

Slides From ATI Professional Development Short Course

OPTICAL COMMUNICATIONS

Instructor:

Dr. James Pierre Hauck

ATI Course Schedule:

<http://www.ATCourses.com/schedule.htm>

ATI's Laser Communications:

http://www.atcourses.com/Laser_RADAR_and_Applications.htm

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LASER COMMUNICATIONS

- What are the Emerging Laser Communications Challenges for Mobile, Airborne and Space-Based Missions?
- Future Opportunities in LaserCom Applications (ground-to-ground, satellite-to-satellite, ground-to-satellite and much more!)
- Overcoming Challenges in LaserCom Development (bandwidth expansion, real-time global connectivity, survivability & more)
- Measuring the Key Performance Tradeoffs (cost vs. size/weight vs. availability vs. power vs. range & more!)
- Tools and Techniques for Meeting the Requirements of Data Rate, Availability, Covertness & Jamming

1. UNDERSTANDING LASER COMMUNICATIONS

- What are the Benefits of Laser Communications?
- How Do Laser Communications Compare with RF and Microwave Systems?
- Implementation Options
- Key Insights on Frequency Regulatory Issues
- Future Role of Laser Communications in Commercial, Military and Scientific Markets

2. DOD's ROADMAP FOR LASER COMMUNICATIONS

- What are DoD's Long-Range Requirements for Laser Communications?
- What is the Role of Laser Communications within the Transformational Comms Architecture?
- Assessing the Impact of Laser Communications on UAVs and Network-Centric Operations
- DoD's Plan for Insertion of Laser Technologies on Legacy Systems

3. LASER COMMUNICATIONS: LATEST CAPABILITIES & REQUIREMENTS

- A Complete Guide to Laser Comms Capabilities for Mobile, Airborne and Space-Based Missions
- What Critical System Functions are Required for Laser Communications?
- What are the Capability Requirements for Spacecraft-Based Laser Communications Terminals?
- Tools and Techniques for Meeting the Requirements of
 - Data Rate
 - Availability
 - Covertness
 - Jamming
- Ground Terminal Requirements
 - Viable Receiver Sites
 - Uplink Beacon and Command
 - Safety

4. LASER COMMUNICATION SYSTEM PROTOTYPES & PROGRAMS

- USAF/Boeing Gapfiller Wideband Laser Comm System---Future Central Node in Military Architectures
- DARPA's TeraHertz Operational Reachback (THOR)---Meeting Data Req. for Mobile Environments
- Elliptica Transceiver---The Future Battlefield Commlink?
- Laser Communication Test and Evaluation Station (LTES)
- DARPA's Multi-Access Laser Comm Head (MALCH): Simultaneous Lasercom to Multiple A/B Users

5. OPPORTUNITIES AND CHALLENGES IN LASER COMMUNICATIONS DEVELOPMENT

- Link Drivers--- Weather, Mobile or Stationary systems,
- Design Drivers--- Cost, Link Availability, Bit Rates, Bit Error Rates, Mil Specs
- Design Approaches--- Design to Spec, Design to Cost, System Architecture and Point to Point
- Where are the Opportunities in Laser Communications Architectures Development?
- Coping with the Lack of Bandwidth---How Can Industry Help?
- What are the Challenges and Solutions in Achieving Real-Time Global Connectivity?
- When Will Enhanced Survivability be Realized?
- Solving the Dilemma of Real-Time Intelligence/Targeting
- Beam Transmission: Making it Work
 - Free-Space Optics- Overcoming Key Atmospheric Effects
 - § Scintillation
 - § Turbulence
 - § Cloud Statistics
 - § Background Light and Sky Brightness
 - § Transmission
 - § Seeing
 - § Availability
 - Underwater Optics
 - Guided Wave Optics

6. EXPERT INSIGHTS ON MEASURING LASER COMMUNICATIONS PERFORMANCE

- Tools and Techniques for Establishing Requirements and Estimating Performance
- Key Performance Trade-offs for Laser Communications Systems
 - Examining the Tradeoffs of Cost vs. Availability, Bit Rate, and Bit Error Rate
 - Examining the Tradeoffs of Size/Weight vs. Cost, Availability, BR/BER, Mobility
 - Examining the Tradeoffs of Power vs. Range, BR/BER, Availability
- Mass, Power, Volume and Cost Estimation
- Reliability and Quality Assurance
 - Flight Qualification
 - Environmental Tests
 - Component Specifics (Lasers, Detectors, Optics)

7. UNDERSTANDING THE KEY COMPONENTS AND SUB-SYSTEMS

- Current Challenges and Future Capabilities in Laser Transmitters
- Why Modulation and Coding is Key for Successful System Performance
- Frequency/Wavelength Control for Signal-to-Noise Improvements
- Meeting the Requirements for Optical Channel Capacity
- The Real Impact of the Transmitter Telescope on System Performance
- Transcription Methods for Sending the Data
 - Meeting the Requirements for Bit Rates and Bit Error Rates
- Which Receivers are Most Useful for Detecting Optical Signals
- Pointing and Tracking for Link Closure and Reduction of Drop-Outs
 - Which Technologies Can Be Used for Link Closure
 - How Can You Keep Your Bit Error Rates Low

LASER COMMUNICATIONS- INTRO & OVERVIEW

- Laser communications refers to the use of light produced by lasers in the near ultraviolet, visible, near, shortwave, and far infrared portions of the electromagnetic spectrum to communicate information.
- In the course we will cover the science, engineering, and technology relevant to laser communications in the unguided mode, i.e. Not fiber optic communications. We will only show a few comparisons.
- A wide range of laser communication systems can be developed, and a few have been over the years. We expect that as the needs for greater bandwidth (data rates), covertness, low probability-of-intercept, and freedom from jamming become more important, that more “free-space-optical comms systems will be put into service.
- Commercial systems may be based on LEDs or Lasers. These can be surveyed on the internet. Military systems are frequently highly proprietary, or classified. Thus we will focus on the science, engineering and technology, and discuss specific military applications within the limits of unclassified data, and export limitations.

