# Optical Network Slicing for 5G: Enabling Flexible and Scalable Connectivity

S. Kokila [1], T. Princess Raichel [2], K. Thiagarajan [3], A. Anburaj [4]
Associate Professor, Sri Venkateswara College of Engineering & Technology[3]
Assistant Professor, Sri Venkateswara College of Engineering & Technology[1,2,4]
Sri Venkateswara College of Engineering and Technology, India.

**Abstract – Optical networks utilize light signals to transfer information rapidly through strands of fiber optic cables, enabling high-speed data communication. They play a crucial role in modern telecommunications, enabling fast and reliable data transfer over long distances. Optical Network Slicing [11] (ONS) is a technology that enables the creation of multiple independent and isolated network slices over a shared optical infrastructure. Optical Network Slicing for 5G, leveraging a SLED (Software-Defined Light path Ethernet) architecture, enables flexible and scalable connectivity by creating virtualized, isolated network segments on shared physical infrastructure. This approach allows for customized network slices tailored to specific services, like ultra-reliable low latency communication (URLLC) for autonomous vehicles, or high-speed, high-capacity connections for enhanced mobile broadband (eMBB). ONS, supported by technologies like Software-Defined Networking (SDN) and Network Function Virtualization (NFV), enables dynamic resource allocation and management, addressing the diverse and evolving requirements of 5G applications.**

**Index Terms – ONS, SLED, SDN, Optical Networks, URLLC**

## 1. INTRODUCTION

Optical networking is an advanced method of communication that sends data using light pulses through fiber-optic cables. It uses various optical tools—like transmitters, amplifiers, and fiber-based infrastructure—to support high-speed data transfer over long distances. Compared to traditional copper wiring, fiber optics offer much higher bandwidth, allowing quicker and more reliable communication. The main components of an optical network include fiber-optic cables, transmitters, receivers, amplifiers, transceivers, Wavelength Division Multiplexing (WDM) technology, optical switches, routers, optical cross-connects (OXCs), and optical add-drop multiplexers (OADMs).**Fiber optic cables**

Fiber optic cables are a type of high-capacity transmission medium with glass or plastic strands known as optical fibers[12].

These fibers carry light signals over long distances with minimal signal loss and high data transfer rates. A cladding material surrounds the core of each fiber, reflecting the light signals back into the core for efficient transmission.

Fiber optic cables are widely used in telecommunications and networking applications due to immunity to electromagnetic interference and reduced signal attenuation compared to traditional copper cables. An optical transmitter plays a key role in fiber-optic communication by converting electrical signals into light-based signals. It does this by using a light source, such as a laser diode or LED, which is adjusted or modulated based on the incoming electrical data to produce corresponding light pulses for transmission. Optical amplifiers are positioned at specific intervals along a fiber-optic network to strengthen weakening light signals. By directly boosting the optical signal without converting it back into electrical form, they help overcome signal loss over long distances and reduce the need for costly optical-electrical conversions.

**Optical Networking Process:**

At the receiving end of a fiber-optic connection, optical receivers convert the light-based signals back into electrical form for further processing or interpretation. Transceivers, short for transmitter-receiver units, are compact devices that combine both transmission and reception functions into one module, allowing data to flow in both directions over fiber-optic cables. They transform electrical signals into light for sending and convert incoming optical signals back into electrical form for processing.

## 2. METHODOLOGY

A. **Dense Wavelength Division Multiplexing (DWDM):** is a technology that multiplexes multiple optical signals with different wavelengths onto a single fiber, increasing network capacity and bandwidth. It enables high-speed data transmission over long distances, making it ideal for telecommunications, data centers, and 5G networks. DWDM offers high capacity, scalability, and flexibility, but requires careful management of signal degradation and inter-channel interference.

B. **Autotunable Optics**: These optics allow for automatic adjustment of wavelengths, enabling efficient communication between devices without manual intervention. Autotunable Optics are advanced optical systems that can automatically adjust their properties, such as wavelength or phase, to optimize performance. They enable efficient and dynamic communication in optical networks, particularly in applications like Optical communication systems, Fiber optic networks, Wavelength division multiplexing (WDM).Autotunable optics improve network flexibility, scalability, and reliability by adapting to changing conditions and requirements.

C. **Four-Level Phase-Amplitude Modulation (PAM4) Encoding**: This encoding technique doubles data transmission rates by using four-level phase-amplitude modulation, which is crucial for 5G transmission. is a modulation technique that uses four amplitude levels to encode data, enabling higher data transmission rates and increased bandwidth efficiency. It's used in high-speed applications like data centers, optical communication systems, and high-speed interconnects, offering advantages like higher data rates and improved signal-to-noise ratio.

