Free Space Optical Communication – Part I - Introduction

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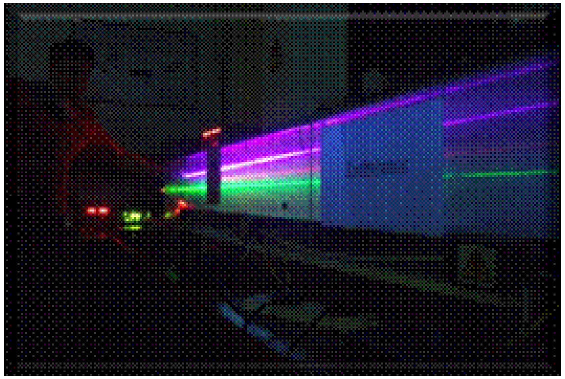
Presentation Outline

- What are the problems?
- Wireless Technologies
- Free Space optics
  - Channel Modelling
    - Fog
    - Turbulence
- Experimental systems
- Summary



Why the need for

The Optical Wireless Communications Technology?

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The World of Telecommunications

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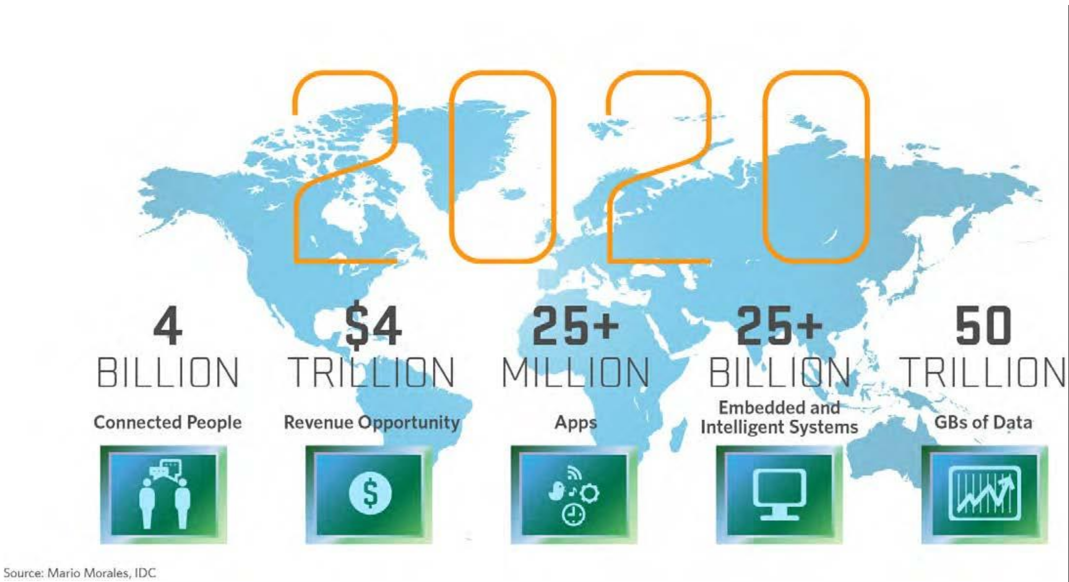
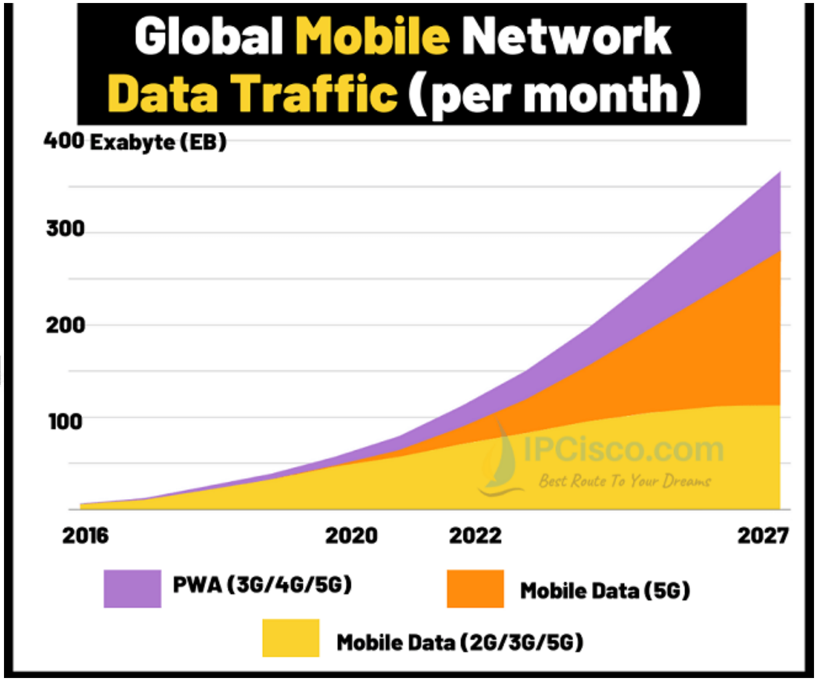
Global Mobile Data Traffic - The Forecast





- **2022 almost 10% of global traffic was 5G.**
- **2027 it is expected that data traffic in 5G will be 60%**
- **> 10 B mobile devices by 2050**
- **About 50% of global households with no access to the internet –** According to the UNESCO 9

https://ipcisco.com/global-mobile-data-traffic-forecast-2027/

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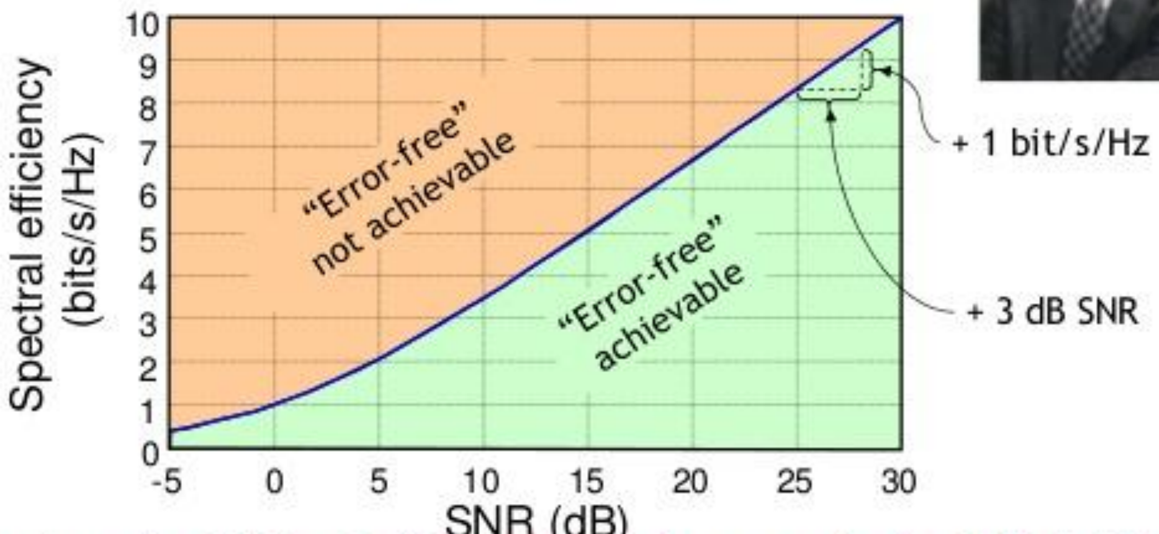
Shannon's Formula for Bandlimited Channels

C: Channel capacity (bits/s) , B: Channel bandwidth (Hz)

SNR: Signal-to-noise ratio → Signal energy / noise energy

C / B → Capacity per unit bandwidth or <u>spectral efficiency</u> (SE)

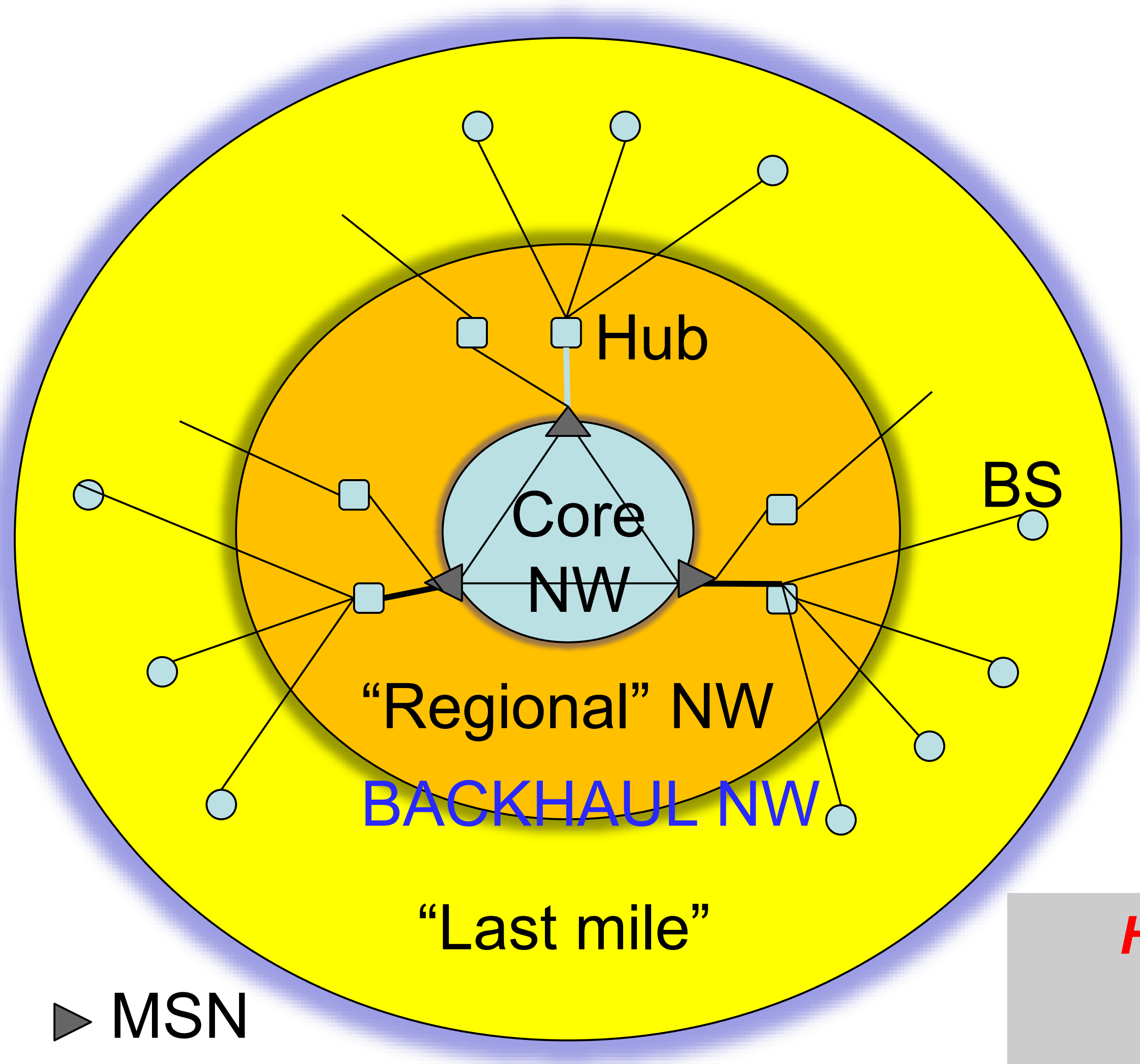
<u>Shannon capacity limit:</u> $SE = C/B = \log_2 (1 + SNR)$



Increasing the SNR by 3 dB increases the capacity by 1 bit/s/Hz per polarization state

- Capacity increases almost linearly with the *B*
- Whereas *S* determines a logarithmic increase
- So, increasing *B* has a much larger impact than increasing SNR

Cellular Network – Complex Scenario



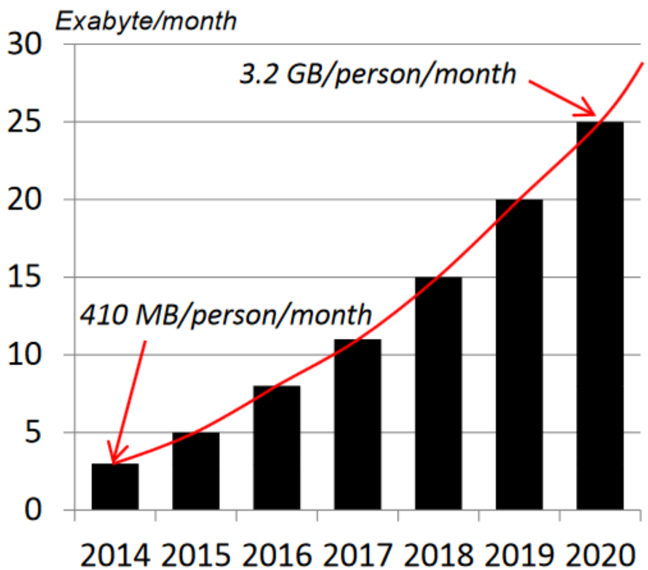
- Growing deployment Of 5G networks and backhaul solutions
- Backhaul covers both the "regional" and "last mile" networks.
- Throughput bottleneck has shifted from radio access network to the backhaul network in cellular networks.

How does one resolve the backhaul bandwidth scaling problem?

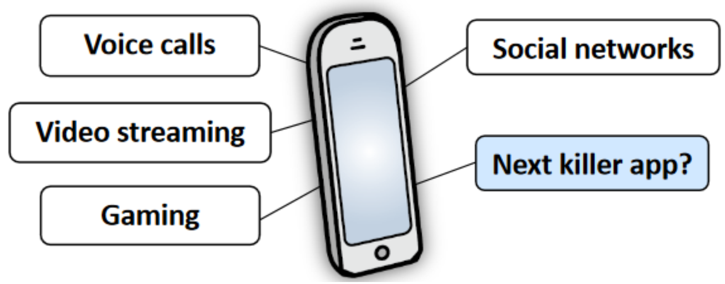
Success of Wireless Communications

Martin Cooper's law

*The number of simultaneous voice/data connections has **doubled** every **2.5 years** (+32% per year) since the beginning of wireless*



Inventor of handheld cellular phones i.e., 1G

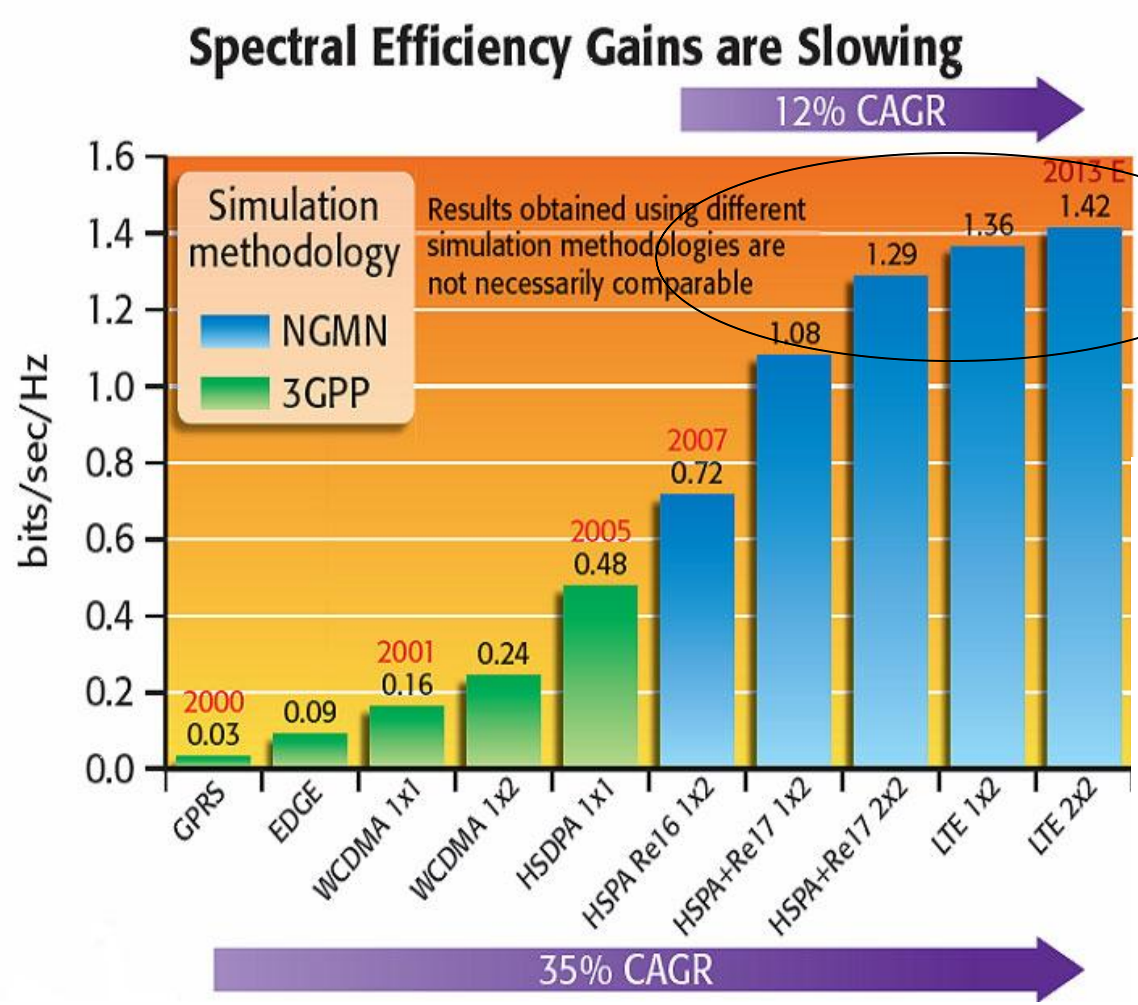


Network

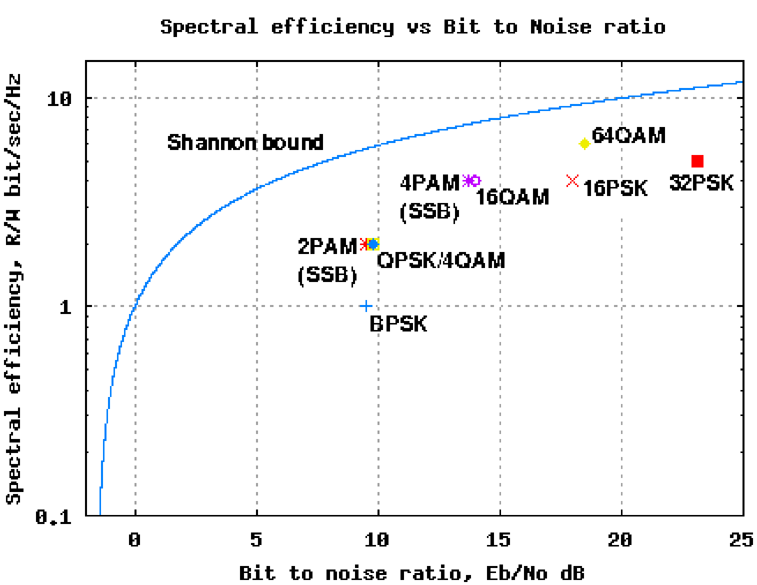
Throughput = Cell density · Available spectrum · Spectrum efficiency