LASER COMMS- INTRO/OVERVIEW CONT'D

- The comm process in the Near Ultraviolet (NUV), Visible (Vis), Near InfraRed (NIR), Shortwave IR (SWIR), and Far or Long Wave IR (LWIR) differs significantly from that based on Radio Frequency (RF) or Fiber-Optic (FO) systems. The carrier frequencies are very large, but direct modulation is typically not feasible (exception is the CO₂ laser). In addition, the comm channel is very dynamic.
- For the higher frequencies (SWIR and higher frequencies), typically we need to use direct detection. For LWIR, we can use Coherent or Heterodyne detection. The potential for Coherent systems at shorter wavelengths exists, but is challenging.
- The higher energy per photon requires a significantly higher beam power to communicate the same amount of data. Thus, most Laser Comms systems will Not operate well in broadcast mode, but are best used as point to point systems.

LASER COMMS- INTRO/OVERVIEW CONT'D

- Thus we will divide this course technically into systems that are coherent, and those that are incoherent. Further, we can divide the systems into ones that require a transmitter on both terminals, and ones that have a transmitter on only one end “retrocomms”. Other subdivisions include systems that have a common transmit/receive aperture (monostatic), and ones that use separate telescopes (bistatic).

LASER COMMS ARCHITECTURES

Coherent/Incoherent

Monostatic/Bistatic

Single Transmitter/ Multiple transmitters

Repeaters

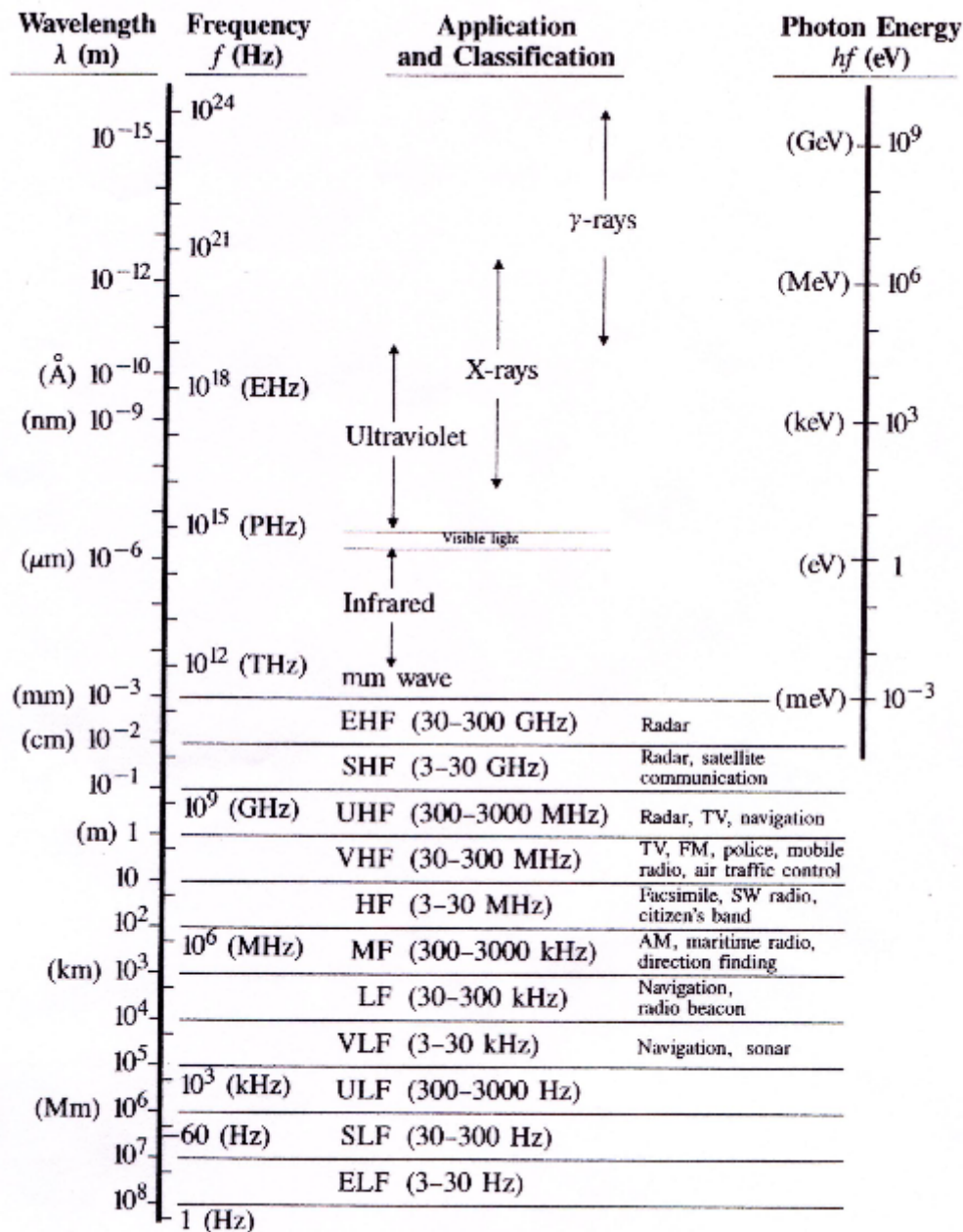


FIGURE 7-9
Spectrum of electromagnetic waves.