D. **Optical Wireless Communication (OWC) Technologies:** OWC technologies, such as Visible Light Communication (VLC), Light Fidelity (LiFi), Optical Camera Communication (OCC), and Free Space Optics (FSO) communication, provide high-speed, low-latency, and secure connectivity, uses light to transmit data wirelessly, offering high-speed, secure, and license-free communication. It includes technologies like Li-Fi and Free Space Optics (FSO), suitable for indoor and outdoor applications, providing benefits like high-speed data transfer, low latency, and enhanced security.

E. **Network Densification:** This involves deploying more cell sites to increase capacity, reduce latency, and improve overall network performance. Network densification in 5G optical networks refers to the process of adding more cell sites or nodes to increase capacity, coverage, and overall network performance. This approach is crucial for meeting the stringent requirements of 5G communication systems, including high data rates, low latency, and massive connectivity.

F. **Multi-Tier Architecture**: Implementing a multi-tier architecture with larger coverage satellite and/or macrocell networks underlying small cells can help meet the demands of future communication systems. A design approach that separates the network into multiple layers or tiers, each with specific responsibilities. This architecture is crucial for meeting the demands of future communication systems, including high capacity, massive connectivity, low latency, and high security.

G. **Advanced Modulation Schemes**: Techniques like orthogonal frequency division multiplexing (OFDM) and space division multiplexing (SDM) are being explored to improve spectral efficiency and reduce latency. Advanced modulation schemes in 5G optical networks refer to techniques used to encode data onto optical signals for high-speed transmission. These schemes enable faster data rates, improved spectral efficiency, and increased network capacity.

**H. Software-Defined Networking (SDN)**: is a forward-looking approach to network management that uses software to control and configure network behavior from a central system.By decoupling the decision-making layer (control plane) from the data transport layer (data plane), SDN allows for flexible adjustments, faster deployments, and comprehensive oversight of network traffic across diverse hardware systems.

**Architecture:**

In traditional networks, every switch or router manages two key roles: deciding how data moves (control plane) and actually moving the data (data plane). Each device has to make its own decisions about traffic flow, which makes managing large networks complicated.

Software-Defined Networking (SDN)[3] changes this by taking the decision-making (control plane) out of individual devices and putting it into a centralized system known as an SDN controller. This controller becomes the brain of the network, allowing administrators to configure and control everything from one place instead of logging into each switch or router separately.

Meanwhile, the switches still handle data movement (data plane), but they now follow instructions from the controller. These instructions come in the form of flow entries, which tell the switch what to do when it sees certain types of traffic—like forward it, drop it, or modify it. If a switch receives a packet it doesn't recognize, it asks the controller what to do next.

**Three Main Layers of SDN**

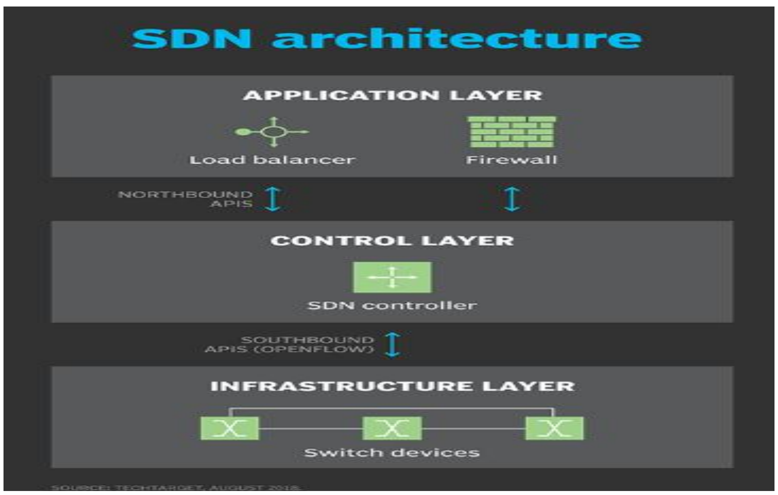


Figure 1: SDN Architecture

**Application Layer**

This top layer in figure 1 [16] includes tools and programs that rely on network data things like traffic analyzers, firewalls, and load balancers.

These apps communicate with the SDN controller to make requests or get updates about what's happening in the network.

**Control Layer**

This is where the SDN controller lives. It's responsible for making smart decisions about routing and policy enforcement.

It gives applications a simplified, high-level view of the network and translates their requests into actions on the hardware below.

