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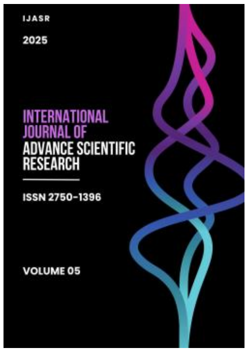

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Research Article

Enhancing Ultra-Dense Connectivity in IMDD Pons With P2MP Flexible Optical Transceivers for Concurrent Upstream and Direct Inter-ONU Communication

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Abstract

Background: The imminent arrival of 6G networks necessitates a fundamental redesign of optical access networks to support unprecedented connection density, ultra-low latency, and extreme bandwidth. Conventional Passive Optical Networks (PONs), while successful for fiber-to-the-home, face significant architectural limitations in meeting these demands. Enabling direct, low-latency communication between Optical Network Units (ONUs) is a critical step, but existing methods often introduce complexity and cost. This article investigates a novel approach using Point-to-Multi-Point (P2MP) flexible optical transceivers within an Intensity Modulation and Direct Detection (IMDD) PON to address this challenge.

Methods: We propose and model a PON architecture where ONUs are equipped with advanced P2MP transceivers. This setup facilitates not only traditional upstream communication to the Optical Line Terminal (OLT) but also direct, concurrent inter-ONU data exchange. The operational principles are based on dynamic subcarrier allocation and sophisticated digital signal processing (DSP) for interference management. We developed a comprehensive simulation framework to evaluate the system's performance under ultra-dense traffic scenarios, analyzing key metrics including Bit Error Rate (BER), network throughput, latency, and, most critically, the maximum number of simultaneous connections the network can provision.

Results: The simulation results demonstrate that the proposed architecture successfully supports simultaneous upstream and high-speed inter-ONU traffic with negligible performance degradation. Compared to traditional PONs, our system exhibits a significant enhancement in connection provisioning capability, effectively handling a much denser user environment. For peer-to-peer traffic, the direct ONU-to-ONU path yields a substantial reduction in latency by eliminating the round-trip delay to the OLT.

Conclusion: The integration of P2MP flexible optical transceivers provides a powerful and efficient solution for enhancing the capacity and flexibility of IMDD PONs. This architecture is a promising candidate for future-proof optical access networks, capable of supporting the demanding connectivity requirements of 6G and beyond.

Keywords

Passive Optical Network (PON), 6G, Inter-ONU Communication, P2MP Transceiver, Ultra-Dense Connectivity, Low Latency, Intensity Modulation and Direct Detection (IMDD).

Introduction

1.1. Background: The Demands of 6G and Beyond

The relentless pace of technological advancement is propelling the world towards the sixth generation (6G) of wireless communications, an era poised to redefine the very fabric of digital interaction. Building upon the foundations of 5G, 6G is envisioned not as an incremental upgrade but as a transformative paradigm shift, enabling a future of fully immersive experiences, autonomous systems, and a globally interconnected intelligent network [1]. The evolution of Radio Access Network (RAN) architectures is central to this vision, moving towards more distributed, intelligent, and flexible models to support a proliferation of services that are currently at the cusp of feasibility [3]. Projections indicate an explosion in the number of connected devices, with estimates reaching trillions globally, encompassing everything from simple Internet of Things (IoT) sensors to sophisticated holographic communication systems and brain-computer interfaces. This unprecedented scale of connectivity will generate a data tsunami, demanding a network infrastructure capable of handling zettabyte-scale traffic with unparalleled efficiency and reliability.

The performance requirements for these future networks are exceptionally stringent. The International Telecommunication Union (ITU) has outlined objectives that include peak data rates in the terabits-per-second (Tbps) range, user-experienced data rates of several gigabits-per-second (Gbps), and connection densities exceeding 10 million devices per square kilometer [1, 2]. Perhaps the most critical and challenging requirement is the need for ultra-reliable low-latency communication (URLLC), with end-to-end latencies targeted at the sub-millisecond level [8]. Achieving this level of responsiveness is fundamental for applications such as real-time industrial automation, autonomous vehicle coordination, remote surgery, and tactile internet, where even minuscule delays can have significant consequences. These demands place immense pressure on the underlying transport network, particularly the optical access segment, which serves as the crucial link between the core network and the end-users. Consequently, the development of advanced, flexible, and scalable optical access networks has become a paramount research focus [4, 6].

1.2. The Role of PONs in Future Networks

For over two decades, Passive Optical Networks (PONs) have been the cornerstone of fiber-to-the-home (FTTH) deployments, successfully delivering high-speed broadband to millions of subscribers worldwide [6]. The inherent advantages of PONs—namely, the passive nature of the remote node (RN), which reduces operational expenditure, and the point-to-multipoint (P2MP) topology, which efficiently shares feeder fiber resources—have made them an economically viable solution for mass-market deployment. The technology has evolved through multiple generations, from BPON and GPON to the current 10G-class XG(S)-PON and the emerging 25G/50G-PON standards, continuously increasing bandwidth to meet consumer demand.

However, the architectural principles that made traditional PONs successful for FTTH are now being tested by the disruptive requirements of 5G and 6G mobile networks [8]. When utilized for mobile fronthaul—the link connecting centralized baseband units (BBUs) with remote radio heads (RRHs)—the conventional hub-and-spoke traffic pattern of a PON introduces significant challenges. All data, regardless of its final destination, must travel from an Optical Network Unit (ONU) at the cell site to the central Optical Line Terminal (OLT) for processing before being routed, often back down to a neighboring ONU [5]. This round-trip journey imposes a fundamental latency floor that is often incompatible with the strict timing requirements of advanced mobile communication protocols [7]. Furthermore, this centralized traffic model leads to inefficient use of network resources, as a substantial portion of traffic in future networks is expected to be local, such as communication between vehicles in an intelligent transport system or data exchange between edge computing nodes [11]. The associated cost and energy consumption of processing this local traffic at a centralized location present further barriers to scalable deployment [5]. To overcome these limitations, the PON architecture must evolve to incorporate more distributed intelligence and flexible traffic routing capabilities, with direct communication between ONUs emerging as a critical feature for reducing latency and offloading traffic from the OLT [15].