1 Transmitters – What transmitters can be used for each comm application?

1.1 Light Sources

1.1.1 Lasers

1.1.1.1 Gas

1.1.1.2 Solid State (crystals)

1.1.1.3 Diodes

1.1.2 LEDs, Lamps etc

1.2 Optical Properties of laser beams for use in optical communications

1.2.1 Laser Resonators

1.2.2 Laser Beams

1.2.2.1 Diffraction-Beam Spreading

1.2.2.2 Beam Divergence Control

1.3 Modulators for encoding of data

1.3.1 Electrical

1.3.2 Electro-Optical

1.3.3 Acousto-Optical

1.3.4 Absorption

1.3.5 Diffraction

- 1.4 Frequency/Wavelength Control for signal to noise improvements
 - 1.4.1 Bandwidth Control
 - 1.4.2 Frequency Selection
 - 1.4.2.1 Non-Linear Optical Frequency Shifters
 - 1.4.2.1 Frequency Up-converters- Harmonic Generators
 - 1.4.2.2 Down-Converters
 - 1.4.2.2.1 Optical Parametric Oscillators
 - 1.4.2.2.2 Raman Shifters

- 1.5 Transmitter telescopes for projecting beams to the receiver
 - 1.5.1 Refractors
 - 1.5.2 Reflectors

- 1.6 Data Transcription methods for sending the data
 - 1.6.1 Coding
 - 1.6.2 Bit Rates
 - 1.6.3 Bit Error Rates

- 2 Transmission of beams in the atmosphere, underwater and in fibers**

- 2.1 Free Space Optics
 - 2.1.1 Absorption
 - 2.1.2 Scattering
 - 2.1.3 Turbulence Beam Steering
 - 2.1.4 Total transmission Losses

- 2.2 Underwater optics
 - 2.2.1 Absorption
 - 2.2.2 Scattering
 - 2.3.3 Total transmission losses

- 2.3 Guided Wave Optics
 - 2.3 Fiber-Optics Properties
 - 2.3.1 Absorption
 - 2.3.2 Scattering
 - 2.3.3 Total Transmission Losses

3 Receivers for data

3.1 Receiver Telescope

3.2 Detectors

3.3. Detector Electronics

4 Pointing and Tracking for link closure and reduction of drop-outs

4.1 Error Sources

4.2 Correction methods

- 5 Applications of Laser Communication Systems**
- 5.1 Ground to Ground
 - 5.1.1 Fixed
 - 5.1.2 Mobile
 - 5.1.3 Line-Of-Sight
 - 5.1.4 Non-Line-Of-Sight
- 5.2 Ground to A/C
- 5.3 A/C to Ground
- 5.4 A/C to A/C
- 5.5 Ground to Sat
 - 5.5.1 Low Earth Orbit
 - 5.5.2 Medium Earth Orbit
 - 5.5.3 Geo-stationary Earth Orbit
 - 5.5.4 Long Range
as above
- 5.6 Sat to Ground
as above
- 5.7 Sat to Sat “Real Free Space”
- 5.8 Under-Water Fixed to Mobile
- 5.9 Under-Water Mobile to Fixed

6.0 Performance of Laser Communication Systems

6.1 Data Rate Requirements

6.2 Availability Requirements

6.3 Coverttness

6.4 Jamming Prevention

6.5 Other User Needs

6.5.1 Cost

6.5.2 Size/Weight and Power

6.5.3 Eye-Safety

6.6 Feedback

7.0 Future Directions for Optical Communications

LASER COMM LINK MODEL

Major Parameters:

Power Transmitted P_t

Beam Angle ϕ_b

Area of Receiver A_r

Range Z

Rcvr
Field
Of
Regard

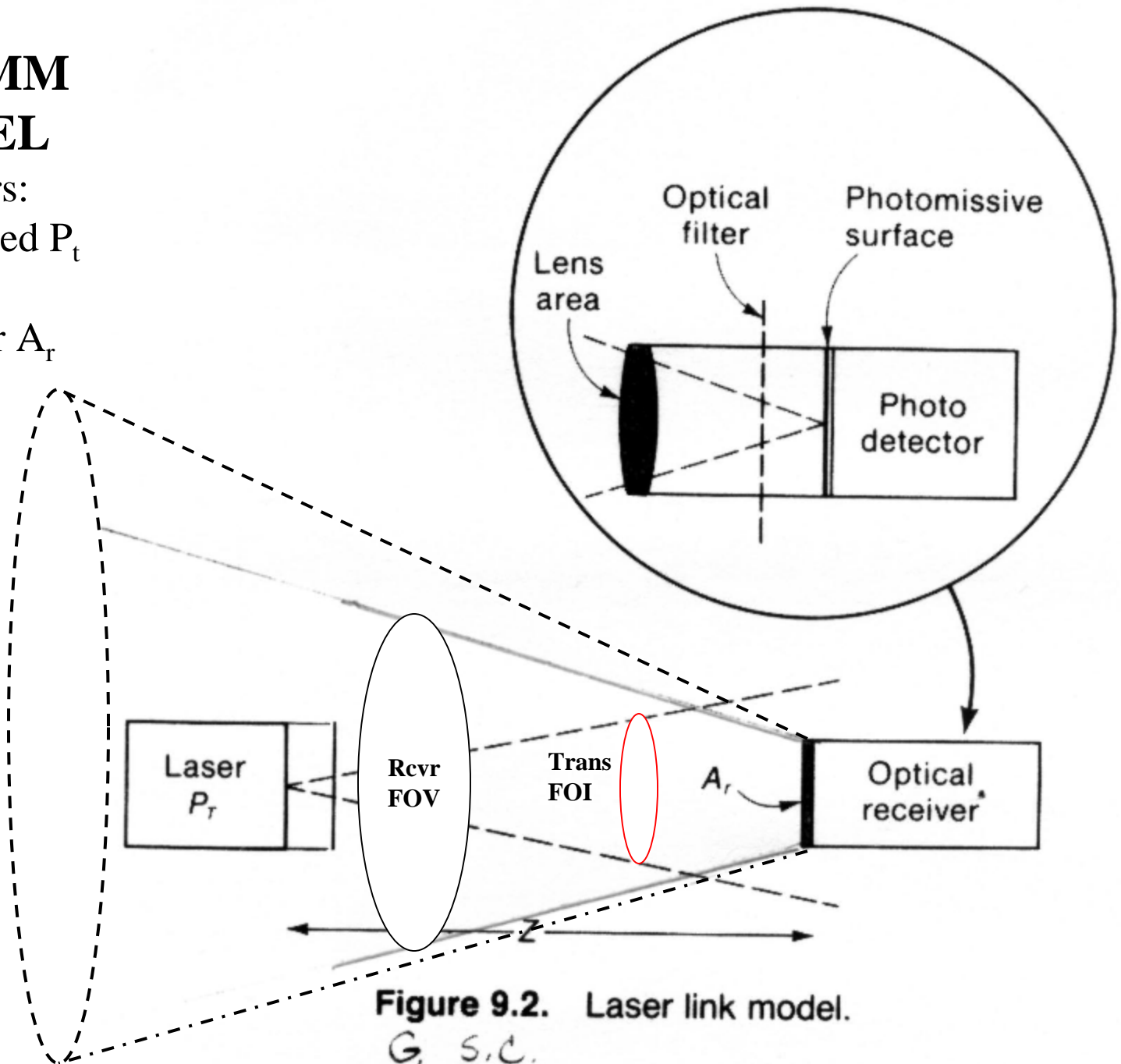


Figure 9.2. Laser link model.

