Optical Wireless Communications – *The Story So Far*

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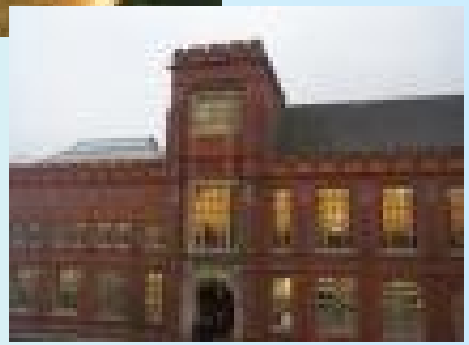
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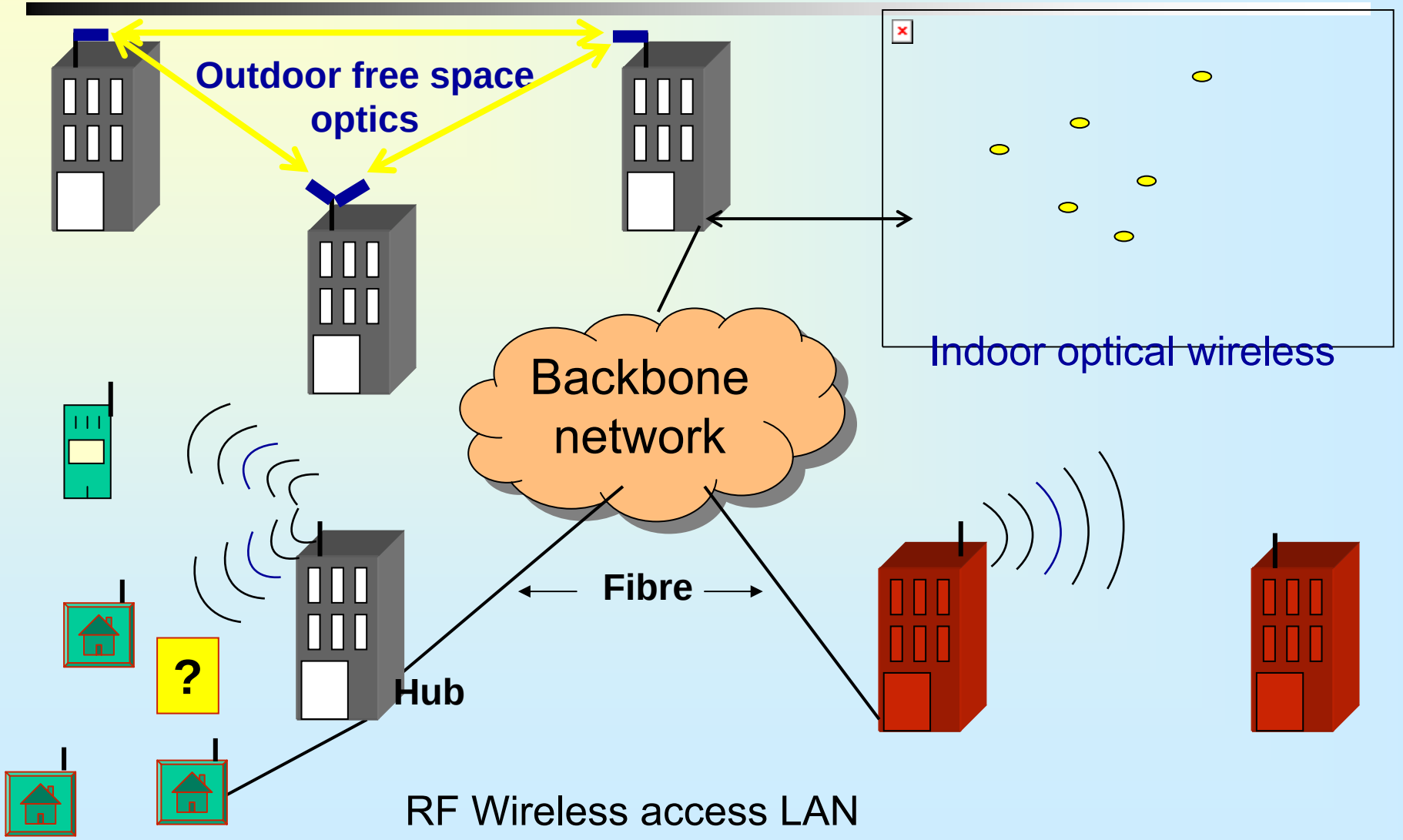
Contents

- Introduction
- Why the need for optical wireless?
- What is optical wireless?
- Indoor optical wireless
- Issues with optical wireless
- Our research work
- Final remarks

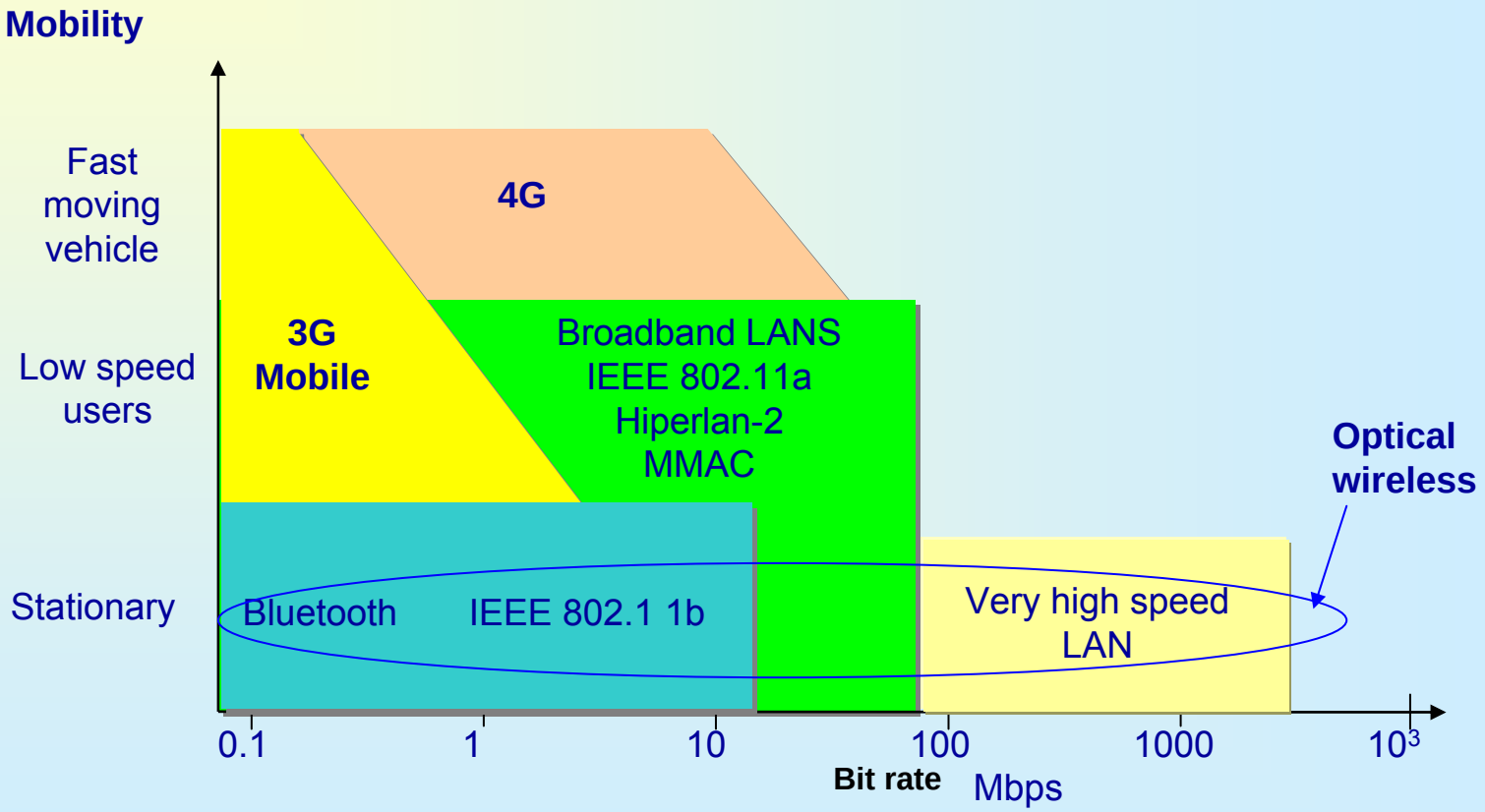
Communication Traffic – What Next?

- Oct. 1999 - The volume of data traffic exceeded, for the first time, voice traffic.
- 1999-2005 - Data traffic increase by over 4,000%.
- Much of this growth comes from the increased demand by Internet and corporate users for:
  - **E**lectronic commerce,
  - **S**torage and backup applications,
  - **V**irtual Private Networks (VPNs),
  - **V**ideo conferencing,
  - **V**oice over IP (VoIP),
  - and other new applications.

