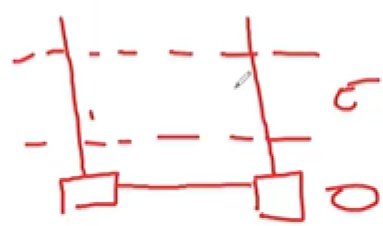
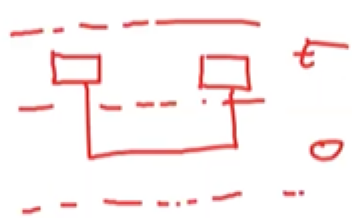
07 - Optical networks - 2nd generation

Second generation of optical network: architecture

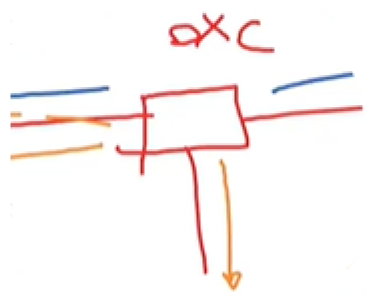
Introduction to second generation of optical networks

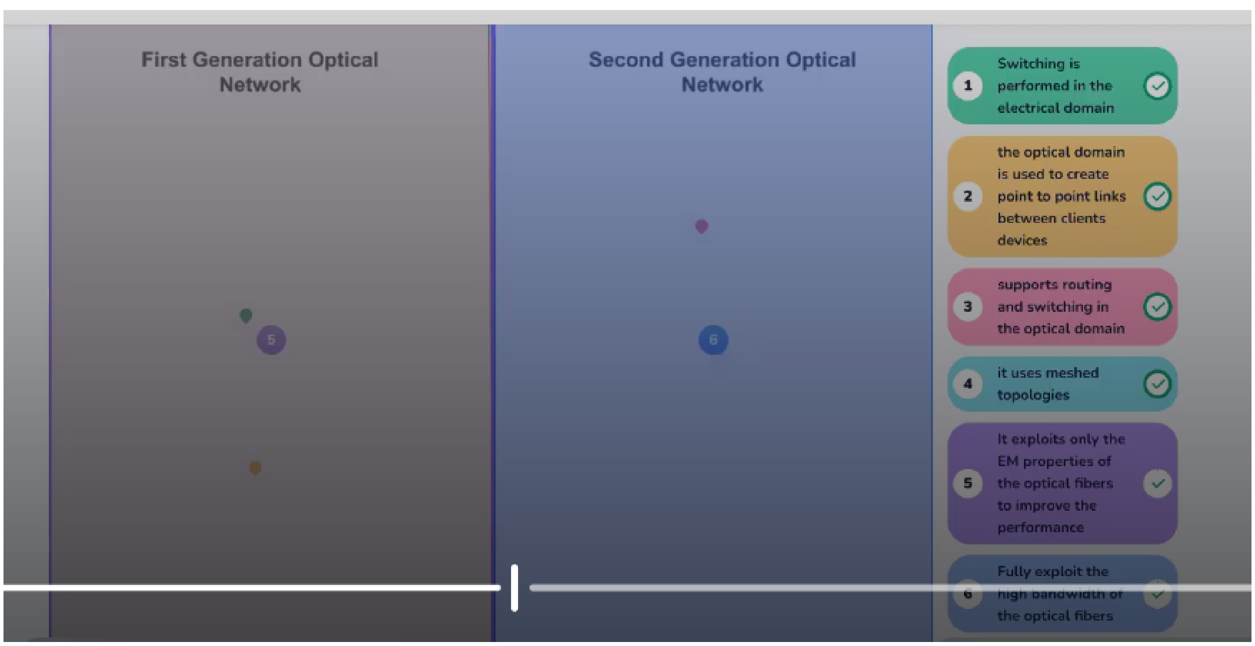
The key advancement in second-generation optical networks is the transition of switching operations from the **electrical domain** to the **optical domain**. This allows for faster and more efficient data handling, as it eliminates the need to convert optical signals into electrical signals for switching processes.