**Infrastructure Layer:**

This is the foundation—made up of the actual physical or virtual switches that move packets.

These switches carry out the orders sent by the controller and make up the data plane.

**NFV (Network Function Virtualization):**

NFV takes things a step further by moving network functions like firewalls, load balancers, or encryption off of special hardware and onto virtual machines. So instead of needing a physical firewall box, you can run it as software on a regular server.

This allows for more flexible and responsive networks, especially in things like 5G or fiber-optic networks[5] where needs can change rapidly. It also makes it easier to allocate resources on demand and launch services faster.

## 3. EMERGING TECHNOLOGIES

OTN[4] is a set of optical network elements connected by optical fiber links that provides transport, multiplexing, switching, management, supervision, and survivability of optical channels carrying client signals. It is specified by the ITU-T G.709 standard and is commonly known as the "digital wrapper" technology. It supports a wide range of client signals (e.g., Ethernet, SONET/SDH, Fibre Channel) without altering their structure and allows multiple lower-rate signals to be combined into a higher-rate signal using Optical channel Data Unit (ODU) containers. Enhances signal integrity over long distances by detecting and correcting errors by Forward Error Correction. Provides robust Operations, Administration, Maintenance, and Provisioning (OAM&P) capabilities, supports both optical and electrical switching for flexible and efficient bandwidth management.

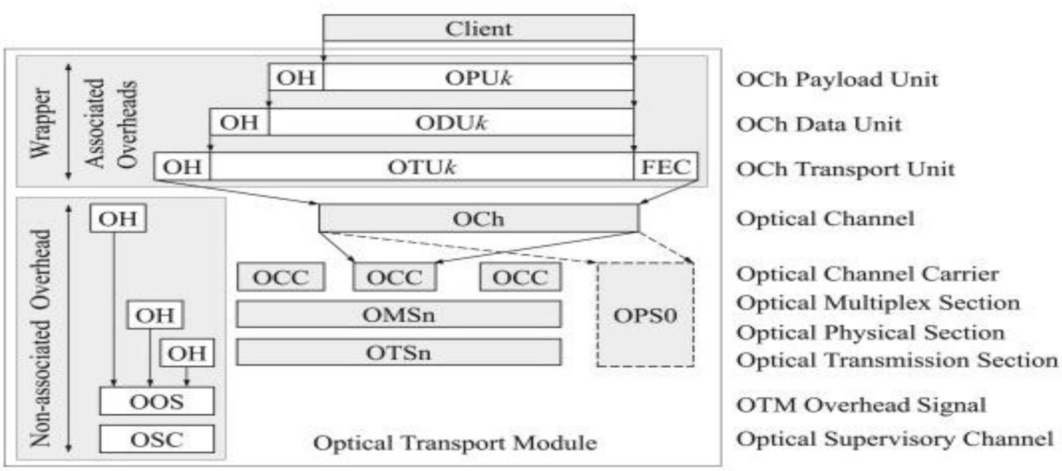


Figure 2: OTN layering architecture

Figure 2. explains clearly about the layering architecture in Optical Transport Network [14]

- Client Signals: These are the original data streams (e.g., Ethernet, SDH, Fibre Channel).
- OPUk (Optical Payload Unit): Encapsulates the client signal.
- ODUk (Optical Data Unit): Adds overhead for path monitoring.
- OTUk (Optical Transport Unit): Adds FEC and section overhead.
- OCh (Optical Channel): Represents the modulated optical signal.
- OMS (Optical Multiplex Section): Manages multiple optical channels.
- OTS (Optical Transmission Section): Handles the physical fiber transmission.

**OTN Frame Structure**

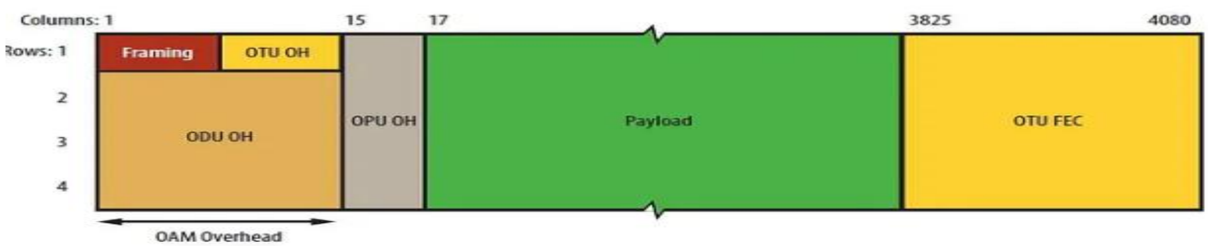


Fig 3: OTN Frame Structure

In fig 3. OTN frame Structure [13] includes:

- Payload area: Carries the client signal.
- Overhead: For management and error correction.
- FEC: For error detection and correction.

