Optical Communications and Networks - Review and Evolution (OPTI 500)

Massoud Karbassian
m.karbassian@arizona.edu
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- Summary
Optical Communications and Photonics

- **Photonics** is the science of generating, controlling, processing *photons*.

- **Optical Communications** is the way of interacting with photons to *deliver the information*.

- The term ‘**Photonics**’ first appeared in late 60’s
Why Photonics?

- **Lowest Attenuation** → Attenuation in the optical fibre is much smaller than electrical attenuation in any cable at useful modulation frequencies
  - Much greater distances are possible without repeaters
  - This attenuation is independent of bit-rate

- **Highest Bandwidth** (broadband) → High-speed
  - The higher bandwidth → The richer contents

- **Upgradability** → Optical communication systems can be upgraded to higher bandwidth, more wavelengths by replacing only the transmitters and receivers

- **Low Cost** → For fibres and maintenance
Fibre-Optic as a Medium

- **Core** and **Cladding** are glass with appropriate optical properties!!!
- **Buffer** is plastic for mechanical protection
How Fibre-Optic Works?

Snell’s Law:

\[ n_1 \sin \phi_1 = n_2 \sin \phi_2 \]
Fibre-Optics

- **Fibre-optic** cable functions as a “light guide”, guiding the light from one end to the other end. (i.e. *Optical Channel*)

- Categories based on *propagation*:
  - Single Mode Fibre (SMF)
  - Multimode Fibre (MMF)

- Categories based on *refractive index*:
  - Step Index Fibre (SIF)
  - Graded Index Fibre (GIF)
Fibre-Optics

Index Profile

Fiber Cross Section and Ray Paths

Typical Dimensions

125 μm (cladding)

8–12 μm (core)

125–400 μm (cladding)

50–200 μm (core)

125–140 μm (cladding)

50–100 μm (core)
## Fibre Types

<table>
<thead>
<tr>
<th></th>
<th>made of</th>
<th>utilized wavelength region</th>
<th>attenuation</th>
<th>core diameter</th>
<th>chromatic dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>POF</td>
<td>PMMA</td>
<td>red (650 nm) or infrared</td>
<td>10 dB/km</td>
<td>500…1000 um</td>
<td>0.3 ns/nm/km (material)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25 ns/km (modal)</td>
</tr>
<tr>
<td>MMF</td>
<td>silica</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; or 2&lt;sup&gt;nd&lt;/sup&gt; window (850 or 1310 nm)</td>
<td>3 / 1 dB/km</td>
<td>62.5 um</td>
<td>-86 ps/nm/km (material)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>70 ns/km (modal)</td>
</tr>
<tr>
<td>SMF</td>
<td>silica</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; or 3&lt;sup&gt;rd&lt;/sup&gt; window (1310 or 1550 nm)</td>
<td>0.35 / 0.2 dB/km</td>
<td>9 um</td>
<td>0 or 17 ps/nm/km (chromatic = material + waveguide)</td>
</tr>
<tr>
<td>&quot;dry&quot; SMF</td>
<td>silica</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; to 3&lt;sup&gt;rd&lt;/sup&gt; window (1310 to 1550 nm) removed H&lt;sub&gt;2&lt;/sub&gt;O absorption peak at 1400 nm</td>
<td>0.35…0.2 dB/km</td>
<td>9 um</td>
<td>0…17 ps/nm/km (chromatic) (depending on wavelength)</td>
</tr>
<tr>
<td>DSF</td>
<td>silica</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; window (1550 nm)</td>
<td>0.2 dB/km</td>
<td>8 um</td>
<td>0…2 ps/nm/km (chromatic)</td>
</tr>
<tr>
<td>NZDF</td>
<td>silica</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; window (1550 nm)</td>
<td>0.2 dB/km</td>
<td>9 um</td>
<td>2…6 ps/nm/km (chromatic)</td>
</tr>
<tr>
<td>DM</td>
<td>silica</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; window (1550 nm)</td>
<td>0.2 dB/km</td>
<td>8 um</td>
<td>-2…-5 ps/nm/km (chromatic)</td>
</tr>
<tr>
<td>DCF</td>
<td>silica</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; window (1550 nm)</td>
<td>0.5 dB/km</td>
<td>6 um</td>
<td>-85 ps/nm/km (chromatic = waveguide + material)</td>
</tr>
</tbody>
</table>
Working Frequency Ranges

- Attenuation happens because:
  - Absorption
  - Scattering losses (Rayleigh, Raman...)
  - Bending losses (micro bending)
Working Frequency Ranges
Working Frequency Ranges