In second-generation optical networks, when signals are in the electrical domain, the incoming signal is digitized, converting it from analog to digital. This process allows the recovery of the binary string encoded in the electrical domain, including all relevant information like addresses. In the optical domain, however, only analog signals are handled, meaning that what enters the switch is a light ray, and no conversion to the electrical domain occurs.





First Generation Optical Network (Points: 1, 5)

1. Switching is performed in the electrical domain.

5. Optical fibers are used only to gain advantages in terms of attenuation and speed.

Second Generation Optical Network (Points: 2, 3, 4, 6)

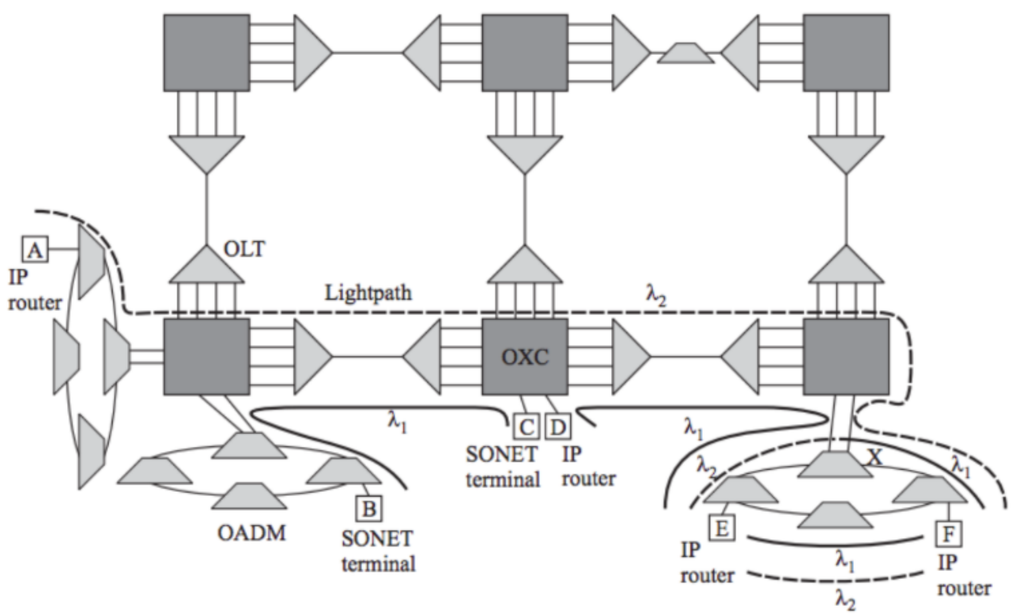
2. The optical domain is used to create point-to-point links between client devices.

3. In the first generation, optics were used solely to establish point-to-point communication. In the second generation, optics support routing and switching in the optical domain.

4. It uses meshed topologies to improve network reliability and scalability.

6. When aggregating tributary flows in TDM, the electronic card must transmit at a speed equal to $N \times \text{input\_dim}$ where N is the number of flows. In WDM, the very large bandwidth of optical fibers is exploited by sending multiple wavelengths λ through the same optical fiber, leaving the electronics untouched.

General architecture



About Point-to-Point Components:

- **Square: Optical Cross Connect (OXC)**

The Optical Cross Connect functions similarly to a router, performing both **switching** and **routing** operations. It is a **multiport device** with a large number of ports, making it suitable for handling extensive network connections.

- **Triangle: Optical Line Terminal (OLT)**

  The Optical Line Terminal marks the **termination of a line**. Two triangles together represent an **optical link**.

- **Trapezoid: Optical Add-Drop Multiplexer (OADM)**

  The OADM is similar to an OXC but operates on a **smaller scale**. It typically has **4 ports**: one **incoming fiber**, one **linking fiber**, and two additional fibers.

The main difference between an OXC and an OADM lies in their **reconfigurability**. The OXC is fully reconfigurable, meaning its operation can be dynamically adjusted as needed. For example, if it detects a red wavelength λ at a specific time t, it can be reconfigured to route that wavelength through a different input and output port, effectively changing how the switching is performed. On the other hand, the OADM is fixed in its configuration and does not allow for dynamic reconfiguration.