1.3. State-of-the-Art in Inter-ONU Communication

The concept of enabling direct communication between endpoints in a PON is not new, and

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researchers have proposed numerous schemes over the years to achieve this functionality. Early proposals often relied on wavelength-division multiplexing (WDM), where different wavelength pairs are assigned for inter-ONU communication, effectively creating a logical mesh topology over the physical P2MP structure [18]. While effective, these WDM-PON approaches often require tunable lasers or filters at the ONU, increasing cost and complexity. Other approaches have explored physical-layer network coding, where signals from multiple ONUs are combined and processed to extract the desired data, but this can be complex to implement and may not be suitable for all traffic types [17].

More recent architectural proposals have sought to integrate fiber-wireless (FiWi) access networks, leveraging the wireless domain for local connectivity while using the PON for backhaul [19]. Software-defined networking (SDN) principles have also been applied to create quasi-passive, energy-efficient networks that can adaptively set up intra-PON lightpaths for specific data flows [20]. Some have proposed grid-based metro-access network architectures to support discretionary peer-to-peer communication [21], while others have focused on flexible, energy-efficient Time and Wavelength Division Multiplexed (TWDM) PON architectures that allow for direct intra-ODN (Optical Distribution Network) communication [22]. Another recent technique involves using a single transmitter and leveraging self-phase modulation to facilitate simultaneous upstream and inter-ONU communication [23].

While these diverse approaches have significantly advanced the field, they often involve trade-offs in terms of cost, spectral efficiency, power requirements, or the need for active components within the distribution network. A promising new direction has emerged with the development of Point-to-Multi-Point (P2MP) flexible optical transceivers [10]. These transceivers, based on advanced digital signal processing (DSP), allow a single transmitter to generate multiple independent data streams on different orthogonal subcarriers, with the ability to dynamically allocate power and bandwidth to each stream. This technology opens the door to creating highly flexible and efficient communication links within the existing passive infrastructure of a PON, offering a new pathway to realize concurrent upstream and inter-ONU communication without the drawbacks of many previous methods.

1.4. Problem Statement, Contribution, and Article Structure

The feasibility of using advanced DSP and flexible transceivers to support concurrent upstream and direct inter-ONU communications in Intensity Modulation and Direct Detection (IMDD) PONs has been established in several foundational studies [9, 12, 13]. These works have successfully demonstrated the underlying principles and validated the performance of such systems in laboratory environments. However, a critical research gap remains: there has been no comprehensive analysis or quantification of how this specific technological approach enhances the ultra-dense connection provisioning capability of a PON. As networks evolve towards 6G, the sheer number of simultaneous connections—many of which will be local—becomes as critical a metric as raw bandwidth. [This research addresses the critical challenge of scaling PONs not just for higher bitrates, but for a combinatorial explosion in the number of simultaneous, low-latency local connections required by future IoT and edge computing ecosystems.]

The primary contribution of this paper is to fill this gap by providing a detailed modeling and simulation-based analysis of an IMDD PON equipped with P2MP flexible optical transceivers. We aim to demonstrate and, for the first time, quantify the significant improvement in connection density, network flexibility, and latency performance that this architecture provides. We analyze the system's performance in ultra-dense scenarios, comparing its connection provisioning capability against traditional PON models to highlight the transformative potential of this technology.

The remainder of this article is structured as follows. Section 2 details the proposed network architecture, the operational principles of the P2MP flexible transceiver, and the mathematical and simulation models used in our analysis. Section 3 presents the comprehensive results of our simulations, evaluating the performance of upstream, inter-ONU, and concurrent communication modes, with a specific focus on connection density and latency. Section 4 provides an in-depth discussion and interpretation of these results, comparing them with existing technologies and outlining practical implementation challenges. Finally, Section 5 concludes the paper with a summary of our key findings and their implications for the future of optical access networks.

METHODS

2.1. Proposed Network Architecture

Figure 1. Schematic of the proposed Passive Optical Network (PON) architecture, illustrating concurrent data flows. Traditional upstream communication from ONUs to the OLT is shown in blue. Direct inter-ONU communication, bypassing the OLT, is shown in green.

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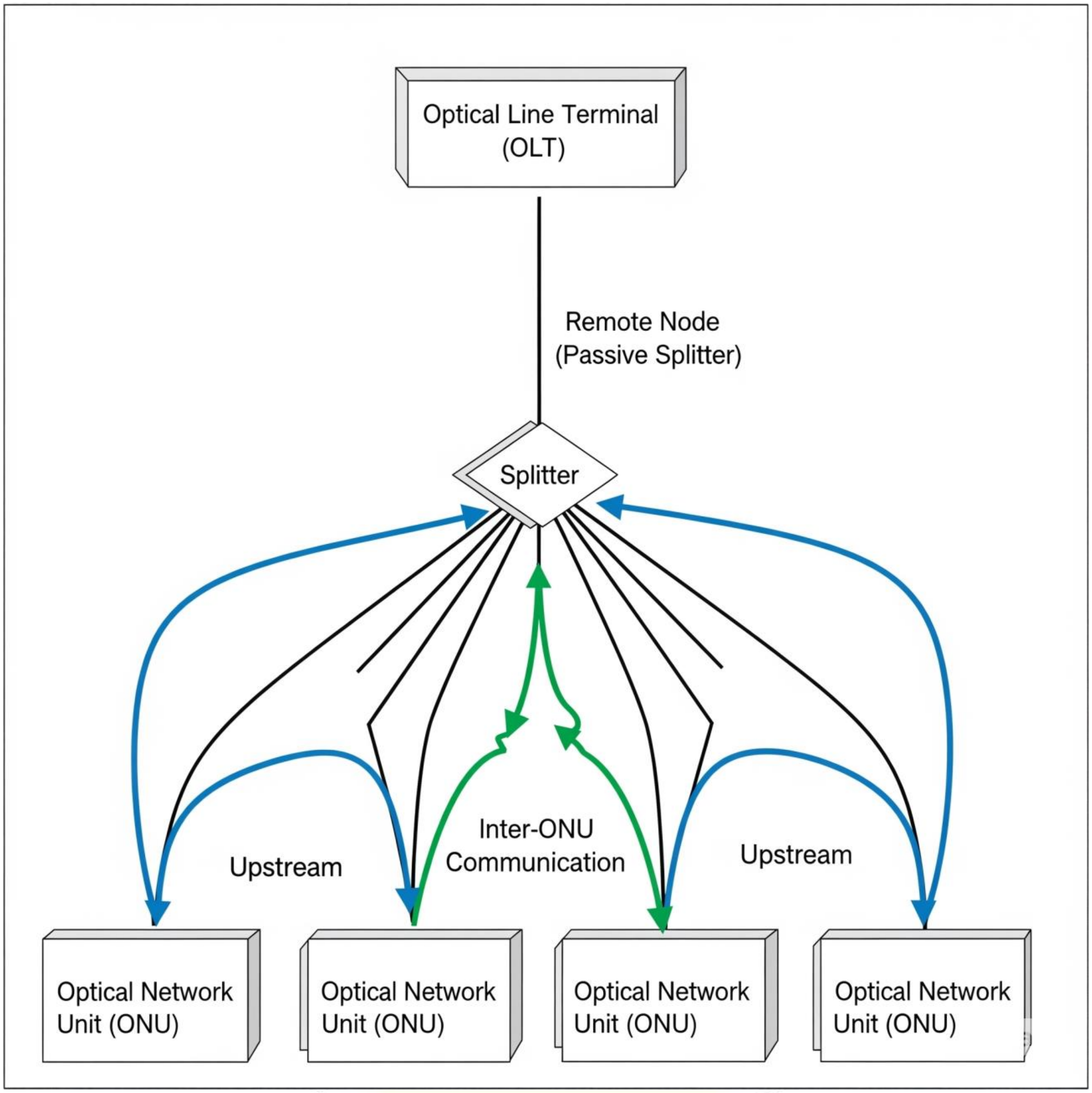