<table>
<thead>
<tr>
<th>Band</th>
<th>Label</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-band</td>
<td>“original”</td>
<td>1260…1360 nm</td>
</tr>
<tr>
<td>E-band</td>
<td>“extended”</td>
<td>1360…1440 nm</td>
</tr>
<tr>
<td>S-band</td>
<td>“short”</td>
<td>1440…1530 nm</td>
</tr>
<tr>
<td>C-band</td>
<td>“conventional”</td>
<td>1530…1565 nm</td>
</tr>
<tr>
<td>L-band</td>
<td>“long”</td>
<td>1565…1625 nm</td>
</tr>
<tr>
<td>U-band</td>
<td>“ultralong”</td>
<td>1625…1675 nm</td>
</tr>
</tbody>
</table>
Wavelength Allocation in WDM

The ITU-T DWDM Grid:

The ITU-T Coarse WDM Grid:
Applications of Photonics

- Data Communications (e.g., Networking, Multimedia)
- Information Storage (e.g. CD, DVD, ...)
- Spectroscopy (e.g. Astronomy)
- Display (e.g. TVs and Monitors)
- Medicine (e.g. Laser Surgeries, Optical Imaging,...)
- Holography (e.g. Star Wars-like telepresence)

- Other optics-related applications
2. Optical Communications

System Approach
Optical Communications Transceiver
Optical Sources – L.A.S.E.R

- **Light Amplification by Stimulated Emission of Radiation** (LASER)
  - “Stimulated Emission” *antonym of* “Spontaneous Emission”.
  - Optical transition stimulated by the effect of electric field of light wave; on the contrary, usually emission occur spontaneously without help of the electric field.

- Laser Diodes (LD) and Light Emitting Diodes (LED)
  - LED emits light by spontaneous emission mechanism, while LD has an optical cavity which enables multiplication of photons by stimulated emission.
Optical Modulators

- **Electro-Optic Modulators (EOM)**
  - Phase Modulators (Lithium-Noibate Crystal)
  - Amplitude Modulators (Mach-Zehnder Interferometer)

- **Acousto-Optic Modulators (AOM)**
  - Deflection (Space)
  - Intensity (Power)
  - Frequency
  - Phase
  - Polarization
Optical Detectors – Photo-Detectors (PD)

- PD converts the incident optical power into electrical one.
  - Avalanche Photo-diode (APD)
  - PIN Photo-detector
Analogue to Digital Converters

- **Sampling:** 3.00 2.01 3.20 3.80 1.97 0.25 2.65
- **Quantizing:** 3 2 3 4 2 0 3
- **Digitizing (Binary Encoding):** 0110100111000100000111
Modulation Formats

Amplitude Shift Keying:
\[ \tilde{A}(t) = A_0(t) \cdot \cos(\omega_0(t) + \varphi_0(t)) \cdot \tilde{a}_0(t) \]

Frequency Shift Keying:
\[ \tilde{A}(t) = A_0(t) \cdot \cos(\omega_0(t) + \varphi_0(t)) \cdot \tilde{a}_0(t) \]

Phase Shift Keying:
\[ \tilde{A}(t) = A_0 \cdot \cos(\omega_0 + \varphi_0(t)) \cdot \tilde{a}_0(t) \]
Modulation Formats - Signaling

Time slot for one bit: bit period $T_{\text{bit}}$

$T_{\text{bit}} = 1/B$

where $B$ is the bit rate (or the data rate or the line rate).

Example: $B = 10 \text{ Gbit/s} \rightarrow T_{\text{bit}} = 100 \text{ ps}$

Non-Return-to-Zero

Return-to-Zero

Duty cycle = \[ \frac{\text{pulse width } \Delta t}{\text{bit period}} \]

$\Delta t$: full width at half maximum FWHM

$d = \Delta t / T_{\text{bit}}$

$d = 1 \rightarrow$ NRZ

$d < 1 \rightarrow$ RZ
External Modulation

Generation of an NRZ signal utilizing external modulation
External Modulation

Generation of a more linear NRZ signal with a finite extinction ratio
Modulation Formats - Signaling

Generation of an RZ signal utilizing external modulation
3. Optical Networking Review
Telecommunication Networks Framework

1-Physical
- Transmits data over the network medium, e.g., Synchronous Optical Network “SONET” or “Optical Transport Network “OTN” protocols operate here.

2-Datalink
- Handles physical addressing, packs data into frames, e.g., Ethernet or Asynchronous Transfer Modus “ATM” operate here.

3-Network
- Routes data between nodes, handles network or logical addressing, e.g., Internet Protocol “IP” operates at this level.

4-Transport
- Transmits data, e.g., Transmission Control Protocol “TCP” operates at this level.

5-Session
- Establishes and maintains communication between applications.

6-Presentation
- Manages data compression, encryption, conversion.