(bit/s in area) (Cell/area) (Hz) (bits/s/Hz/Cell)

Spectral Efficiency Slowing Down



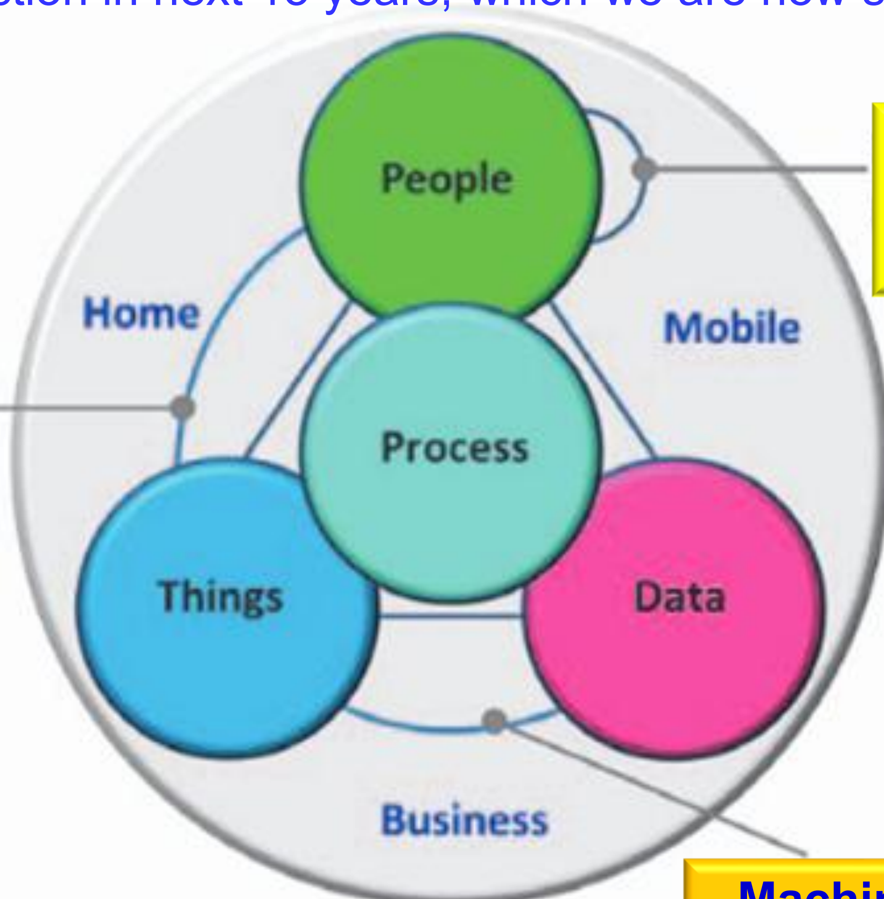
Saturation of The spectrum efficiency gains of cellular systems



Source: Qualcomm

Internet of Things

According to the EU Commission, which stated in 2009 that IoT will be changing the way our societies function in next 15 years, which we are now seeing it happening



People to People (P2P)

People to Machine (P2M)

Machine to Machine (M2M

[1]- Commission of the EC, "Internet of Things — An action plan for Europe," EU, Brussels, 2009

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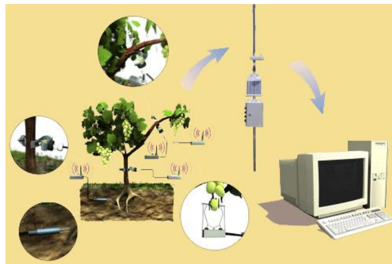
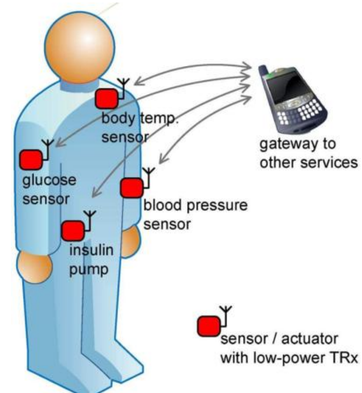
Wireless Sensor Network - Applications





Healthcare

Shipping

Intelligent Transportation System

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Future Wireless Networks

The Evolution of Mobile Networks

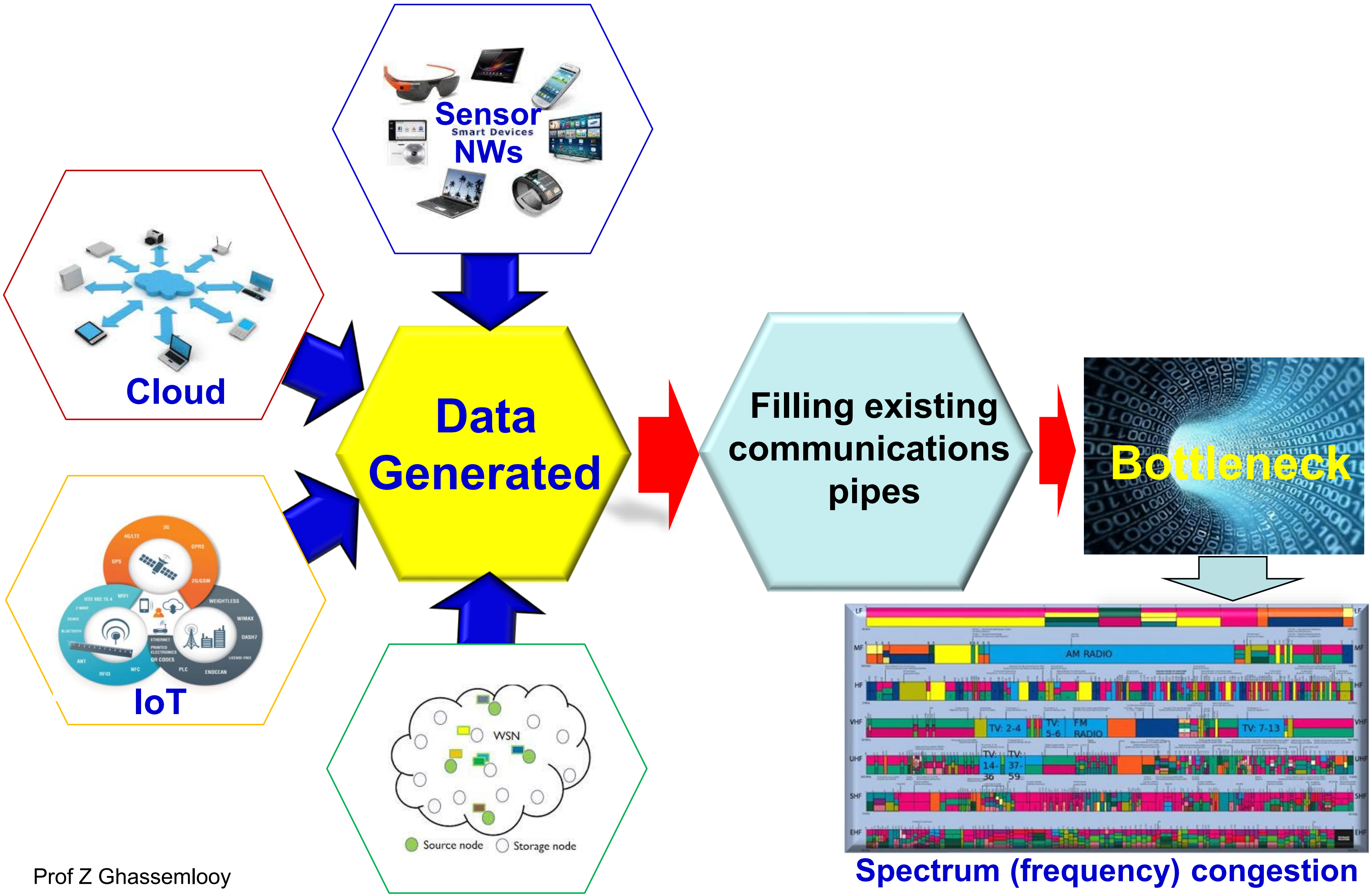
From 1G to 5G – Transforming Connectivity

1G 1980s	2G 1990s	3G 2000s	4G 2010s	5G 2020s
Analog Voice	Digital Voice & Text	Mobile Broadband	Fast & Reliable Internet	Intelligent Connectivity
Analog voice calls	Digital voice calls	Mobile internet access	High-speed mobile internet	Ultra-fast speeds & low latency
Circuit-switched networks	SMS, Basic data services	Video calls, Multimedia (MMS)	HD video streaming, Online gaming	Massive IoT, Smart applications
~2.4 kbps	~9.6–64 kbps	~0.2–2 Mbps	~10–100 Mbps	~0.1–10 Gbps
Limited capacity (voice only)	Improved capacity and coverage	Better coverage, Global roaming	All IP network, Low latency	Network slicing, Ultra-reliable
≈ 1980–1990	≈ 1990–2000	≈ 2000–2010	≈ 2010–2020	≈ 2020 and beyond

Key Enablers

- Improved Spectrum Use
- Advanced Antennas & Technologies
- Smarter Devices & Chipsets
- Cloud & Edge Computing
- AI & Automation

Global Data Traffic - So Where Are We Heading To??



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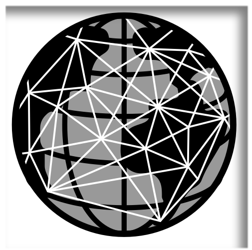
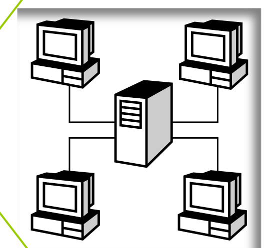
The "Last Mile" Bottleneck

WANs
- Fibre based
- >2.5 Gbps

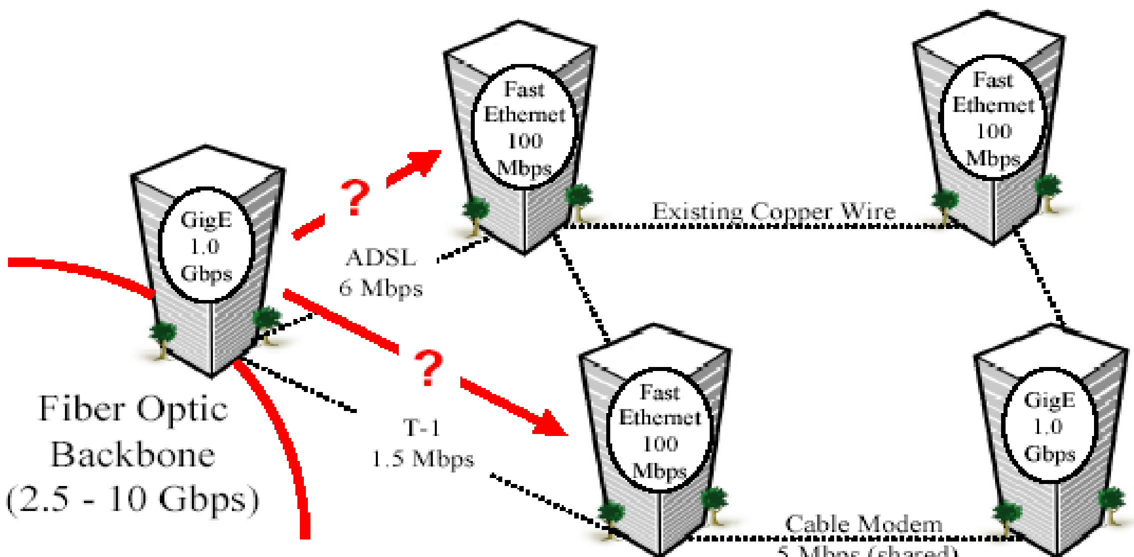


The connections in between are typically a lot slower (0.3-1.5 Mbps)

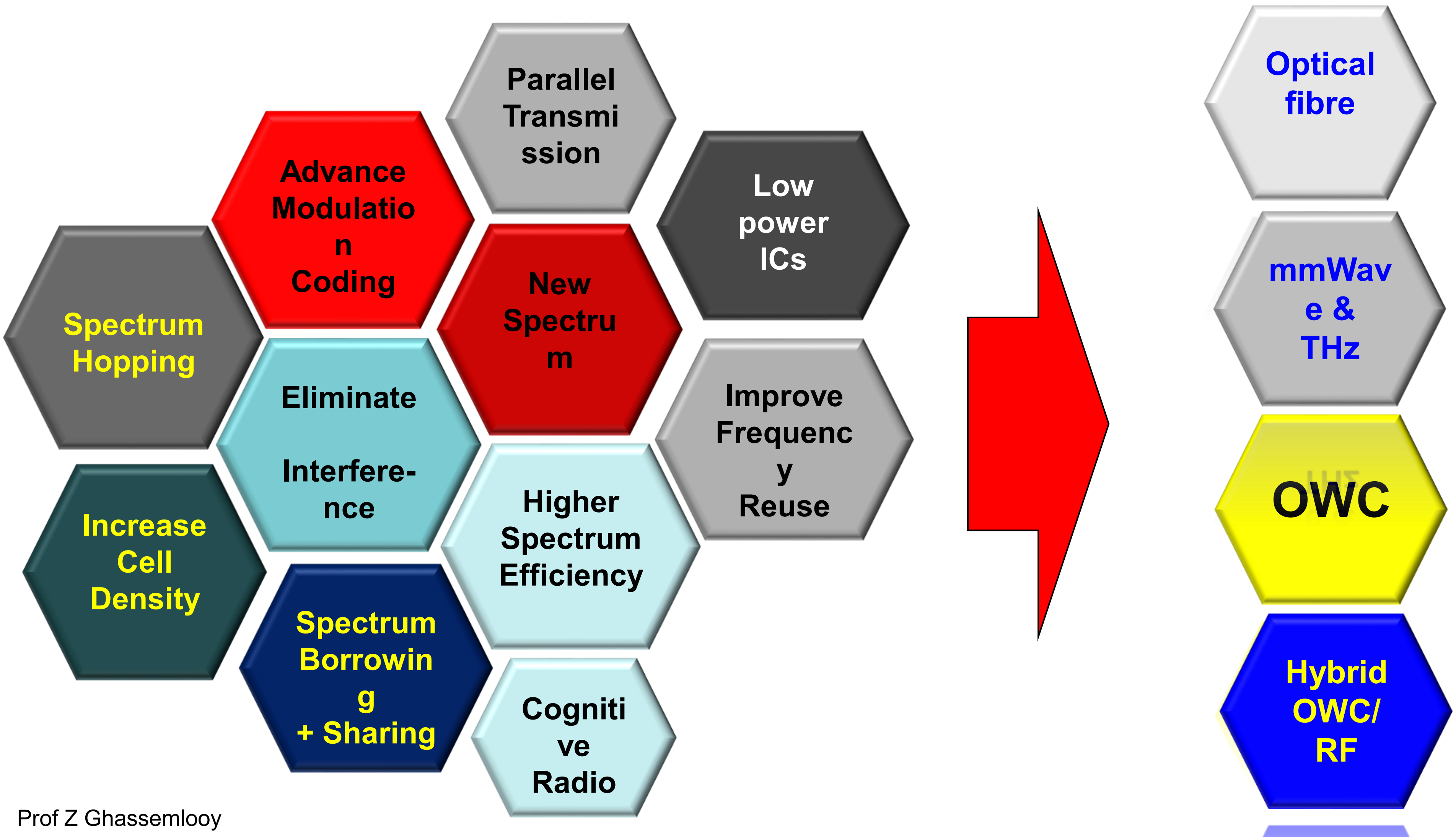


LANs in buildings
- >100Mbps

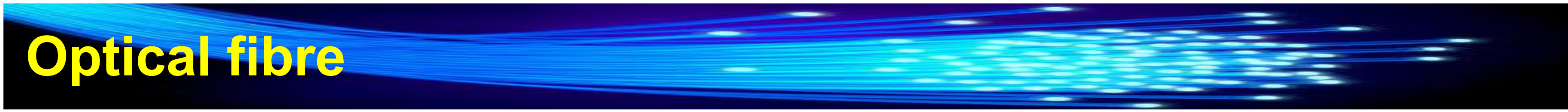
Still there are buildings and homes not having direct connections to the very high speed (2.5-10 Gbps) fibre optic backbone. These buildings are in close approximately of the fibre backbone.



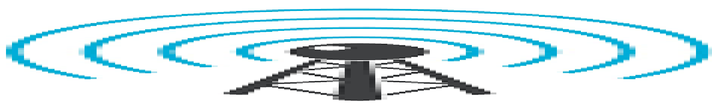
How to Overcome the Spectrum Congestion?



How to Overcome the Spectrum Congestion?



Terrain dependent | Long rollout time (months) | High capital costs ($30-35k/km)



- Highly regulated spectrum
- Affected by interference
- High energy usage
- Limited range at high data rates

Not feasible in places with no existing fixed infrastructure, complex regulations

Wireless – OWC

Huge spectrum
- IR: 175 THz
- UN: 750 PHz
- VL: 375 THz

Unique features
- IR: High speed
- UV: NOLS, secure com.
- VL: Green, wide cover.