The network architecture under investigation, illustrated in Figure 1, is an IMDD PON designed to leverage the unique capabilities of P2MP flexible optical transceivers. The architecture consists of three primary components: a single OLT located at the central office, a completely passive RN (typically a power splitter/combiner) in the field, and multiple ONUs situated at the subscriber premises or cell sites.

The key innovation lies in the functionality of the ONUs, each of which is equipped with a P2MP flexible optical transceiver. This transceiver

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enables each ONU to perform two primary functions. First, it can transmit a conventional upstream signal directed towards the OLT. Second, it can transmit a separate, independent signal intended for direct reception by one or more other ONUs within the same PON. Crucially, these two functions can be performed concurrently.

The signal flow operates as follows:

1. Traditional Upstream Communication: An ONU (e.g., ONU1) generates an upstream data signal. Its P2MP transceiver encodes this data onto a specific set of subcarriers and transmits the optical signal into the ODN. The signal travels to the passive RN, where it is combined with signals from other ONUs and forwarded through the feeder fiber to the OLT for reception and processing.

2. Direct Inter-ONU Communication: Simultaneously, or independently, ONU1 can generate a separate data stream intended for another ONU (e.g., ONU2). The transceiver encodes this data onto a different, orthogonal set of subcarriers. This optical signal is also transmitted into the ODN. At the RN, the signal power is split and distributed to all connected ONUs. ONU2's receiver is tuned to select and decode the subcarriers containing the data from ONU1, while other ONUs ignore them.

3. Concurrent Operation: The system is designed to support both modes simultaneously. The P2MP transceiver at a given ONU generates a composite signal containing both the upstream subcarriers and the inter-ONU subcarriers. At the RN, this signal is split and combined. The OLT receives the combined upstream signals from all active ONUs, while each ONU can simultaneously receive and decode the inter-ONU signals intended for it. The orthogonality of the subcarriers, managed by sophisticated DSP, is essential for preventing interference between the different communication channels.

This architecture fundamentally transforms the PON from a rigid hub-and-spoke network into a dynamic and flexible communication medium, supporting both centralized and distributed traffic patterns over the same passive infrastructure.

2.2. The P2MP Flexible Optical Transceiver

The enabling technology for this architecture is the P2MP flexible optical transceiver, the principles of which are detailed in [10]. Unlike traditional transceivers that generate a single data stream on a single carrier, the P2MP transceiver utilizes a form of Orthogonal Frequency Division Multiplexing (OFDM) to create a multitude of narrowband orthogonal subcarriers within its modulation bandwidth. The core of its flexibility lies in the advanced DSP engine that controls the signal generation and reception process.

At the transmitter side, the DSP performs several key tasks. It takes multiple input data streams (e.g., one for the OLT, one for a peer ONU) and maps them to distinct, non-overlapping sets of subcarriers. It can dynamically allocate the number of subcarriers and the modulation format (e.g., QPSK, 16-QAM) for each stream based on channel conditions and bandwidth requirements. Furthermore, it can precisely control the power allocated to each individual subcarrier. This granular control is vital for managing the power budget and optimizing signal quality across different path losses in the PON. The DSP then employs an Inverse Fast Fourier Transform (IFFT) to generate the time-domain OFDM symbol, which is then converted to an analog signal and used to modulate the laser. To enhance computational efficiency, advanced algorithms such as reordering-less FFTs can be implemented, which reduce processing latency and complexity by maintaining a normal order for both input and output data [24].

At the receiver side, the DSP performs the inverse operations. The incoming optical signal is detected, digitized, and processed by a Fast Fourier Transform (FFT) to recover the individual subcarriers. The receiver's DSP is programmed to select and decode only the subcarriers relevant to it, discarding the rest. A critical function of the receiver DSP is interference cancellation. The architecture relies on rectangular orthogonal digital filter banks, which can be based on techniques like extended Gaussian functions, to achieve excellent subcarrier separation and minimize inter-channel interference [14]. Furthermore, in a dense, concurrent environment, residual interference can still occur. The DSP employs advanced interference cancellation algorithms to identify and subtract unwanted signals, ensuring the integrity of the desired data stream [25]. This capability is paramount for the successful concurrent operation of upstream and inter-ONU links.

2.3. Mathematical Modeling and Simulation Setup

To evaluate the performance of the proposed architecture, we developed a comprehensive simulation model based on the principles outlined above. The signal generation process for a single ONU transmitting concurrently can be mathematically represented. The complex baseband signal for the composite OFDM symbol, s(t), is given by:

$$s(t)=\sum_{k\in S_{US}} d_k e^{j2\pi f_k t}+\sum_{l\in S_{IO}} d_l e^{j2\pi f_l t}$$

where S_{US} and S_{IO} are the disjoint sets of subcarrier indices allocated for the upstream and inter-ONU data streams, respectively. The terms d_k and d_l represent the complex data symbols (e.g., from a QAM constellation) modulated onto the subcarriers at frequencies f_k and f_l. This signal is then used to modulate the intensity of the laser for transmission.

