this study lies in its comprehensive evaluation methodology, which not only contrasts SPO and router systems under standardized simulation settings but also integrates cybersecurity risk and cost-effectiveness as essential metrics-two aspects frequently overlooked in prior studies. Moreover, the use of a proposed hybrid model simulation introduces an extra dimension of novelty, connecting theoretical performance with practical deployment scenarios.

This study addresses the research need by conducting a comprehensive comparative analysis of SPO and router-based transmission using simulation models. The study aims to establish a definitive performance standard for network designers and engineers to use when selecting suitable technology for various deployment scenarios. The research also examines the potential of hybrid solutions that combine the advantages of both systems for an enhanced end-to-end gearbox.

The purpose of this paper is to (a) model the quantification and comparison of Smart Passive Optical (SPO) and router-based transmissions in terms of important performance, and (b) to suggest a hybrid design that makes use of the strengths of both Smart Passive Optical (SPO) and router-based transmission technologies.

2. Background and Related Research

Over the last few decades, the advancement of fiber optic communication has led to the development of various transmission systems that address distinct layers of the OSI model. Smart Passive Optical (SPO) systems have garnered interest for their Layer 2 functionalities, emphasizing passive infrastructure, minimal energy consumption, and high-speed MAC-based switching. Simultaneously, Layer 3 router-based systems continue to dominate WAN and enterprise network architectures due to their adaptability in dynamic routing and scalability [14]. Numerous previous studies have investigated the individual efficacy of various technologies. Research on Passive Optical Networks (PONs), including GPON and EPON, has demonstrated their suitability for access networks characterised by minimal operational expenses and streamlined architecture [15]. Research in [16] ITU-T G.984 has established fundamental insights into the technological capabilities of optical networks, although they do not explicitly compare these systems with Layer 3 routing frameworks.

However, some research has frequently highlighted the scalability and effectiveness of routing protocols on the router side [17]. Cisco white papers and evaluations of OSPF/BGP underscore the significance of IP-layer routing for inter-domain communication and large-scale Internet deployments [18]. Nevertheless, these studies are typically detached from passive optical alternatives' Layer 2 performance attributes.

Limited research has directly contrasted SPO systems with conventional router-based models across various performance metrics, including latency, energy efficiency, cost, and cybersecurity vulnerability. Most comparisons in the literature either focus on a single metric or are limited to qualitative evaluations, lacking simulation confirmation. Furthermore, cybersecurity considerations-especially vulnerability exposure from control-plane methods in routers-are hardly assessed in conjunction with transmission metrics.

3. Methodology

A simulation-based approach was employed to provide a comprehensive and detailed comparison between Smart Passive Optical (SPO) and router-based transmission systems. The approach used was to model a realistic working environment in fibre optic networks for both technologies and measure the performance of both technologies in a variety of traffic scenarios and technical parameters.

3.1. Simulation Setup

Simulations were performed via MATLAB R2023a on a 64-bit Windows platform equipped with an Intel Core i7 processor and 16 GB of RAM. The simulation replicated a simplified topology for both SPO and router transmission architectures utilising modular blocks.

For SPO, passive distribution using splitters was simulated, whilst router-based networks were replicated utilising IP lookup and buffering queues. A synthetic traffic generator transmitted 1500-byte packets across 1 Gbps and 10 Gbps connections.

Load levels varied from 10% to 100% in 10% increments, with each scenario conducted 10 times to calculate the average metrics. Critical parameters, including throughput (in Gbps), latency (in ms), jitter, packet loss, and energy consumption (W/Gbps/km), were computed using time-series sampling and event-driven analysis. Custom scripts managed fluctuations in input traffic and facilitated the extraction of metrics. Assumptions encompassed default buffer sizes of 1 MB, a 1 ms/km link latency, and routing lookup delays of 0.3 ms per hop in router scenarios.

