Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

# Optimized Fiber Backhaul Planning and Energy Management for Ultra-Dense 5G Networks

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**Abstract: The rapid increase in mobile data traffic, fueled by smart devices and latency-sensitive real-time services, has expedited the rollout of ultra-dense 5G small cell networks in urban environments. While small cells provide substantial improvements in network capacity and latency, the deployment of a massive number of small cells raises critical issues in terms of energy efficiency and effective backhaul provisioning. This paper proposes a holistic design and optimization framework for energy-efficient fiber-based backhaul networks specifically for ultra-dense 5G networks. A comparison study of fiber and wireless backhaul solutions is also performed, and the benefits of fiber-optic backhaul solutions in terms of reliability, scalability, and latency are highlighted. To overcome the energy challenges posed by the dense small cell deployment, the proposed solution includes the integration of Passive Optical Network (PON), dynamic traffic-aware bandwidth allocation, and adaptive sleep mode strategies for unused network infrastructure. Performance analysis using simulation results shows that hybrid fiber-wireless networks can provide energy savings of up to 30-35% without impacting the gigabit throughput and sub-millisecond latency requirements. The proposed solution provides a scalable and cost-effective solution for sustainable 5G network infrastructure development.**

**Keywords: 5G Networks, Fiber Backhaul, Energy Efficiency, Passive Optical Networks (PON), Ultra-Dense Networks**

## 1. INTRODUCTION

The huge increase in mobile data traffic, fueled by the widespread adoption of smart devices and bandwidth-hungry applications, has made ultra-dense 5G small cell networks an essential component of next-generation urban communications [1], [2]. Small cells, or miniature base stations with low power consumption, are deployed in high density to satisfy the demanding performance requirements of 5G, such as high data rate transmission, low latency, and ubiquitous coverage, where traditional macrocells are inadequate [5], [6]. Small cell networks enable revolutionary technologies such as autonomous vehicles, smart cities, and Industry 4.0 solutions [1], [9].

However, the densification of network infrastructure brings forth new challenges, especially in the area of backhaul connectivity and energy efficiency [3], [4], [7]. The backhaul network, which connects small cells to the core network, has to support a huge increase in data rates. Although wireless technologies like mmWave and microwave provide flexibility for rapid deployment, they are prone to low reliability and bandwidth in ultra-dense networks [3], [6]. On the other hand, fiber-optic backhaul provides much faster speeds, extremely low latency, scalability, and high reliability, making it the technology of choice for 5G transport networks [2], [5]. Although it has many benefits, large-scale fiber deployment faces challenges such as high CAPEX costs, complex civil works, and longer deployment times [6], [10]. Moreover, as the density of small cells increases, cumulative energy consumption becomes a critical concern. Recent studies indicate that more than 50% of total energy consumption in dense small cell networks arises from computation and radio transmission functions, particularly when massive MIMO and mmWave technologies are employed [3], [7]. This growing energy demand raises serious concerns regarding operational expenditure (OPEX), carbon footprint, and long-term sustainability of 5G ecosystems. Several research efforts have addressed energy-efficient backhaul strategies for ultra-dense deployments.

Several studies have explored fiber- and wireless-aware infrastructure models for ultra-dense 5G small cell deployment, emphasizing balanced trade-offs between energy efficiency and network performance [1]. Comparative studies of various backhaul technologies such as fiber, microwave, mmWave, satellite, and laser links have shown that fiber is one of the most energy-efficient and sustainable technologies for dense 4G/5G networks [2]. Energy-efficient models for backhauled 5G small cells supporting massive MIMO-assisted mmWave communication have been developed, along with detailed studies on the configuration design to reduce energy consumption in ultra-dense networks [3], [8]. Green communication systems have attracted considerable interest, and energy-efficient backhaul solutions have been