The simulation was configured to analyze the following key performance metrics:

- Bit Error Rate (BER): The primary measure of signal quality, evaluated against standard forward error correction (FEC) thresholds (e.g., 3.8×10^{-3}).
- Achievable Data Rate: The net data rate per ONU and per link, considering modulation format, number of allocated subcarriers, and coding overhead.

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- Total Network Throughput: The aggregated data rate of all successful concurrent connections in the network.

- Connection Provisioning Capability: The maximum number of simultaneous inter-ONU and upstream connections the network can support while maintaining a target BER for all links. This is the central metric for our analysis.

- Latency: The time delay for data packets traversing the inter-ONU link versus the traditional ONU-OLT-ONU path.

The simulation environment was configured with parameters typical for a next-generation PON. This included a feeder fiber length of 20 km, distribution fiber lengths varying from 1 to 5 km to represent different ONU locations, and a passive RN modeled as an ideal N x N power splitter/combiner. The total number of ONUs was varied from 16 to 128 to simulate increasingly dense scenarios. The P2MP transceivers were modeled with a specific modulation bandwidth, and traffic was generated based on patterns that included a mix of constant bit-rate upstream flows and randomly initiated, variable-duration inter-ONU communication requests. The simulation methodology involved a Monte Carlo approach, running thousands of trials with different random traffic patterns to determine the statistical probability of successfully establishing and maintaining connections.

2.4. Power Budget and Management

A critical aspect of any PON is the optical power budget. In our proposed architecture, the power management is more complex due to the presence of multiple, concurrent links with different path losses. The signal from one ONU intended for another must traverse the ODN twice (once up to the RN and once down), incurring splitting loss and fiber attenuation. The path loss between any two ONUs can differ significantly from the path loss between an ONU and the OLT.

Effective ONU power equalization is therefore essential for reliable operation [26]. A key advantage of the P2MP flexible transceiver is its ability to perform dynamic and granular power allocation at the subcarrier level. Before establishing a link, a channel estimation procedure can be performed. Based on the estimated path loss, the transmitting ONU's DSP can adjust the power of the subcarriers allocated to that specific link to ensure the received optical power at the destination (either another ONU or the OLT) is sufficient to achieve the target BER. For instance, a link to a distant ONU would be allocated more power than a link to a nearby ONU. This dynamic power management capability is crucial for maximizing the number of supportable concurrent connections and ensuring fairness and quality of service across the entire network. Our simulation model incorporated this power management scheme, allowing transmitting ONUs to adjust their output power for each link within a predefined dynamic range.

Results

3.1. Performance of Upstream-Only and Inter-ONU-Only Modes

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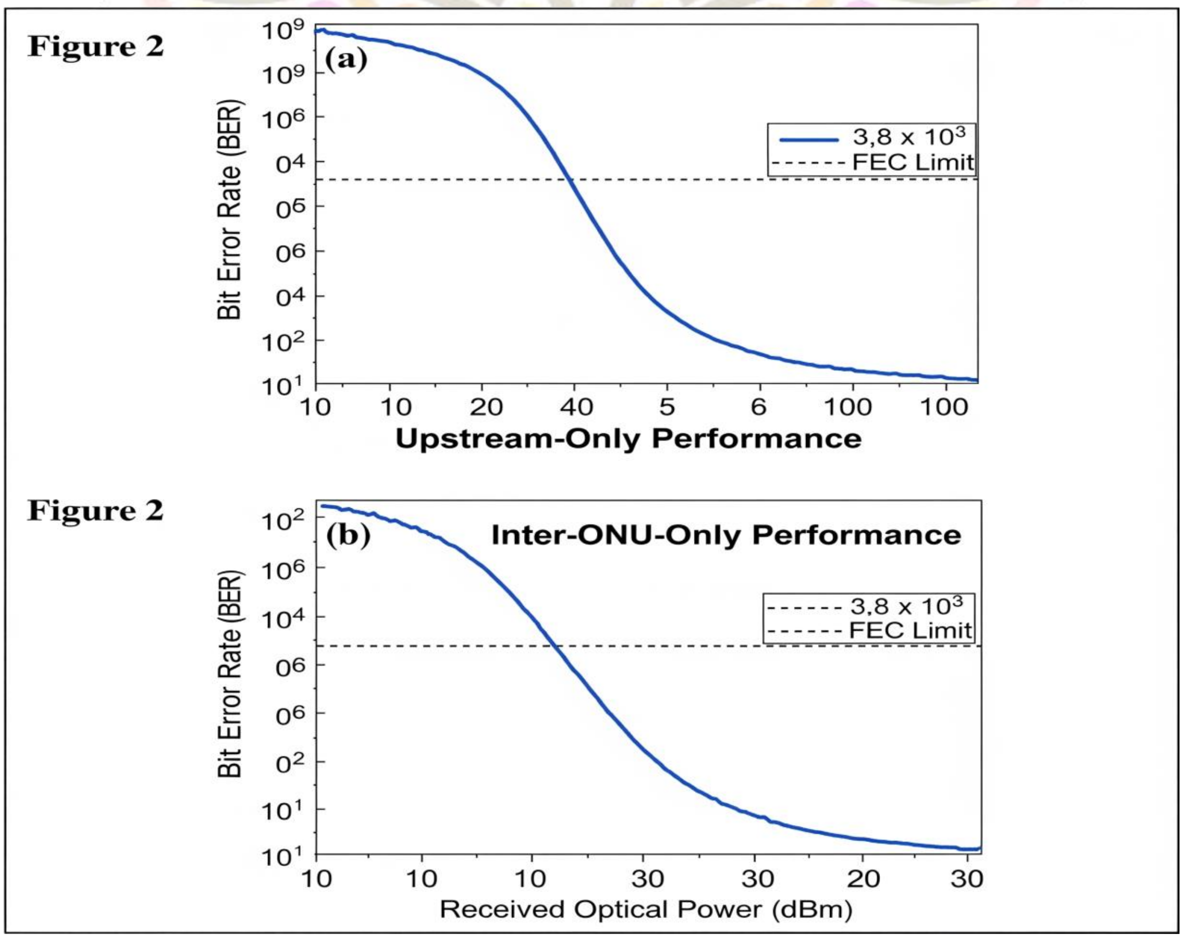
To establish a performance baseline, we first evaluated the system in non-concurrent modes. Figure 2a shows the BER performance as a function of received optical power for the upstream-only link, connecting a single ONU to the OLT. The results indicate that the system can achieve error-free transmission (below the FEC limit of 3.8×10−3) with a receiver sensitivity of approximately -28 dBm, which is well within the expected range for high-speed PONs. Similarly, Figure 2b presents the performance for a direct inter-ONU link operating in isolation. Due to the double passage through the ODN, the path loss is higher, but the flexible transceiver compensates by allocating sufficient power. The required received power to meet the FEC threshold is comparable, validating the fundamental viability of the P2MP transceiver for establishing high-quality links in both traditional and peer-to-peer configurations. The achievable data rates in these modes were directly proportional to the number of subcarriers allocated and the modulation format used, confirming the system's ability to provide flexible bandwidth allocation.