Bandwidth 10 – 100X compared to RF

Noise
- Lower noise & higher SNR

Bandwidth
- 10 – 100X of RF
- Less input power

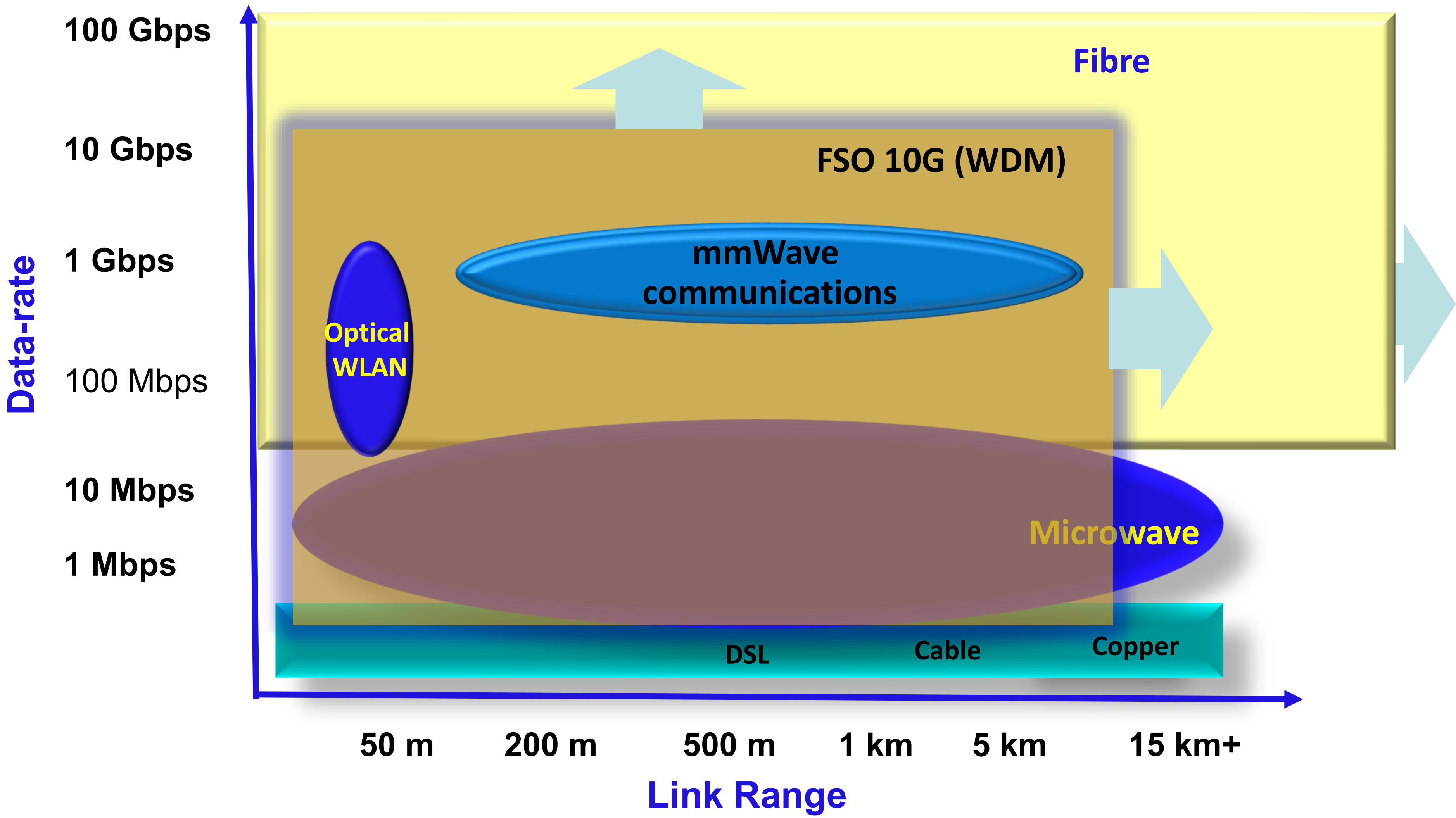
Immunity to EMI
- Inherent security
- No RF radiation

License free
- UK: $35B for 140 MHz of 3G spectrum
- USA- AT&T:$1.9B for 30 MHz of spectrum

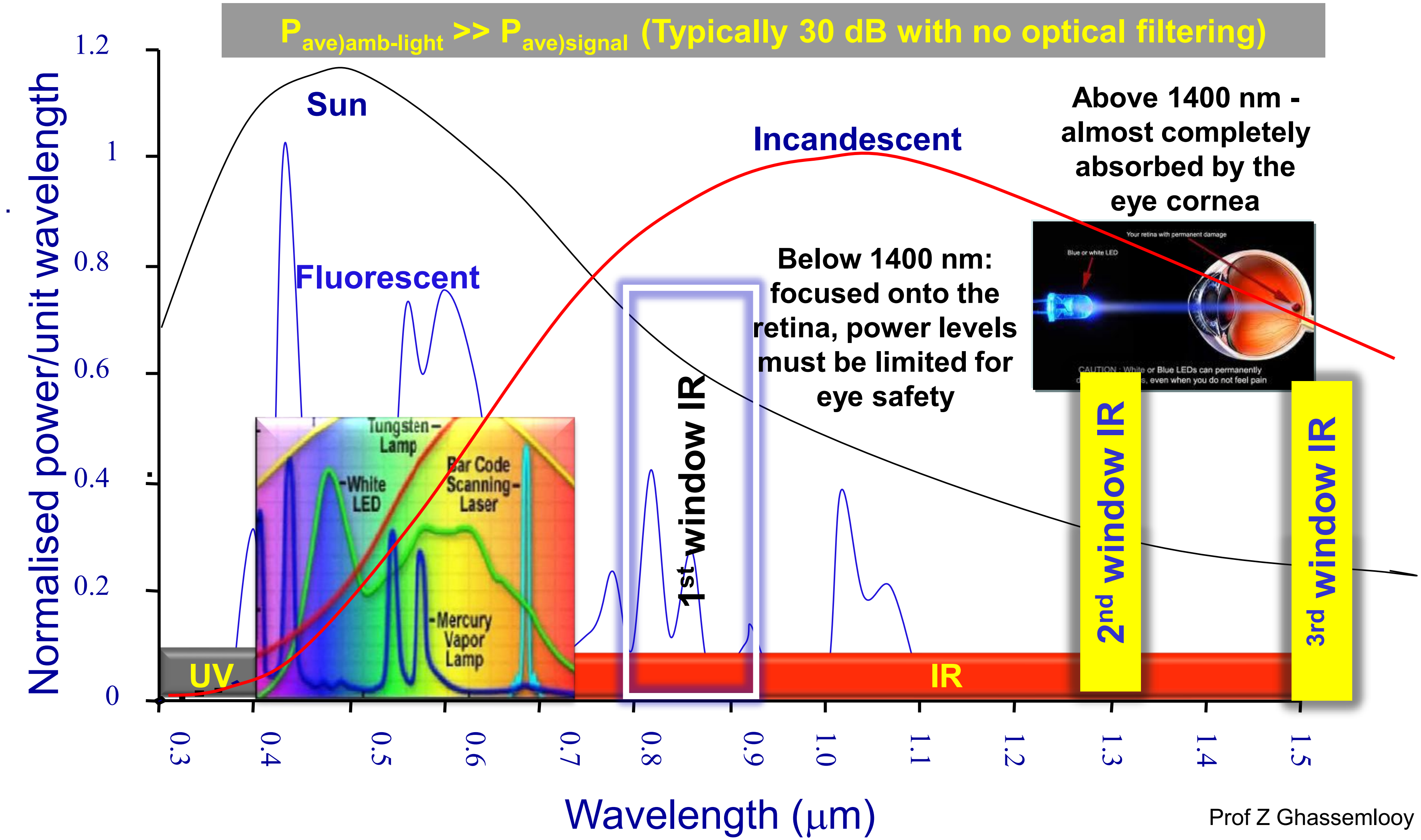
But mobility is the major issue

NASA. (2021). Laser Communications Relay Demonstration (LCRD). Space Technology Mission Directorate. https://www.nasa.gov/mission_pages/tdm/lcrd/index.html .

Wireless – Technology (Long distance)



OWC - Transmission Windows & Power Spectra of Ambient Light Sources



FSO – Main Features

Short wavelength infrared band of 900-1700 - Used in FSO because of light going through obstacles such as fog.

1550 nm - Commonly preferred wavelength, considered 'eye-safe', and InGaAs APDs shows peak sensitivity at this wavelength.

Best for line-of-sight communication - Where optical fibre or RF systems may not be feasible.

Rapid deployment - A few hours, 2 days for microwave, and a few months for fibre)[1], easy and fast upgrade

Improve data interoperability - FSO has an inherently low probability of detection or intercept → less need for complex encryption/decryption.

Multifunctionality – Communication and sensing

1- https://transcelestial.com/
https://www.qinetiq.com/en/what-we-do/mission-support-and-operations/cyber-and-intelligence/secure-solutions/secure-communications-solutions/free-space-optical-communications

FSO - Features

Spatial confinement

- Using narrow laser beams with directional properties.
- Offering a high degree of spatial reuse
- Inherent security at the physical layer → eavesdropping becoming difficult
- Easy to deploy with lower installation costs.

Low latency

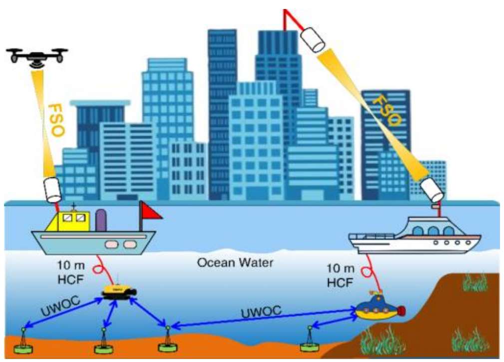
Scalability

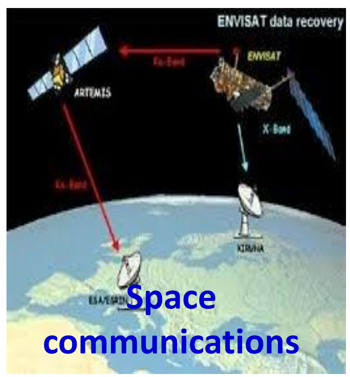
Ideal for large-scale deployment, i.e., in smart cities and IoT applications

Ultra high bandwidth

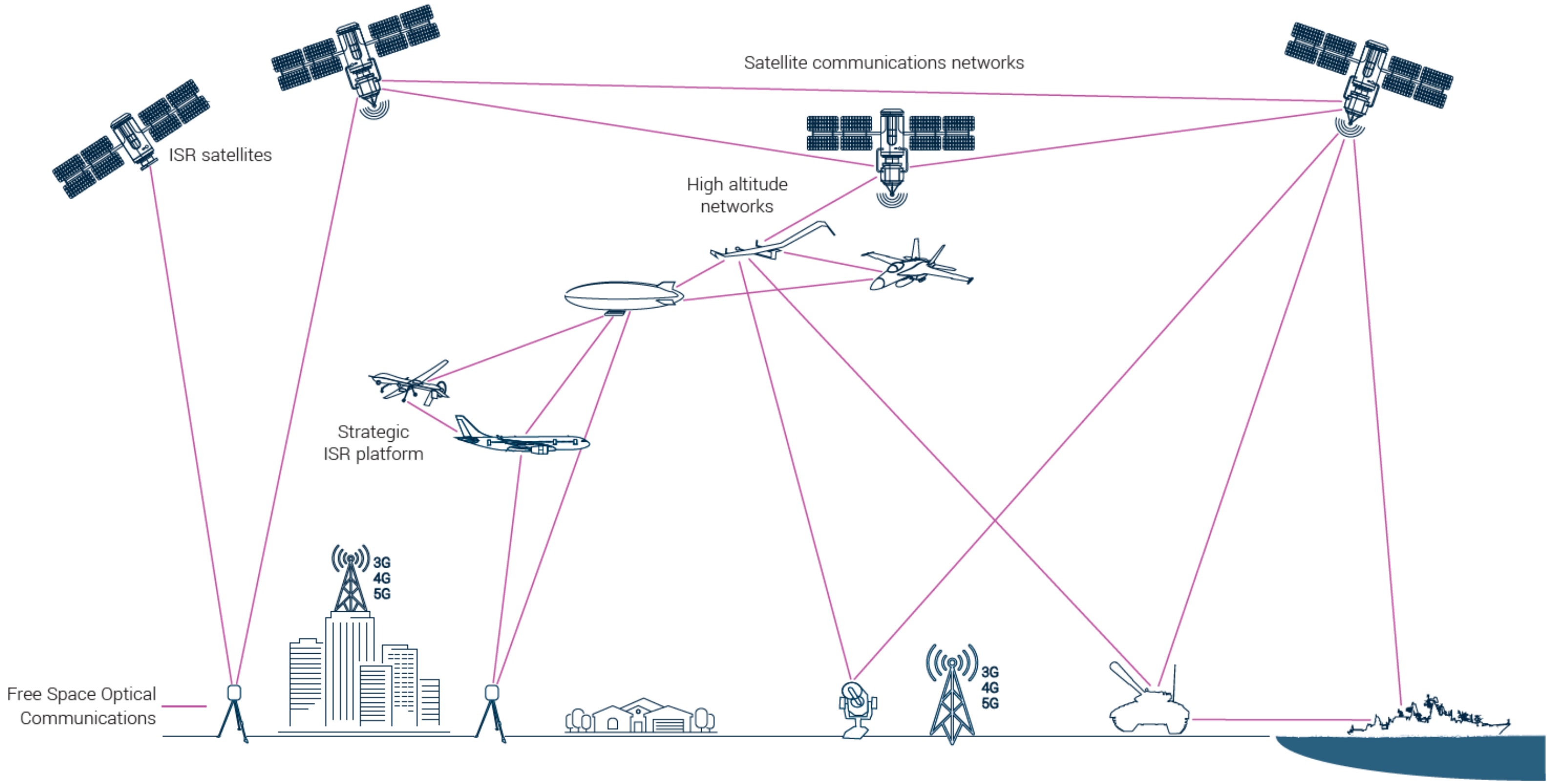
1- https://transcelestial.com/

FSO - Applications





FSO - Applications



- Link availability contributes to the achievable data rate.
- Data rate can be increased using relays, constellations and/or networks of ground stations.

https://www.qinetiq.com/en/what-we-do/mission-support-and-operations/cyber-and-intelligence/secure-solutions/secure-communications-solutions/free-space-optical-communications

FSO – Fundamental

FSO – Introduction

FSO Tx/Rx

Free space

FSO Tx/Rx

High data rates: Tens of Gbps, or Tbps using coherent systems

Baseband unit

Core network

Baseband unit

Access network

Network Layout

Point-to-Point

Point-to-Multipoint

Mesh

Ring Topology

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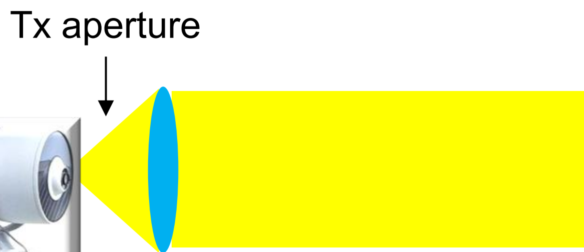
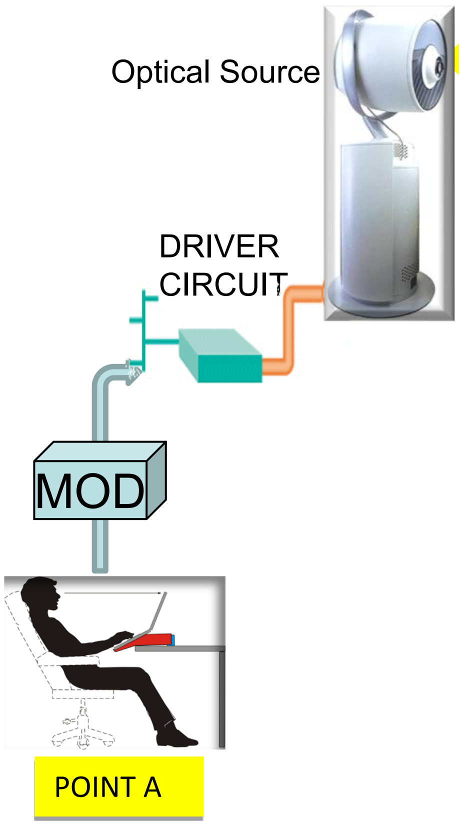
M. Alzenad, "FSO-Based Vertical Backhaul/Fronthaul Framework for 5G+ Wireless Networks," IEEE Commun. Mag., vol. 56, no. 1, Jan. 2018, pp. 218–24.