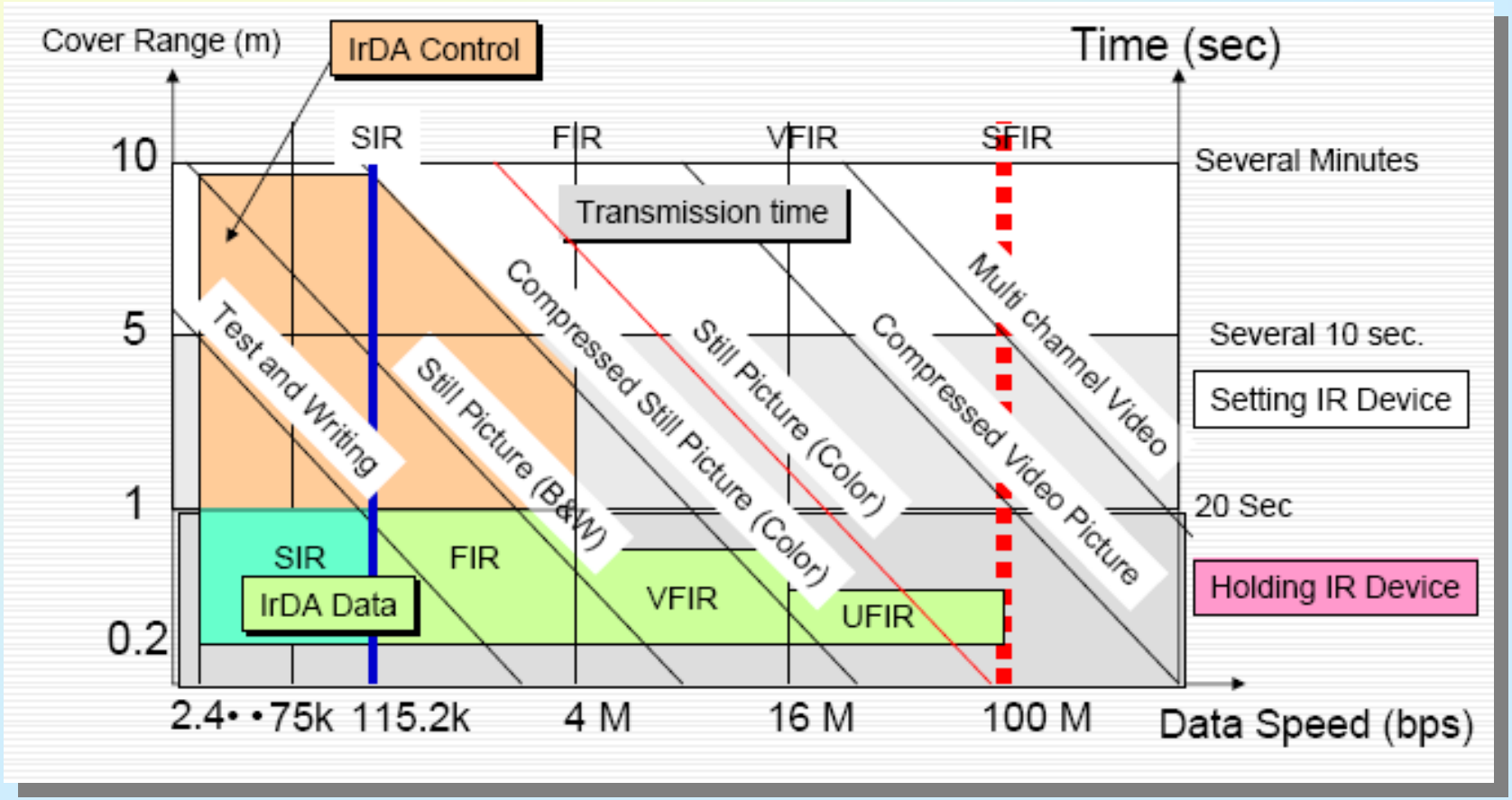
Communication System – The Last km and m



Mobility vs Bit rates



OW Transmission Speed, Time and Coverage Range



Optical Wireless Communication – What Does It Offer?

- Abundance of unregulated bandwidth
  200 THz in the 700-1500 nm range
- No multipath fading
  intensity modulation and direct detection
- Secure data transmission
- Higher capacity per unit volume (bps/m^3),
  due to neighbouring cells sharing the same frequency
- Cost effective at rates near 100 Mbps
- Small cell size and long range (a few meters to a few km)
- At 800-890 nm and 1550 nm absorption effects are minimal.
- Flexibility
  - deployment in a wide variety of network architectures.
  - installation on roof to roof, window to window, window to roof or wall to wall.

OWC – Disadvantages

- Multipath induced dispersion (non-line of sight) – *limiting bandwidth to a few tens of MHz.*
- Limited range: *ambient noise is the dominant noise (20-30 dB larger than the signal level)*
- Requires access points interconnected via a wired backbone to cover large area
- Transmitted power limited by the eye safety
- High power requirement (in particular outdoor)
- SNR can vary significantly with the distance and ambient noise
- Receiver sensitivity
- Large area photo-detectors: *limits the bandwidth*
- Costly (on small scale) compared to RF

OW Systems - Characteristics

- Interface with the existing:
  - network switch, hub, bridge or router via multimode fibre (850 nm or 1310 nm).
- Connect directly to copper/fibre interfaces.
- Can be protocol transparent or locked to a particular protocol depending on the user's needs.

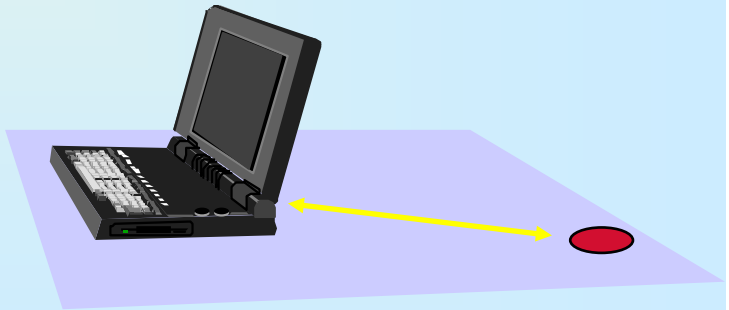
Current Standards and Bodies

1- **Infrared Data Association (IrDA)**

- 1993, by HP, IBM, and Sharp (*now* 130 *members*)
- 9.6 kbps – 4 Mbps
- Line of sight links: *Coverage area 1-2 meters*

key Features:

- Simple and low cost implementation ($2.0 / unit)
- Wide beam, easy alignment
- Low power requirement
- Directed, point-to-point connectivity
- Efficient and reliable data transfer



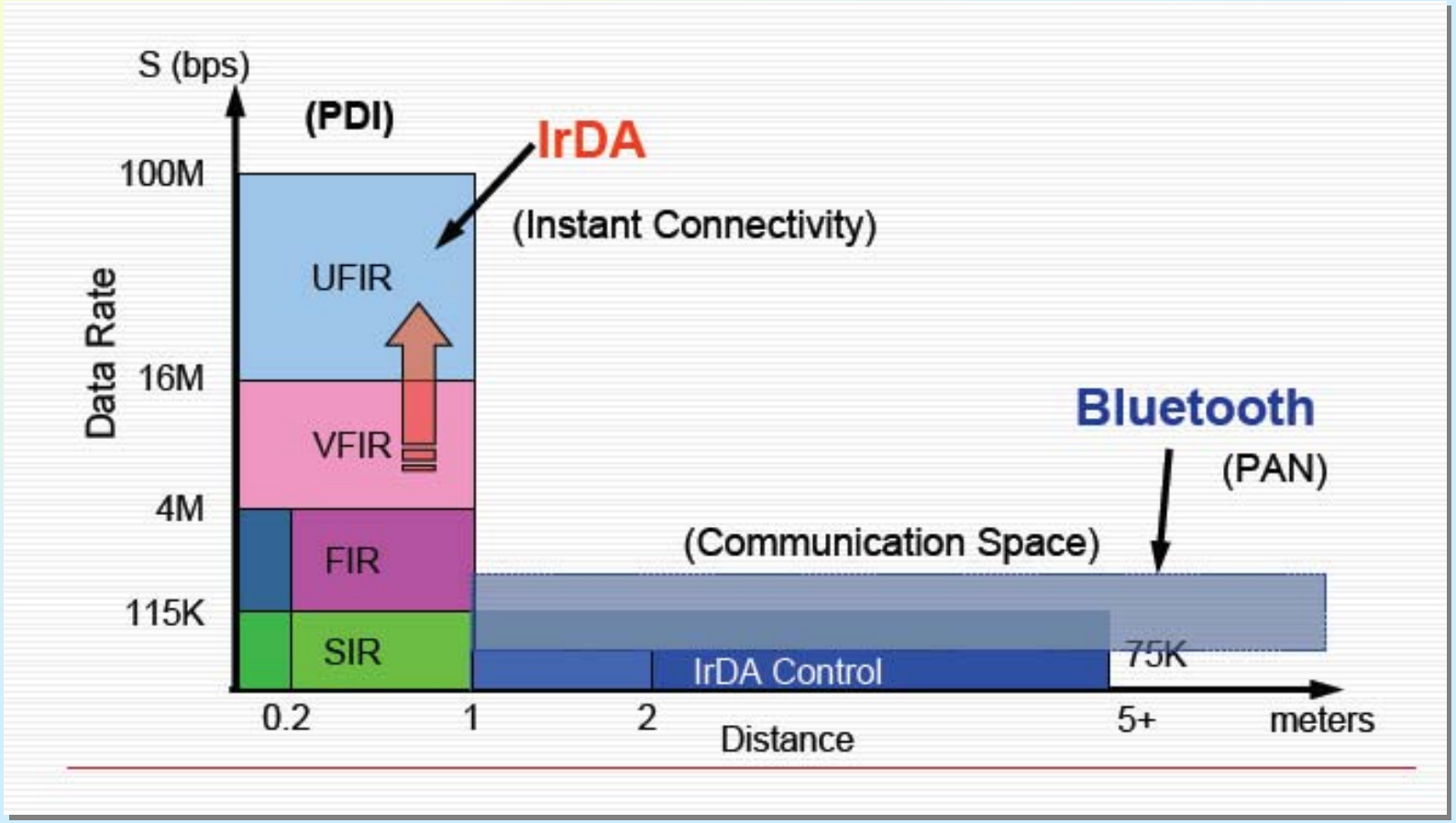
For more see http://www.irda.org/

IrDA - Applications

- Transfer Digital Images Using IrDA
- PC + Printers
- Vending machines,
- Car navigation systems
- Blood pressure monitors.
- Bank ATMs + Point-and-pay payment services,
- Picture and music file transfers: **between mobile devices, and kiosk data distribution to mobile devices.**
- The added IrDA functionality will also allow users of IR-equipped mobile phones and PDAs to conduct financial transactions and more easily share data between devices.