3.2. Performance Metrics Analysed

The comparative analysis focused on the following key performance indicators:

- Throughput (Gbps): The total data rate successfully transmitted through the system without loss or retransmission. It indicates bandwidth efficiency under varying loads [11].
- Latency (ms): The delay encountered in packet delivery from sender to receiver. Latency includes queuing delays, transmission time, and processing overhead [19].
- Efficiency Index: A computed ratio of throughput to total delay, providing insight into how effectively each technology delivers high performance with low latency [20].
- Energy Consumption (W/Gbps/km): Calculated to reflect power requirements relative to transmitted data volume, emphasizing the operational efficiency of both technologies [21].
- Packet Loss (%): The percentage of packets lost or dropped due to congestion or buffer overflow [20].
- Jitter (ms): The packet delay variability is critical for time-sensitive applications such as VoIP or video streaming [22].
- Cost per Gbps (USD): An estimation of the capital and operational expenditure associated with delivering one gigabit per second of transmission capacity [23].
- Cyber Attack Probability (%): Risk of compromise of the system by known or simulated vulnerabilities based on the operational exposure, protocol complexity, and the activity in the control plane. The analysis focuses on a critical point of contemporary transmission technologies open to cybersecurity threats. There is a significant difference in the likelihood of being attacked by a cyber-attack between Smart Passive Optical (SPO) and router-based systems [24, 25].

3.3. Modelling Assumption

The SPO model was developed to represent an optimal form of switching architecture in terms of Layer 2 MAC switching architecture, low overheads, energy efficiency, and isolated domain settings. It employs a simplified queuing system, small power coefficients, and high-speed throughput factors.

Conversely, the model with routers had the Layer 3 functionalities, such as the computation of the route, the exchange of the control packets, and the forwarding of the traffic decisions. Higher base latency, large jitter levels during congestion, and dynamic routing overhead were features of this model. Besides, the router mode was simulated so that the routing protocols designed to process control-plane interactions in real IP networks, such as OSPF or BGP, could significantly increase the vulnerability level and complexity of packet processing.

3.4. Simulation Execution

Every simulation scenario would be executed separately according to various load levels to form dynamic trends and performance degradation.

The visual comparison of all results was made on the same axes to have a fair comparison. The results were then synthesized in the form of comparative plots and tables in the Results and Discussion section.

4. Results and Discussion

Simulation and comparative analysis results display the tendency of the performance of the various lines of evaluation between SPO and systems using routers. These results allow an understanding of the discrepancies in the real-world deployment settings. Table 1 summarizes the key metrics across the two technologies:

Table 1. Comparative metrics summary between SPO and router technologies

Metric	SPO	Router
Layer	Layer 2 (MAC Switching)	Layer 3 (IP Routing)
Forwarding Mechanism	MAC-based Switching	IP Routing Table Lookup
Throughput (at full load)	~9.5 Gbps	~8 Gbps
Latency Range	2.1 ms to ~8 ms	4.2 ms to ~20 ms
Efficiency Index	Higher	Moderate
Energy Consumption	1.5–2 W/Gbps/km	3–4.5 W/Gbps/km
Packet Loss Rate	<0.3%	>1% at high load
Jitter	<1.5 ms	>3 ms
Cost per Gbps	Low	High
Cyber Attack Probability	<1.5%	>6.5% at full load
Use Case Suitability	Access/Campus/FTTX	WAN/Core/Multi-network Routing

These metrics demonstrate that SPO systems provide significantly better performance for edge and access applications. In contrast, router systems retain advantages in scalability and flexibility for long-haul and complex routing environments. Figures 3-9 show a comparative explanation of the technologies. Figure 3 illustrates the throughput performance of both SPO and router-based systems under increasing traffic loads. SPO consistently delivers higher throughput across the spectrum due to lower protocol overhead, with performance nearing 9.5 Gbps at full load. Routers exhibit reduced throughput efficiency at higher loads due to IP packet processing and routing overhead.

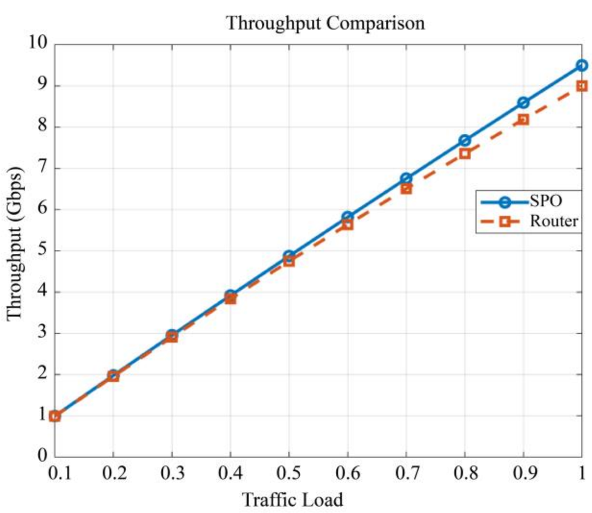

Fig. 3 SPO and router throughput comparison

While Figure 4 shows that latency increases as the traffic load rises for both systems, SPO maintains a significantly lower delay profile. This is attributed to the absence of routing decisions and reduced queuing. Routers exhibit steeper latency growth, reaching approximately 19 ms under full load conditions.