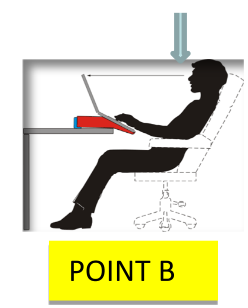
FSO – Introduction





Optical Source

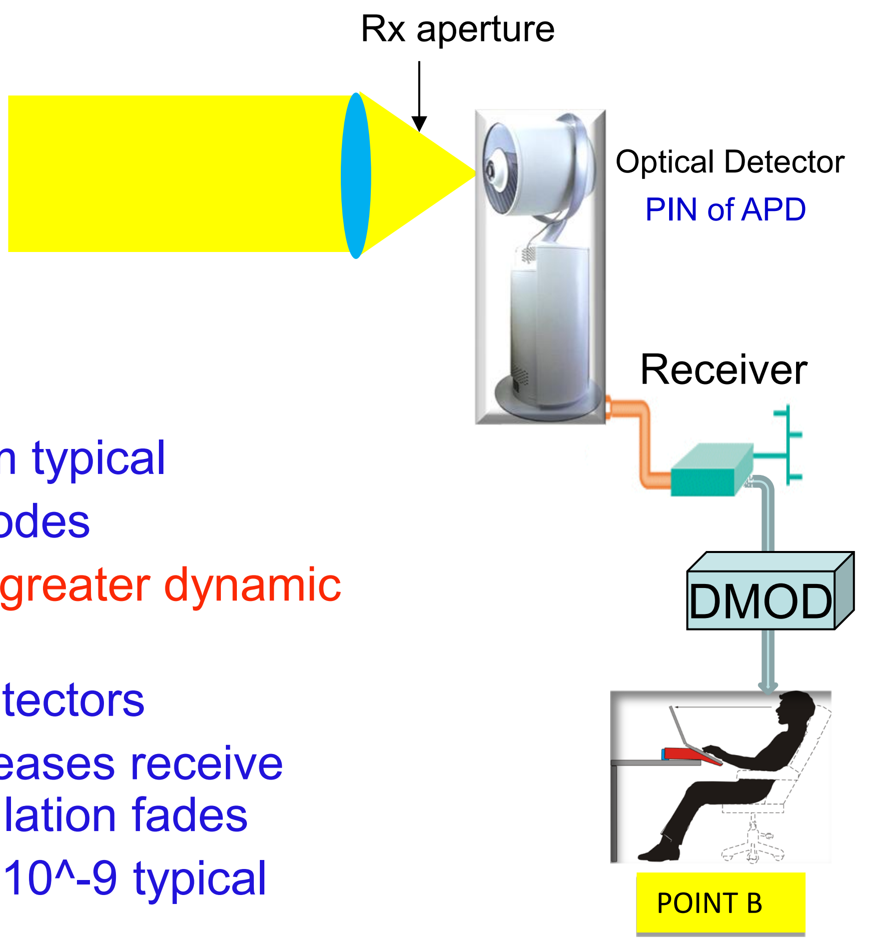
- LED (single or multiple)
  - >1 mW typical
- Laser (single or multiple)
  - 10-20 mW up to 100 mW
- 785 or 850 nm, 1310 &1550n nm
- Eye safety limit: 1.5 mW/cm^2 at 785 nm
- Multiple transmitters boost power, may also reduce scintillation fades



FSO – Introduction

Detector

- PIN Diodes: -43 dBm typical
- Avalanche Photo Diodes
  - -53 dBm typical, greater dynamic range
- Single or multiple detectors
- Larger aperture increases receive power, reduces scintillation fades
- Design goal: BER < 10^-9 typical

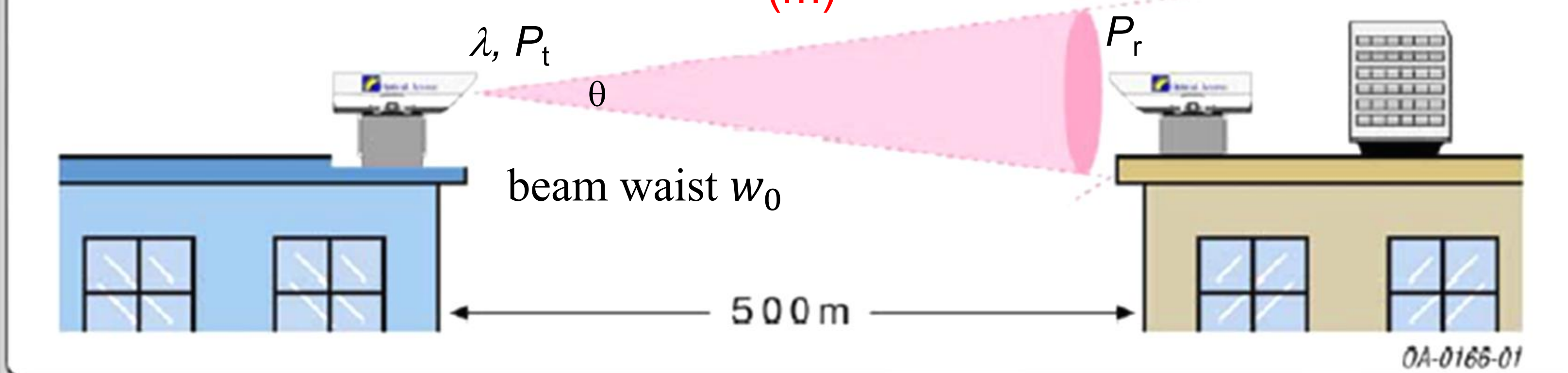


FSO – Beam Divergence

Radio waves tends to spread out broadly, whereas optical beams can be made much narrower.

1° ≈ 17 mrad → 1 mrad ≈ 0.0573°

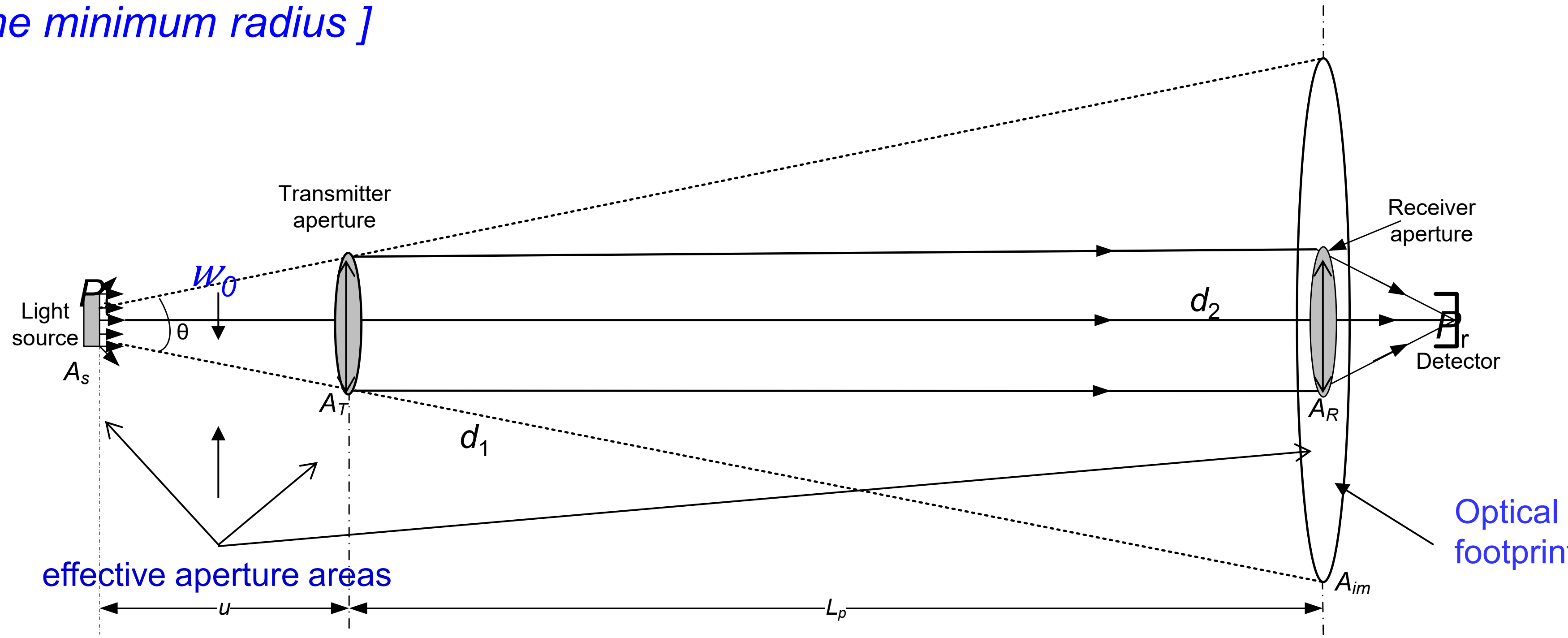
Small angle approximation: Angle (in milliradians) * Range (km) ≈ Spot Size (m)



Divergence Angle θ (mrad)	Range *L* (km)	Spot Diameter at the Rx
0.5	1.0	~0.5 m (~20 in)
2.0	1.0	~2.0 m (~6.5 ft)
4.0 (~ ¼ deg)	1.0	~4.0 m (~13.0 ft)

FSO – Beam Divergence

Beam is collimated using a lens to reduce the geometrical loss *[θ is kept small, and w_0 is the minimum radius]*



Received signal:

$$y(t) = \mathcal{R}h(t)x(t) + n(t)$$

Channel gain

Noise

Rx responsivity

Transmitted data

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FSO – Beam Divergence

Beam divergence

A classical engineering trade-off

Little divergence as possible

The Rx seeing and capturing more of the transmit power

Beam intensity at a distance may exceed allowed regulatory limits

Higher signal-to-noise ratio

Lower bit error rate

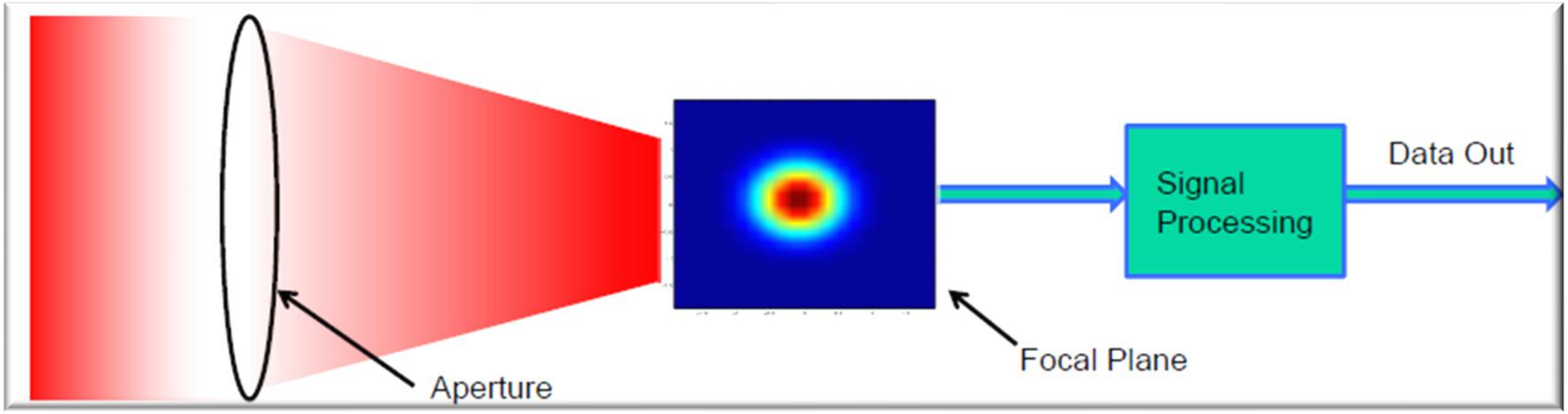
A wider beam means the link will be far less sensitive to misalignment due to vibration and motion

The link will be far less sensitive to misalignment due to vibration and motion

Lower signal-to-noise ratio

Higher bit error rate

FSO – Beam Divergence



Required Power: in the focal plane to support specified data rate

$$P_{r-rq} = P_{r-min} / L_b L_j L_{ef} L_{tu} \eta_{det} \eta_{imp} \eta_{cod} \eta_{int}$$

$P_{r\text{-}min}$ – Minimum (ideal receiver) received power
L_b – Detector blocking loss
L_j – Jitter loss
L_{ef} – Efficiency loss

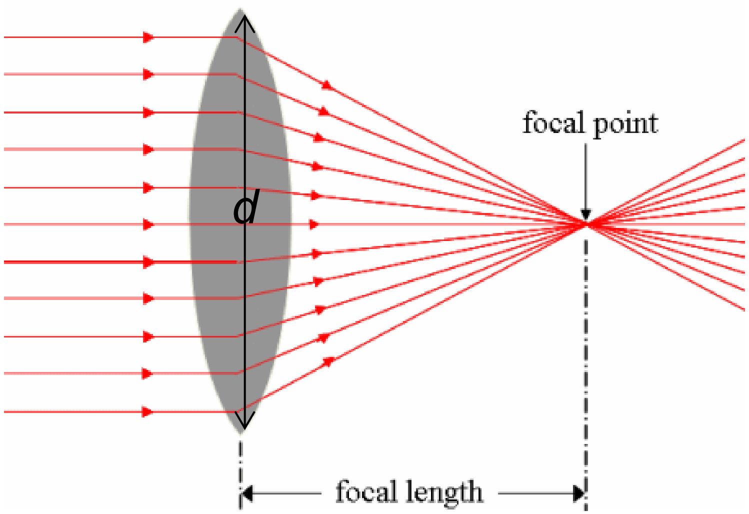
η_{det} – Detector efficiency
η_{imp} – Implementation efficiency
η_{cod} – Coding efficiency
η_{int} – Interleaver efficiency in the signal processing unit

Interleaving combats this by mathematically scrambling the bits or symbols before transmission, then reordering them in reverse at the receiver.

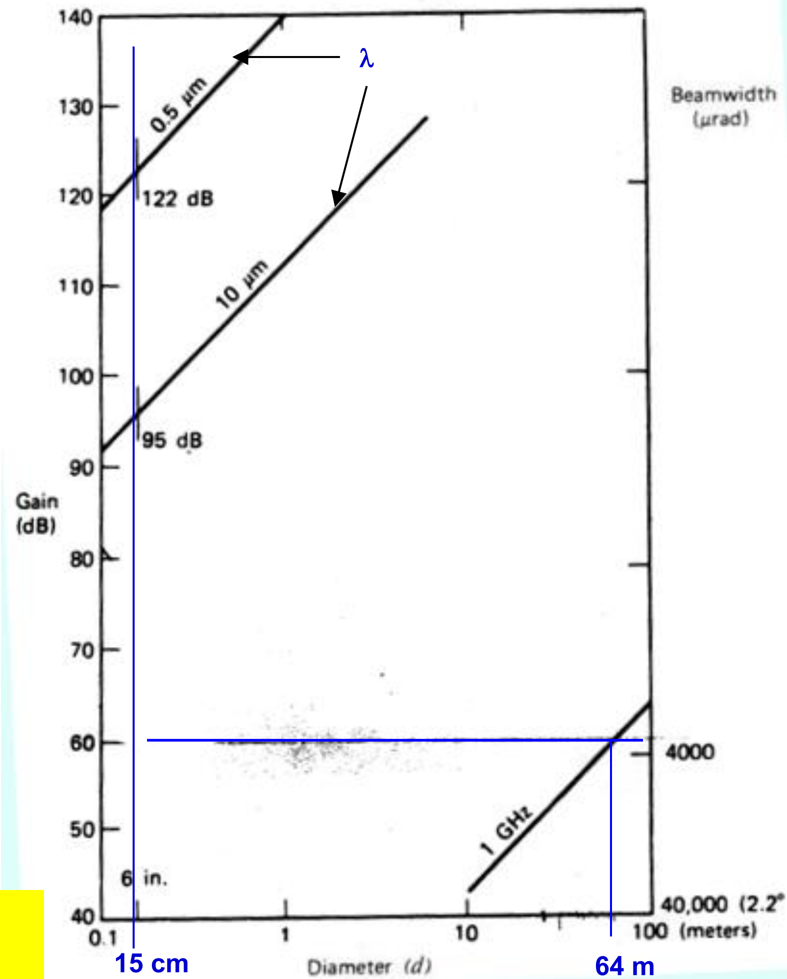
FSO – Antenna Gain

Antenna gain $G_t = 16/\theta^2$

Where the divergence angle $\theta = \lambda/d$

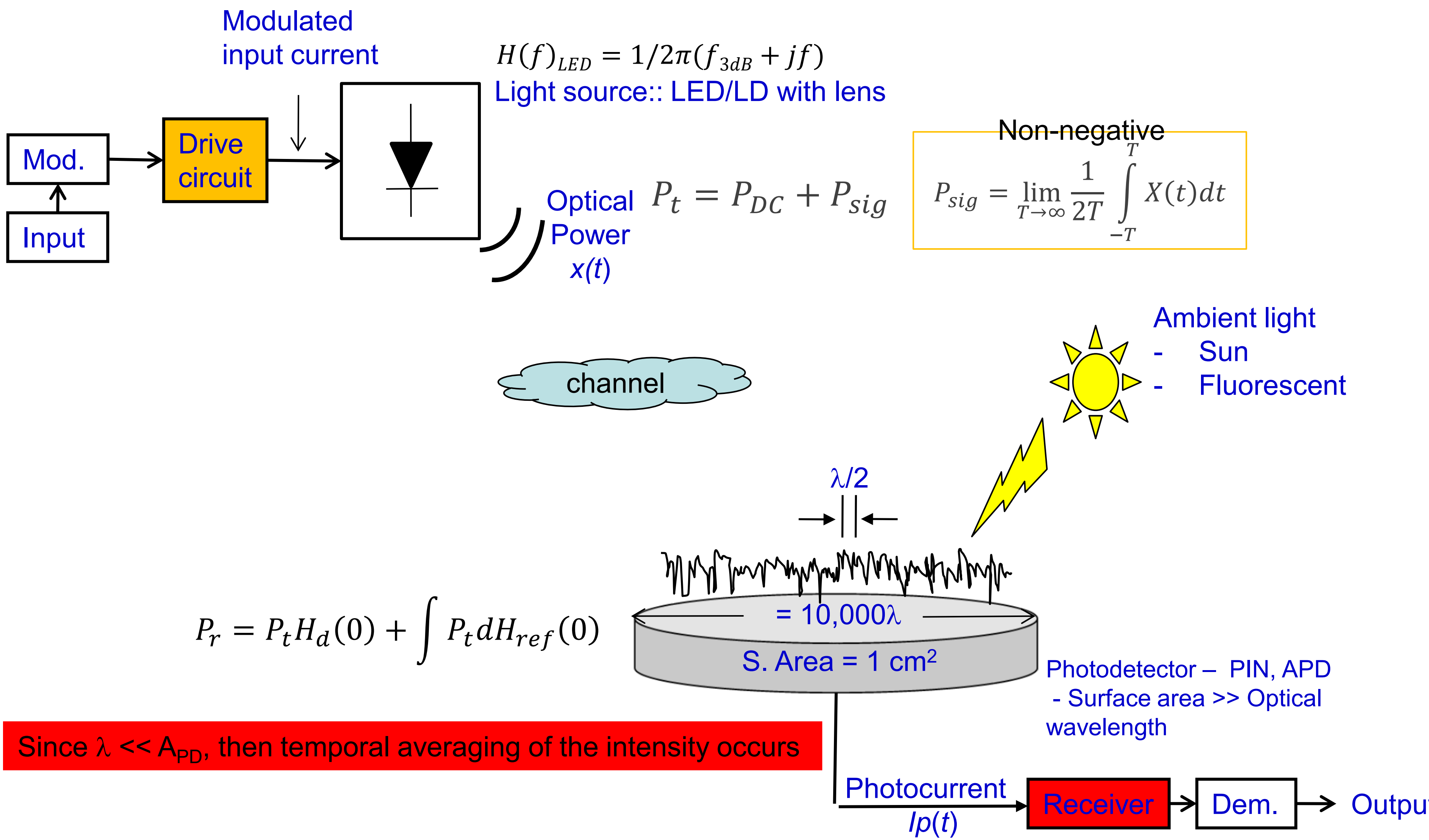


Comparison between optical and RF



E.g.: 15 cm lens antenna at 6x10^14 Hz has 122 dB Gain, compared to an improvement over an RF antenna of 64 m generating gain of 60 dB !