The Main Features of IrDA & Bluetooth



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Current Standards and Bodies – *cont.*

2- IEEE 802.11 standard for wireless LANs -

- 1st *version approved in* 1997, *it specifies:*

  - 3 *physical layers, 2 using radio with spread spectrum modulation and one using IR.*

  -*The IR physical layer specifies:*

    . 800-900 *nm range,*

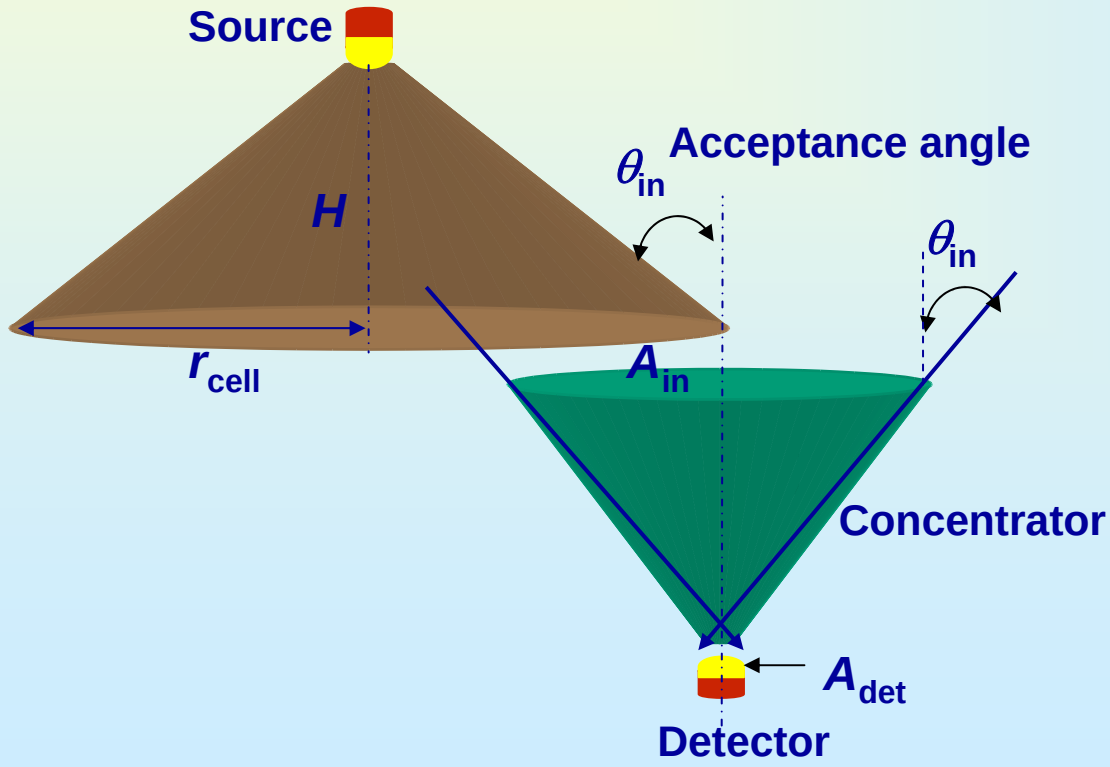
    . *bit rates of* 1 *or* 2 *Mbps using diffuse propagation.*

Optical Components

- Sources:
  - Laser (VCSEL)
    - Broad bandwidth
    - Power (10 mW)
    - High cost
    - Safety issues
  - LED (resonance cavity)
    - Relaxed eye safety
    - Low cost
    - Limited bandwidth
- Detectors:
  - Good sensitivity
  - Cost effective
  - Large area photodiode (PIN or APD)
    - Very high input capacitance
    - Poor sensitivity
    - Low power

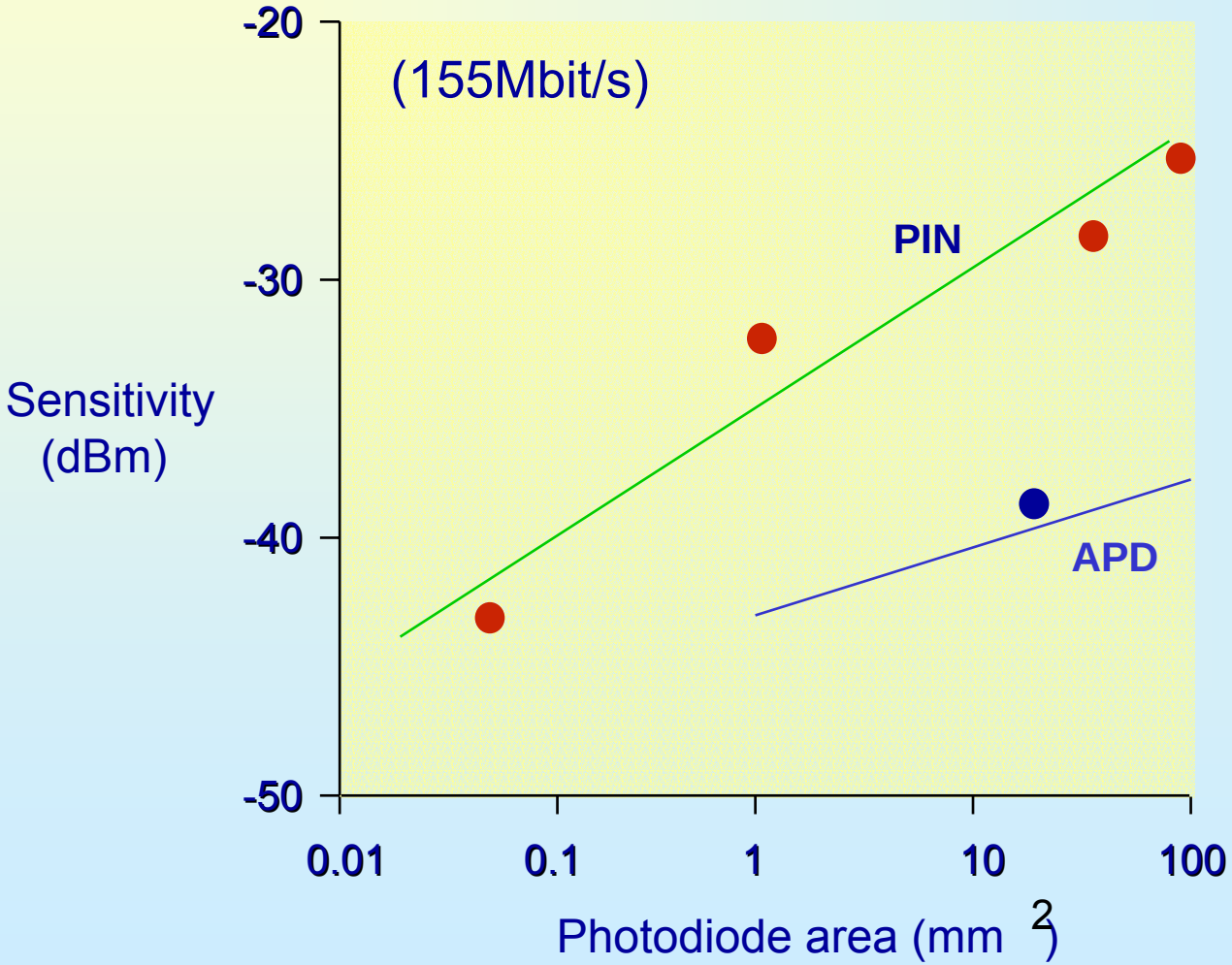
Optical Concentrator

- The optical gain $G = A_{in}/A_{det} = n^2/\sin^2\theta_{in}$
- The minimum power launch for maximum cell size



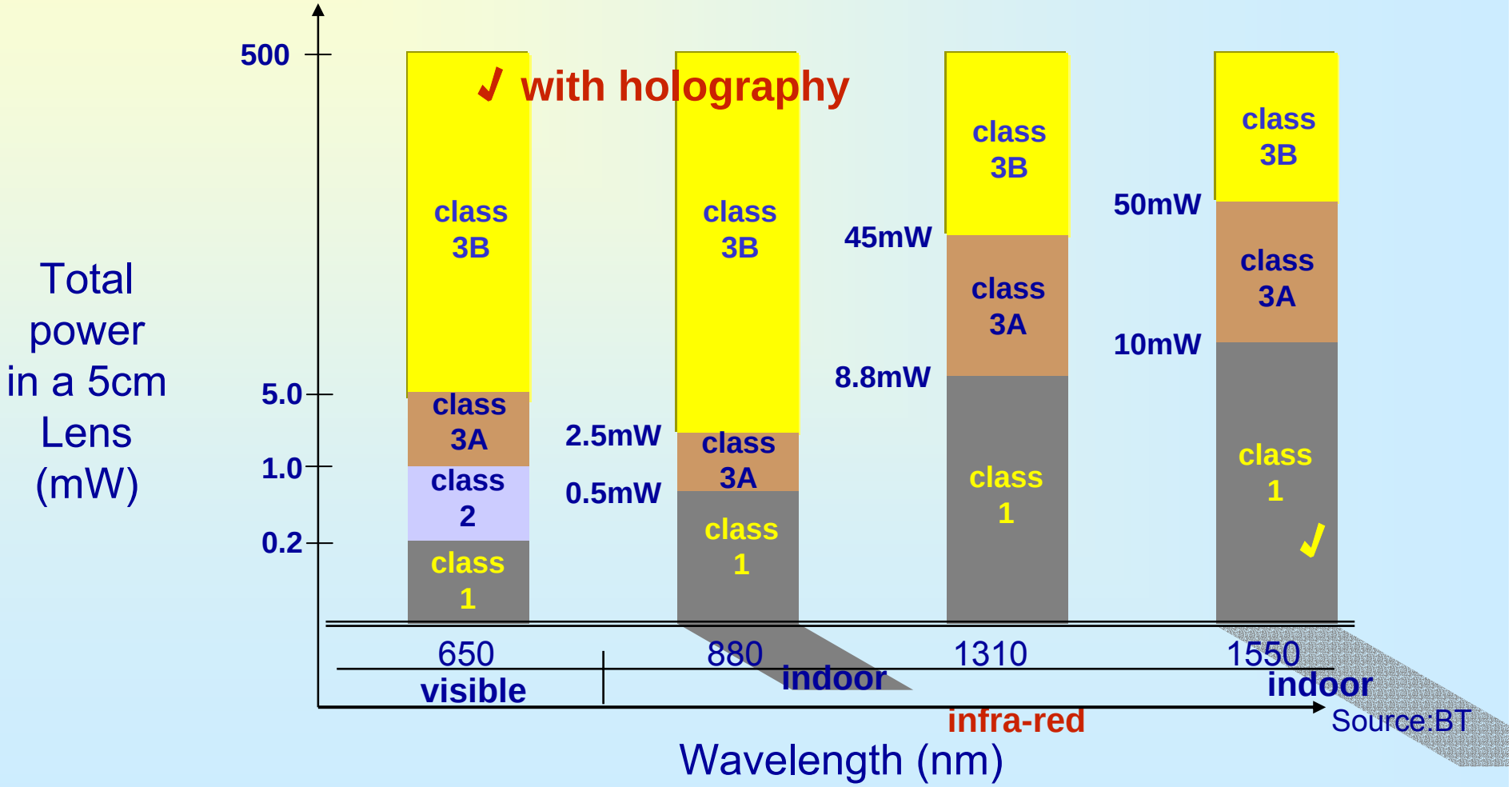
$$P_{la} = \frac{P_r A_{cell}}{G A_{det}}$$