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

designed to decrease environmental effects without compromising network performance [4]. Energy-efficient resource allocation schemes for hybrid fiber-wireless backhaul networks in ultra-dense networks have been studied [6], and optimization algorithms have been developed to maximize backhaul power savings while meeting Quality of Service requirements [7]. Aspects related to the implementation of small cells via the use of urban infrastructure have also been considered [10], as well as cost-effective and energy-efficient fiber deployment techniques for massive 5G deployment [9]. Although the current literature covers hybrid backhaul approaches and energy-efficient algorithms, some research gaps still exist. First, the majority of the literature focuses on either wireless backhaul optimization or energy modeling [11], without much emphasis on the integration of Passive Optical Networks as a systematic fiber approach for ultra-dense networks. Second, there is a lack of importance given to the simultaneous deployment of dynamic bandwidth allocation and adaptive sleep mode approaches in fiber backhaul designs [12]. Third, very few studies have presented a comprehensive architecture that tackles energy efficiency, cost optimization, QoS support [16-18], and scalability for future 6G development [13-15]. Therefore, a holistic design-oriented solution incorporating fiber backhaul using PON, intelligent resource management, and adaptive power-saving techniques is still an open research issue.

To address the identified research issues, this paper presents an energy-efficient fiber backhaul solution specifically designed for ultra-dense 5G small cell networks. The proposed solution incorporates Passive Optical Networks (PON), dynamic traffic-aware bandwidth management, optimized small cell to access point assignment, and intelligent sleep mode management. The main research goals of this paper are: (i) to minimize the overall backhaul power consumption in ultra-dense 5G networks; (ii) to design an optimal assignment strategy in capacity-constrained scenarios; (iii) to provide reliable high-throughput connectivity; and (iv) to examine the trade-off between energy efficiency and network performance.

The rest of this paper is organized as follows: Section 2 describes the proposed methodology and system design for energy-efficient fiber backhaul in 5G networks. Section 3 describes the simulation results and performance analysis. Finally, Section 4 concludes this paper and provides future research directions.

## 2. PROPOSED METHODOLOGY

The aim of the proposed methodology is to design an energy- and cost-efficient fiber backhaul solution for ultra-dense 5G small cell networks. The proposed solution encompasses network planning, optimal technology choice, analytical energy modeling, and deployment optimization through analytical and heuristic approaches. The proposed solution focuses on scalability, preservation of Quality of Service, and long-term sustainability even in high traffic density environments. The following Fig. 1 depicts the proposed Energy-efficient 5G fiber backhaul.

### 2.1 Network Design Overview

The proposed system architecture is intended to facilitate high-capacity, low-latency communication in ultra-dense urban environments, with minimal overall power consumption. The system architecture will feature a hierarchical fiber backhaul structure that utilizes Passive Optical Network (PON) or Wavelength Division Multiplexed PON (WDM-PON) technology. The key elements of the proposed system architecture are:

1. **Small Cells (SCs):** Low-power radio access nodes that are densely packed to improve coverage and capacity.
2. **Optical Network Units (ONUs):** These are installed at each small cell location and act as an interface between the optical fiber infrastructure and the radio access nodes.
3. **Optical Line Terminal (OLT):** This is installed at the central office location and is tasked with the management of traffic from the multiple ONUs.
4. **PON/WDM-PON Infrastructure:** Serves as the main fiber backhaul transport. The conventional PON supports shared bandwidth, while the WDM-PON provides distinct wavelengths to each small cell, thus enhancing isolation and scalability.
5. **Centralized Control Unit:** It is designed based on Software-Defined Networking (SDN) and Network Function Virtualization (NFV) concepts to manage bandwidth allocation, routing, and energy-saving features such as sleep modes.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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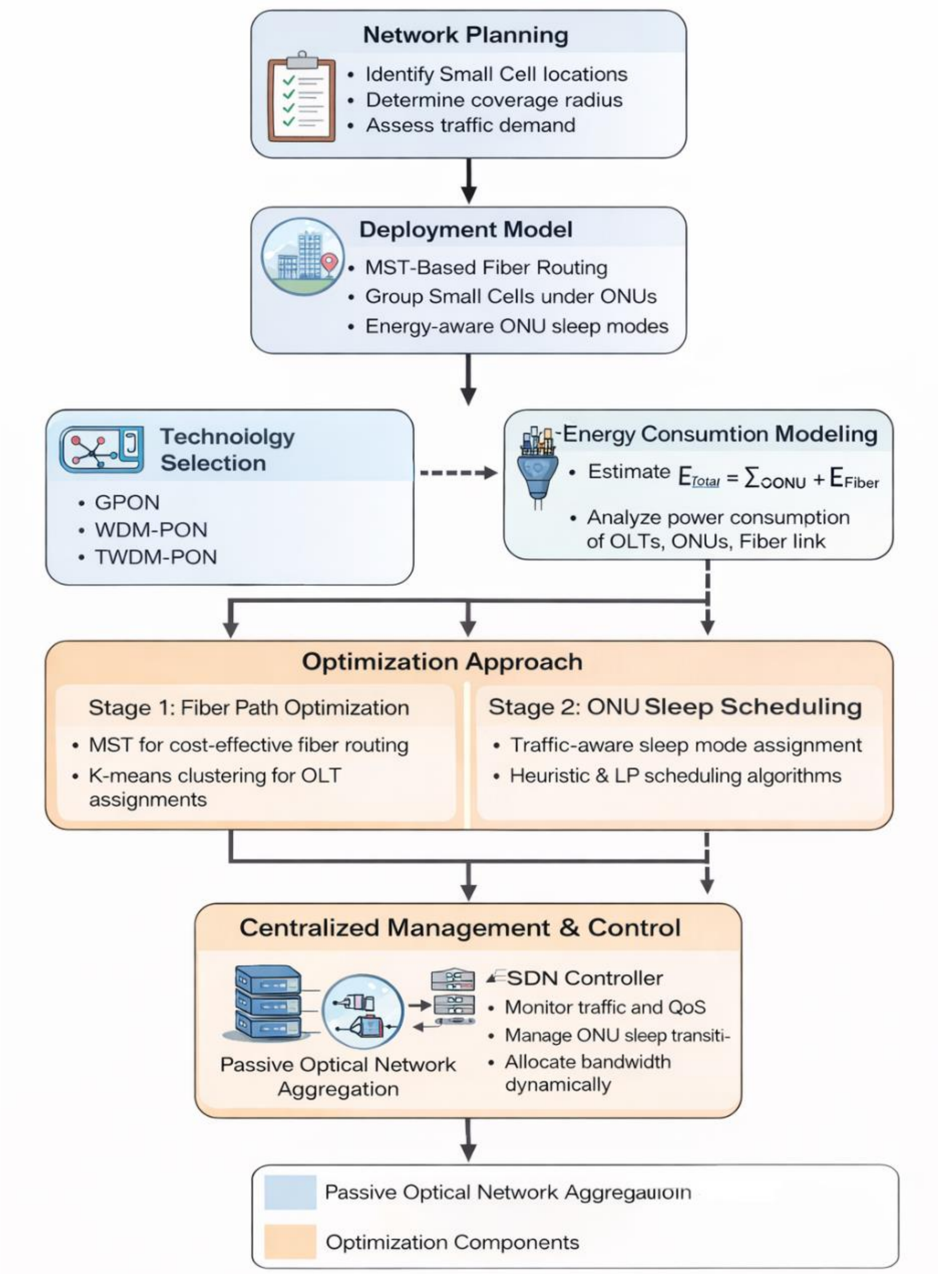


Fig. 1 Proposed Energy-efficient 5G fiber backhaul diagram

This architecture enables dynamic traffic adaptation, efficient spectrum utilization, and centralized energy management across the network.

Table 1: Components of the Proposed Fiber Backhaul Architecture

| Component | Description |
|---|---|
| **Small Cell (SC)** | Provides radio access to end-users; connected to the ONU for backhaul transmission |
| **Optical Network Unit (ONU)** | Interfaces between the optical fiber network and the small cell equipment at each deployment site |
| **Optical Line Terminal (OLT)** | Aggregates upstream and downstream traffic from multiple ONUs at the central office |

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

| | |
|---|---|
| **PON / WDM-PON** | Fiber-based optical medium enabling shared or wavelength-dedicated backhaul connectivity |
| **Central Controller (SDN/NFV-based)** | Manages dynamic bandwidth allocation, routing optimization, and adaptive power management |

*2.2 Deployment Model*

The deployment model is developed to provide scalable coverage, optimal fiber use, and low power consumption in ultra-dense 5G networks. The assumptions of the deployment model are as follows:

1. **Coverage Radius:** The coverage area of each small cell (SC) has a radius of 100-200 meters, ensuring high spatial reuse and better signal quality in ultra-dense urban environments.
2. **Fiber Topology:** The optical fiber is connected from the central office (CO) to each Optical Network Unit (ONU) through passive optical splitters (in PON systems) or wavelength dedicated links (in WDM systems).
3. **Passive Infrastructure Preference:** Passive optical components like splitters, couplers, and multiplexers are preferred over active repeaters in order to reduce additional energy consumption.
4. **Energy-Aware ONUs:** The ONUs are assumed to support adaptive sleep modes, which allow dynamic power reduction during low traffic periods without affecting the Quality of Service (QoS).

The architecture balances the cost of infrastructure, power consumption, and network performance by using passive optical distribution and centralized intelligence for control and optimization.

*2.3 Technology Selection for Fiber Backhaul*

In order to determine the most appropriate backhaul technology for ultra-dense 5G networks, three popular variants of Passive Optical Network are considered: GPON (Gigabit Passive Optical Network), WDM-PON (Wavelength Division Multiplexed PON), and TWDM-PON (Time and Wavelength Division Multiplexed PON). The factors considered for comparison of these variants are bandwidth, wavelength, power, scalability, and cost of deployment.

Table 2: Comparative Analysis of Optical Backhaul Technologies

| Technology | Maximum Bandwidth | Wavelength Capacity | Relative Power Usage | Scalability | Deployment Cost |
|---|---|---|---|---|---|
| **GPON** | Up to 2.5 Gbps | 1–2 wavelengths | Low | Moderate | Low |
| **WDM-PON** | Up to 10 Gbps | 8–32 wavelengths | Medium | High | Medium |
| **TWDM-PON** | 40–100 Gbps | 32–64 wavelengths | High | Very High | High |

*2.4 Energy Consumption Modeling*

Energy efficiency is a primary design objective in ultra-dense 5G backhaul networks. To quantitatively evaluate the performance of the proposed architecture, an analytical energy consumption model is formulated. The total energy consumption of the fiber backhaul system is expressed as:

$$E_{Total} = E_{OLT} + \sum_{i-1}^{N} E_{ONU,i} + E_{Fiber} \quad (1)$$

where: $E_{Total}$ = Total energy consumption of the backhaul network; $E_{OLT}$ = Energy consumption of the Optical Line Terminal; $E_{ONU,i}$= Energy consumption of the *i*-th Optical Network Unit; N = Total number of deployed ONUs (equal to

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

number of small cells); $E_{Fiber}$r = Energy associated with optical transmission losses and amplifier compensation (if active amplification is required)

Component-Level Energy Modeling is done by following steps:

1. **OLT Energy Consumption ($E_{OLT}$):** The OLT is always on and works to accumulate and deliver traffic. The OLT power consumption is proportional to the number of active ports, traffic intensity, and switching fabric usage..

2. **ONU Energy Consumption ($E_{ONU}$):** he ONU has a large energy contribution due to its scale of deployment. However, adaptive sleep mode techniques enable the ONU to go into low-power idle modes during periods of low traffic..

3. **Fiber Transmission Energy ($E_{Fiber}$):** The power consumption of passive fiber cables is negligible. However, indirect power costs are incurred for signal compensation, such as optical amplifiers in extended reach systems..

Table 3: Power Consumption Characteristics of Backhaul Components

| Component | Typical Power Consumption (W) | Sleep Mode Support | Operational Notes |
|---|---|---|---|
| **OLT** | 25–50 W | Partial | Remains continuously active; limited energy reduction through port-level management |
| **ONU** | 5–15 W | Yes | Can transition to idle or low-power mode during reduced traffic conditions |
| **Fiber Link** | ~0.1 W per km (indirect) | Not Applicable | Passive medium; energy mainly associated with signal loss compensation |

*2.5 Optimization Approach*

To reduce both energy and deployment cost in ultra-dense 5G fiber backhaul networks, an optimization framework is proposed. The proposed framework is a two-stage process.