Another distinction lies in their **position within the network**. OXCs are typically deployed in **core networks**, where high capacity and greater flexibility are essential. In contrast, OADMs are more commonly found in **access or metro networks**, where the demands are less complex, and the need for advanced reconfiguration is minimal.

In the image, the **core network** typically uses a **mesh topology**, ensuring high reliability and flexibility in routing. At the **edge of the network**, the topology is generally a **ring** and is primarily composed of **Optical Add-Drop Multiplexers (OADMs)**.

At the **very edge of the network**, we find the **clients**, which can include **IP routers** and **SONET** devices (Synchronous Optical Networking, a standardized protocol for transmitting digital data over optical fiber). This architecture enables a **single infrastructure** to serve various types of clients, demonstrating the **transparency**

property of the network. Transparency means that the network does not impose restrictions on who or what it serves, which is particularly advantageous for business interests, as it allows the same infrastructure to support a broader range of clients.

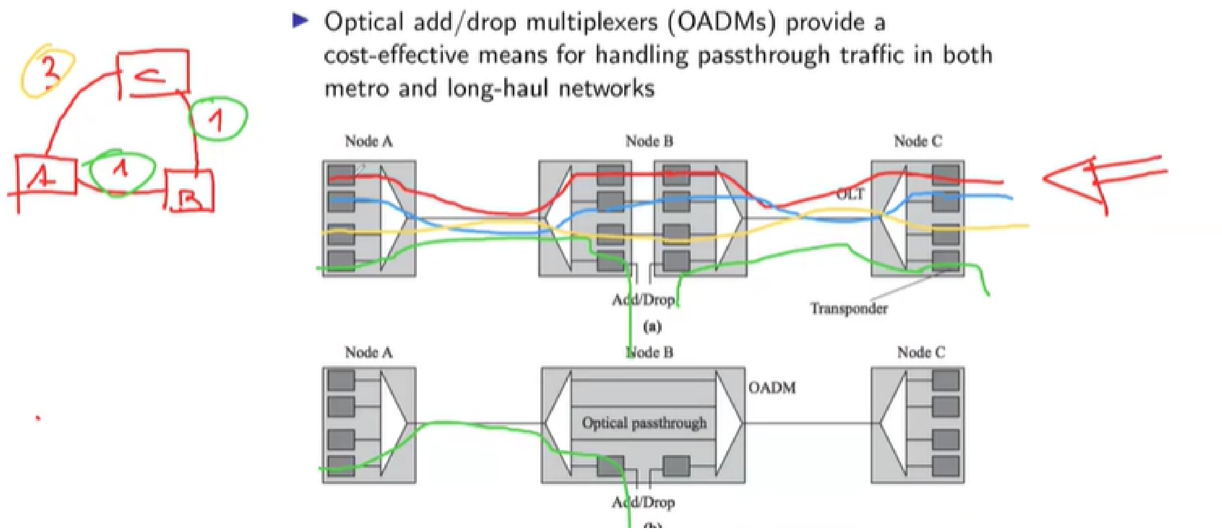
To clarify the concept of transparency, we can consider an example of a transport service. A **school bus**, which transports only children, is **not transparent**, as it is designed for a specific type of client. In contrast, **ATAC (the public transport service)** is **transparent**, as it serves all types of clients using the same infrastructure. Similarly, a transparent network can serve multiple types of clients, maximizing its utility and adaptability.

Flow of lightpaths

A **lightpath** is the interconnection between two clients. Depending on the technology, the wavelength (color of the ray) must remain the same from source to destination. If a wavelength change is needed, the signal must be converted from the optical to the electrical domain and then sent using a different laser with the new color.

If the signal remains in the optical domain, the wavelength must stay consistent throughout the path. Since multiplexing is based on wavelengths, if two users request the same wavelength, the second user may find it occupied and their request can be rejected. This issue can be addressed using **wavelength switching** to find a path with the desired wavelength available or through routing techniques to choose a suitable path.