Receiver Sensitivity Vs. Detector Area



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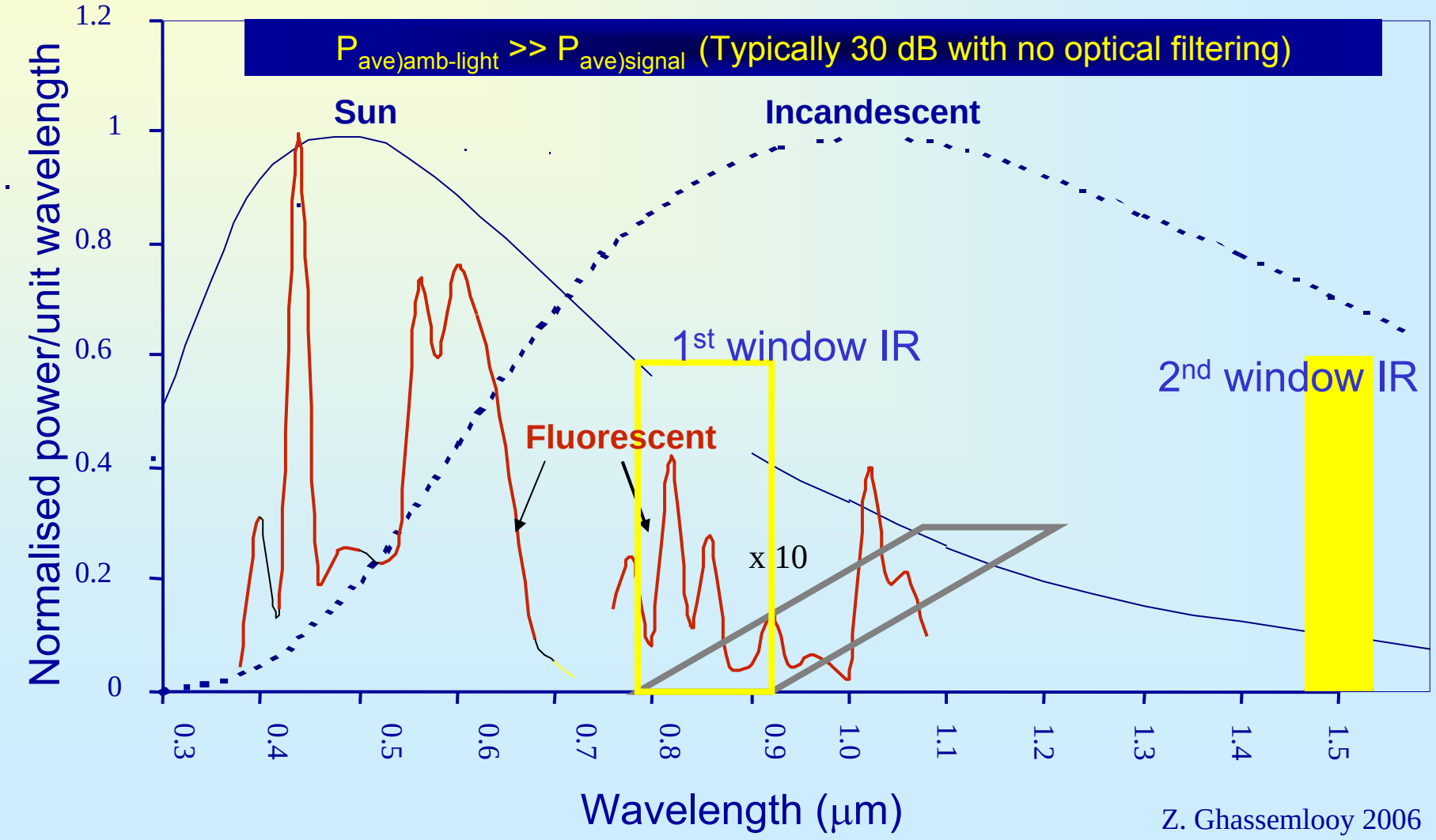
Safety Classifications - Point Source Emitter



Eye Safety

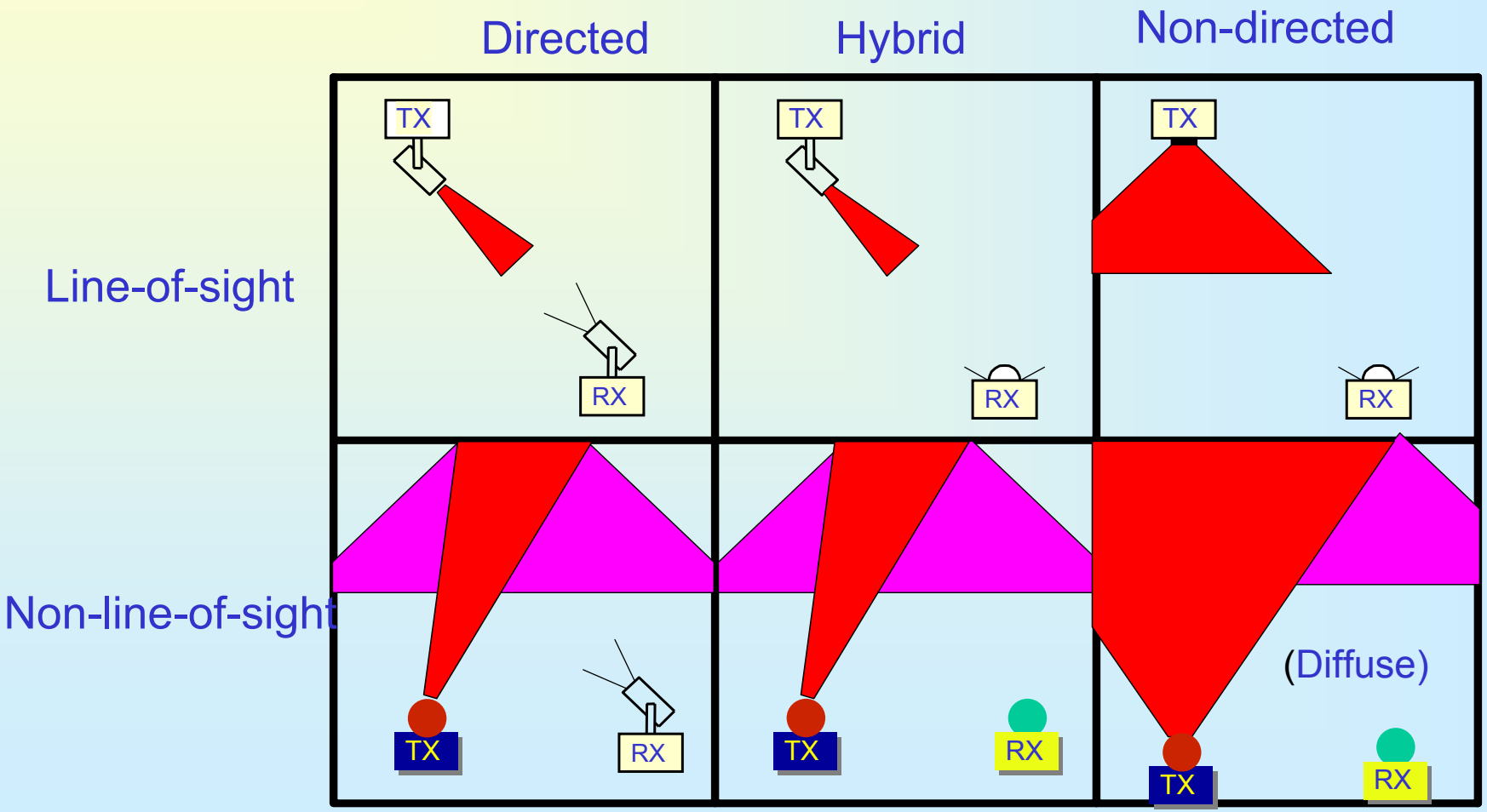
- 780 - 950nm: due to the availability of low cost LEDs, laser diodes and silicon photodetectors. However, radiation in this wavelength can be focussed onto the retina, causing thermal damage.
- Infrared transceivers should conform to class 1, a few W,(inherently safe) of the IEC 825 standard. The eye safety limit is a function of the viewing time, wavelength and apparent size of the optical source.
- Class 3B laser can be used by passing the beam through a hologram.
- Transmitted optical power is limited by the average power level, i.e. the average power for a pulse train of duration 100s must not exceed the power of a single pulse of duration 100s.