G. S.C.



LC02

TRANSMITTERS

LASER COMMUNICATIONS

A COURSE BY

Dr. James Pierre Hauck

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LASER COMMUNICATIONS

LASER TRANSMITTERS:

GAS LASERS-

CO₂

SOLID STATE LASERS-

Diode Pumped Yttrium Crystals (DPY)

Diode lasers

Laser Diode Arrays

Er Fiber Lasers

Quantum Cascade Lasers

FREQUENCY/WAVELENGTH SHIFTERS-

HARMONIC GENERATORS

OTHER NLO SHIFTERS

JPH Laser Exp.

| LASER | Wavelength (nm) | Pav(W) | Pp(W) | RESEARCH | DESIGN | DEVELOPMENT | ASSEMBLY | TEST | COMMENT |
|--|-----------------|--------|-----------------|----------|--------|-------------|----------|------|----------------|
| Ar:Xe/EBSDL | 1,730 | | 10 ⁶ | x | X | X | | | with UCI |
| Argon Ion | 400-550 | 20 | | | X | X | | X | with ALC |
| CO/DC:WGL | 5,000-5,500 | 3 | | X | X | X | X | X | @ RI |
| CO2:Conventional | 9,100-11,000 | 10 | | | | | | X | @RI |
| CO2/DC: WGL | 9,100-11,000 | 20-150 | | X | X | X | X | X | @RI |
| CO2/Pulsed:WGL | 9,100-11,000 | 4 | 10 ⁴ | X | X | X | X | X | @RI |
| CO2/TEA | 9,100-11,000 | 10 | 10 ⁷ | X | x | X | X | X | @RI |
| Nd:YAG, Arc Lamp Pumped | 1,064, 1,340 | 10-270 | | X | X | X | X | X | @SAIC |
| Nd:Yttrium, Diode Pumped | 1,048-1,064 | | | X | X | x | | | @XES |
| Nd:YAG, Flash Lamp Pumped | 1,064 | 40 | 10 ⁷ | x | x | | | X | @SAIC |
| Nd:PPLN | 1,048 | | | x | | | | | @XES |
| Dye/Flashlamp pumped | 600-700 | 0.1 | 10 ³ | x | X | X | X | X | @UCI |
| Erbium:YAG, FLP | 2,900 | 2 | 10 ⁴ | X | X | X | X | X | @PLS |
| Excimer:XeCl:X-ray | 308 | 40 | 10 ⁸ | X | X | X | X | X | @NED/NRTC |
| Excimer:KrF | 248 | 10 | 10 ⁷ | X | | | | X | @NED |
| Free Electron Laser | 10,000-100,000 | | | X | x | X | | | with LLNL |
| HeNe- Green | 524 | 0.001 | | X | X | | | | @NED |
| HeNe- Red | 632 | 0.006 | | X | X | X | X | X | @RI, NED, etc. |
| HF/DF | 2,100-3,800 | 10 | | X | x | | | | @RI |
| Ho:YAG | 2,100 | 1 | | X | X | x | | | with JMAR |
| Titanium Sapphire, FLP | 660-1100 | 20 | 10 ⁵ | X | X | X | X | X | @NED, GDLSL |
| Titanium Sapphire, Laser Pumped | 750-900 | 1 | | X | | | | x | @SAIC |
| Cr:LiSAF/FLP | 750-900 | 2 | | X | | | | | @XES |
| Cr:Al2O3 (Ruby) | 694 | | 1 | X | | | | | @UCI |
| GaAs | 780-860 | 0.1 | 1 | X | | | | X | @GDLSL, Boe, |
| GaAs Laser Diode Arrays | 808, 860 | 20 | 10 ³ | X | | X | | X | @Boe, SEA |
| GaN | 370-480 | 0.03 | | x | | | | | with Nichia |
| InGaAs | 1,400-1,600 | 0.1 | | x | | | | | various |
| Optically Pumped Semiconductor | 460, 480 | 0.04 | | x | | | | | Coherent |
| Quantum Cascade Lasers | 3,000-16,000 | 0.1 | 0.2 | x | | | | x | QCL, Alpes |
| Code: | | | | | | | | | |
| Ar = Argon | | | | | | | | | |
| Xe= Xenon | | | | | | | | | |
| YAG= Yttrium Aluminum Garnet | | | | | | | | | |
| Cr:LiSAF = Chromium:Lithium Strontium Aluminum Fluoride | | | | | | | | | |
| EBSDL = Electron Beam Sustained Discharge Laser | | | | | | | | | |
| X-ray = X-ray Preionized Laser | | | | | | | | | |
| X = significant hardware experience | | | | | | | | | |
| x = analysis, study or evaluation | | | | | | | | | |
| WGL = WaveGuide Laser | | | | | | | | | |
| Note: This chart does not include laser wavelength conversion such as second harmonic generation, third harmonic generation, Raman, etc. | | | | | | | | | |

JPHPS - LCO2

20

CANDIDATE LASER COMM TRANSMITTERS

| LASER | Wavelength (nm) | Pav(W) | Pp(W) |
|---------------------------------|------------------------|---------------|-----------------------|
| CO2/DC: WGL | 9,100-11,000 | 20-150 | |
| CO2/Pulsed:WGL | 9,100-11,000 | 4 | 10⁴ |
| Nd:Yttrium, Diode Pumped | 1,048-1,064 | | |
| Nd:PPLN | 1,048 | | |
| GaAs | 780-860 | 0.1 | 1 |
| GaAs Laser Diode Arrays | 808, 860 | 20 | 10³ |
| GaN | 370-480 | 0.03 | |
| InGaAs | 1,400-1,600 | 0.1 | |
| Quantum Cascade Lasers | 3,000-16,000 | 0.1 | 0.2 |