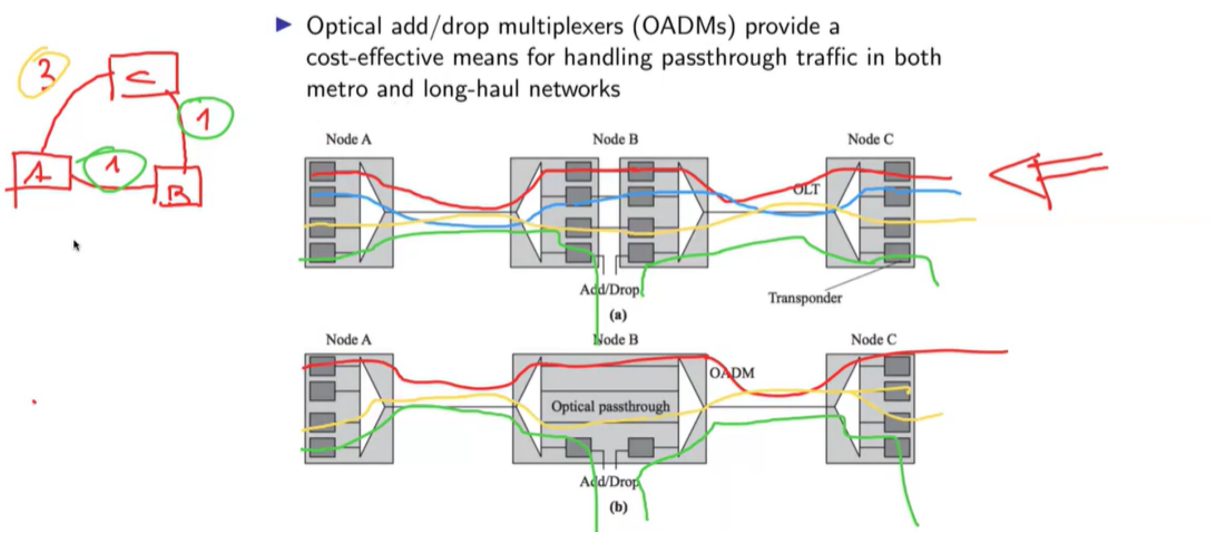
Example: find lightpath given a certain configuration



This solution work but has a significant drawback: it requires **16 transponders**, which are expensive, consume a lot of power, and take up considerable space. To address this, a more cost-effective approach is to use **Optical Add-Drop Multiplexers (OADM)**, which reduce the number of required transponders.

At a central node, most of the traffic is **optical passthrough**—traffic that simply passes through without requiring processing. OADMs enable selective multiplexing, avoiding the need to demultiplex all the traffic every time.

This can be compared to the **Grande Raccordo Anulare (GRA)**, a highway around Rome. Most of the traffic on the GRA is passthrough, but occasionally, vehicles enter or exit at specific points (analogous to the "add" and "drop" functions in OADM). Similarly, OADMs allow local traffic to join or leave the main optical highway without affecting the bulk of passthrough traffic.



In the second scenario, we can observe that transponders are no longer used. This means there is no need for devices to **convert wavelengths** or perform other related functions, significantly reducing costs, power consumption, and complexity.