Power Spectra of Ambient Light Sources



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Classification of Indoor OW Links



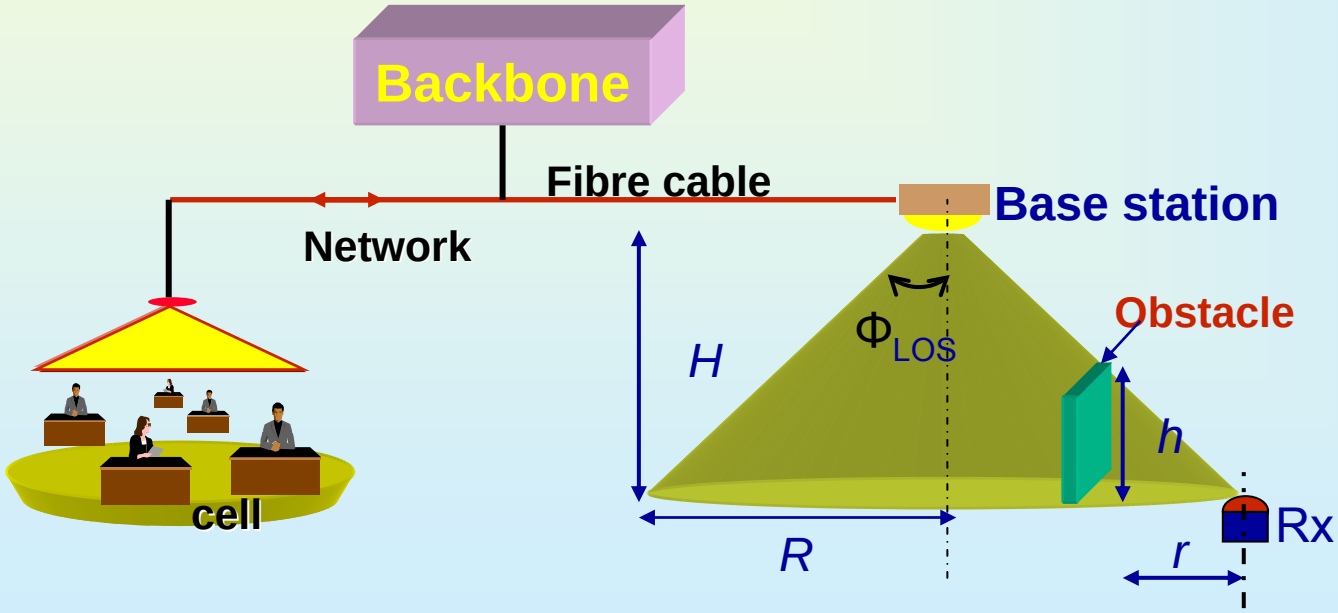
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1- Line Of Sight (LOS) Systems

- Narrow low power transmit beam
- Narrow field-of-view receiver
  - No multi-path induced distortion
  - Efficient optical noise rejection and a high optical signal gain
  - Suitable to point-to-point communications only (out-door and in-door).
  - Can support mobile users using steering and tracking capabilities.

OLOS Applications - Optical Telepoint

- 10 Mbps/cell of 10 m^2 [LED + PIN]
- 155 Mbps/cell of 5 m^2
- Gbps/cell of 0.25 m^2 [Laser + APD]



For full connection, the maximum semi-angle
$\Phi = \arctan(r/h)$

Rx field-of-view (half acceptance angle) ≥ $\Phi_{LOS} = 27°$.

LOS LAN – Cellular (a star topology)



Single large cell: Single wide cone source

- blocking, increased power (i.e. reduced power efficiency)

Multiple cells: Multiple Low power source

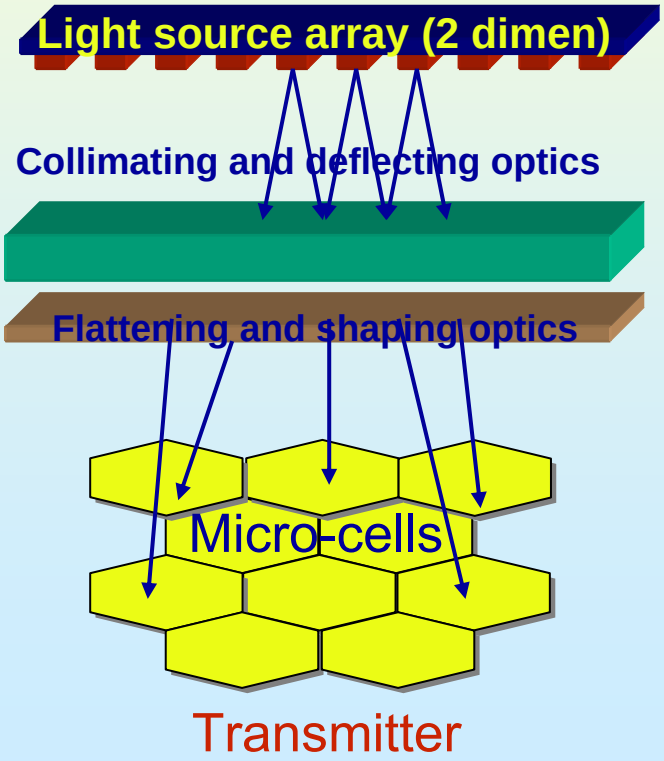
- roaming

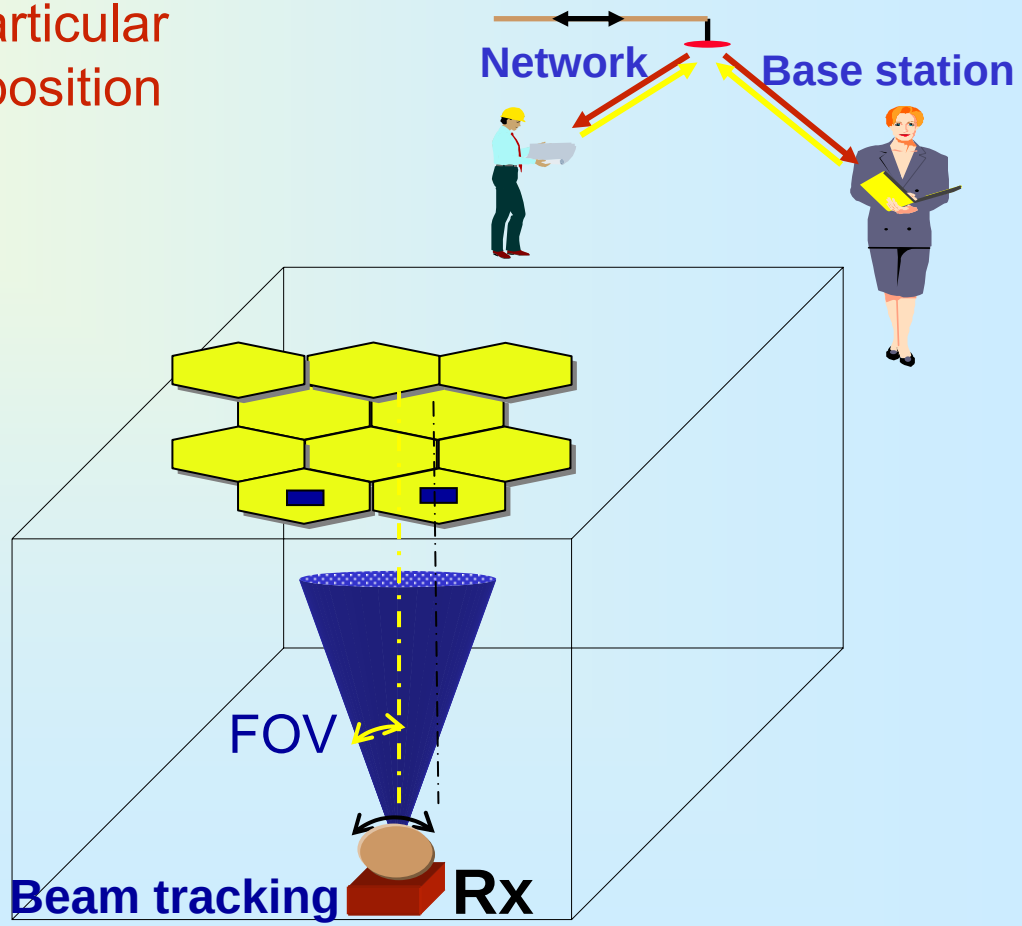
Source BT

LOS - Tracking Telepoint System

Combination of narrow LOS + cellular configuration

- Light beam is deflected into a particular angle depending on the spatial position of the source in the array.