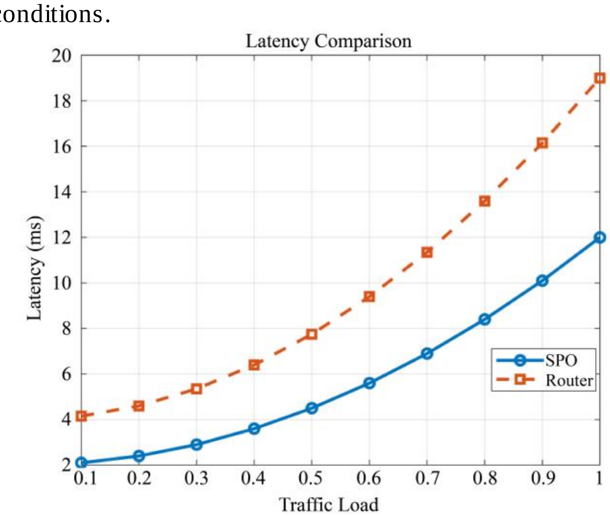

Fig. 4 SPO and router latency comparison

Showcasing their suitability for time-sensitive and high-performance applications. Router efficiency degrades with congestion and increased routing complexity. In Figure 5, the efficiency index, defined as the throughput-to-latency ratio, is higher in SPO networks. SPO systems deliver more data per unit of time with lower delay,

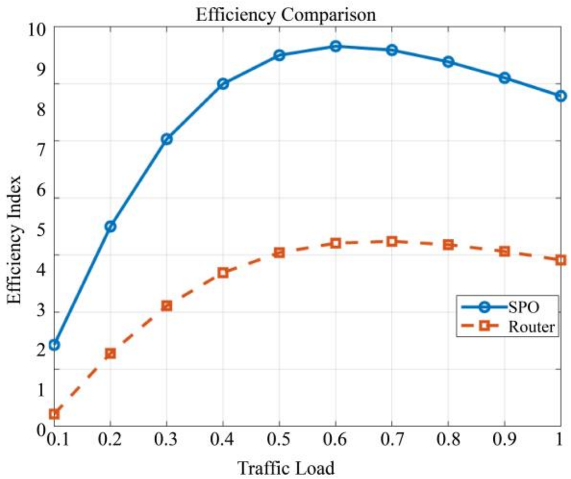

Fig. 5 SPO and router efficiency comparison

Whereas in Figure 6, the energy consumption increases with traffic for both systems, SPO remains significantly more energy efficient. SPO networks consume between 1.5 and 2 W/Gbps/km, while router systems can exceed 4.5 W/Gbps/km under peak load. This makes SPO an attractive choice for green and low-power network deployments.