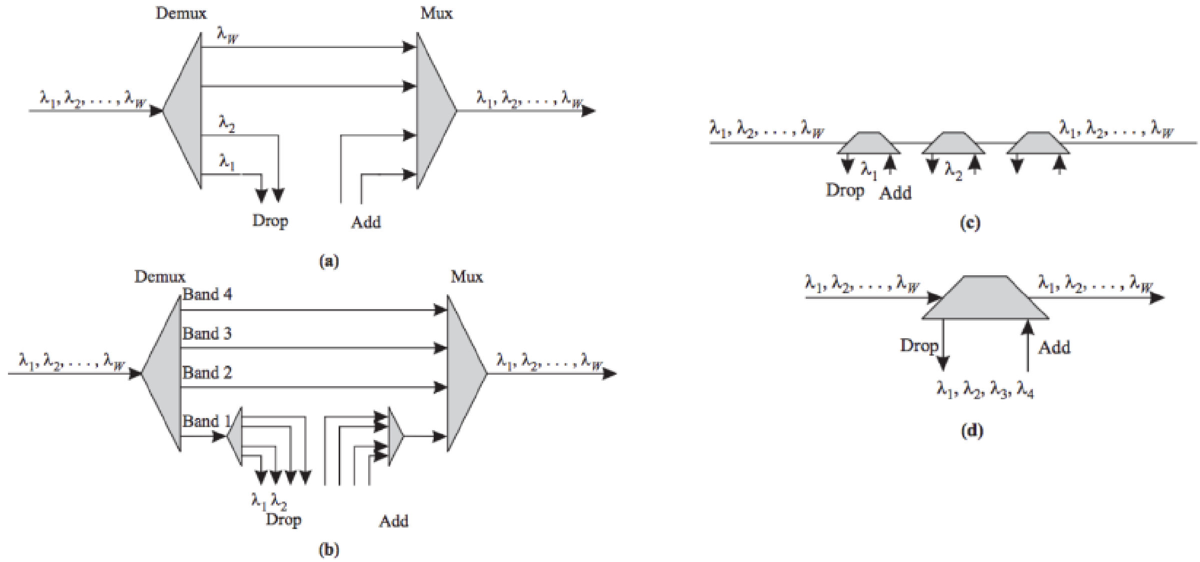
OADM (Optical Add-Drop Multiplexer)

OADM (Optical Add-Drop Multiplexer) is composed by

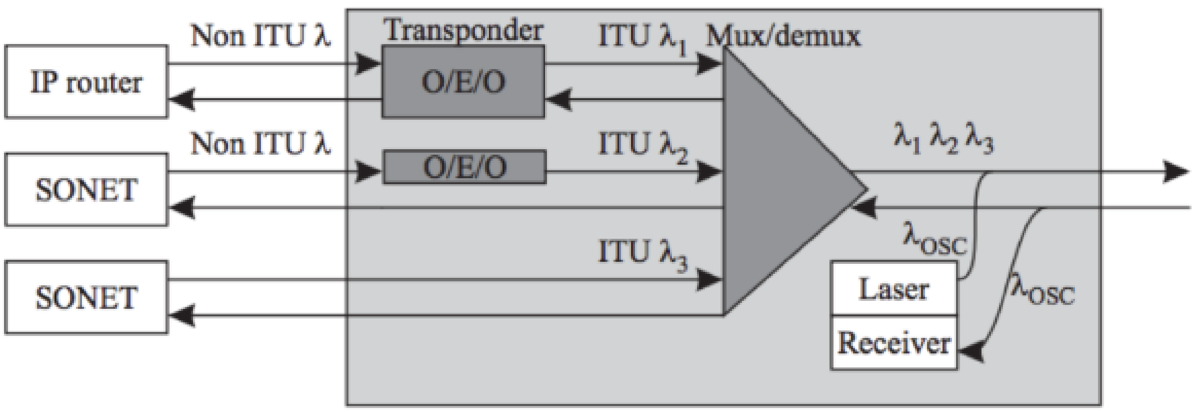
- **3 fibers** for passthrough traffic.
- **1 fiber** for add/drop operations.

At the **ingress**, there is a **demultiplexer**, which takes the input signal (a light beam composed of different wavelengths, like a rainbow) and physically divides it into its constituent colors. This is achieved using a physical device, similar to a prism, which automatically separates the wavelengths.

The same wavelengths are always dropped and added, allowing the OADM to manage specific local traffic while leaving the passthrough traffic unaffected.



OLT (Optical Line Terminal)



Optical line terminal

An OLT is one of the two endpoints in an **end-to-end optical connection**. It typically includes **transponders**, a **wavelength multiplexer**, and an **optical amplifier** to boost the signal's power.