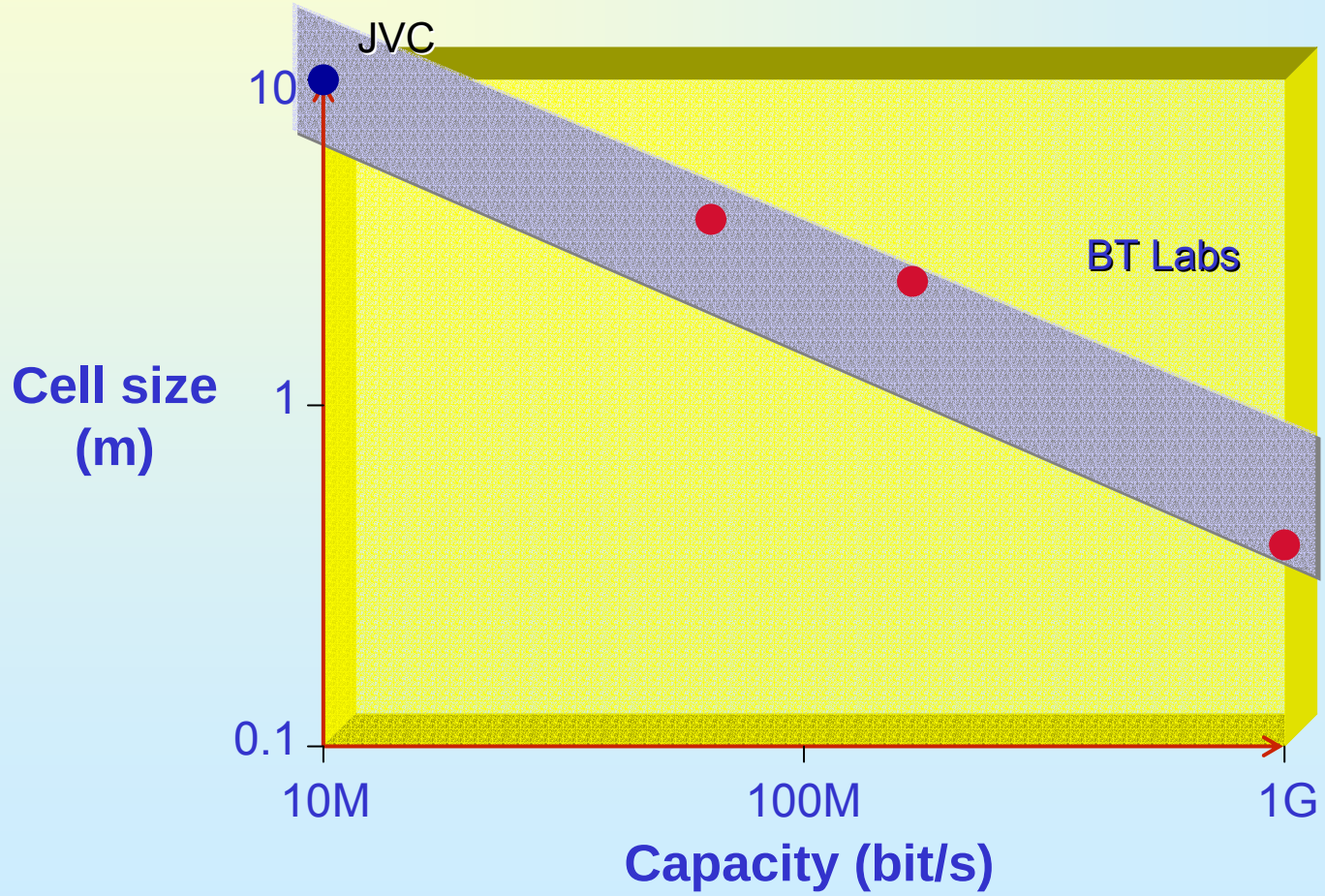


Tracking Telepoint System *contd.*

- **What does it offer?**

  - Automatic beam alignment
  - Automatic tracking (electronically)
  - Allows roaming
  - Power saving by switching off the unused sources
  - Increase transmission capacity:
    - Different source being modulated at different data rate
  - Increase transmission bandwidth:
    -The pixels in the detector array with low capacitance because of small size
  - Better ambient light rejection
    - Narrow field of view

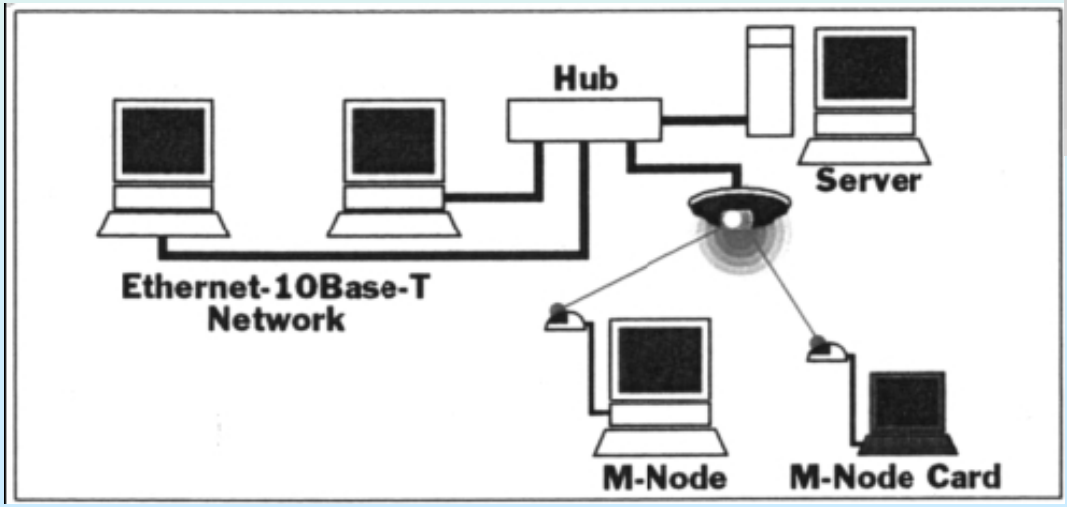
Cell Size Vs. Capacity



Source BT

JVC- Infrared Wireless LAN Satellites

- Satellites are unlimited node wireless / wired Ethernet hubs
- High speed 10 Mbps data throughput
- Full Ethernet IEEE802.3 compliant
- Range: 10 m standard node, and 7 m with M-node and
- Direct Satellite-Laptop connection with M-node and M-nod Card
- Versatility of ceiling or wall installation





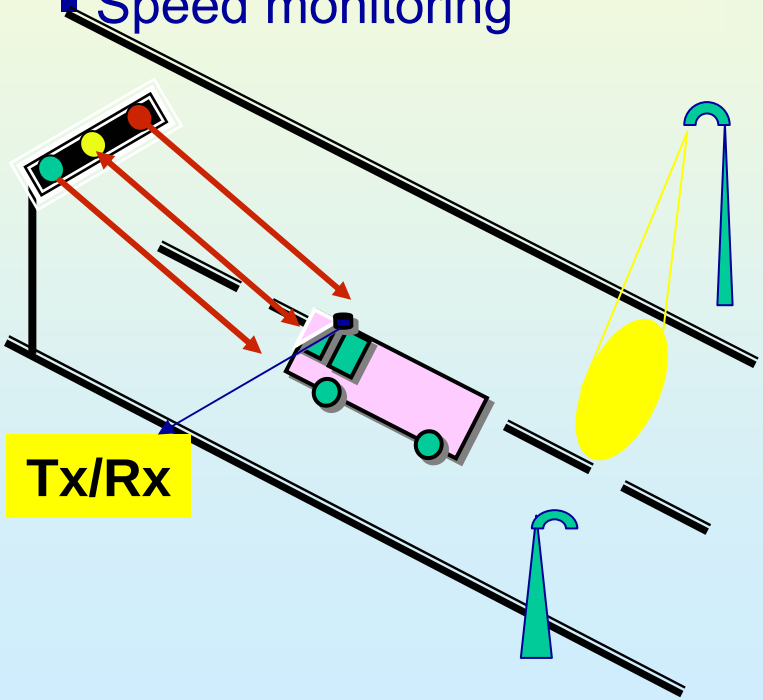


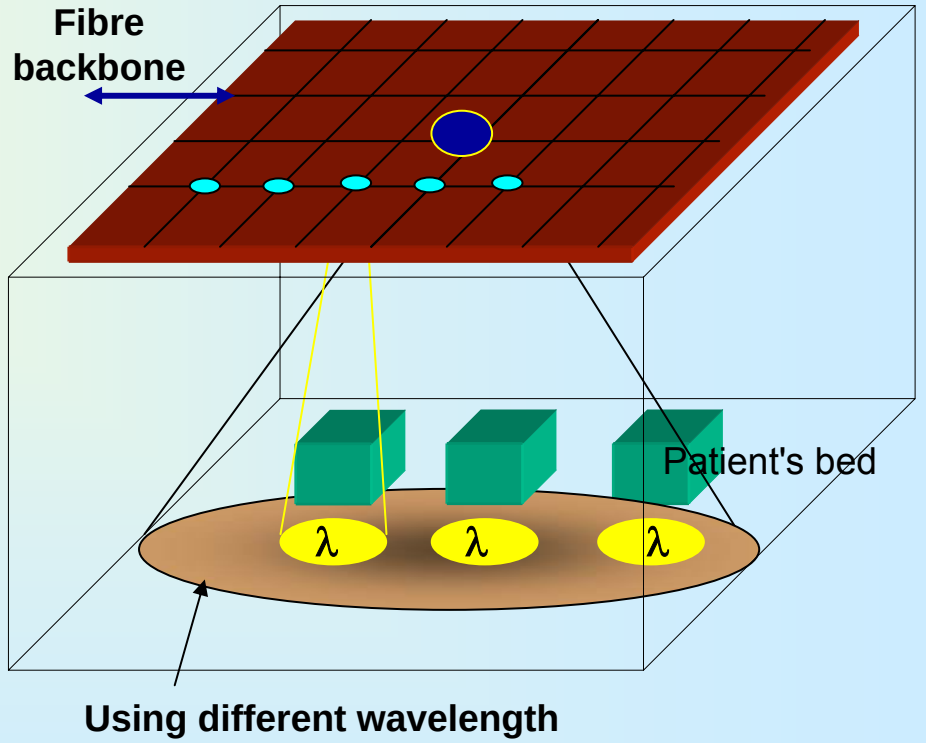


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LOS – Traffic Information/Hospital

- Real time traffic information (traffic jam, accident, parking space etc.)
- Local information
- Speed monitoring





Full patient's medical record

- X-Ray
- Sound, video, images, etc.