FSO – System Concept



OWCs – System Model

Note - The optical channel differs from conventional electrical or radio systems as the channel input *X*(*t*) is nonnegative i.e.:

$$X(t) \geq 0$$

And the average transmitted optical power $\overline{P}_{\mathrm{t}}$ is given by:

$$\overline{P}_{\mathrm{t}} = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)\,dt$$

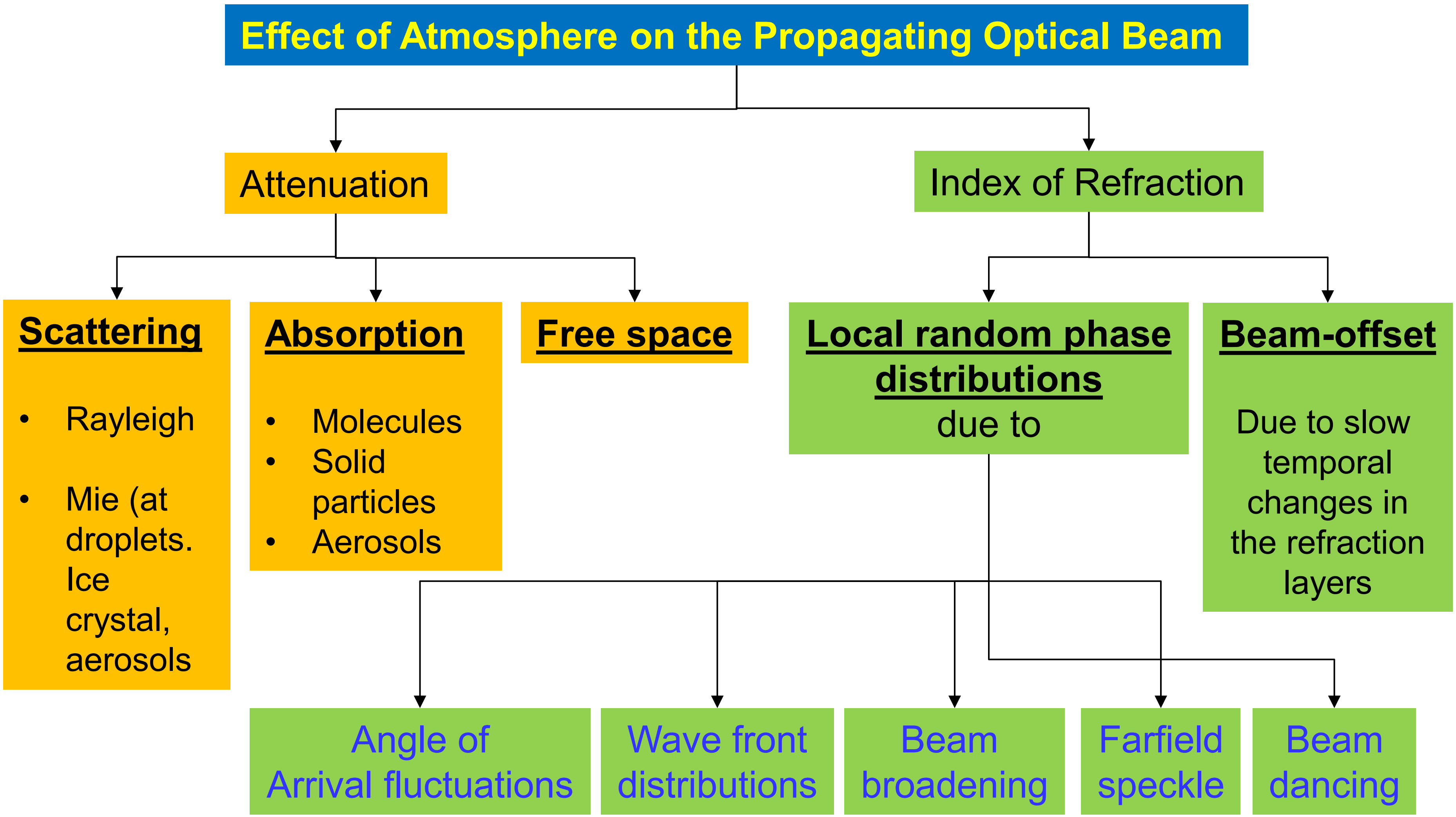
Rather than the usual time-average of $|X(t)|^2$ in RF systems, the average received optical power is given by:

$$\overline{P}_{\mathrm{r}} = H(0)\,\overline{P}_{\mathrm{t}}$$

where *H*(0) is the channel DC gain given by:

$$H(0) = \int_{-\infty}^{\infty} h(t)dt\,.$$

FSO – Channel Effects



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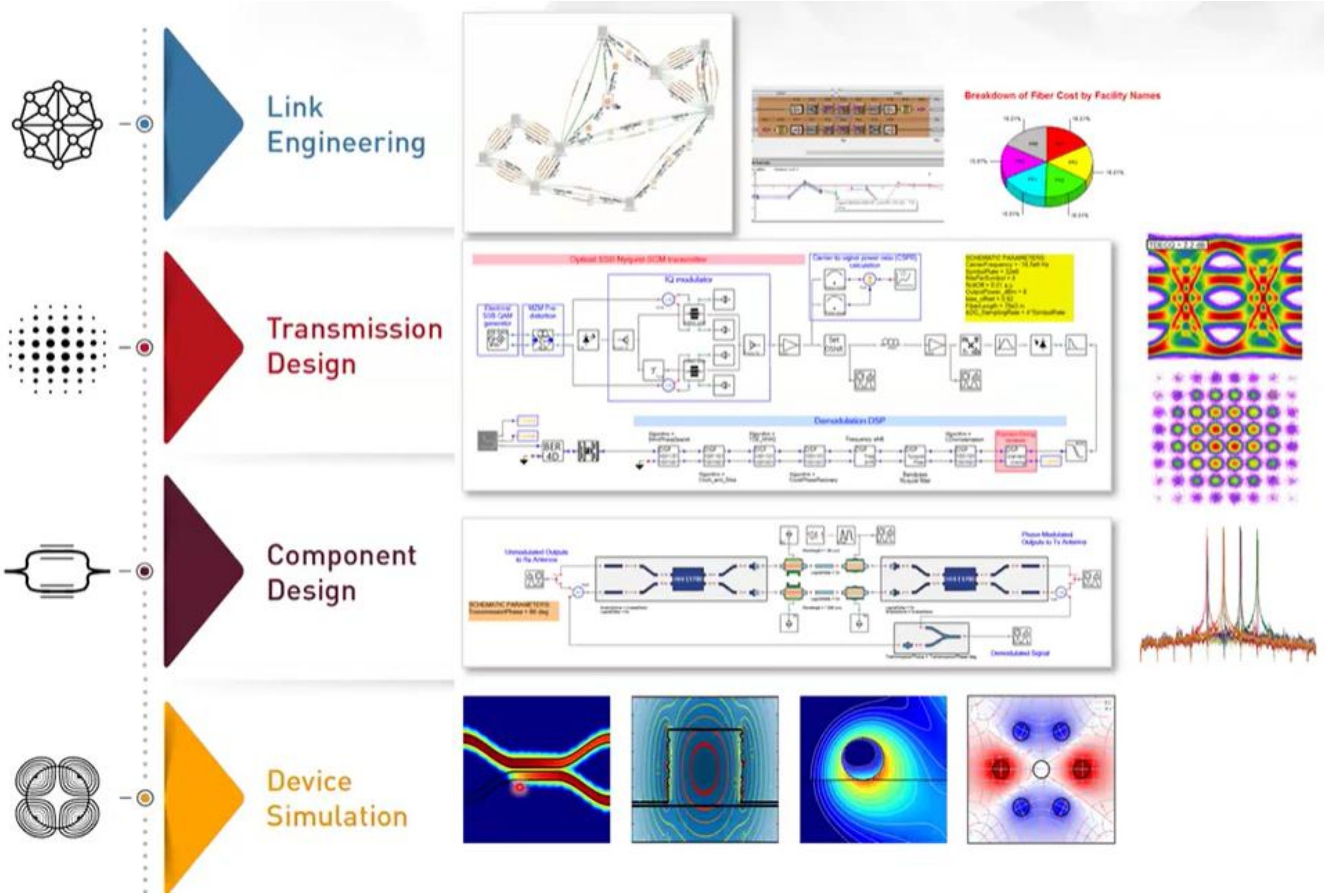
FSO – System Modelling

VPI - Photonic Simulation and Engineering Framework



https://www.optica.org/events/webinar/2025/12_december/simulation_and_design_framework_for_free-space_optical_communication/

FSO – Received Signal

Average received power: $P_r = P_t G_t G_r L_{fs} L_{at} L_{bs} L_{ge} L_{po} L_{co} \eta_t \eta_r$

Or

$$P_r = P_t L_{fs} G_t G_r = P_t \frac{4A_r}{L_p{}^2 \Omega_b} \cong P_t \left(\frac{4}{\pi}\right)^2 \frac{A_t A_r}{L_p{}^2 \lambda^2}$$

Radiation solid angle $\Omega_b \cong \frac{\pi \theta_b^2}{4}$

P_t - Transmit power
G_t & G_r – Tx and Rx aperture gains
L_{fs} – Free space loss
L_{co} – Coupling loss between Tx & lens, and Rx & lens
L_{at} - Atmospheric loss

L_{bs} - Beam spreading loss
L_{po} - Pointing loss
η_t & η_r Transmit & Receive efficiencies

L_{at} and L_{po} – are random variables defined by their respective PDFs

FSO – Alignment

FSO is a line-of-sight link, therefore, the Rx should be visible to the Tx.

Use the built-in telescope imaging system or an alignment camera or both to move the Tx or the Rx unit within each other view

Fine adjustment - To bring the beam exactly within the aperture of the Tx and the Rx.

Locking in place the Tx and the Rx units. Some systems also include dynamic beam alignment to maintain proper aim

FSO – Fundamental Equations

Parameter	Equation
Tx gain	$G_t = 16/\theta^2$ Note: $\theta = \lambda/d$
Free space loss	$L_{fs} = \left(\frac{\lambda}{4\pi L_p}\right)^2$
Rx gain	$G_r = (\pi d_2/\lambda)^2$
Radiation solid angle	$G_r = (\pi d_2/\lambda)^2$
Geometry loss	$L_{geo} = \frac{A_R}{A_T} = d_2^2/(d_1 + \theta L_p)^2$
Atmospheric loss	$L_{at} = \exp[-K(\lambda)L]$ $K = K_{abs} + K_{sca}$
Beam spreading loss	$L_{bs} = \frac{w_r(I)}{w_{eff}(I)}$ $w_r(I) = w_o^2 + (2L_p/kw_o)^2$

Detector field of view = Detector size D_{det} /focal length f

FSO – Attenuation Link Budget

Example - Typical link budget for 2.5 Gbps, 2 km link, and λ 1550 nm

Link Budget for the FSO Link

Parameters	No Tracking	With Tracking
Transmitter		
Power	30 dBm	30 dBm
Losses	3 dB	3 dB
Mis-pointing allowance	6 dB	3 dB
Channel losses	30 dB	14 dB
Receiver losses	3 dB	3 dB
Receiver sensitivity	–23 dB	–23 dB
Link safety margin—*for weather conditions*	5 dB	27 dB

“Optical Wireless Communication Systems: Channel Modelling with MATLAB”, Z.Ghassemlooy.

FSO – Modulation & Detection

	IM-DD	Coherent
Modulation parameters	Intensity (Amplitude) - Simple and low cost - For terrestrial FSO	Amplitude, phase and frequency - I and Q components - Increasing the spectral efficiency - Costly - The need for the local oscillator at the Rx
Detection method	Direct detection	Heterodyne or homodyne detection • At higher power usage
Adaptive control	Not needed	Needed for carrier phase and state of polarization
Performance	** - Low cost	*** • Higher receiver sensitivity • Rejecting the background induced shot noise and the thermal noise • Reducing effects of turbulence - High cost

FSO – Light Sources and Detectors

Light source

- Wavelength range: 750-1600 nm
  - 1500 nm
  - 1300 nm – Narrow line and high power DFBs + high power optical amplifiers

- Laser – More coherent beam, high data rate and longe rage
  - Vertical cavity surface emitting laser
  - Fabry–Perot and distributed feedback

For efficiency, reliability, and suitability

- LED – Low data rates and at 700-900 nm

- Medium to high power across a wide temperature range

- Long mean time between failures - ensuring reliable performance over long periods

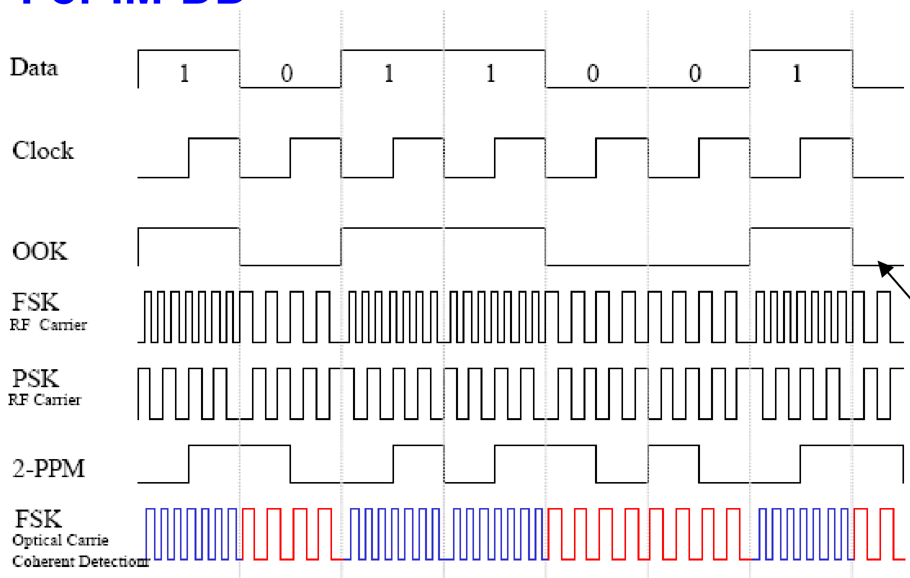
- Eye safe

FSO – Light Sources

Features	Laser	LED
Output power	High	Low
Optical spectral width	0.01 – 5 nm	25 – 100 nm
Modulation bandwidth	Hundreds of GHz	Tens of THz
Electrical/optical-conversion efficiency	30 – 70 %	10 – 20 %
Eye safety	Need extra precautions	Considerably eye safe
Directionality	Very focus and collimated	Broad beam
Reliability	High	Moderate
Coherence	Coherent	Non-coherent
Temperature sensitivity	Highly sensitivity to temperature	Low sensitivity to temperature
Drive and control circuit	Complex with threshold and temperature compensation	Simple to use and control
Cost	High	Moderate to low
Harmonic distortion	Low	High
Receiving filter	Narrow- low noise floor	Wide- high noise floor

FSO – Modulation Format

For IM-DD

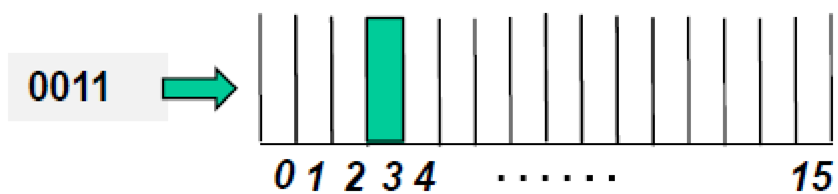


The most simple

Pulse-Position-Modulation (PPM)

log2*M* bits are represented by a single pulse out of M slots (here *M*=16).