**Wavelength Division Multiplexing (WDM)** is a technology used in fiber-optic communications to increase bandwidth by allowing multiple data streams to be transmitted simultaneously over a single optical fiber. It achieves this by using different wavelengths (or colors) of laser light to carry different signals.

WDM works by **multiplexing** (combining) multiple optical carrier signals on a single optical fiber by using different wavelengths of laser light. Each wavelength carries a separate data stream. At the receiving end, a **demultiplexer** separates the combined signal back into individual data streams.

There are two main types:

**CWDM (Coarse Wavelength Division Multiplexing):**

- Uses fewer channels (typically 8 or 16).
- Wavelength spacing is wider (20 nm).
- Lower cost and power consumption.
- Suitable for shorter distances (up to ~80 km).

**DWDM (Dense Wavelength Division Multiplexing):**

- Supports many more channels (up to 160 or more).
- Narrower spacing (0.8 nm or less).
- Higher cost but supports long-distance transmission (hundreds of km with amplification).
- Used in backbone networks and undersea cables.

Multiplexer → Transmitters (Optical Fiber) → Demultiplexer

- Transmitters: Each one sends data using a unique wavelength (color).
- Multiplexer: Combines all wavelengths into a single optical signal.
- Optical Fiber: Carries the combined signal over long distances.
- Demultiplexer: Splits the signal back into individual wavelengths.
- Receivers: Each one receives data from a specific wavelength.

**Passive Optical Networks (PONs)** are a type of fiber-optic telecommunications technology used to provide broadband network access to end-users. They are called "passive" because they use unpowered (passive) optical splitters to divide a single optical fiber into multiple signals, serving multiple premises without requiring electrical power in the distribution network.

Optical Line Terminal (OLT) is located at the service provider's central office and sends downstream data to users and receives upstream data.

Optical Network Unit (ONU) / Optical Network Terminal (ONT) is located at the user's premises and converts optical signals to electrical signals and vice versa.

Optical Splitter is a passive device that splits one optical signal into multiple signals it typically supports 1:32 or 1:64 splits.

| Type | Downstream | Upstream | Use Case |
|---|---|---|---|
| **GPON** (Gigabit PON) | 2.5 Gbps | 1.25 Gbps | Widely used in FTTH (Fiber to the Home) |
| **EPON** (Ethernet PON) | 1 Gbps | 1 Gbps | Ethernet-based, popular in Asia |
| **XG-PON** | 10 Gbps | 2.5 Gbps | Next-gen high-speed networks |
| **NG-PON2** | 40 Gbps | 10 Gbps | Supports multiple wavelengths |

- **Cost-effective**:Fewer active components reduce maintenance and power costs.
- **Scalable**: Easily supports many users with a single fiber.
- **High Bandwidth**: Ideal for modern internet, IPTV, and VoIP services.
- **Secure**: Optical fibers are difficult to tap without detection.

**Radio over Fiber (RoF)** is a technology that combines radio frequency (RF) and optical fiber transmission to deliver wireless signals over long distances with minimal loss. It's widely used in modern wireless communication systems, especially in 5G, distributed antenna systems (DAS), and remote radio heads (RRH).

RoF involves modulating a light signal with a radio signal and transmitting it over an optical fiber. At the receiving end, the optical signal is converted back into an RF signal and transmitted wirelessly.

1. **Central Station (CS)**:
    - Generates and modulates RF signals.
    - Convert RF to optical signals using a laser.
2. **Optical Fiber Link**:
    - Carries the modulated optical signal to remote sites.
    - Offers low loss and high bandwidth.
3. **Remote Antenna Unit (RAU)**:
    - Converts optical signals back to RF.
    - Transmits RF signals wirelessly to end-users.

| Technique | Description | Use Case |
|---|---|---|
| **Analog RoF** | Direct modulation of RF onto optical carrier | Low complexity, used in DAS |
| **Digital RoF** | Digitizes RF signal before optical transmission | Higher fidelity, used in 5G |
| **Hybrid RoF** | Combines analog and digital methods | Balances cost and performance |

- **Low Signal Loss**: Optical fibers have much lower attenuation than coaxial cables.
- **Centralized Processing**: Simplifies network management and reduces equipment at remote sites.
- **High Bandwidth**: Supports wide RF spectrum, ideal for 5G and beyond.
- **Scalability**: Easily supports multiple antennas and cells.