LOS – Video Transmission

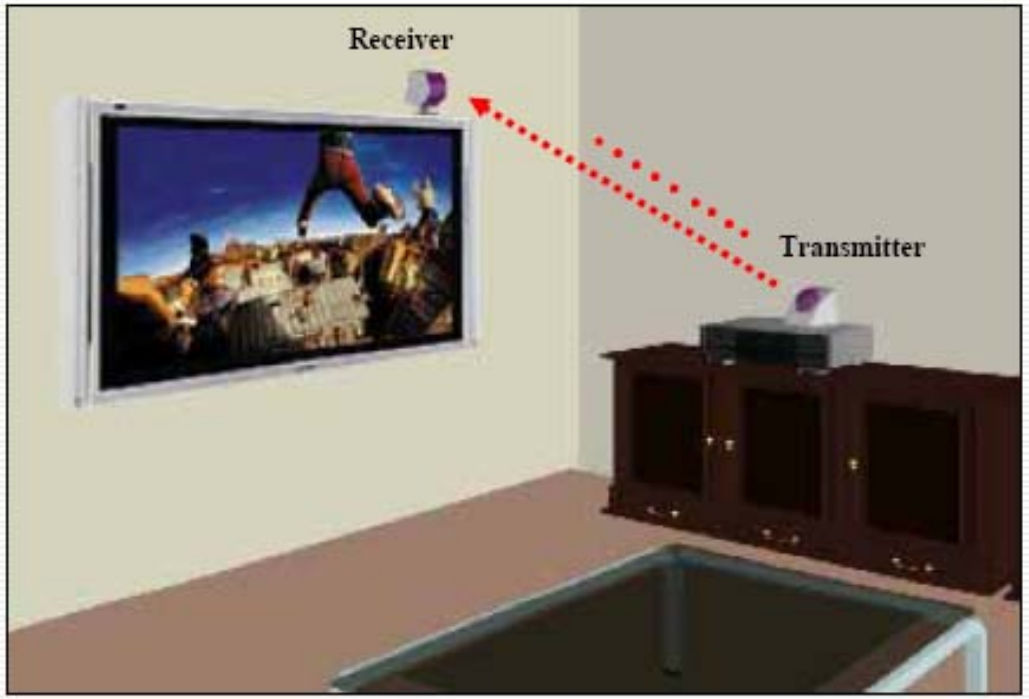
Hivision Optical wireless Video transmission system



Optical Transmitter



Optical Receiver



by JVC

LOS - Others

Next Generation Infrared Killer Application





IrRADIO Transmitter
500kbyte/sec
MP3 and Java Objects

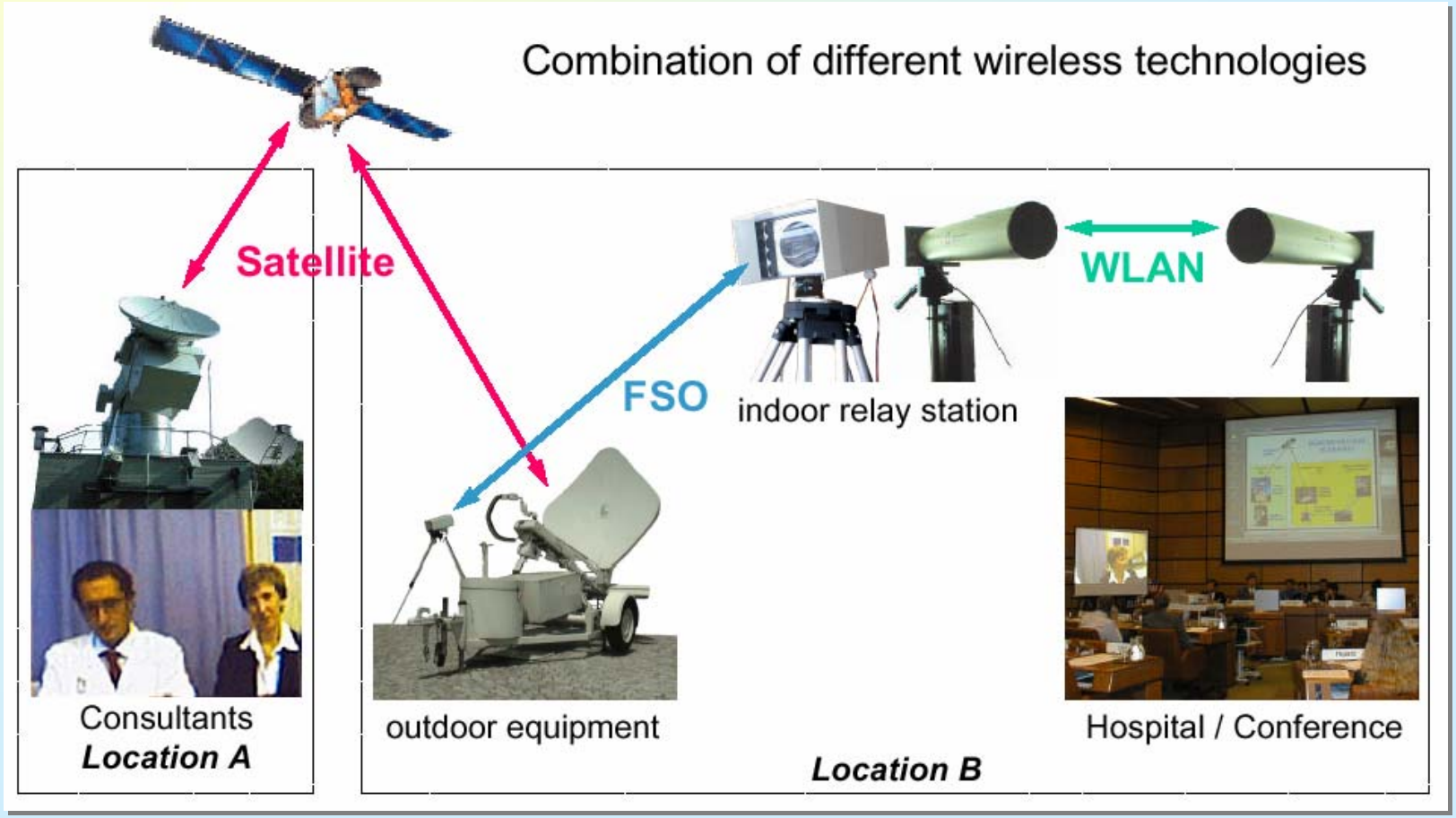


IrRADIO Receiver
10Mbytes Capacity
MP3 decoder player

Infrared Radio (IrRadio/IrShower) Application

- Broadcast MP3, Java (Infrared Downstream data)
- Use IrDA FIR physical layer and IrBRC Protocol

LOS - Hybrid Systems

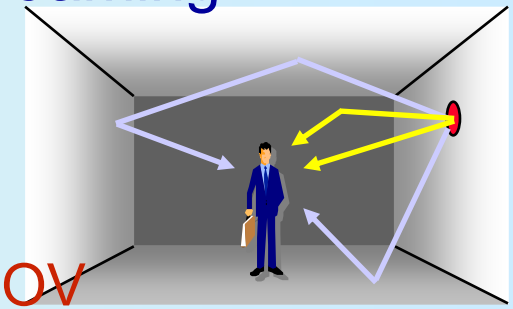


Video-conference for Tele-medicine CIMIC-purpose and disaster recovery

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2- Diffuse System

- Single or multiple source and detector
- Robust to blocking and shadowing & allows roaming
- Limited data rate – multipath propagation
- High signal path loss:
  - receiver with a large effective area and wide FOV



- Ideal to point-to-multipoint (star and mesh topologies)
- Emitted beam modelled as Lambertain:

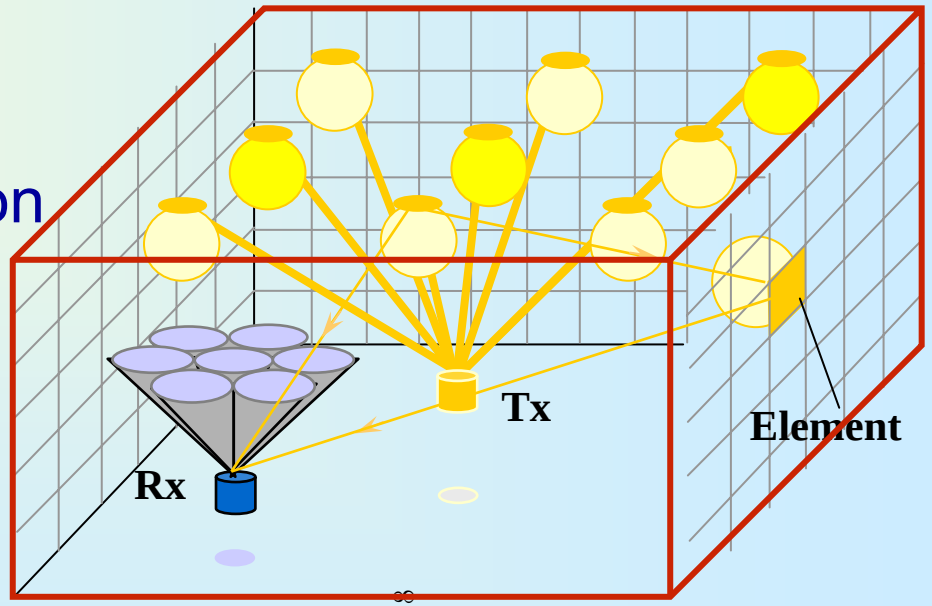
n is the Lambert exponent, P_t is transmitted power, θ is the angle between the initial direction of light and the direction of maximum power (normally<60o).

$$P(\theta) = \frac{n+1}{2\pi} P_t \cos^n \theta$$

3- Quasi Diffuse (Multi-Spot Diffusing (MSD))