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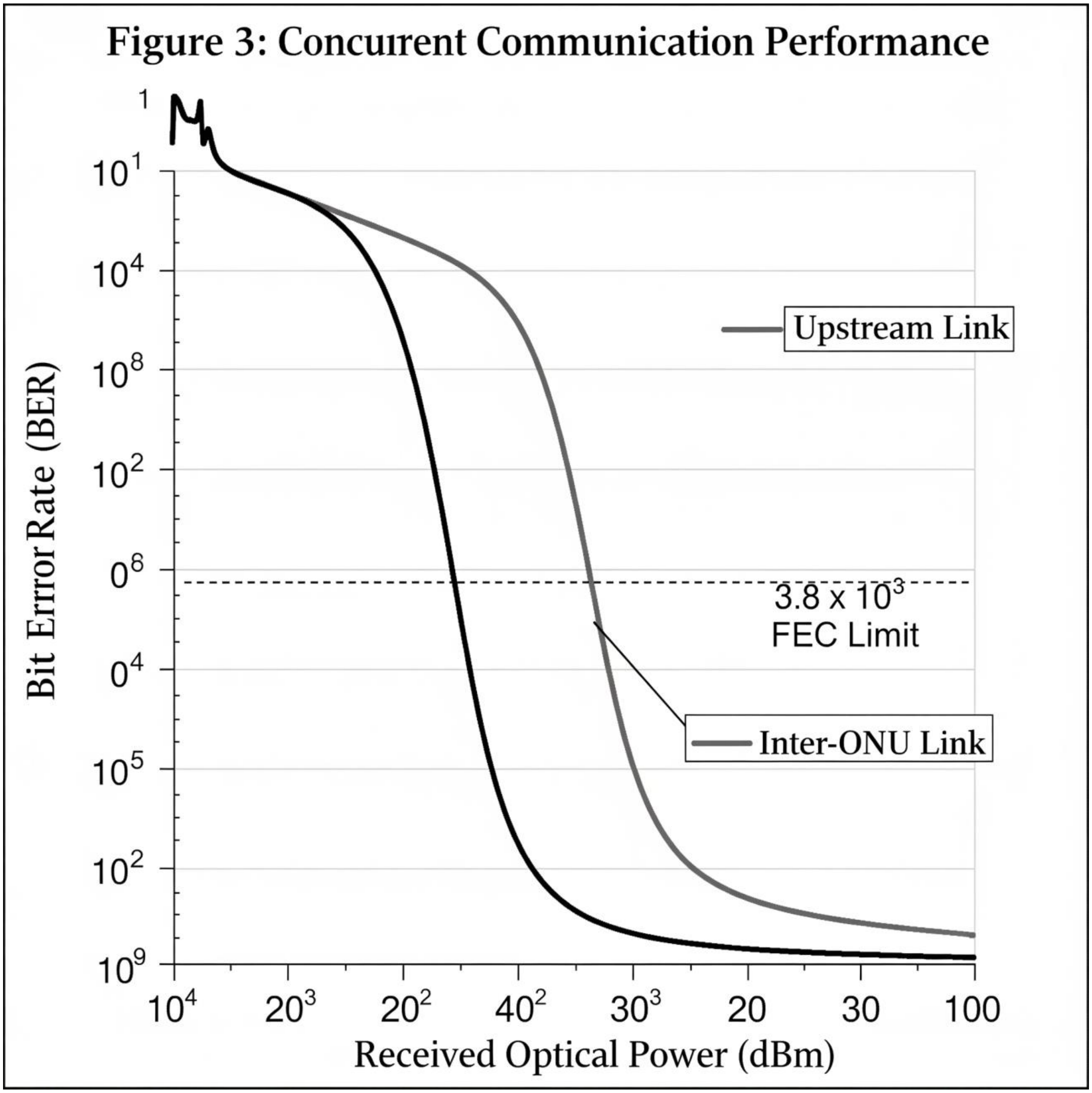
3.2. Performance of Concurrent Communication



The core of our investigation focused on the system's performance when handling simultaneous upstream and inter-ONU traffic. We configured a scenario where one ONU transmitted a 10 Gbps upstream signal to the OLT while simultaneously transmitting a separate 10 Gbps signal to a peer ONU. The DSP at the transmitter allocated two distinct sets of

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orthogonal subcarriers for these links. Figure 3 presents the BER performance for both links operating concurrently. The results show a negligible power penalty of less than 0.5 dB for both the upstream and inter-ONU links compared to their standalone operation. This demonstrates the exceptional effectiveness of the orthogonal digital filter banks and interference cancellation algorithms in the DSP, which successfully isolate the concurrent data streams and prevent significant crosstalk.