7-Application
- Allows applications to access network services, e.g., File Transfer Protocol “FTP” and Simple Mail Transfer Protocol “SMTP” operate here.
Example: Email

Transmission of the e-mail message
Fiber-optic Network Scenarios

- Fibre in the Backbone (e.g. SONET)
- Fibre in the Access Networks (e.g. PON)
- Fibre in the Satellite Base-Stations (e.g. GPS)
- Radio over Fibre (e.g. CATV)
- Optical-Wireless Communications systems (e.g. Mobile Communications)
## Network Topologies

<table>
<thead>
<tr>
<th>Who Uses it?</th>
<th>Span (km)</th>
<th>Bit Rate (bps)</th>
<th>Multiplexing Technique</th>
<th>Fibre</th>
<th>Laser</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Core/Long Haul</strong></td>
<td>~$10^3$s</td>
<td>100’s of Gbps</td>
<td>DWDM/TDM</td>
<td>SMF</td>
<td>DFB</td>
<td>APD</td>
</tr>
<tr>
<td>Phone Company, Gov’t(s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Metro/Regional</strong></td>
<td>~$10^2$s</td>
<td>10’s of Gbps</td>
<td>DWDM/CWDM/TDM</td>
<td>SMF</td>
<td>DFB</td>
<td>APD/PIN</td>
</tr>
<tr>
<td>Phone Company, Big Business</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Access</strong></td>
<td>~10s</td>
<td>56kbps-1Gbps</td>
<td>TDM/SCM/CDM</td>
<td>SMF/MMF</td>
<td>DFB/FP</td>
<td>PIN</td>
</tr>
<tr>
<td>Small Business, Consumer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Core** - Combination of switching centres and transmission systems connecting switching centres.

**Access** - That part of the network which connects subscribers to their immediate service providers.

DCF : Dispersion Compensated Fibre, DFB: Distributed Feed-Back Laser Diode
Optical Multiple-Access Technologies

- Also called *local-loop, first-mile access, last-mile access*.

- Allows multiple users to access the network resources simultaneously.

- Methods:
  - Time-Division Multiple-Access (TDMA)
  - Wavelength-Division Multiple-Access (WDMA)
  - Code-Division Multiple Access (CDMA)
Multiple-Access Techniques

- **FDMA**: Frequency Division Multiple Access
- **TDMA**: Time Division Multiple Access
- **CDMA**: Code Division Multiple Access

**Time-frame vs Frequency**
- **FDMA**: Channels are assigned to users in frequency domain.
- **TDMA**: Channels are assigned to users in time domain.
- **CDMA**: Channels are assigned to users by spreading their signals.

**Maximum Bandwidth**
- **1, 2, 3, or 4**: Sequential in time.
- **1, 2, 3, and 4**: Coincident in time.
Multiple-Access Techniques

WDM

\[ \lambda_1 \quad \lambda_2 \quad \lambda_3 \]

User 1

User 2

User 3

Time, t

Wavelength, \( \lambda \)

TDM

\[ t_1 \quad t_2 \quad t_3 \]

User 1

User 2

User 3

Time, t

Wavelength, \( \lambda \)

CDMA

User 3

Code 3

User 1, Code 1

User 2, Code 2

Time, t

Code, C
Network Topologies (Core) – SONET/SDH

- Synchronous Optical Network / Synchronous Data Hierarchy (SONET/SDH) is the TDM-based Network

<table>
<thead>
<tr>
<th>SONET</th>
<th>Bit Rate (Mbps)</th>
<th>SDH</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC-1</td>
<td>51.84</td>
<td>-</td>
</tr>
<tr>
<td>OC-3</td>
<td>155.52</td>
<td>STM-1</td>
</tr>
<tr>
<td>OC-12</td>
<td>622.08</td>
<td>STM-4</td>
</tr>
<tr>
<td>OC-24</td>
<td>1244.16</td>
<td>STM-8</td>
</tr>
<tr>
<td>OC-48</td>
<td>2488.32</td>
<td>STM-16</td>
</tr>
<tr>
<td>OC-96</td>
<td>4976.64</td>
<td>STM-32</td>
</tr>
<tr>
<td>OC-192</td>
<td>9953.28</td>
<td>STM-64</td>
</tr>
<tr>
<td><strong>OC-768</strong></td>
<td><strong>39813.12</strong></td>
<td><strong>STM-256</strong></td>
</tr>
</tbody>
</table>

SONET Bit Rate (Mbps) | SDH
--- | ---
OC-1 51.84 | -
OC-3 155.52 | STM-1
OC-12 622.08 | STM-4
OC-24 1244.16 | STM-8
OC-48 2488.32 | STM-16
OC-96 4976.64 | STM-32
OC-192 9953.28 | STM-64
**OC-768** **39813.12** | **STM-256**