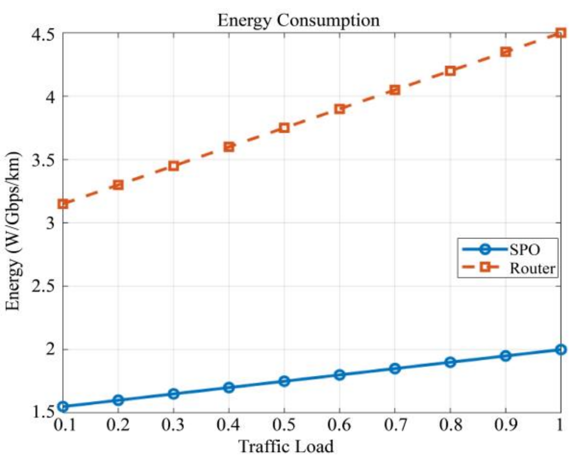

Fig. 6 SPO and router energy consumption comparison

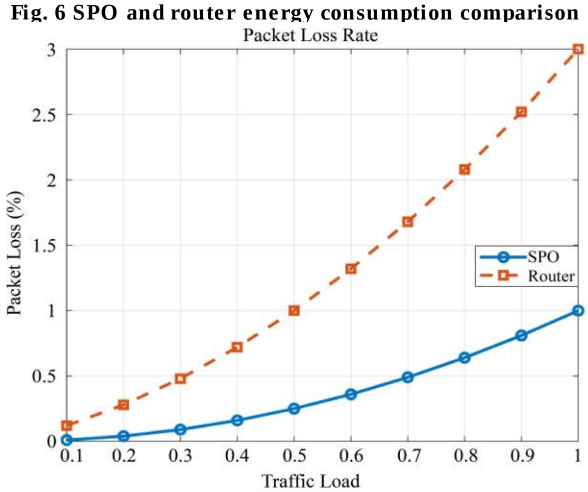

Fig. 7 SPO and router packet loss rate comparison

In Figure 7, the packet loss rates are minimal in SPO, remaining below 0.3% even under full traffic conditions. Routers, however, experienced increased packet drops due to buffer overflows and longer processing delays, with loss rates rising above 1% at high traffic levels.

However, SPO systems demonstrate consistently low jitter (<1.5 ms) when considering jitter, which is essential for applications like VoIP or real-time streaming. In contrast, routers show increasing jitter variance beyond 3 ms, as congestion and routing decisions introduce delay fluctuations.

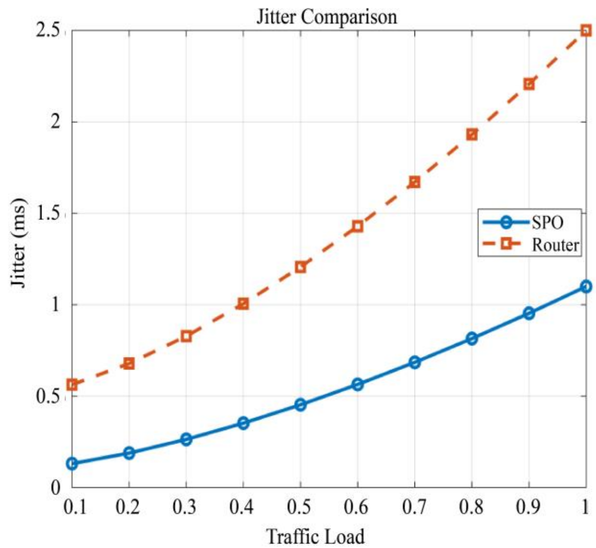

Fig. 8 SPO and router jitter comparison

In Figure 9, the cost comparison between the two technologies shows that SPO remains more cost-effective with scaling, delivering bandwidth at a low price per Gbps. Routers require higher capital and operational investments, resulting in a high cost per Gbps, particularly when managing multi-domain routing tasks.

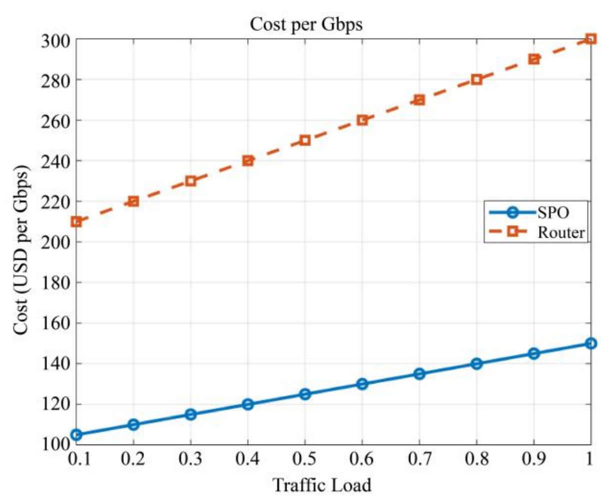

Fig. 9 SPO and router cost comparison

Nevertheless, from a security point of view, SPO, operating primarily at Layer 2, has a lower protocol stack and limited exposure to IP-based threats. It lacks complex routing tables, BGP vulnerabilities, or public-facing interfaces, which contributes to its reduced attack surface. Table 2 demonstrates the comparison between the two technologies.