LASER TRANSMITTER CHARACTERISTICS

- Beam Quality - Require maximum illumination at the receiver, and good beam uniformity to achieve greatest range and SNR.
- The amount the beam diverges is compared to the “diffraction limit”
 - $\phi_t = 2.4 \lambda (\text{XDL}) / D_b = (\text{XDL}) \phi_{dl}$ where
 - ϕ_t = the full angular divergence of the transmitted beam (assumed circular)
 - λ = the transmitter laser wavelength
 - XDL = the number of times diffraction limited
 - D_b = the transmitter aperture diameter
 - Examples:
 - $\lambda = 1 \mu\text{m}$, XDL = 1, $D_b = 1 \text{ mm}$, $\phi_t = 2.4 \text{ milliradians} = 0.14^\circ = 8.5 \text{ arcmin}$
 - $\lambda = 0.8 \mu\text{m}$, XDL = 25, $D_b = 20 \text{ mm}$, $\phi_t = 2.4 \text{ milliradians} = 0.14^\circ = 8.5 \text{ arcmin}$
 - $\lambda = 10 \mu\text{m}$, XDL = 1, $D_b = 10 \text{ mm}$, $\phi_t = 2.4 \text{ milliradians} = 0.14^\circ = 8.5 \text{ arcmin}$
- The beam quality of low power gas lasers and diode pumped solid state lasers is usually nearly diffraction limited, while semiconductor diode lasers are many time diffraction limited.
- The figure of merit for the transmitter is Radiance = Watts/area/solid angle

MORE LASER BEAM PARAMETERS

- Beam Uniformity - Require beam uniformity to avoid “drop-outs”
- The Power/Area = Irradiance I or M(W/m² or W/cm²)
- Uniformity = $\Delta I / I = (I_{\text{peak}} - I_{\text{valley}}) / I_{\text{average}}$
- The uniformity of the transmitted beam is determined by the number of transverse modes present in the beam, and optics quality. For a single transverse mode, a Gaussian beam profile may be obtained. For a large number of modes, a Super-Gaussian beam with a relatively flat top can be obtained. Beams with a small number of modes tend to be more non-uniform.
- The number of transverse modes oscillating can be estimated from:
 - “Fresnel Number” = $N_F = D_1^2 / (4 \lambda L) = 25 D_1^2 (\text{mm}) / \lambda(\text{um}) / L(\text{cm})$
 - Typically low Fresnel number lasers have low power output
 - Uniformity of the beam at the output, may not result in a uniform beam in the “far field”

TRANSMITTER BRIGHTNESS (RADIANCE)

- At the receiver, the quantity of interest is the irradiance, $I(\text{W}/\text{m}^2)$. The irradiance depends on the transmitter brightness in the far field
 - $I(Z) = I_o \{ (\pi D_b^2/4) / [(\pi D_b^2/4) + \pi (\phi_t Z)^2/4] \} \sim I_o D_b^2 / (\phi_t Z)^2 = L / Z^2$
 - where $L = I_o D_b^2 / (\pi \phi_t^2/4) = P_t / (\pi \phi_t^2/4)$ is the brightness (radiance)
 - The transmitter brightness depends on the science and engineering of the laser source, and for each type has fundamental limits
 - Brighter transmitters provide better comm links with smaller transmit telescopes
- Narrow linewidth of the laser can improve receiver signal to noise ratio as more of the background radiation can be filtered
 - Linewidth $\delta \lambda$ or $\delta f = \delta \nu$
 - Ultra-narrow (kHz to GHz) or $(\delta f / f \text{ less than } 10^{-6})$ can use atomic filters
 - Narrow (GHz to THz) can use optical bandpass filters
- The combination of high radiance and narrow linewidth produces high spectral brightness, which makes the beam visible in ambient illumination



LC03

OPTICAL MODULATORS

LASER COMMUNICATIONS

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JPHS - LC03

SIGNAL MODULATION

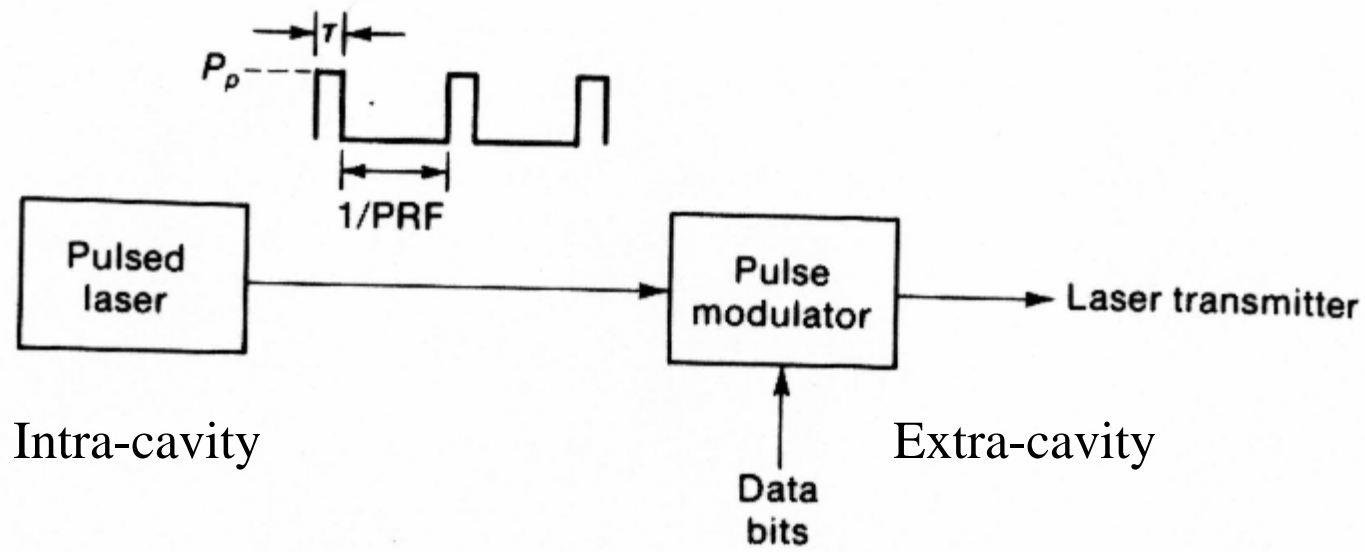
- Modulation Devices
 - Electro-optic
 - Acousto-optic
 - Absorption band-edge
- Modulation Formats
 - Frequency Modulation
 - Amplitude Modulation
 - Pulse Position Modulation
- Coding
 - On-off
 - Non-return to zero
 - Several others
 - (multi-level coding inappropriate for Op Comms due to variable link loss)