**Stage 1: Fiber Path Optimization**

The first stage of the framework aims to reduce capital expenditure (CAPEX) in fiber deployment while ensuring coverage and latency requirements are met.

1. **Minimum Spanning Tree (MST)–Based Routing:** An MST algorithm is used to find the best fiber routing topology that connects the central office to the small cell clusters in a manner that minimizes the total trenching distance and, consequently, the fiber installation cost.

2. **Clustering-Based OLT Assignment:** A clustering algorithm (e.g., K-means) is employed to group small cells (SCs) according to their geographical location and traffic demand.

This stage performs optimization of infrastructure planning, taking into account the constraints of maximum allowable latency and coverage radius.

**Stage 2: ONU Sleep Scheduling Optimization**

The second stage focuses on the reduction of operational expenditure (OPEX) by optimizing energy management.

1. **Traffic-Aware Idle Detection:** A heuristic or linear programming approach is used to detect ONUs that are working below a certain traffic level.

2. **Adaptive Sleep Mode Scheduling:** ONUs are put into sleep or low-power modes during off-peak traffic periods (such as nighttime) while maintaining latency and QoS constraints.

The objective function of the optimization procedure can be written as:

$$Minimize\ E_{Total} = \sum P_{active} + \sum P_{sleep} + C_{Fiber} \quad (2)$$

International Journal of Engineering Research & Technology (IJERT)
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Vol. 15 Issue 02 , February - 2026

Subject to: Latency constraint: $T \leq T_{max}$; Traffic demand constraint: Capacity ≥ $\lambda_{user} \times N_{sc}$; and Connectivity constraint: All SCs must remain reachable via OLT

Table 4: Optimization Variables and System Constraints

| Parameter | Description |
|---|---|
| $N_{sc}$ | Number of deployed small cells |
| $L_{Fiber}$ | Total fiber length in the network |
| $P_{active}$ , $P_{sleep}$ | Power consumption in active and sleep modes |
| $T_{max}$ | Maximum allowable latency |
| $\lambda_{user}$ | Average traffic demand per small cell |

*2.6 Network Management and Control Framework*

For the purpose of enabling real-time adaptation and intelligent energy management, the proposed architecture includes an SDN-based centralized controller. The controller carries out the following tasks:

1. **Dynamic Traffic and Bandwidth Management:** It monitors the traffic load among the ONUs and manages the bandwidth allocation dynamically.
2. **Sleep Mode Orchestration:** It relies on historical traffic analysis and predictive modeling to identify the optimal sleep patterns for the ONUs.
3. **QoS Prioritization:** It provides higher priority to latency-sensitive traffic (such as URLLC traffic) to ensure uninterrupted service.

The communication between the SDN controller, OLT, and ONUs is supported by standardized southbound protocols such as OpenFlow or NetConf. This centralized control paradigm enables intelligent, real-time optimization of backhaul resources while preserving scalability and reliability.

## 3. Results and Discussions

This section assesses the performance of the proposed energy-efficient fiber backhaul topology design in relation to energy efficiency, cost, scalability, and network performance. The simulation environment was developed using a custom-built system model developed in MATLAB and NS-3. The assessment of the simulation takes into consideration ultra-dense networks with a small cell deployment of 100 to 500 small cells in a 2 km² urban area. The aim of the simulation is to measure the energy efficiency gains realized by optimizing fiber paths and ONU sleep times while meeting the latency and throughput requirements of 5G networks. The simulation parameters are presented in Table 5.

Table 5: Simulation Parameters

| Parameter | Value |
|---|---|
| Number of Small Cells | 100–500 |
| Cell Radius | 150 meters |
| ONU Power (Active / Sleep) | 10 W / 2 W |
| OLT Power | 40 W |
| Fiber Attenuation | 0.2 dB/km |
| ONU Sleep Threshold | 0.1 Mbps |
| User Traffic Pattern | Diurnal (Peak: 8 AM – 10 PM) |