- High peak power
- Low average power



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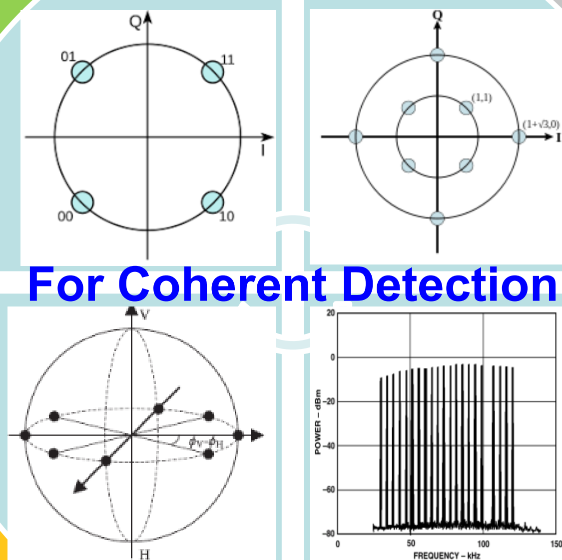
FSO – Modulation Format

- Multilevel phase-shift keying
- Quadrature amplitude modulation
- Multilevel polarization shift keying
- Discrete multi-tone

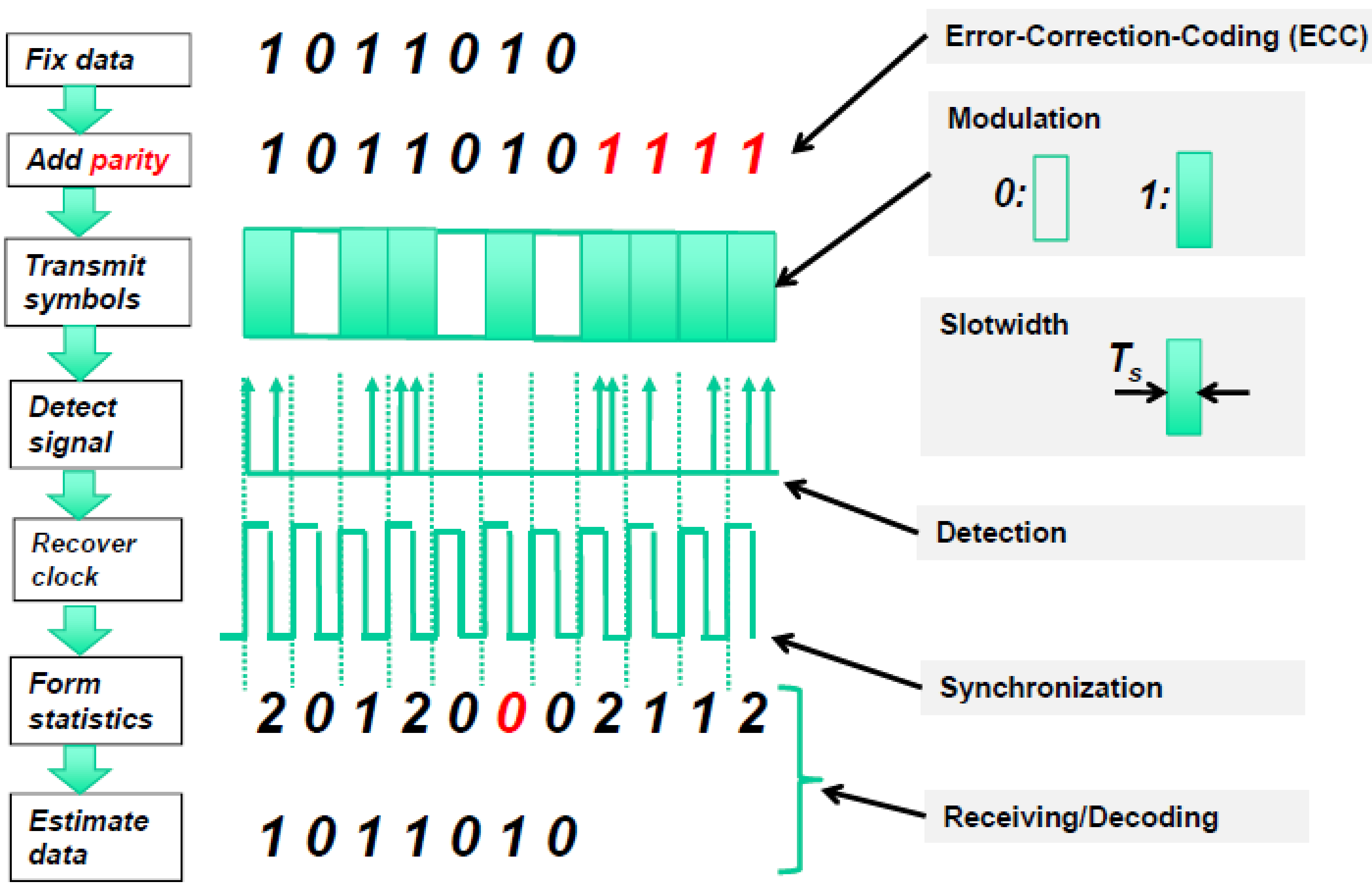
For Coherent Detection



- 100 Gbps bi-directional quadrature amplitude modulation link between a ground station and light aircraft over 10–20 km transmission range [1].
- A 1.6 Tbps 16-channel QPSK link over between two building at 80 m [2].
- 13.16 Tbps 54-channel QPSK employing tip/tilt stabilisation scheme over a a turbulent channel of 10.45 km long [3].
- 2 Tbit/s Free-space optical communication using small optical terminals mountable on satellites and high altitude platform stations [4]

1- Chen, C. et al. Demonstration of a bidirectional coherent air-to-ground optical link. In Free-Space Laser Communication and Atmospheric Propagation XXX Vol. 10524 (eds Hemmati, H. & Boroson, D. M.) 120–134 (International Society for Optics and Photonics SPIE, 2018), https://doi.org/10.1117/12.2292848; 2- Parca, G., Shahpari, A., Carrozzo, V., Beleffi, G. M. T. & Teixeira, A. L. J. Optical wireless transmission at 1.6-Tbit/s (Gbit/s) for next-generation convergent urban infrastructures. *Opt. Eng.* **52**, 116102. https://doi.org/10.1117/1.OE.52.11.116102 (2013); Dochhan, A. *et al*. 13.16 tbit/s free-space optical transmission over 10.45 km for geostationary satellite feeder-links. In *Photonic Networks; 20th ITG-Symposium*, 1–3 (2019); [4] https://www.nict.go.jp/en/press/2025/12/16-1.html

FSO – Signal Processing Steps



Sam Dolinar, et al, Jet Propulsion Laboratory, 2012

FSO – Photodetection

- Converts optical radiation to an electrical signal (photoelectric effect)
- A square law p-n junction sensor
- The photo-current $I \propto P$ (the square of the incident optical field)

Features

- Excellent linearity
- Wide spectral response (λ range)
- Low noise
- Long life and rugged
- Compact and light weight

FSO – Light Detectors

Si - At the shorter wavelengths

InGaAs

- At the longer wavelengths
- Used in all cases
- Not used below 850 nm

PIN | **APD** | **SPD**

Commonly used PDs in FSO (PIN, APD)

FSO – Light Detectors -APD

InGaAs	▪ exhibit peak sensitivity at the 2nd transmission window of 1550-1600 nm. ▪ Its sensitivity at 1550 nm was limited by the device internal noise, limiting the range and data rates
Noiseless InGaAs™ [1]	▪ For detecting exceptionally low levels of light, down to single photons, helping maintain signal integrity over long transmission range and under changing atmospheric conditions. ▪ Offering 12 times the sensitivity of traditional InGaAs APDs, represents a potential 10.79 dB improvement in the FSO link efficacy, before other noise sources such as amplifiers are considered.

Developed by Phlux Technology in 2024

1- https://phluxtechnology.com/latest/free-space-optical-communication-high-data-rate-connectivity-from-the-ground-up

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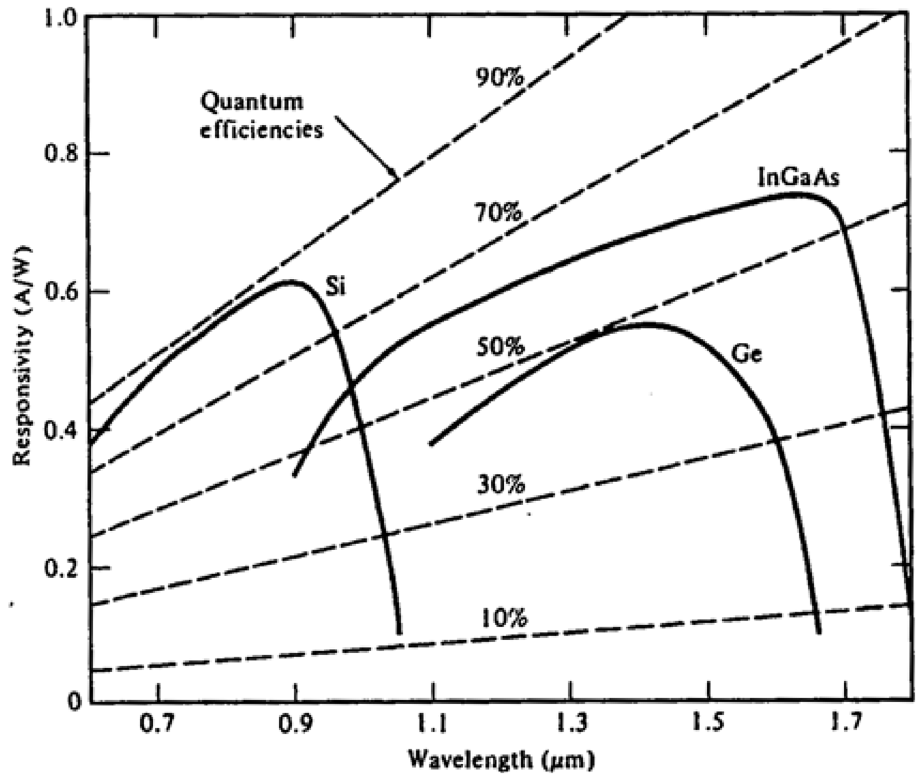
FSO – Light Detectors

Characteristics	PIN	APD
Modulation bandwidth	Tens of MHz to tens of Ghz	Hundreds of MHz to tens of Ghz
Photocurrent gain	1	$10^2 - 10^4$
Special circuitry required	None	Temperature compensation circuitry
Linearity	High	Low- suited to digital applications
Cost	Low	Moderate to high
Bias voltage (V) for Si	45 – 100	220
Capacitance (pF) for Si	1.2 – 3	1.3 – 2



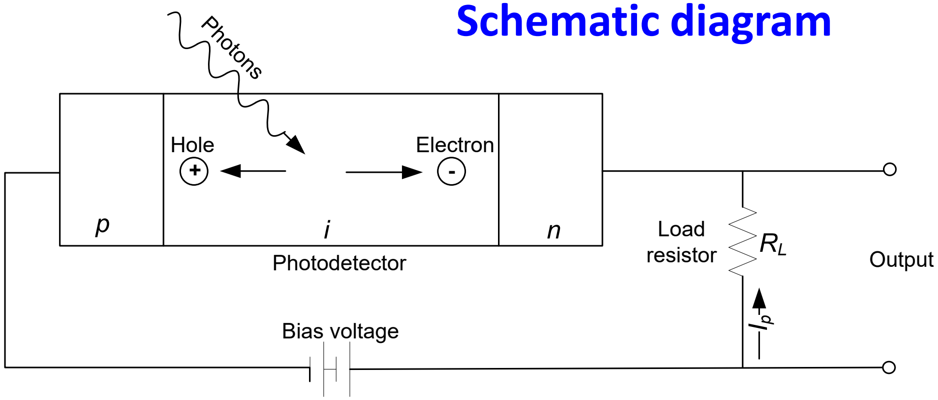
The maximum detectable wavelength $\lambda = \frac{1240}{E_g}$ (nm)

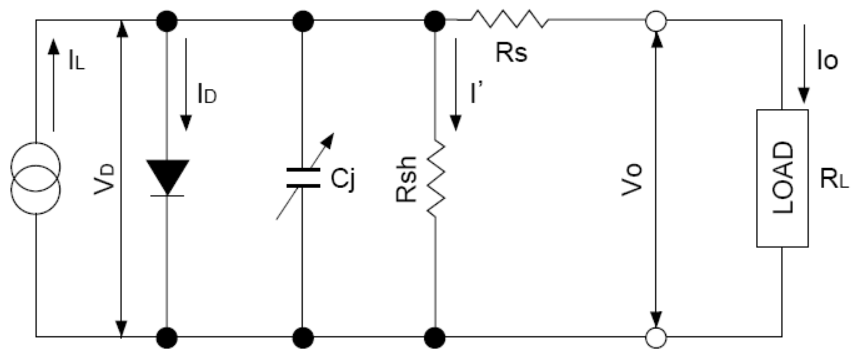
E_g → Bandgap energy

Z.Ghaseemlooy, W. Poopola, and S. Rajbhandri, "Optical wireless communications, system and channel modelling with matlab," *CRC Press, London, UK,* 2012.

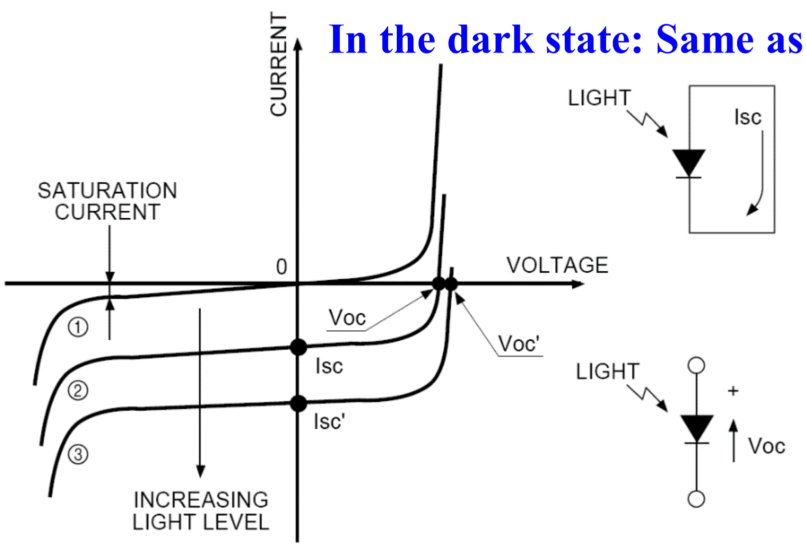
FSO – Photodetection

Schematic diagram



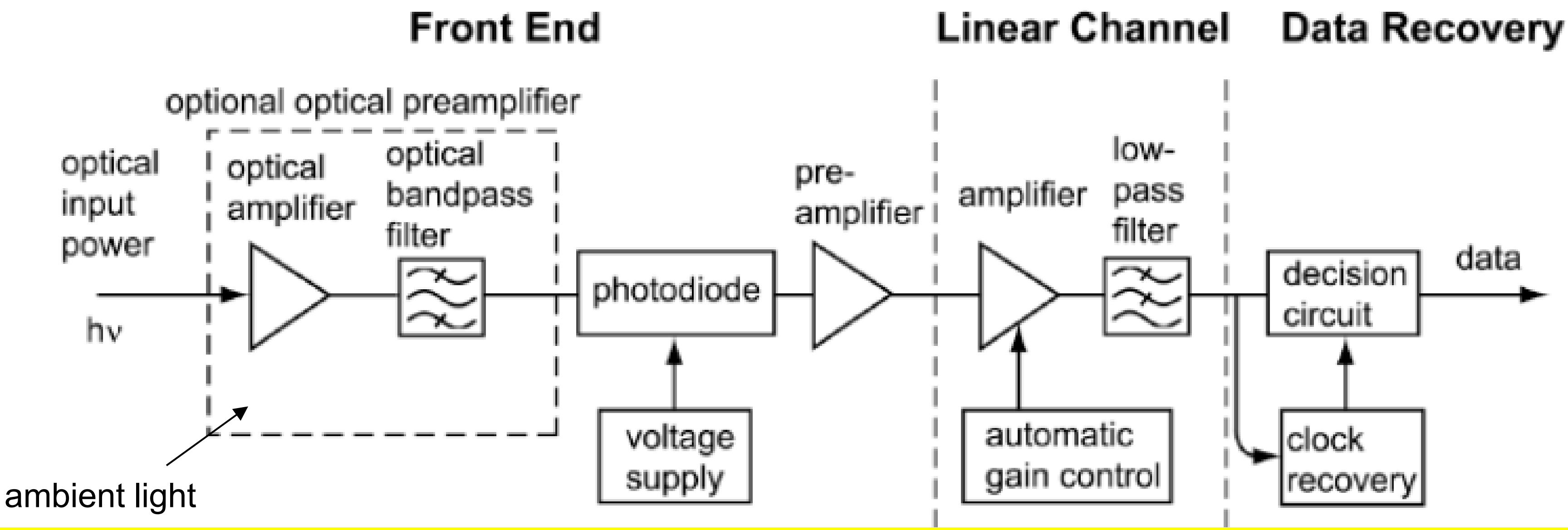


In the dark state: Same as a diod



- I_L : Current generated by the incident light (proportional to the amount of light)
- I_D : Diode current
- Cj : Junction capacitance
- Rsh : Shunt resistance
- Rs : Series resistance
- I' : Shunt resistance current
- V_D : Voltage across the diode
- Io : Output current
- Vo : Output voltage

FSOs – Direct Detection



- **Detection based on optical power/intensity**
- **Signals can only be encoded using one degree of freedom**
- **Also known as the envelope detection**
- **For an instantaneous incident power *P*(*t*), the instantaneous PD current *i*(*t*) is:**

Quantum efficiency

Photodetector gain factor

$$i(t) = \frac{\eta_{qe} q\lambda}{hc} M P(t)$$

Instantaneous incident power

FSO – Coherent - Detection

Maintain both polarisation and phase information - Mixing the received signal with a local oscillator → extra degrees of freedom to data encoding → effective use of the channel capacity

Homodyne detection

- Higher detection sensitivity
- Need for a very accurate optical phase-locked loop (PLL) → Challenging and costly

Heterodyne detection

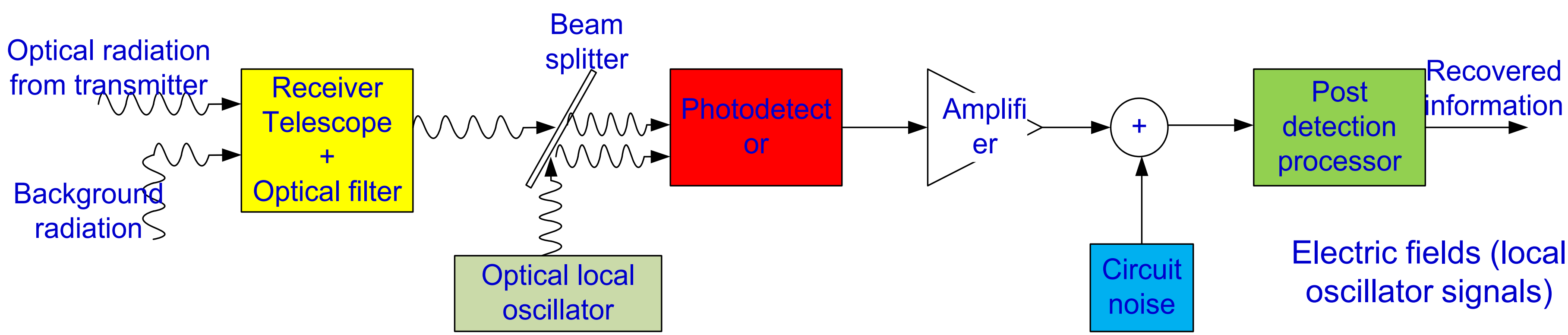
- Widely used
- No need for PLL Low cost → low cost

The use of digital signal processing techniques facilitated the use of spectrally efficient modulations and effective compensation schemes for any impairments.

Belmonte, A. & Kahn, J. M. Capacity of coherent free-space optical links using atmospheric compensation techniques. Opt. Express 17, 2763–2773.