MODULATION AND DEMODULATION

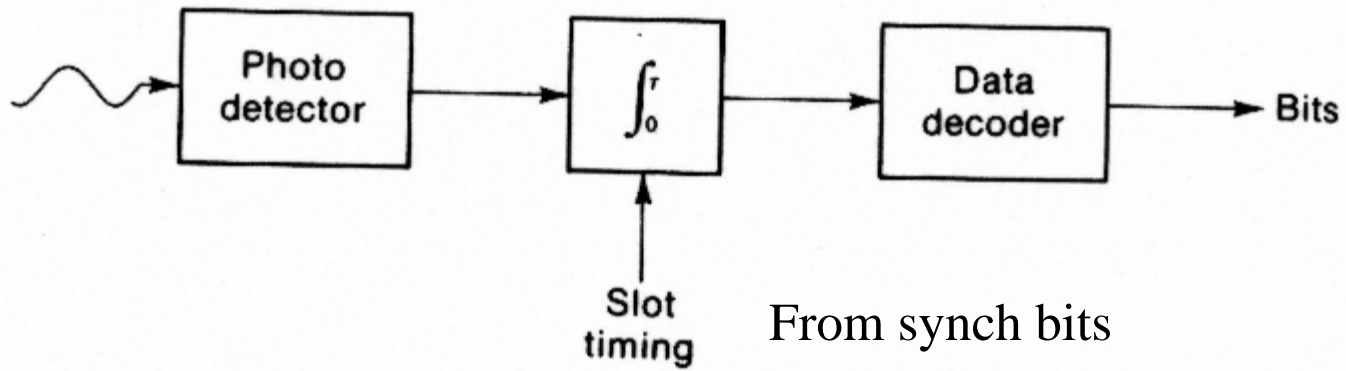
- Amplitude Modulation with On-off key coding is the most common because most Op Comms Systems are direct detection (NOT coherent)
- Each time bin either contains a bit (pulse) or does not and is a 1 or 0
- Sets of bits are sent to synchronization the clocks as the range varies
- Frequency modulation can be used with coherent lasers (mainly CO₂, but others may be feasible)
- Frequency modulation has the best noise suppression, but is more difficult to implement with most laser systems.
- Specialized AM modulation schemes can be utilized for retrocomms (more later)

MODULATION ARCHITECTURES

- Modulation can be accomplished either intra-cavity (IC-inside the laser resonator), or extra-cavity (EC- on the laser beam)
- Intra-cavity modulation can be produced by modulating the gain or loss
- Electro-optic (E/O) and acousto-optic (A/O) modulators can be used either intra-cavity or on the beam
- E/O and A/O can both be used to produce either AM or FM
- Usually, an IC modulator will require less drive voltage & power, but is more complex to implement and requires a higher gain laser



a.



b.

Figure 9.17. Pulsed-laser digital modulation system. (a) Pulsed transmitter. (b) Receiver decoder.

ELECTRO-OPTIC DEVICES

- The Electro-optic modulator functions by rotating the plane of polarization of the light, such that a polarization dependent loss or polarization dependent transmission leads to amplitude modulation.
- An alternative approach is to use the E/O device as a phase shifter intra-cavity, in which case it induces both a phase and frequency shift which then may lead to AM or FM

LASER BEAM MODULATORS CHOICES

ACOUSTO-OPTIC

Lower insertion loss
Higher speed
Lower voltage
Contrast up to 90%
Usually used for low power
Small aperture
Rugged materials
Easily AR coated
AM or FM
Used IC AM
Used EC FM

ELECTRO-OPTIC

Up to 6 dB loss
Usually adequately fast
Usually kV, but lower V feasible
Higher contrast up to 99.9%
Higher laser power
Larger aperture
Adequately rugged
AR OK
AM or FM
Used IC AM
Used IC FM

M-ARY PULSE POSITION MODULATION

- Information can be encoded by putting a pulse in each bin (Binary), if the transmitter can generate pulses at high Pulse Repetition Frequency (PRF). If the bin size is small (as limited by laser pulse length, atmospheric delays, and detector speed), but the laser PRF is limited, a hybrid approach called M-ARY Pulse Position Modulation (PPM), can be used.
- Intensity M bins | T_d = dead time so that laser does not have to put pulses into two adjacent bins
-
- $T = 1/PRF$ | bin size T_{bin} ; $M * T_{bin} + T_d = T$
- bits/sec = bit rate = $BR = PRF * \log_2 M$,
- for $E = E_{min}$, Power $\sim PRF$, $BR/P = \log_2 M$,
- so it is not very advantageous to use large M
- example- $T_{atm} = 10 \text{ us}$, $T_{bin} = 10T_{atm} = 100 \text{ us}$, $T_d = 1 \text{ ms}$

| Case | M | PRF | BR | BR/P | Comment |
|------|-----|-----|------|------|---------|
| 0 | 1 | 900 | 909 | NA | Binary |
| 1 | 2 | 833 | 833 | 1 | |
| 2 | 8 | 555 | 1655 | 3 | |
| 3 | 64 | 135 | 810 | 6 | |
| 4 | 256 | 38 | 304 | 8 | |