Simulation analysis shows that the ONU sleep scheduling mechanism can effectively decrease the total energy consumption of the ONUs during periods of low traffic. When the traffic in a small cell falls below the 0.1 Mbps threshold, the ONUs enter sleep mode, lowering energy consumption from 10 W to 2 W. For a 500 small cell network: 1) Without sleep scheduling, the total energy consumption of the ONUs remains unchanged. 2) With adaptive sleep scheduling, the maximum daily energy savings is 30-34%. 3) Energy savings are most noticeable between 11 PM and 6 AM when user activity is low. The total energy consumption grows linearly with the number of deployed small cells, but the percentage energy savings remains the same regardless of network size, ensuring that the optimization framework is scalable. The

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

following Fig. 2 depicts the variation of energy savings and average power consumption for various time intervals of a day in the proposed sleep-aware backhaul framework. It can be noted that the maximum energy savings are achieved during the off-peak hours (00:00-06:00), where the energy savings are around 50%. This substantial amount of energy savings is mainly due to the low traffic demand during the night hours, which allows a substantial number of Optical Network Units (ONUs) to go to sleep. Consequently, the cumulative power consumption reduces substantially during these hours.

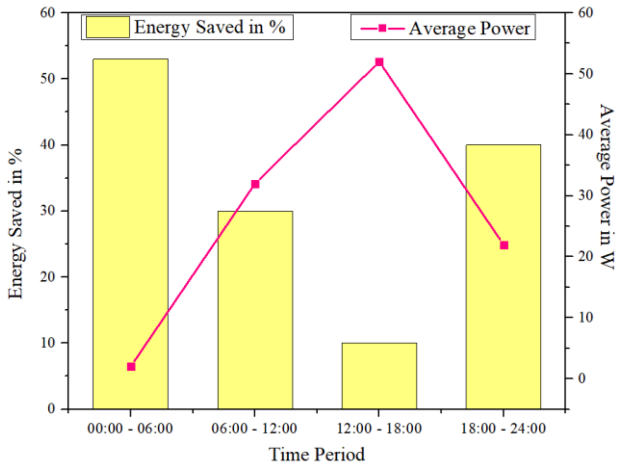


Fig. 2: Energy Saving and Average Power Consumption by Time Period.

During transition phases (06:00-12:00 and 18:00-24:00), moderate energy savings of 30-40% are realized. Despite the increased user traffic during these phases, the adaptive traffic threshold function still enables selective ONU turning off without affecting service availability. Conversely, only minimal energy savings of about 10% are measured during peak phases (12:00-18:00), where most of the ONUs are turned on to support high throughput demands. The average power consumption graph shows an inverse proportionality with energy savings, peaking during peak traffic hours and troughing during off-peak periods. These findings validate that the proposed diurnal traffic-aware sleep scheduling scheme can indeed lower daily energy consumption without disrupting network stability and performance demands.

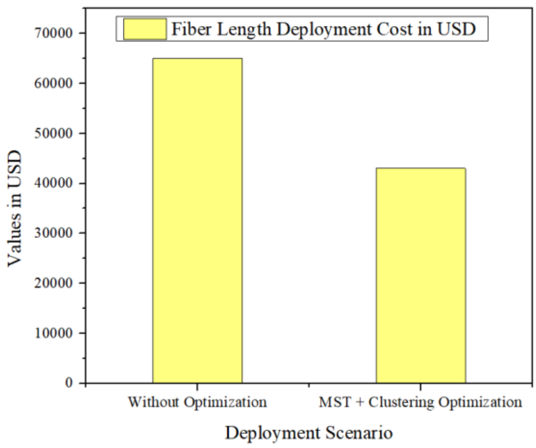


Fig. 3: Impact of Optimization on Fiber Backhaul Development.

The following Fig. 3 shows the effect of the proposed Minimum Spanning Tree (MST)-based routing and clustering optimization on total fiber length and cost of deployment. A significant decrease of about 33% in fiber length is noticed when optimization methods are used compared to a non-optimized deployment approach. This, in turn, directly affects the trenching requirements and installation costs. The cost of deployment is also seen to have a proportional decrease of about 33%, which emphasizes the efficacy of combining graph-based routing with clustering optimization for OLT assignment. By clustering small cells that are geographically close and reducing redundant fiber paths, the network becomes more structurally optimized and balanced for load distribution at the aggregation points.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