The **transponder** plays a crucial role as it originates or terminates the optical signal, acting as a **boundary between the optical and electrical domain**s. It converts signals into specific wavelengths suitable for optical transmission. For example, a router with an optical interface is equipped with a transponder to handle such tasks. However, in many cases, it’s unclear whether a device includes a transponder or, if it does, what wavelength it supports.

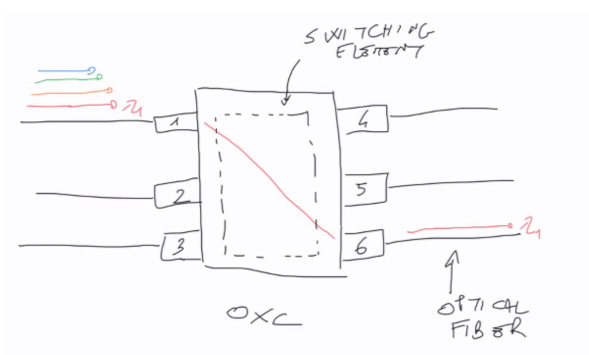
One key function of the OLT is to take the incoming signal and convert it to the correct wavelength for the network.

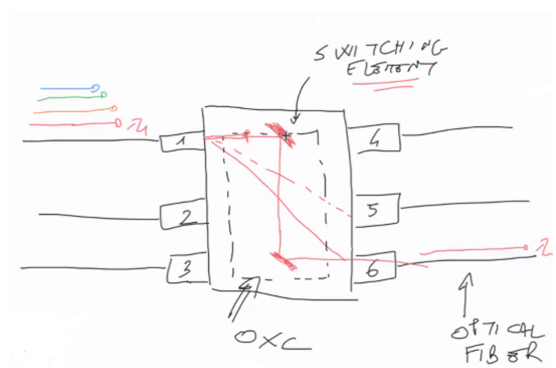
In addition to wavelength conversion, the transponder also adds **overhead** information by performing encapsulation, including adding an **OTN header** (Optical Transport Network header). It also creates and manages the **Optical Supervisory Channels (OSC)**, which are terminated by the OLT for network management purposes.

OCX (Optical crossconnect)

An **Optical Cross-Connect (OXC)** is a device in optical networks that can be compared to a **router or switch** in the electrical domain. It is equipped with **multiple ports**, with each port connected to an incoming optical fiber.

For instance, if a **lightpath** enters through **port 1** and must be directed to **port 6**, the OXC is responsible for handling the signal. If multiple wavelengths λ_i are present on port 1, the OXC must correctly **multiplex and route each wavelength** to its appropriate destination, ensuring no interference or misdirection of the optical signals.





To change the direction of a **light ray** within an optical device, the **phenomenon of reflection** is exploited by using mirrors. These mirrors can dynamically adjust the path of the light.

When we describe a device as **reconfigurable**, it means that the **positions of the mirrors** can be altered to create a new path for the light ray, enabling the device to redirect optical signals flexibly. This capability is essential for adaptive routing and switching in optical networks.

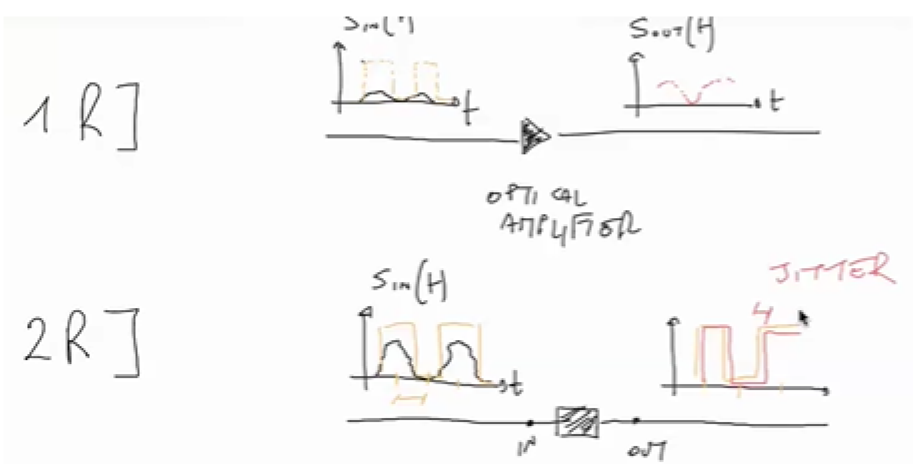
Optical layer

How it work

The **Data Link layer** provides **link connectivity** services, which require fulfilling several functionalities, such as **routing** (necessary in a mesh topology). This layer consists of a **stack of functionalities** designed to ensure reliable data transfer across the network.