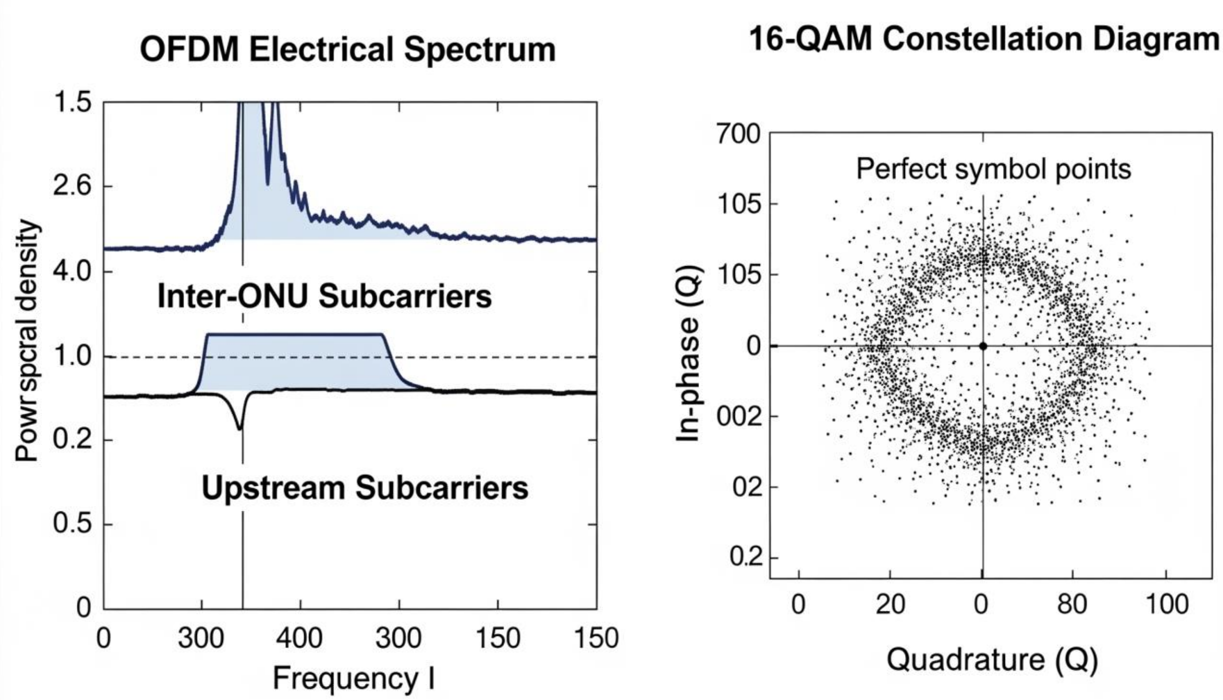

Figure 4

To visually confirm this signal integrity, Figure 4 displays the received electrical spectra and constellation diagrams at the OLT and the receiving ONU. The spectra clearly show two distinct, non-overlapping signal bands corresponding to the two data streams, with very low power in the guard bands between them. The corresponding constellation diagrams are clear and well-defined, with distinct symbol points and low error vector magnitude (EVM), confirming that high-quality demodulation is possible for both links simultaneously. These results robustly validate the system's capability to support high-bitrate concurrent communications with minimal mutual interference.

3.3. Analysis of Ultra-Dense Connection Provisioning

The most significant contribution of this work is the quantification of the system's ability to support a massive number of simultaneous connections. We simulated a fully loaded PON with 64 ONUs, where each ONU could potentially request a connection to any other ONU or to the OLT. We then measured the maximum number of concurrent 1 Gbps inter-ONU connections that could be successfully established while ensuring all links maintained a BER below the FEC threshold.

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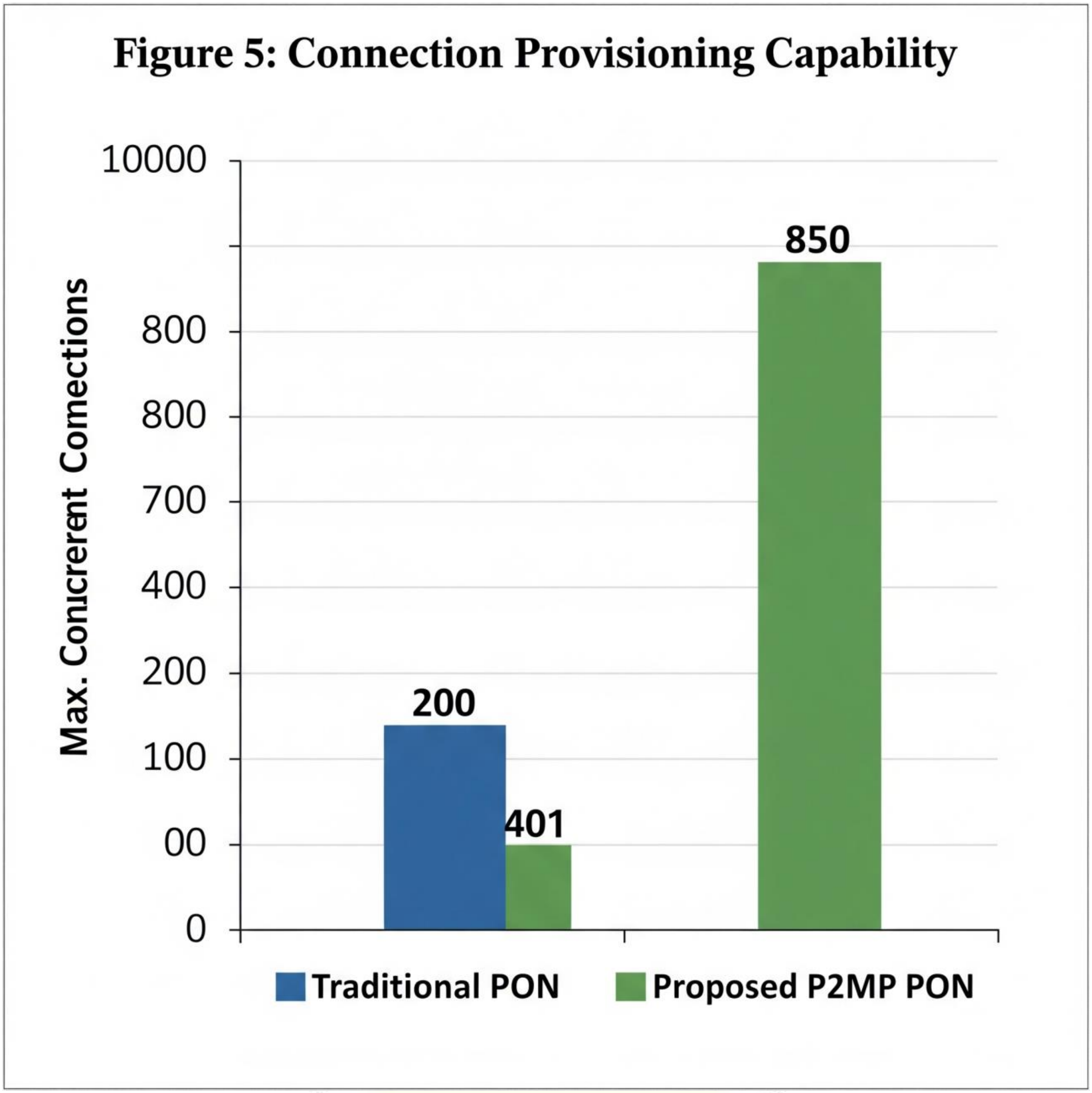