MODLATORS SUMMARY

- Simplest modulator is direct (diodes)
- EO and AO are commonly used for DPY
- Absorption edge modulators seem attractive



LC04
TELESCOPES AND
DETECTORS
LASER COMMUNICATIONS
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TELESCOPES AND DETECTORS

- Telescopes-
 - Catoptric- reflective
 - Dioptric - refractive
- Detectors
 - Photodiodes
 - Avalanche Photodiodes
 - Photoconductors
 - Photomultipliers
 - Array Detectors

BEAM PROPAGATION - FOUR CASES

- 1-True Free Space (in vacuum losses are beam spreading and optics)
- 2-Atmospheric (as above plus losses include absorption and scattering)
- 3-Underwater (as above, but may need to include surface loss)
- 4-Fibers
- Absorption is due to atoms, molecules, particulates
- Scattering is caused by atoms, molecules, particulates and refractive index variations
- Beam losses can also result from beam directional changes caused by refractive index variations
- Time dependent refractive index changes are called turbulence
- Beam spreading losses can be controlled for short range, but may dominate for long range (such as GEO and interplanetary)
- Absorption losses can be limited by choice of wavelength, but are rarely negligible
- Scattering is ever-present, and extremely variable



Fundamentals of FO Communications

Advanced Technology Institute

Part 1

- What is telecommunications?
- Telecommunication concepts
- Fiber-optic system concepts
- Fiber system design concepts



Issues for Optical Fibers

- **Attenuation as a function of wavelength**
- **Collection of light into the fiber (coupling)**
- **Transmission mode**
- **Pulse Spreading and transmission capacity**
- **Tolerance for splicing and connecting fibers**
- **Operating wavelengths**
- **Tolerance to high temperature and environmental abuse**
- **Strength and flexibility**
- **Cost**

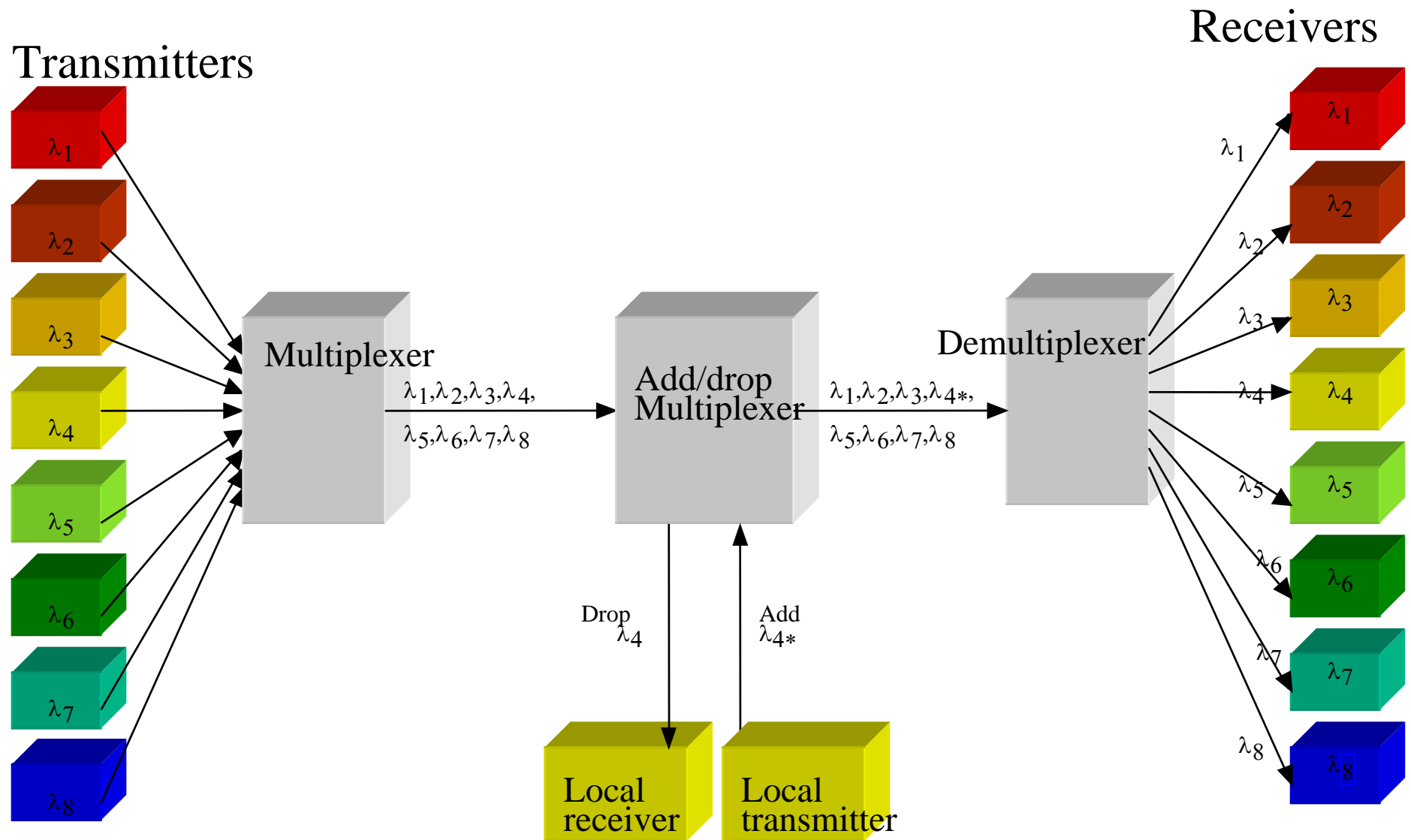
Wavelength-division multiplexing

- Transmits signals at many wavelengths through one fiber
- Multiplies fiber capacity
- Distinct from time-division multiplexing
 - TDM interleaves slow signals to make one fast one
 - WDM sends multiple signals at similar speeds to increase capacity
 - DWDM = dense WDM
- Each wavelength is an *optical channel*