In an **all-optical subnetwork**, the infrastructure is primarily realized in the **optical domain**. However, analog signals degrade faster than digital ones. To maintain signal integrity over long paths, it is sometimes necessary to **regenerate** the signal, not just amplify it. Regeneration involves restoring the signal's original quality and characteristics. This process requires electronics, specifically a **transponder (OEO - Optical-Electrical-Optical)**, to perform the regeneration by converting the optical signal to an electrical signal and back to

Regeneration type



Signal regeneration is crucial to maintain the quality of optical signals over long distances. Here's a summary of the three types of regeneration:

- **1R (Amplification):**In this method, the signal is amplified in the **optical domain** using optical amplifiers. It simply boosts the power of the signal but does not restore its original form. As a result, excessive amplification becomes useless if the signal is already too degraded. The main advantage of 1R is that it is **fully transparent**, as it operates purely in the optical domain.

- **2R (Reshaping):** This process involves amplification in the **electrical domain**. It reshapes the signal by clipping light pulses and restoring the degraded signal's form. While the data rate can be recovered by analyzing pulse timing, the clock is not restored. This method is **partially transparent**, as it requires conversion to the electrical domain.
- **3R (Reshaping and Retiming):** Building on 2R, this method not only reshapes but also adjusts the timing of the pulses. A **threshold mechanism** determines the presence of pulses, but it does not fully recover the clock, which can lead to **jitter**—errors in signal offset. Over multiple regenerations, jitter can accumulate, causing distortions. This method is **not fully transparent** because it depends on electrical conversion and timing adjustments.

Note that we lose transparency from optical to electrical domain.