## 4. CHALLENGE IN OPTICAL NETWORKING

**5G Network Slicing**

Network slicing[8] is a key challenge in 5G optical networks that need to support network slicing to ensure isolated and secure transmission of different services., a key innovation in 5G.[1] divides a single network infrastructure into multiple virtual networks. Each "slice" functions independently and is tailored to specific applications or service types.

This section outlines how slicing enables telecom operators to build, modify, and scale virtual networks rapidly. It also introduces various slicing strategies and models, including static/dynamic slices and service-specific categories such as Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and Reduced Capability (RedCap).

With slicing, operators can assign virtual network layers with distinct configurations aligned to different service-level agreements (SLAs) and performance metrics such as speed, coverage, and latency.

Speed-related performance indicators include peak throughput, latency, and average download rates. However, coverage still depends on infrastructure like small cells and the radio access network (RAN), rather than slicing alone.

Each network slice is securely isolated and safeguarded using 5G-specific security protocols, such as Authentication and Key Agreement (5G-AKA), EAP-AKA, and the Subscription Concealed Identifier (SUCI). These technologies secure user identities, ensure encrypted access, and uphold data confidentiality. IPsec encryption may also be applied to safeguard control signaling and external communications.

Security can be further strengthened with advanced tools such as slice-specific firewalls, zero-trust models, and artificial intelligence for real-time threat analysis and defense.

**Scalable, Flexible, and Application-Specific:**

Unlike earlier mobile network generations, 5G slicing[10] allows for customized networking using intelligent software control. Through technologies like Software-Defined Networking (SDN) and Network Functions Virtualization (NFV), operators gain flexibility[2], automation, and optimal resource use.

This makes it possible to launch or adjust virtual networks quickly, without needing to upgrade or expand physical hardware continuously.

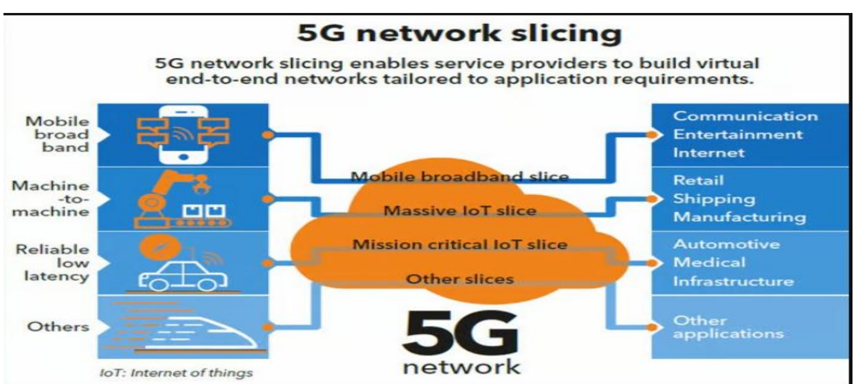

Figure 4. Using network slicing, providers can deliver custom performance and pricing solutions for targeted sectors [15].

Network operators including MNOs, MVNOs, and private enterprises—can build specialized service slices. Healthcare providers might deploy separate slices for mission-critical surgery with ultra-low latency, another for patient communication, and one for hospital data handling.

Banks could use high-security slices for secure transactions, a second for fraud detection powered by AI, and a third for high-speed trading systems.

In automotive systems, slices may support real-time communication, infotainment, and advanced driver-assist technologies.

Smart manufacturing plants can assign dedicated slices to automation systems, monitoring tools, voice services, and robotics, each operating without bottlenecks.

**Static vs Dynamic Network Slicing**

**Static Slicing:** Fixed resources are reserved for specific network slices. This is useful for situations where performance can't vary—like emergency services or automated systems[7].

**Dynamic Slicing:** Resources are adjusted in real time based on demand. This makes better use of available capacity and helps networks adapt quickly when needs shift.

Dynamic slicing allows organizations to scale and change their virtual networks quickly, with minimal manual effort. It supports automation and flexible network management[6].

## 5. CONCLUSION

Optical network slicing is poised to revolutionize the way we approach connectivity in 5G networks[9]. By leveraging the flexibility and scalability of optical networking, service providers can create customized network slices that cater to diverse use cases and applications. This technology has the potential to unlock new revenue streams, improve network efficiency, and enable innovative services. As the demand for high-bandwidth and low-latency connectivity continues to grow, optical network slicing will play a vital role in shaping the future of telecommunications

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