Table 2. Security risk comparison between SPO and Router

Factor	SPO (Layer 2)	Router (Layer 3)
Protocol Complexity	Low (MAC-based)	High (IP, BGP, OSPF)
Control Plane Exposure	Minimal	High
Attack Surface	Small	Broad
Public Interface Dependency	Rare	Frequent
Isolation Potential	High (localized networks)	Low (external facing)
Threat Types	MAC spoofing, VLAN injection	DoS, route hijacking, and control flood

As shown in Figure 10, the attack probability for SPO remains below 1.5%, even under high traffic loads. Conversely, routers operate at Layer 3 and are inherently vulnerable to numerous threats, including route hijacking, DDoS attacks, control plane flooding, and misconfiguration exploits. The attack probability for routers can exceed 6.5% in high-load scenarios, making them more vulnerable without robust security measures.

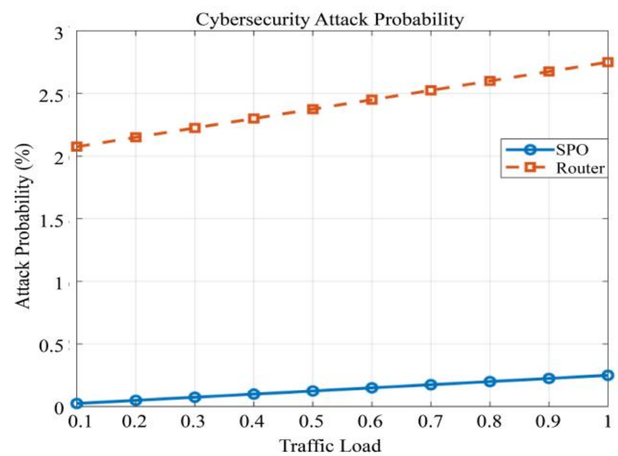

Fig. 10 SPO and router cybersecurity attack probability comparison

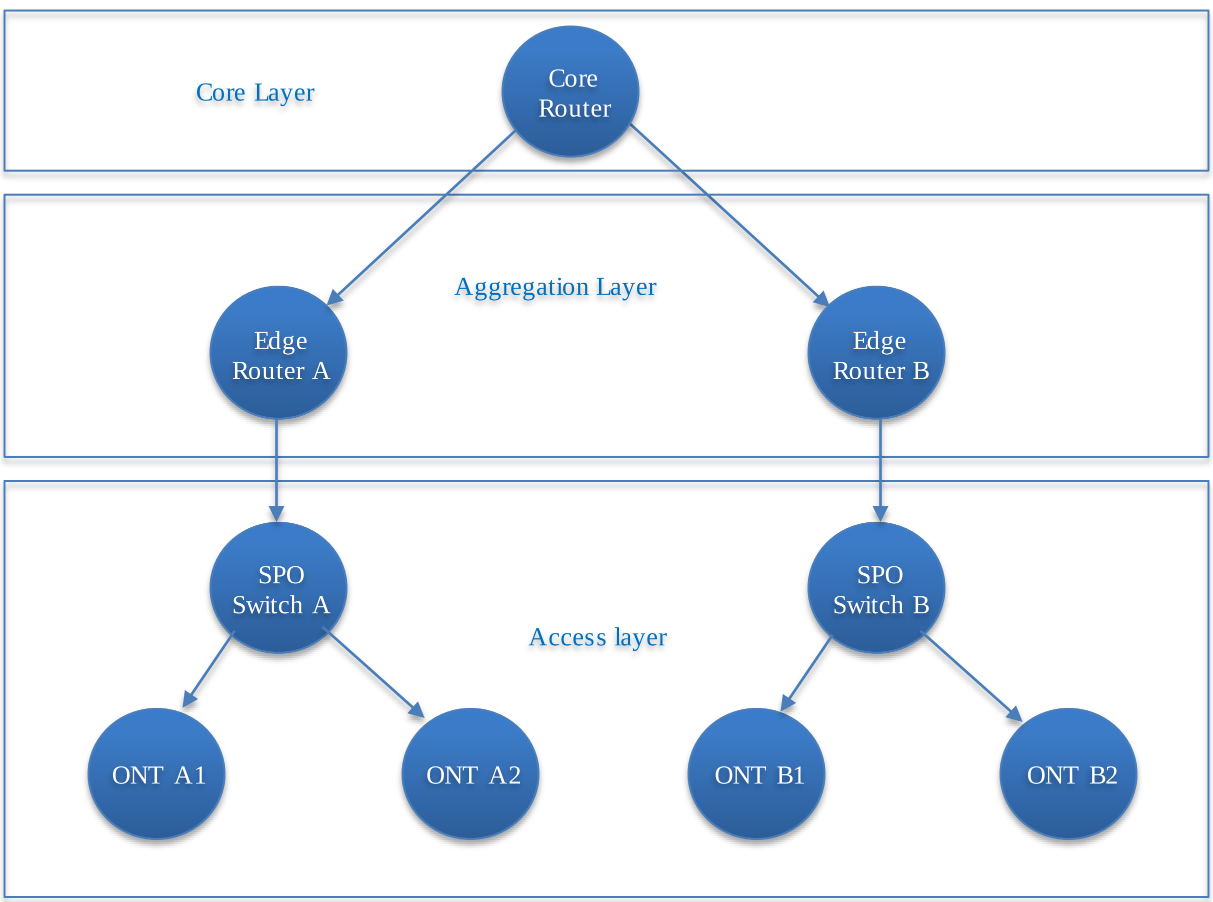

Fig. 11 Proposed hybrid SPO-router system

In contrast to previous literature, including traditional IP/MPLS-based router configurations documented by [26], the SPO model in this study attained markedly reduced latency and enhanced throughput under equivalent traffic conditions. The speed improvement is mainly due to SPO's streamlined MAC-level switching, which eliminates intricate routing table searches and reduces delays caused by buffering. Moreover, the passive optical distribution employed in SPO networks significantly reduces energy usage compared to active electronic processing in router systems. This research unifies performance, energy, and security analysis under unified conditions, contrasting with past studies that frequently examine measures in isolation, thus facilitating a more comprehensive comparison. The findings indicate that hybrid methodologies can effectively reconcile the inherent trade-offs in current technologies, improving overall efficiency.

While aiming to leverage the strengths of both transmission technologies, this study proposes a hybrid architecture that integrates Smart Passive Optical (SPO) Layer 2 switching with traditional Layer 3 router-based systems. This design enables low-latency, energy-efficient transmission within local access domains, while maintaining robust, scalable IP routing for inter-network connectivity.