Technology evolution

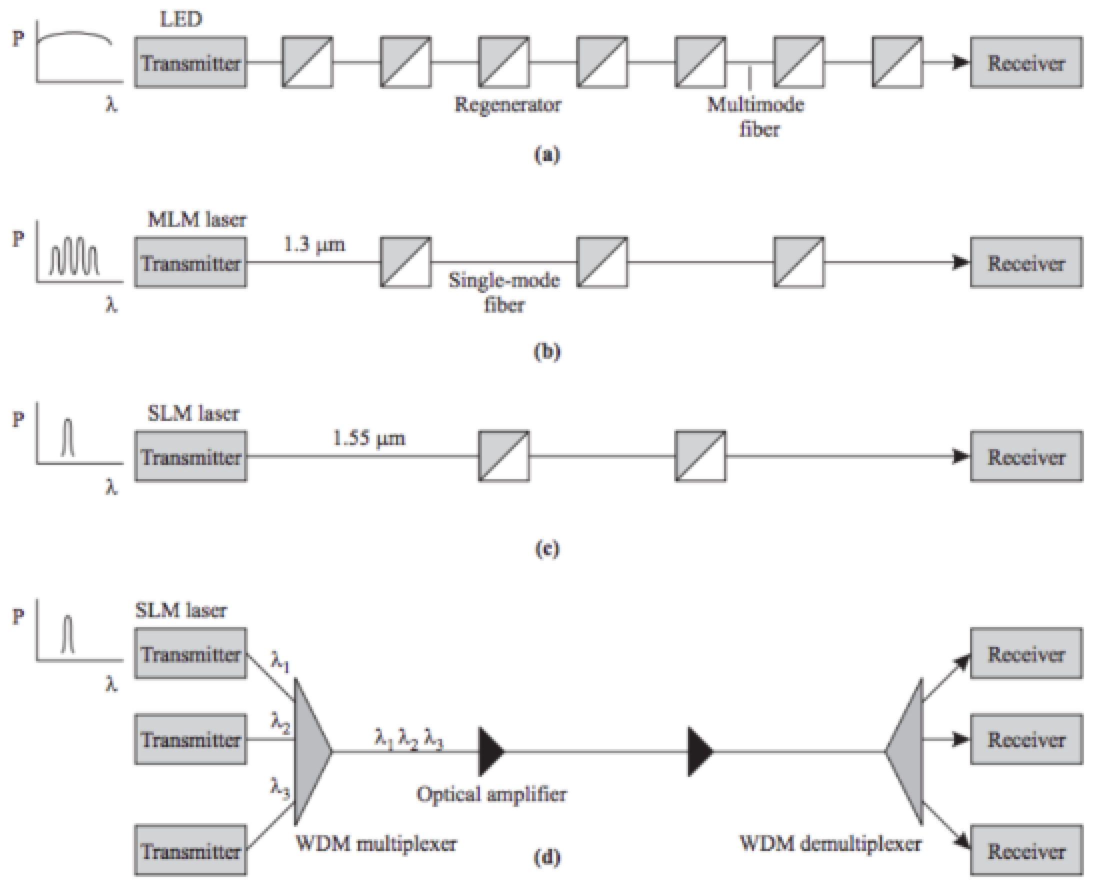


Figure 1.13 Evolution of optical fiber transmission systems. (a) An early system using LEDs over multimode fiber. (b) A system using MLM lasers over single-mode fiber in the 1.3 μm band to overcome intermodal dispersion in multimode fiber. (c) A later system using the 1.55 μm band for lower loss, and using SLM lasers to overcome chromatic dispersion limits. (d) A current-generation WDM system using multiple wavelengths at 1.55 μm and optical amplifiers instead of regenerators. The P-λ curves to the left of the transmitters indicate the power spectrum of the signal transmitted.

Grey mean is working in the electrical domain, white in optical domain. If bot you continually pass betwen these two domains.

The first generation of optical networks relied heavily on **electronic processing** and **Time Division Multiplexing (TDM)** for data transmission. Switching was performed entirely in the **electrical domain**, requiring constant conversion between optical and electrical signals. This process introduced significant inefficiencies, increased costs, and required numerous **regenerators** to counteract signal degradation due to various dispersive phenomena.

Challenges and Limitations:

- **WDM** (Wavelength Division Multiplexing) was not feasible due to the **large size of light rays** (wavelengths) generated by earlier light sources like LEDs.
- Signal degradation was exacerbated by **intermodal dispersion** and other losses, necessitating frequent regeneration.

Improvements to Light Sources:

1. **LED (Light Emitting Diode):** Early light source, inefficient for long-distance optical communication due to high dispersion.
2. **MLM (Multi-Laser Mode):** Improved precision over LEDs, but still suffered from **chromatic dispersion** due to the broader spectrum of emitted light.
3. **SLM (Single-Laser Mode):**
    - Introduced the concept of transmitting a **single light ray** with a narrower wavelength.
    - Reduced **multimodal dispersion** by using fibers with a smaller core, improving signal quality and reducing degradation over long distances.

Mitigating Chromatic Dispersion:

- **Narrower Wavelength Windows:** Using SLM transmitters with more precise wavelength control.
- **Thinner Fiber Cores:** Engineering fibers with smaller cores to reduce multimodal dispersion and enhance signal stability.

The second generation marked the transition to more efficient and scalable systems by adopting **Wavelength Division Multiplexing (WDM)**. In this generation:

- **WDM Multiplexing:** Enabled the simultaneous transmission of multiple light rays (wavelengths) through the same optical fiber, greatly increasing bandwidth.
- **Optical Amplifiers:** Replaced regenerators, reducing reliance on electrical domain processing and maintaining signals entirely in the optical domain.

- **Advanced Transmitters:** Used SLM lasers and other technologies to provide precise, stable light sources for long-distance, high-capacity communication.

This shift allowed second-generation networks to reduce electrical processing and exploit the full potential of optical fibers, making them more efficient, scalable, and capable of handling modern data demands.