**Note**: The diagram is not drawn to scale.
Network Topologies (Access) - **PON**

- **Passive Optical Networks (PON)**
  - No active elements or O/E and E/O conversion

- **Different Flavours**
  - CDMA-PON
  - WDM-PON
  - TDM-PON
    - ATM-PON (APON or BPON)
    - Ethernet-PON (EPON)
    - Gigabit-PON (GPON)
Fiber has the capability to transmit hundreds of wavelengths
Cost effective only in long haul links with Dense WDM (DWDM)
With low cost Coarse WDM (CWDM) equipment this is possible even in the access front
Once the fiber is in place, additional wavelength can be launched at both ends by replacing transceivers
# TDM-PON Standards

<table>
<thead>
<tr>
<th>TDM-PON</th>
<th>Downstream</th>
<th>Upstream</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>APON</td>
<td>155 Mb/s</td>
<td>155 Mb/s</td>
<td>ITU-T (FSAN)</td>
</tr>
<tr>
<td></td>
<td>622 Mb/s</td>
<td>155 MB/s</td>
<td></td>
</tr>
<tr>
<td>BPON</td>
<td>155 Mb/s</td>
<td>155 Mb/s</td>
<td>IEEE 802.3ah</td>
</tr>
<tr>
<td></td>
<td>622 Mb/s</td>
<td>622 MB/s</td>
<td></td>
</tr>
<tr>
<td>EPON</td>
<td>10 Mb/s – 1 Gb/s</td>
<td>10-1000 Mb/s</td>
<td>ITU-T G.983 (FSAN)</td>
</tr>
<tr>
<td>GPON</td>
<td>1.244 Gb/s</td>
<td>155 Mb/s</td>
<td>ITU-T G.983</td>
</tr>
<tr>
<td></td>
<td>2.488 Gb/s</td>
<td>622 Mb/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.244 Gb/s</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>2.488 Gb/s</td>
<td></td>
</tr>
</tbody>
</table>

FSAN: Full Services Access Network ([www.fsanweb.org](http://www.fsanweb.org))
Optical CDMA

- Accommodate **large number of users**
- No need for **user-slot-allocation** in contradiction to TDMA and WDMA
- Support **variable bandwidth** services

**CDMA Concept**

**CDMA Signalling**
Incoherent Optical CDMA

- Intensity modulated signals detected via photodetector.

**Advantages:**
- System simplicity
- Low implementation costs

**Disadvantages:**
- Low performance due to:
  - Sensitive to laser’s phase noise
  - Sensitive to laser’s relative intensity noise
  - Vulnerable to self- and cross-phase modulations
- Highly insecure
Incoherent Optical CDMA Transceiver

Basic Incoherent Receiver Structure
OTDL based OCDMA Encoder

PPM Modulated Signal

Splitter 1:w

Code: 100 100 100 100 010

Combiner w:1

PPM-OCDMA Signal

3Tc

6Tc

9Tc

13Tc

PPM-OCDMA Encoder with OTDLs
Receiver with Interference Cancellation

Receiver with MAI Cancellation
Coherent OCDMA Basic Transceivers

- Coherent Rx is more sensitive due to optically mixed signals.

**Advantage:**
- Improved performance due to higher SNR
- High degree of wavelength selectivity

**Disadvantages:**
- Sensitive to laser phase noise
- Sensitive to fibre dispersions
- Complicated FBG or AWG requirements
BPSK-OCDMA Transceivers

External Phase Modulator Block Diagram

Injection-locking Phase Modulator Block Diagram
4. Optical Networking

Evolution
Optical Networking – Today

- **Opportunity:**
  - Development of erbium-doped fibre amplifiers (EDFA)
  - Removing E/O and O/E conversion – Photonic Balancing

- **Technology (development since 1994):**
  - 1.55 µm single-mode, narrow-band semiconductor lasers
  - Single-mode, low-attenuation, dispersion-shifted silica fibres
  - 1 – 100+ Gbps
Optical Networking – Tomorrow

- We still need optical processing in higher layers than physical in the future:
  - All-Optical Networks: without E/O and O/E
  - All-Optical Processing: Fibre-to-the-PC
  - Service-Oriented Optical Networks (SOON)
  - All-Optical Heterogeneous Networks

- They provide *cheap, multi-Tbps, HD media-rich* communications.
Summary

- We reviewed:
  - Photonics and Optical Communications
  - Applications of Photonics
  - How Fibre-Optic Works
  - Basic Optical Communications Characteristics
  - Major Elements of Optical Transceivers
  - Modulation Formats and Signalling
  - Present and Future State of Optical Networking
Questions...

Massoud Karbassian
m.karbassian@arizona.edu