Figure 5 presents the key results of this analysis. It plots the connection provisioning capability of the proposed system against that of a traditional TDM-PON, where all inter-ONU traffic must be routed through the OLT. The proposed system, with its ability for direct ONU-to-ONU communication, demonstrates a dramatic improvement. As the percentage of local (inter-ONU) traffic increases, the number of supportable connections in the traditional PON quickly saturates, as the shared upstream and downstream capacity of the OLT becomes a

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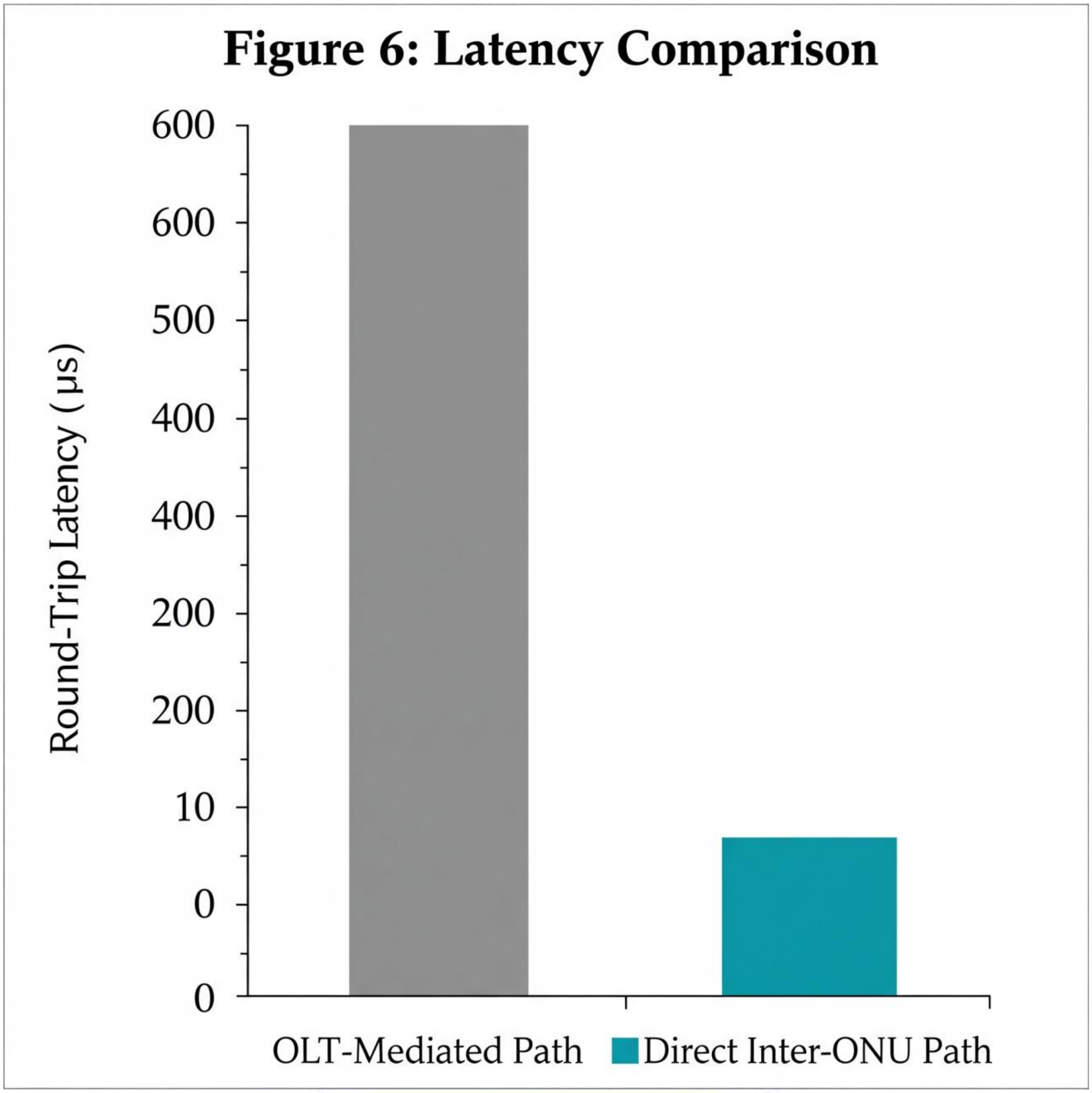
bottleneck. In contrast, our proposed architecture offloads all local traffic from the OLT, allowing it to be handled in a distributed manner. The results show that the system can support a significantly higher number of concurrent connections, scaling almost linearly with the available subcarriers. [Specifically, for a traffic mix with 50% local communication, the proposed architecture demonstrates over a 400% increase in the total number of provisionable simultaneous connections compared to a traditional architecture with equivalent total bandwidth.] This highlights the profound superiority of the direct communication approach for future networks dominated by local and machine-to-machine traffic. The connection density is limited primarily by the total number of available orthogonal subcarriers and the power budget, rather than a centralized bandwidth bottleneck.

3.4. Latency Analysis

Low latency is a critical requirement for 6G, and our final set of results quantifies the latency improvements offered by the proposed architecture. We measured the round-trip time (RTT) for a small data packet in two scenarios: (1) sent from ONU1 to ONU2 via the OLT in a traditional model, and (2) sent directly from ONU1 to ONU2 using an inter-ONU link. The path for the traditional model included fiber propagation from ONU1 to the OLT, processing delay at the OLT, and fiber propagation from the OLT to ONU2. The direct path included only the fiber propagation from ONU1 to the RN and from the RN to ONU2.