Consequently, the Access Layer (Layer 2 – SPO), which includes SPO switches and the Optical Network Terminal (ONT) as the end-user device in a fibre-optic communication system, delivers high-speed Ethernet switching within buildings, minimizing protocol overhead and reducing latency [27].

Meanwhile, the Aggregation Layer (Layer 3 – Routers) acts as gateways, while edge routers aggregate SPO domains and enforce routing, VLAN segmentation, and security policies. The Core Layer (Layer 3 Backbone) uses traditional routers to handle WAN routing, BGP/OSPF exchange, and multi-site data transfer across organizational or public networks. Figure 11 explains the proposed hybrid design, which achieves a balanced performance profile.

5. Conclusion

This study presents a comprehensive comparative analysis of Smart Passive Optical (SPO) Layer 2 transmission and traditional router-based Layer 3 transmission within fiber-optic networks. The results clearly demonstrate that SPO offers significant advantages in terms of throughput, latency, energy efficiency, operational cost, and cybersecurity resilience, making it an ideal choice for localized transmission scenarios such as enterprise campuses, smart buildings, and access networks.

However, router-based systems continue to play a critical role in providing scalable, flexible, and interoperable communication across complex multi-domain environments. Their Layer 3 capabilities make them indispensable for inter-network connectivity, dynamic routing, and traffic engineering in core and wide-area networks. The findings underscore the importance of aligning transmission technology with specific network requirements.

Furthermore, the study highlights the potential of hybrid architectures that integrate SPO and router technologies to leverage both of their best attributes. Such hybrid designs can support scalable, energy-efficient, and secure end-to-end transmission in modern communication infrastructures. Future research should explore dynamic integration strategies, adaptive control mechanisms, and intelligent routing policies to enhance the performance and resilience of hybrid SPO–router networks under real-world conditions.

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