FSO – Coherent Detection

- Signals encoded using amplitude, phase and even the frequency of the lightwave
- Such receivers, teamed with high-order modulations, achieve much higher spectral efficiency than PPM or OOK with photon counting.
- More practical than IM/DD systems for applications requiring extremely high data rates.
- Practical for (i) link over the atmosphere; (ii) systems limited by the background noise



Photocurrent at the output of photodetecor, which operates as a square-law device

$$i_{IF-c}(t) = RM(E_c + E_L)^2$$

Electric fields (local oscillator signals)

Electric field (received optical)

- Heterodyne detection: $i_p(t) = RA_LA_c\cos[(\omega_L - \omega_{co})t + (\theta_L - \theta_c)]$
- Homodyne detection: $i_p(t) = R[A_LA_c\cos(\theta_L - \theta_c)]$

It offers

1. A relatively easy means of amplifying the photocurrent by simply increasing the local oscillator power.
2. Improved SNR. By increasing local oscillator power so that its inherent shot noise dwarfs the thermal and the shot noise from other sources
3. The shot noise limited receivers offer improved sensitivity, by up to 20 dB, compared to the IM-DD schemes
4. DSP techniques can be used to compensate for transmission impairments since full electric field information is available
5. High spectral efficiency - due greater flexibility in modulation formats. Information can be encoded in amplitude and phase, or alternatively in both in-phase (I) and quadrature (Q) components of a carrier
6. Compatibility with ubiquitous optical fibre-based systems

Ip, E., Lau, A. P. T., Barros, D. J. F. & Kahn, J. M. Coherent detection in optical fiber systems. Opt. Express 16, 753–791.

FSO – Coherent Detection

The frequency of an optical source drifts over time:

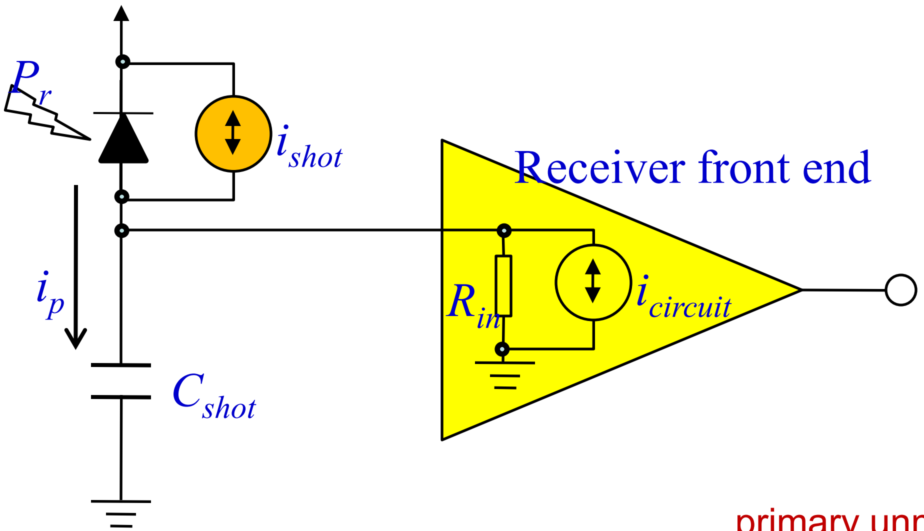
- So, $(\omega_L - \omega_{co})$ needs to be monitored at the input of electrical detector and
- Local oscillator frequency ω_{co} varies accordingly to keep IF centre frequency constant.

But

Due to laser phase noise, θ_c and θ_L are not absolutely fixed, they fluctuate.

Atmospheric turbulence causes phase θ_c and amplitude A_c to fluctuate as well.

FSO – Noise Sources in DD



- Quantum noise (shot noise)

$$\sigma^2_{q-pin} = 2q\langle i\rangle B$$

$$\sigma^2_{q-adp} = 2q\langle i\rangle BFM^2$$

bandwidth of the electrical filter

primary unmultiplied dark and the surface leakage currents

- Dark Current and Excess Noise $\sigma^2_{db} = 2qI_d M^2 FB$ $\sigma^2_{ds} = 2qI_l B$
- Background Radiation shot noise $\sigma^2_{bg} = 2qBR(I_{sky} + I_{sun})$
- Thermal Noise $\sigma^2_{th-D} = \dfrac{4\kappa T_e B}{R_L}$
- Intensity Noise – due to amplitude fluctuation of the optical signal, usually expressed in terms of relative intensity noise (RIN) $\sigma^2_{in-D} = \eta_{RIN}(RMP_r)^2 B$

FSO – Noise Sources in DD

Dark current

Transmitter noise

} Practically negligible

Thermal noise: TZ resistor

Low: Very high-rate systems: short diode response time, easy impedance matching with RF front-end	Large: Lower-rate systems: reduced thermal noise, improved receiver sensitivity

PIN: Thermal-noise-limited

APD: Shot-noise-limited

F. Xu, M.A. Khalighi, and S. Bourennane, "Impact of Different Noise Sources on the Performance of PIN- and APD-based FSO Receivers," *COST IC0802 Workshop, IEEE ConTEL Conference,* June 2011, Graz, Austria, pp. 279-286

FSO – Noise Sources in DD

- Signal intensity - Typically tens to hundreds of μW
- Background radiation shot noise:
  - Scattered sunlight by hydrometeors (clouds/fog) : several μW
  - Reflected sunlight: ~ hundreds of μW
  - Direct sun light: up to 10 mW (<1 hour per year)
  - Poisson random process - Classical model
  - For a large average number of the received photons ⇒ Distribution is Gaussian
  - The effective received noise is modeled by a zero-mean Gaussian random process.

$$\sigma_{bg}^2 = 2qBR\left(I_{sky} + I_{sun}\right)$$

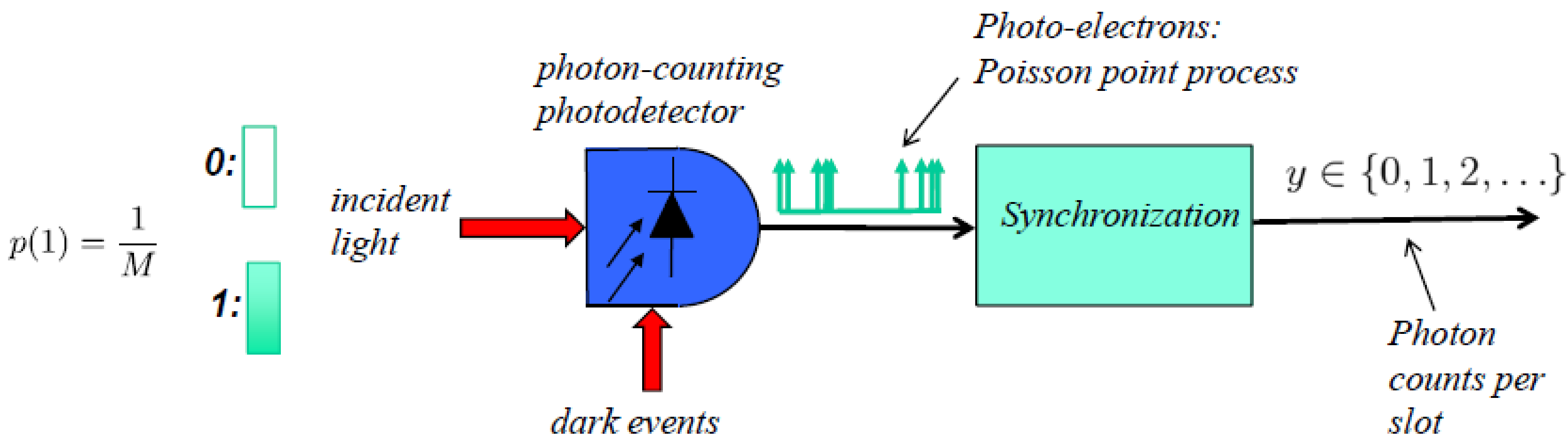
Impact:

- Variable offset in the converted electrical signal
- Performance degradation (reduced SNR): reduced effective receiver sensitivity
- Worst case: **link outage** because of the saturation of the receiver

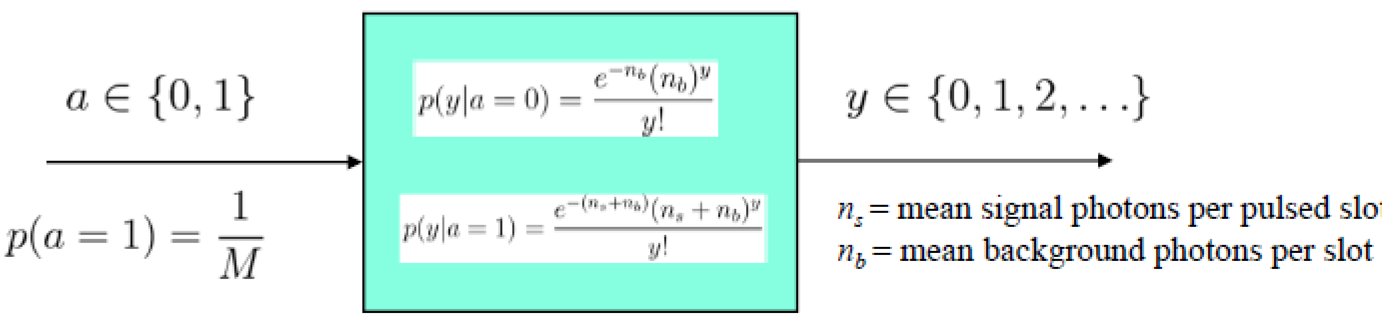
How to reduce BR - Band-pass and spatial filtering prior to photodetection.

R. M. Gagliardi and S. Karp, *Optical Communications*, 2nd. ed. New York, NY: Wiley, 1995
M.A. Khalighi, F. Xu, Y. Jaafar, and S. Bourennane, "Double-Laser Differential Signaling for Reducing the Effect of Background Radiation in Free-Space Optical Systems," *IEEE/OSA Journal of Optical Communications and Networking (JOCN),* vol.3, no.2, Feb. 2011, pp. 145-154

FSO – Intensity Modulation and Photo-Counting Channel Model

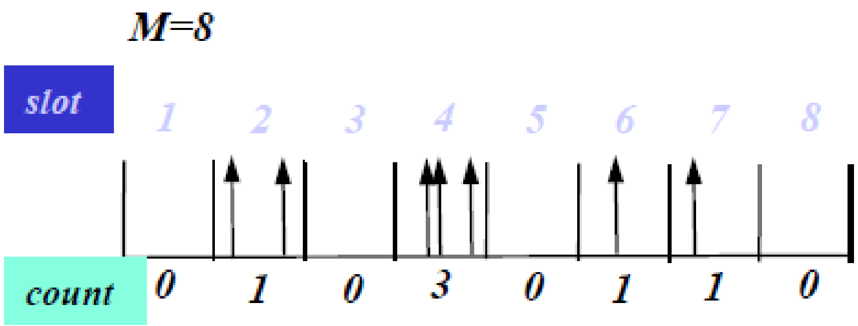


Equivalent Channel model: Binary input, Poisson-distributed integer output



Sam Dolinar, et al, Jet Propulsion Laboratory, 2012

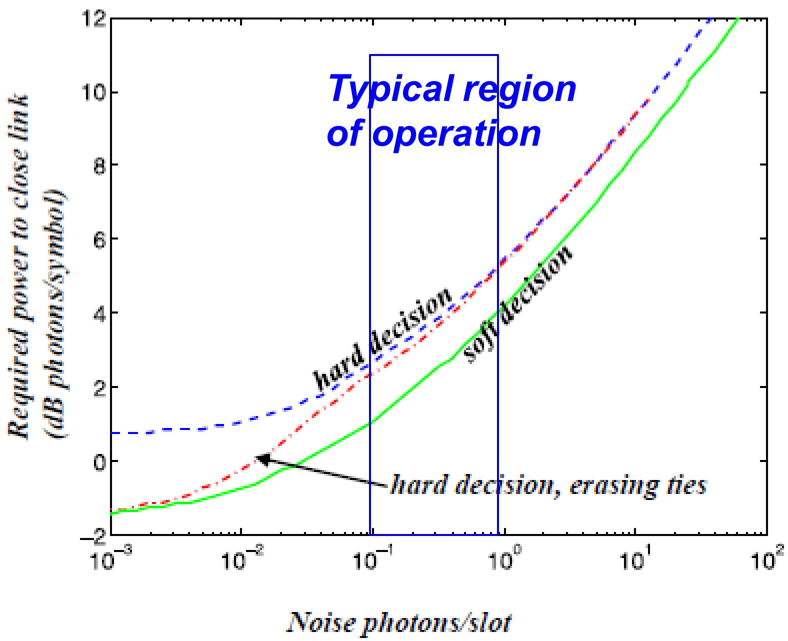
FSO – Photo Counting Process



Hard decision $\hat{x} = 01101$

Soft decision

$$p(x = 000/y) = 0.05$$
$$p(x = 001/y) = 0.2$$
$$p(x = 010/y) = 0.05$$
$$p(x = 011/y) = 0.05$$



Capacity, hard and soft decisions
M = 16, Average power to achieve
C = 1/8 bits/slot

Sam Dolinar, et al, Jet Propulsion Laboratory, 2012

FSO – System Performance Indicators

$$SNR_{IM-DD} = \frac{I_p^2}{N_T} = \frac{(RMP_r)^2}{\sigma_q^2 + \sigma_d^2 + \sigma_{bg}^2 + \sigma_{th}^2 + \sigma_{in}^2}$$

$$BER = 0.25\{erfc[(I_1 - I_{th})/\sqrt{2\sigma}] + erfc[(I_0 - I_{th})/\sqrt{2\sigma}]\}$$

Given that:

$$I_{th} = (\sigma_0 I_1 + \sigma_1 I_0)/(\sigma_1 + \sigma_0)$$

$$BER = 0.5\mathrm{erfc}(\frac{Q}{\sqrt{2}}) \qquad Q = (I_1 - I_0)/(\sigma_1 + \sigma_0)$$

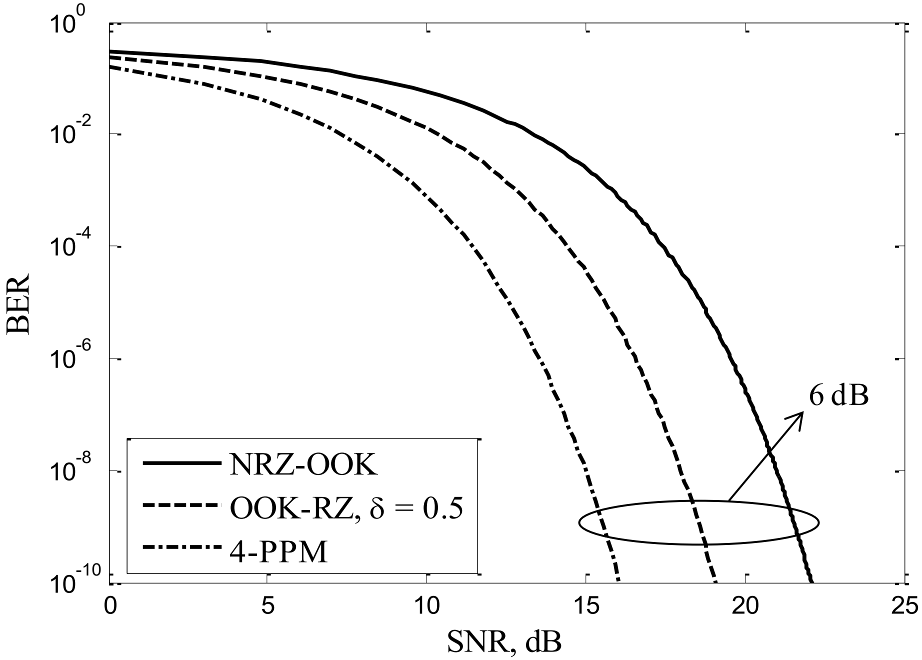
$$SNR_{IM-DD} = \frac{RP_r}{2qB}$$

For shot noise limited conditions, also referred to as the SNR in the quantum limit

$$SNR_{IM-C} = \frac{RP_r}{2MB_c}$$

For a coherent receiver with a sufficiently large optical LO power, the shot noise due to the optical LO is the dominant term

FSO – System Performance Indicators



Modulation Scheme	Optical Power	Bandwidth Requirement
OOK- NRZ	P_o	R_b
OOK- RZ	$P_o - 3$	$2R_b$
L- PPM	$P_o - 5\log_{10}\left[\left(L/2\right)\log_2 L\right]$	$LR_b / \log_2 L$

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FSO – Link Availability

Determined by the BER

BER on its own is no use until it is translated into something more useful, i.e., the number of frames with an error:

Ethernet frames - 1500 byte frames and BER of 10^{-6} → one bad frame in every 83.