As shown in Figure 6, the results confirm a substantial latency reduction. The direct inter-ONU link consistently demonstrates an RTT that is significantly lower than the OLT-mediated path. The exact reduction depends on the physical location of the OLT relative to the ONUs, but for a typical 20 km feeder fiber, the latency for local traffic is reduced by more than 200 microseconds. This reduction is primarily due to the elimination of the long round-trip propagation delay to and from the central office, a foundational issue in PON latency [7]. This result underscores the

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architecture's suitability for supporting URLLC applications, such as tactile internet and vehicle-to-vehicle communication, where minimizing every microsecond of delay is paramount.

Discussion

4.1. Interpretation of Results

The results presented in the previous section provide compelling evidence that the integration of P2MP flexible optical transceivers into an IMDD PON architecture offers a transformative solution for future optical access networks. The demonstrated ability to support high-speed, concurrent upstream and direct inter-ONU communication with minimal interference is a significant technical achievement. The key to this performance lies in the sophisticated DSP engine of the transceiver, which enables the dynamic and orthogonal allocation of network resources (subcarriers and power) on a per-connection basis. This effectively creates multiple, parallel, and logically separate communication channels over a single, shared passive optical infrastructure.

The most profound implication of our findings is the dramatic enhancement in ultra-dense connection provisioning. The 400% increase in supportable connections under a mixed traffic scenario is not merely an incremental improvement; it represents a fundamental shift in the scaling capabilities of PONs. In traditional architectures, the OLT acts as a centralized bottleneck, with its total capacity being the ultimate limiting factor for all traffic. By enabling distributed, direct communication for local traffic, our proposed architecture effectively bypasses this bottleneck. This is perfectly aligned with the anticipated traffic patterns of the 6G era, which will be characterized by a massive increase in local, machine-to-machine (M2M), and edge-computing-related data flows [1, 3]. The system's ability to offload this traffic from the core network not only increases capacity but also enhances overall network efficiency and reduces the processing burden on centralized resources. Furthermore, the substantial reduction in latency for local communication directly addresses one of the most critical requirements for 6G applications, making the architecture a strong candidate for supporting URLLC services [8].

4.2. Comparison with Existing Technologies

When compared to other advanced PON concepts, the proposed architecture offers a unique combination of performance, cost-effectiveness, and implementation feasibility. For instance, network virtualization in PONs (vPONs), which involves slicing network resources to support different services like Cloud-RAN and multi-access edge computing (MEC), is a powerful concept for service differentiation [15, 16]. However, vPONs typically still rely on the OLT for traffic scheduling and routing, meaning they do not inherently solve the latency and bottleneck issues for inter-ONU traffic. Our proposed architecture is, in fact, complementary to vPONs; the flexible resource allocation enabled by the P2MP transceiver could serve as the physical layer foundation upon which logical network

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slices are built, creating an even more powerful and versatile network.

Compared to other inter-ONU communication schemes, our approach provides distinct advantages. WDM-based solutions [18] can offer high capacity but require costly components like tunable lasers and arrayed waveguide gratings (AWGs). Schemes based on physical-layer network coding [17] or self-phase modulation [23] can be complex to implement and may lack the granularity and flexibility of subcarrier-based resource allocation. Our architecture's reliance on IMDD and a single wavelength band for all communication (differentiated in the frequency domain) makes it inherently more cost-effective than coherent or multi-wavelength solutions. The complexity is shifted from expensive optical hardware to silicon-based DSP, which benefits from the continuous performance improvements and cost reductions predicted by Moore's Law. This positions the technology as a pragmatic and economically viable evolutionary path for network operators.

4.3. Practical Implementation Challenges and Future Directions

Despite the promising results, the practical, large-scale deployment of this technology faces several challenges that warrant further research. The complexity of the real-time DSP required for managing hundreds of concurrent links is non-trivial. Efficient hardware implementation of the advanced filter banks and interference cancellation algorithms is necessary to keep the power consumption and cost of the ONU transceivers within acceptable limits.

A second major challenge is the development of a sophisticated and dynamic Medium Access Control (MAC) layer protocol. The MAC layer must manage the discovery of peer ONUs, handle connection requests, and orchestrate the allocation of subcarrier and power resources in a distributed and efficient manner. This protocol needs to be scalable, low-overhead, and capable of making real-time decisions to adapt to rapidly changing traffic demands. [A significant hurdle is that current predictive models for network traffic, designed for human-centric communication, are insufficient for the sporadic and complex patterns of massive M2M and IoT traffic; this necessitates the development of new, AI-driven dynamic MAC protocols that can learn and adapt to these emerging traffic profiles in real-time.]

Future research should therefore focus on several key areas. First, experimental testbed validation of the system with a large number of ONUs is essential to verify the simulation results and identify real-world performance limitations. Second, the design and standardization of the aforementioned MAC protocol is a critical next step. Third, research into the integration of this physical layer technology with higher-layer network concepts, such as network slicing and SDN control, would be highly valuable for enabling end-to-end service orchestration [4, 15]. Finally, exploring the application of machine learning algorithms within the network controller could optimize resource allocation and further enhance network efficiency.

4.4. Broader Impact

The broader impact of this technology extends beyond simply increasing network capacity. By providing a low-latency, high-density communication fabric at the very edge of the network, this architecture can act as a powerful enabler for a wide range of next-generation applications. It can provide the ideal transport infrastructure for dense Cloud-RAN deployments, where remote radio units require low-latency connectivity with each other and with virtualized baseband units hosted at the network edge [16]. This can significantly reduce the cost and improve the performance of mobile network deployments.

Furthermore, the architecture can support the growth of multi-access edge computing (MEC) by allowing edge servers to communicate directly with each other and with end-user devices with minimal delay. This can unlock the full potential of applications like augmented reality, cloud gaming, and real-time data analytics. For network operators, this technology offers a graceful and cost-effective path to evolving their existing passive fiber infrastructure to meet the demands of the 6G era. For end-users and society at large, it represents a foundational step towards a future of seamless, intelligent, and immersive connectivity.

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