WDM Technologies

- **A beam comprised of a number of different wavelengths is incident on a reflective or transmissive mirror that allow a particular wavelength to be separated. This process is continued until each wavelength is on a separate optical path (see figure 15.8). This process can be performed one wavelength at a time, or in “blocks” as in figure 15.9.**
- **An alternative to using MLD mirrors is to use Fiber Bragg Gratings, as shown in figure 15.10. Such an arrangement, picking off one wavelength at a time is referred to as a circulators.**
- **Making the device work in both directions is shown in figure 15.11, and can be used to separate wavelengths in correlation with different physical locations.**
- **Fused-Fiber Couplers are inherently wavelength sensitive, and can be used for WDM as shown in figure 15.12**
- **A Mach-Zehnder Interleaver is another type of interferometer for combining or separating different wavelengths as shown in figure 15.13. The relationship for wavelength separation is shown on page 381.**
 - $\Delta v = c/2/n/\Delta L$
 - **a multistage interleaver is shown in figure 15.14**

WDM system – Fig. 15.1





System and Optical NetWorking

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Part 2:

Global networks and standards

- Evolution of global networks
- Circuit and packet switching
- Transmission standards & hierarchy
- Global network structure



Global Network services

- Telegraphy: now obsolete
- Telephony: standard, base of present telecommunications network
- Video: standard, often via satellite
- Data: growing tremendously with Internet
- Networks converge as services digitize
- Most services now digital
 - Video is an exception



Single-Channel System Design

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Part 5:

Fiber System Design

- Design goals
- Optical amplifiers & equalization
- WDM
- System bandwidth
- Dispersion management
- Nonlinear effects
- Optical networking
- Optical switching



Design goals

- Depend on application
- Long-haul systems
 - High-speed transmission
 - Maximum throughput over scarce fibers
 - Trade-offs favor expensive terminals
- Metro/Regional Systems
 - Fiber plant less costly
 - More terminals per fiber-km
 - Trade-offs favor reducing terminal costs



Optical Networking System Design

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Optical Networking

- Managing signals as optical channels
- Add/drop single wavelength
- Separate signals by optical channel
- Switching signals by wavelength
- Easier to manipulate than TDM channels
- Improves granularity
- Uses optical switching
- Slowed by end of bubble



Standard wavelength bands

- O-band Original 1260-1360 nm
- E-band Extended 1360-1460 nm
- S-band Short 1460-1530 nm
- C-band Conventional 1530-1565 nm
- L-band Long 1565-1625 nm
- U-band Ultra-long 1625-1675 nm



Global Telecommunications Applications

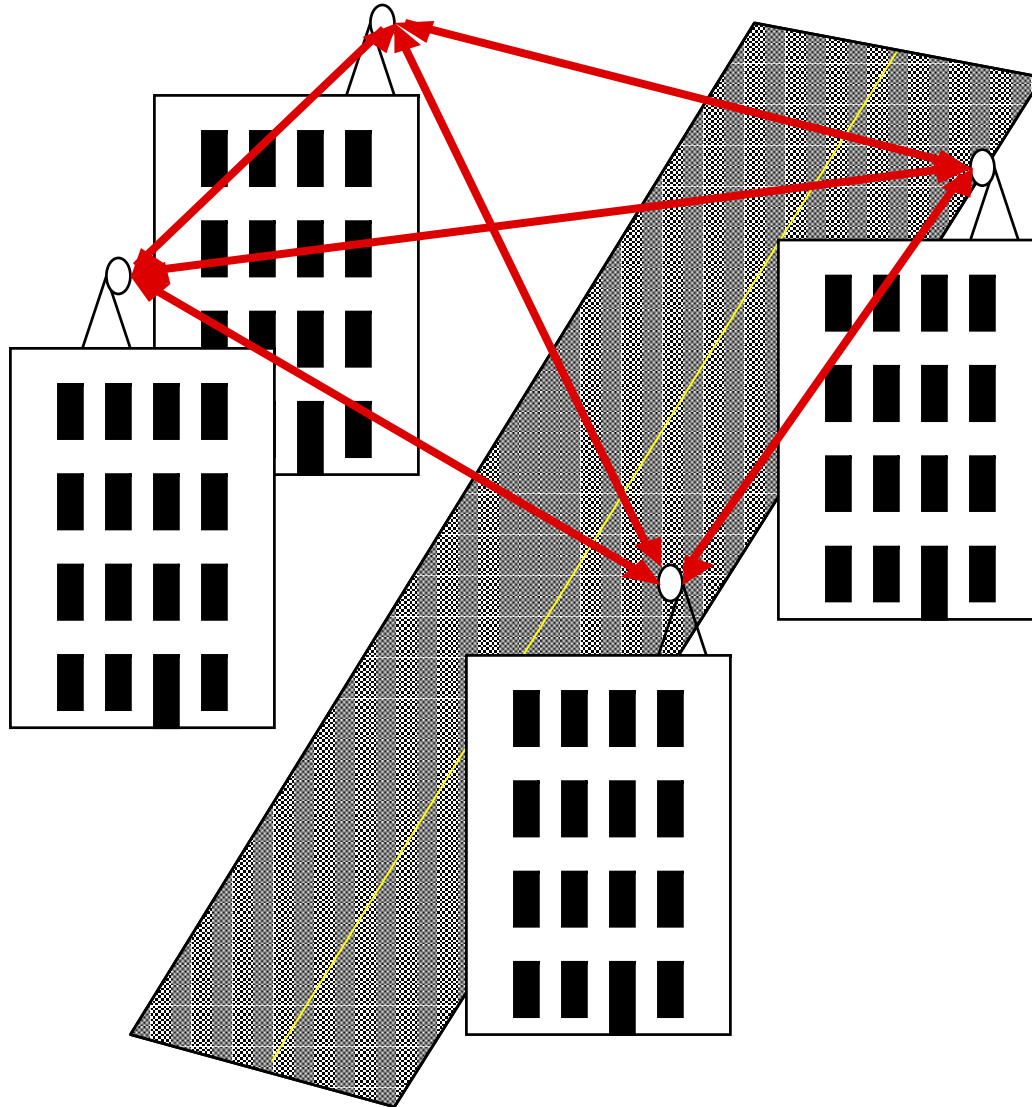
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Internet Access and Local-Area Networks

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