99.999% - With a BER of 10^{-6}

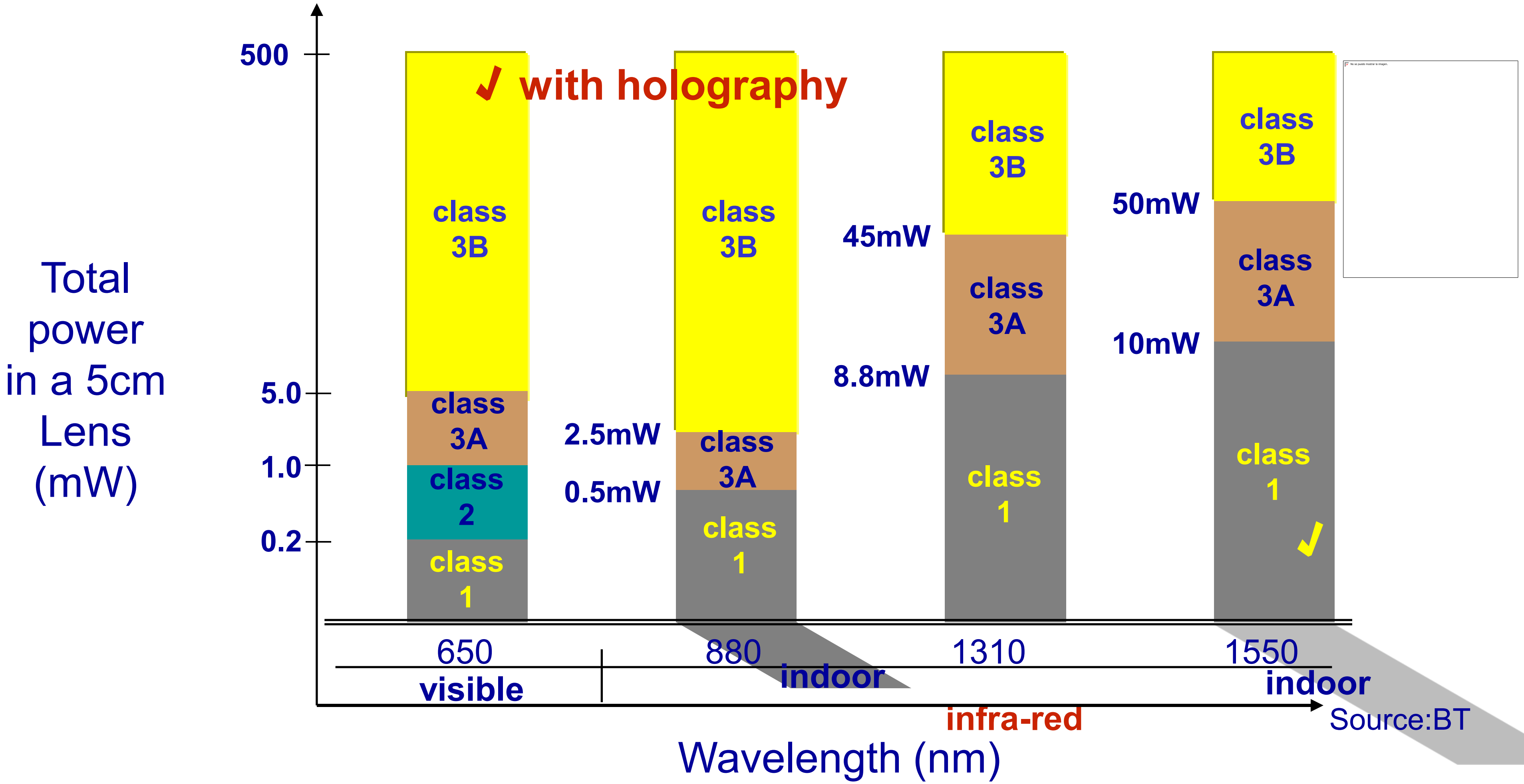
- For distance > 200 m, 99.9% , or 99.99% at best.
- BER and availability percentages – Outline how much time the link is unavailable.

99.999 – 5 minutes / year

99.99 – 53 minutes / year

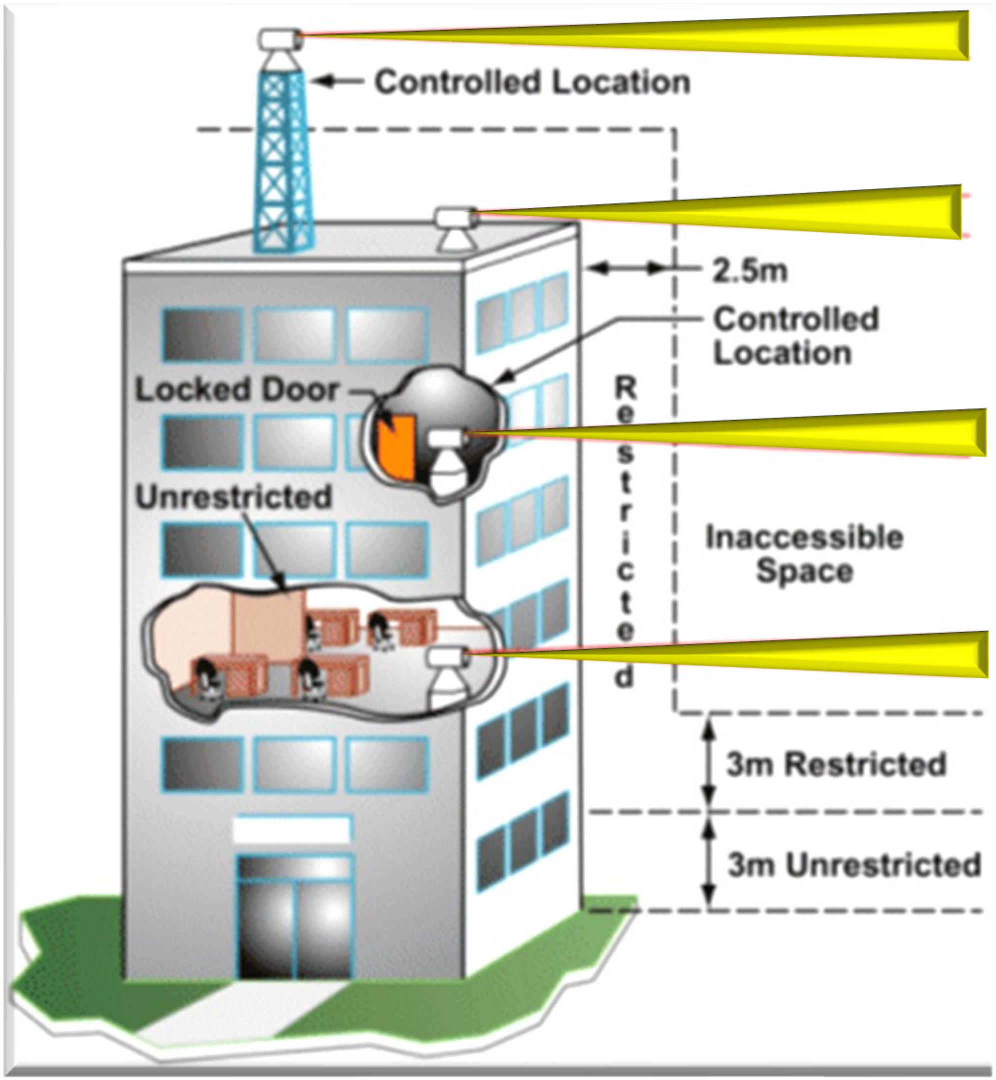
99.9 – 8 hours 43 minutes / year

Safety Classifications - Point Source Emitter



- Class 1 systems can be installed in Unrestricted locations
- Class 1M systems can be installed in Restricted areas
- Class 3B and above only in Controlled locations

FSO – Laser Classes



- Class 1 - systems can be installed in unrestricted locations
- Class 1M - installed in restricted areas, where someone cannot look directly at them
- Class 3B - only in controlled locations

FSO – Challenges

High cost of implementation – Mostly for smaller organizations or individuals

Adoption in volume

New materials, devices, Coding, and modulation schemes

Leveraging more of what is already being developed in optical fibre communication

Complex setup and alignment process– Require precise alignment and optimization of the optical components to minimize interference and maximize data transmission.

FSO – Challenges

Lack of radiation hardened electrical components for space applications

Scalability and Reliability

For 5G/6G and beyond wireless networks

Network architecture → Mesh topology → Increase coverage area

Hybrid architectures (RF-FSO) →

- Improve link availability under all weather conditions
- RF link is generally more tolerant of imperfect pointing and weather
- RF is good for broadcast or wide coverage matters.

+ Edge computing → Reduce latency critical in 5 and 6G

FSO – Challenges

Scalability and Reliability

AI/ML dynamic resource and traffic management

WDM technology → Increase capacity

Distributed control mechanisms

Link availability

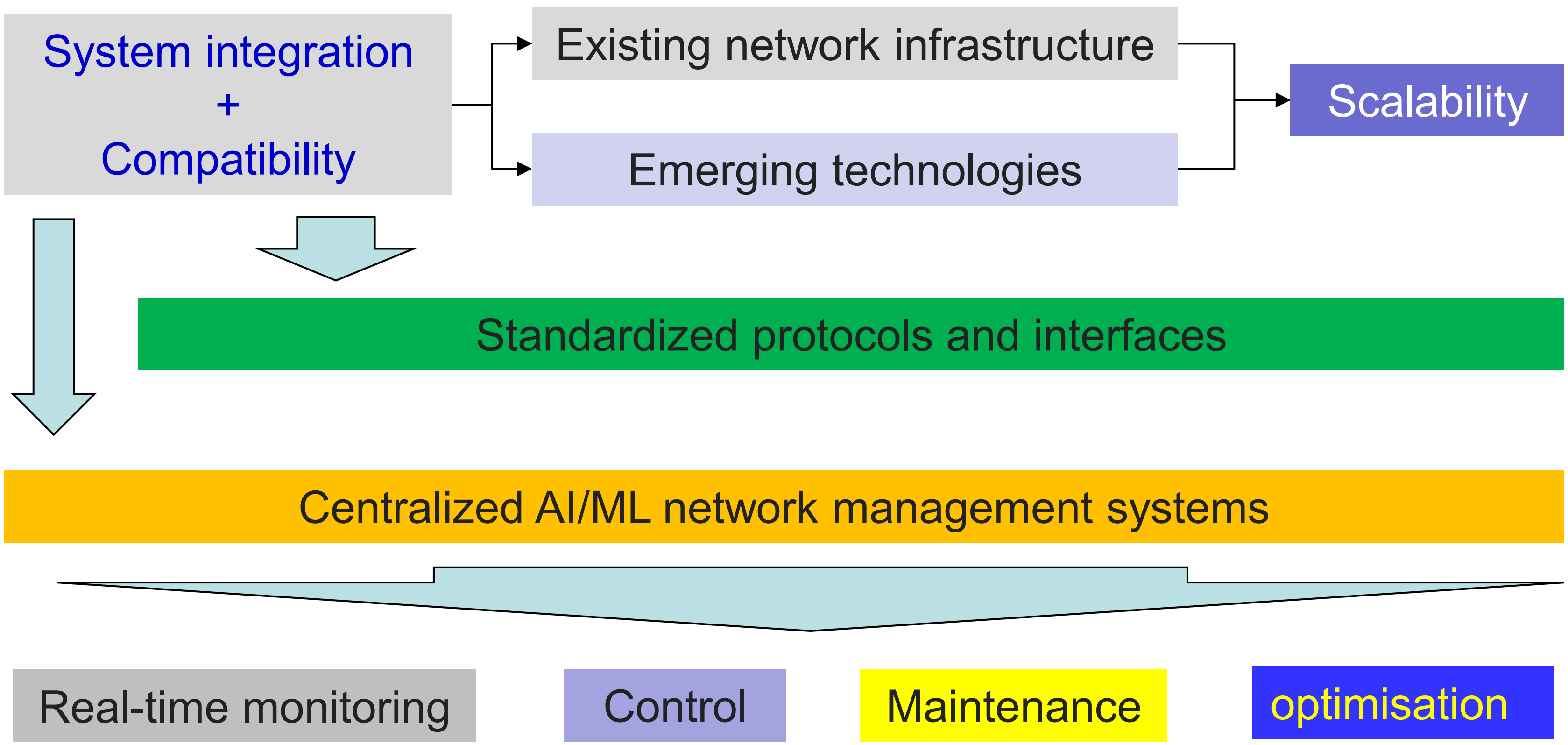
Important in space scenarios

Low Earth orbit satellites - might only have a few minutes of downlink time every 90 minutes.

Using relays, constellations and/or networks of ground stations link availability of downlink can be increased up to 100%.

FSO – Challenges

Scalability and Reliability



FSO – Challenges

Standards

- At higher data rates above 1Gbps for long-range FSO links - IEEE
- Waveforms
- Pointing acquisition and tracking
- Signal processing or encoding

Critical for space communication

Regulatory Issues

- Spectrum allocation
- Safety
- Environmental regulations
- International, national and regional laws

Adaptive Transmission – AI, ML and Software Define Radio/Optic

FSO – Challenges

Environmental factors – Link operation under all weather conditions

- Space
- Terrestrial

→ **Adoptive optics**

Security Enhancements – Quantum key distribution

Global awareness

This has started to increase due to its use in space communications, but needs more

So, if it is good for space application then it is for terrestrial too.

SWaP-C (Size, Weight, Power and Cost)

FSO – Challenges

Space Communications

Up/Down high-speed links through atmosphere

Turbulence pre-compensation schemes

On-board satellite routing

Seamless inter-operability with terrestrial NWs

High power optical amplifiers – Up to 100 W

WDM transmission

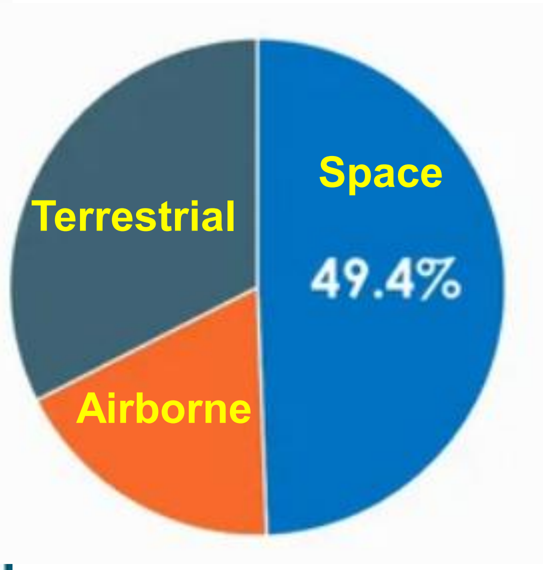
Adopting existing FSO technology for the Moon distance

Deep space communication - > millions of km

FSO - Communication Market

- **The global FSO communication industry - Valued at $1.4 Bn in 2024**
  - Estimated to grow at a CAGR of 31.6% from 2025 to 2035
  - Expected to reach $27.2 Bn by the end of 2035
  - North America dominated the consumer staples market – A share of 31.2% in 2024.

Market share by sector

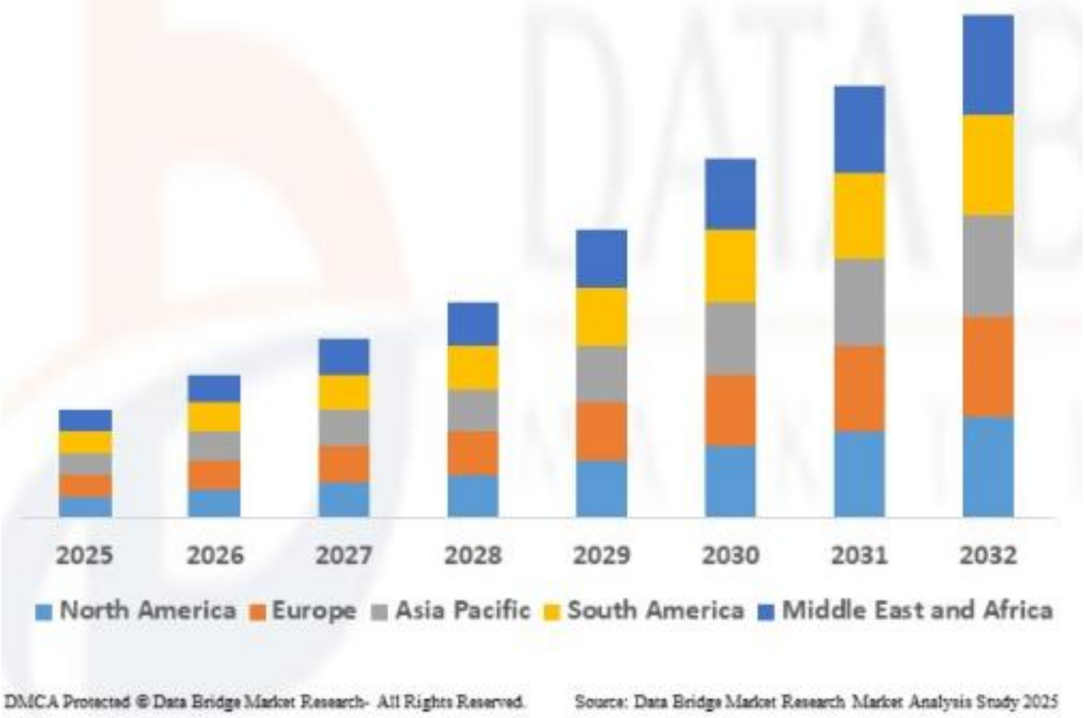


https://www.transparencymarketresearch.com/free-space-optics-market.html

FSO - Communication Market

Region

- **North America**
  - U.S., Canada, Mexico
- **Europe**
  - UK, Germany, France, Rest of Europe
- **Asia-Pacific**
  - China, Japan, India, South Korea, Rest of Asia-Pacific
- **LAMEA**
  - Latin America, Middle East, Africa



https://www.databridgemarketresearch.com/reports/global-free-space-optical-communication-market?srsltid=AfmBOoqcgwLjm7DmGMh_CwCDaRYsBHUko-uxwdQV7Qtzf7odXJ_i6zZ7

https://www.alliedmarketresearch.com/free-space-optic-communication-market-A08077

FSO - Communication Market – New Opportunities

- **Integration –**
  - FSO with Li-Fi for high-speed wireless networks
  - FSO with optical fibre for very high-speed networks
  - FSO with RF over fibre for high-speed wireless networks

  - Use in smart cities and industrial IoT applications

FSO - Communication Market

Companies

Axiom Optics (USA)
Wireless Excellence Limited (UK)
fSONA Networks Corp (Canada)
Mynaric AG (USA)
Viasat, Inc. (USA)
Plaintree Systems Inc. (Canada)
Opto-Link Corporation Limited (USA)
QinetiQ (UK)
Cailabs (France)
TrellisWare Technologies, Inc. (USA)
General Dynamics Mission Systems (USA)
Collinear Group (USA)

L3Harris Technologies, Inc. (USA)
Laser Light Communications (USA)
Lumentum Operations LLC (USA)
Exail (France)
Oledcomm (France)
EC System (Czech Republic)
Mostcom JSC. (Russia)
CACI International Inc (U.S.)
Aircision (Netherland)
Enlightrd
Transcelestial Tech (Singapore)
Alapo (France)
Others …

https://www.alliedmarketresearch.com/free-space-optic-communication-market-A08077

FSO – Summary

- Offers high throughput and long-distance communications.
- Has potential across many sectors - aerospace, defence and the electronics industry.
- Technological advancements, i.e., new materials and manufacturing processes, are driving the demand for low cost, and reliable FSO systems
- Market is highly competitive – Due to the strong presence of existing vendors

Next

FSO - Challenges