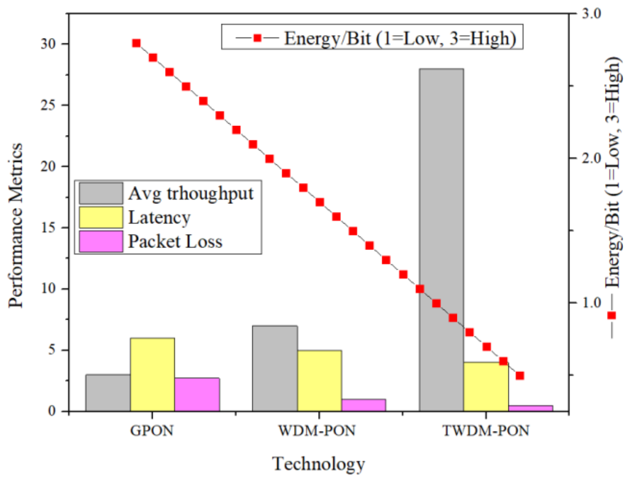


Fig. 4: Comparison of PON Technologies for 5G Backhaul.

These results clearly show that infrastructure-level optimization plays a crucial role in improving cost-effectiveness, thus making the ultra-dense 5G fiber backhaul network economically feasible. The following Fig. 4 shows a comparative performance analysis of GPON, WDM-PON, and TWDM-PON systems for 5G backhaul networks. The results clearly indicate that the data rate improves dramatically as the architecture progresses from GPON to TWDM-PON. GPON supports an average data rate of about 2 Gbps, making it suitable for moderate-density networks. WDM-PON supports an improved data rate of about 7 Gbps, thanks to the wavelength division multiplexing technique that separates the wavelengths and avoids contention. TWDM-PON supports the highest data rate, exceeding 25 Gbps, thus being capable of handling extremely dense 5G networks.

Latency results also show improved performance with the progressive use of three technologies. GPON has relatively higher latency values owing to the bandwidth sharing technique, whereas WDM-PON and TWDM-PON have better wavelength management techniques, thus reducing latency. Packet loss values also reduce with the increasing availability of bandwidth, and TWDM-PON has the most stable transmission.

However, it is also seen from the figure that there is a trade-off between performance and energy consumption. Although TWDM-PON has the best performance and lowest latency, it consumes relatively higher amounts of power and has higher installation costs. GPON is still the most energy-efficient technology but has no scalability for future ultra-dense networks. WDM-PON is found to be a balanced technology, which has relatively better performance with moderate energy consumption.

## 4. CONCLUSIONS

This paper has discussed an energy-efficient fiber backhaul network design specifically targeted for ultra-dense 5G small cell networks. By combining PON-based infrastructure with topology optimization algorithms such as MST routing and clustering, the proposed approach has been able to lower the cost of deployment by a substantial margin while preserving high capacity and low latency performance. Additionally, the application of traffic-aware ONU sleep scheduling has been able to provide a noticeable reduction in operational energy costs, especially during the off-peak period, thus reducing the overall energy consumption and carbon footprint without affecting the QoS. Notwithstanding these encouraging results, the issues of long-term scalability, legacy telecom network integration, and dynamic traffic patterns still assume significance. More advanced PON flavors like WDM-PON and TWDM-PON will assume pivotal importance in meeting the future requirements of capacity augmentation, and more advanced SDN-based orchestration will be required to handle the dynamic traffic patterns. In summary, the proposed solution offers a cost-effective, sustainable, and future-proof vision for the fiber-optic 5G backhaul network, which can also be applied to the future 6G network architecture. Further experimental and deployment studies can help enhance its feasibility.

## DECLARATIONS

**Acknowledgments**
The authors are greatly thankful to the Fiber Optic Research Lab (FORC) provided by the Thapar Institute of Engineering and Technology, Patiala, for supporting our research.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

### Ethical Approval
Not Applicable

### Funding
The authors declare that no funds or grants were received for this manuscript.

### Competing Interests
The authors do not have any known conflicts of interest related to this research.

### Authors' Contributions
Dr. Harpreet Kaur has contributed to the work idea, writing, results, and original draft of the manuscript. Dr. R. S. Kaler provided supervision for this work.

### Availability of data and materials
Not applicable.

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