- One-to-many and many-to-one communications
- No alignment
- High data rate
- No multipath induced distortion
- Tolerance to shadowing and blockage (Rx consists of multiple elements)
- Better ambient light rejection

(due to narrow FOV)



$$h(t) = \sum_{k=0}^{\infty} h^{(k)}(t)$$

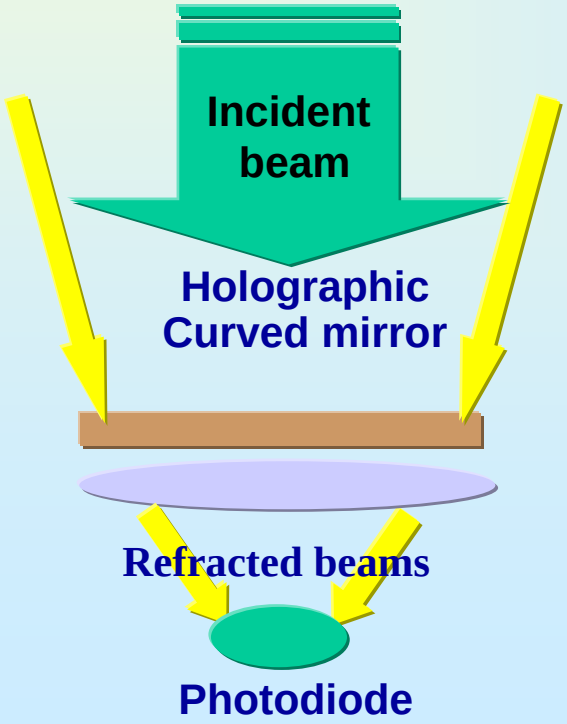
S. Jivkova, et al, and G. Yun and M. Kavehrad

Quasi-diffuse (MSD) – Transmitter

- **Separate laser + conventional lens for each spot** [J. Carruthers et al 2000]
  - Complex and costly - 8-10 lasers to cover a standard size room
  - Power efficient – switching off the unused sources
- **Holographic techniques (diffraction grating) using a single laser** [M. R. Pakravan, et al, 1997]
  - But - Non-homogeneous optical power distribution
- **Computer generated holograms**
  - Wavefront with prescribed amplitude and phase distribution
- **Two-dimensional array of semiconductor light sources**
  - Allowing a reconfigurable transmitter output
  - Each light source create a single diffusing spot on the room ceiling,
  - Power efficient – switching off the unused sources
  - Spatial diversity.

Multi-Spot Diffusing Configuration – Receiver

- The poor power efficiency (due to narrow FOV + eye safety limit) is compensated by the use of an optical concentrator.
- Optical band-pass filter: to reduce ambient light and therefore improve the signal-to-noise ratio.



S. Jivkova, et al

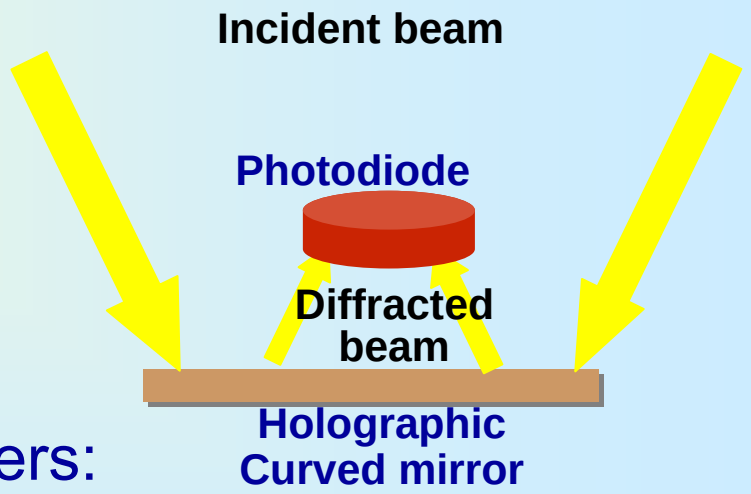
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Quasi-diffuse (MSD) – Receiver

Uses a holographic curved mirror to improve SNR by:

- Reflecting concentrated light to the detector with a narrow spectral range
- Filter the ambient light by diffracting light from a very narrow spectral range
- Low weight and cost

[S. Jivkova and M. Kavehrad, 2001]

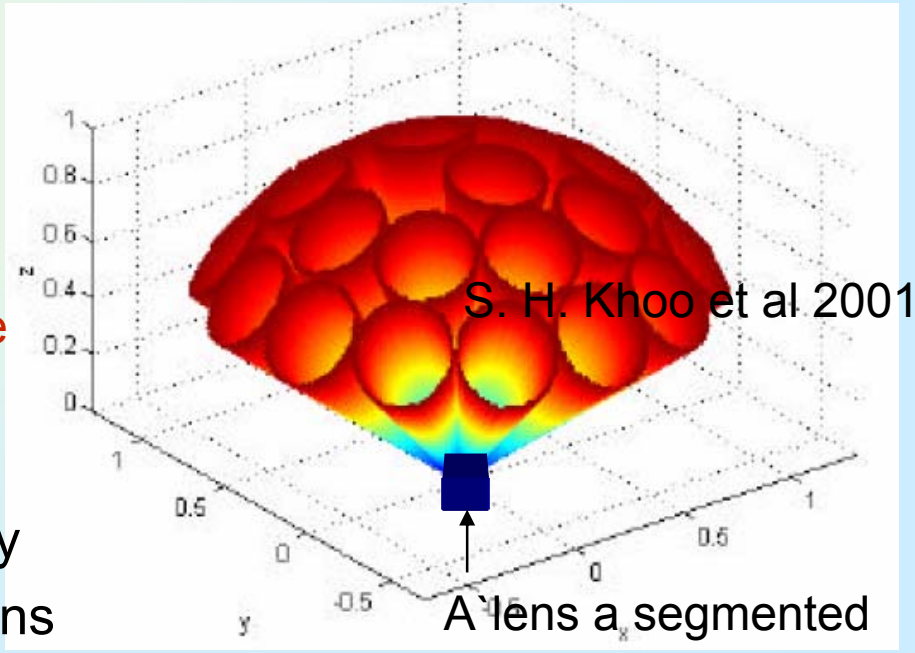


- Compared with a bare receiver it offers:
  - 6 dB lower path loss
  - 11 dB higher SNR [M. R. Pakravan, et al, 2003]

Quasi-diffuse (MSD) – Angle Diversity

- Complex!
- Imaging angle-diversity receiver - Yun and Kavehrad 1992.
  - Can simultaneously achieve
    - a high optical gain and
    - a wide field of view
  - Can significantly reduce
    - the effects of ambient light noise
    - co-channel interference
    - multipath distortion

  (unwanted signals are generally received from different directions to that of the desired signal.)

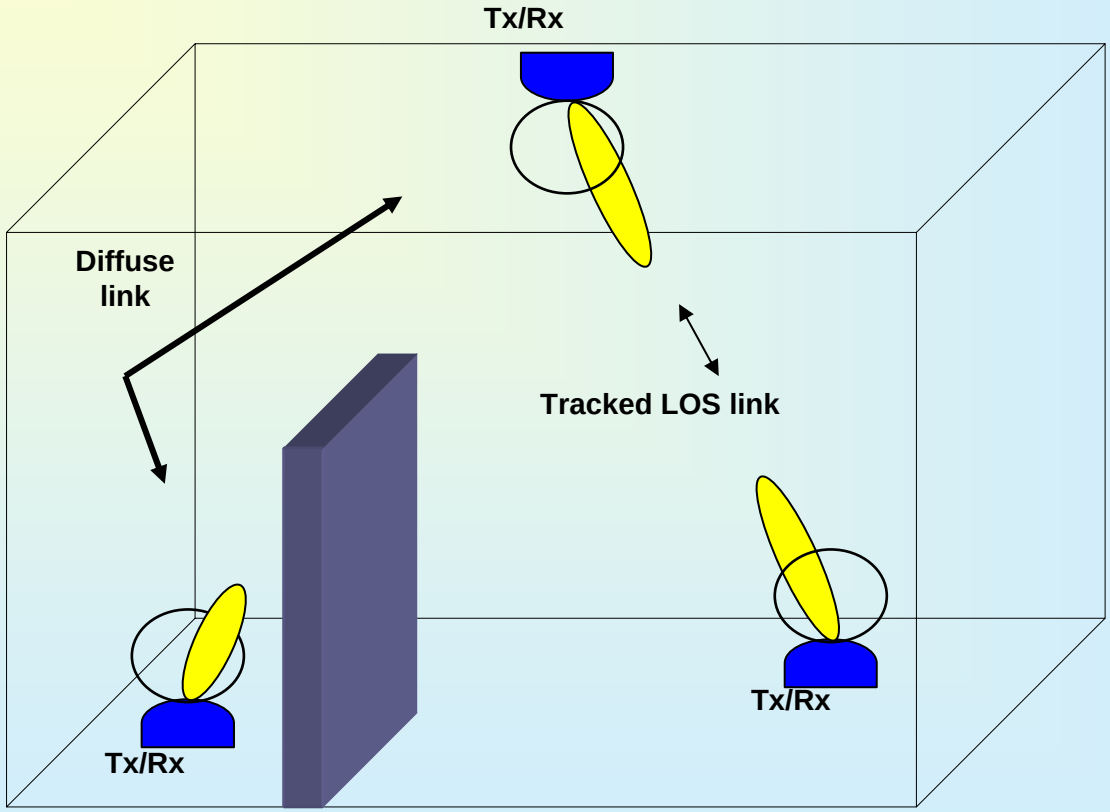


S. H. Khoo et al 2001

A lens a segmented photodetector array

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4- Hybrid Diffuse and Tracked LOS links



Transreceiver – Parameters and link blockages

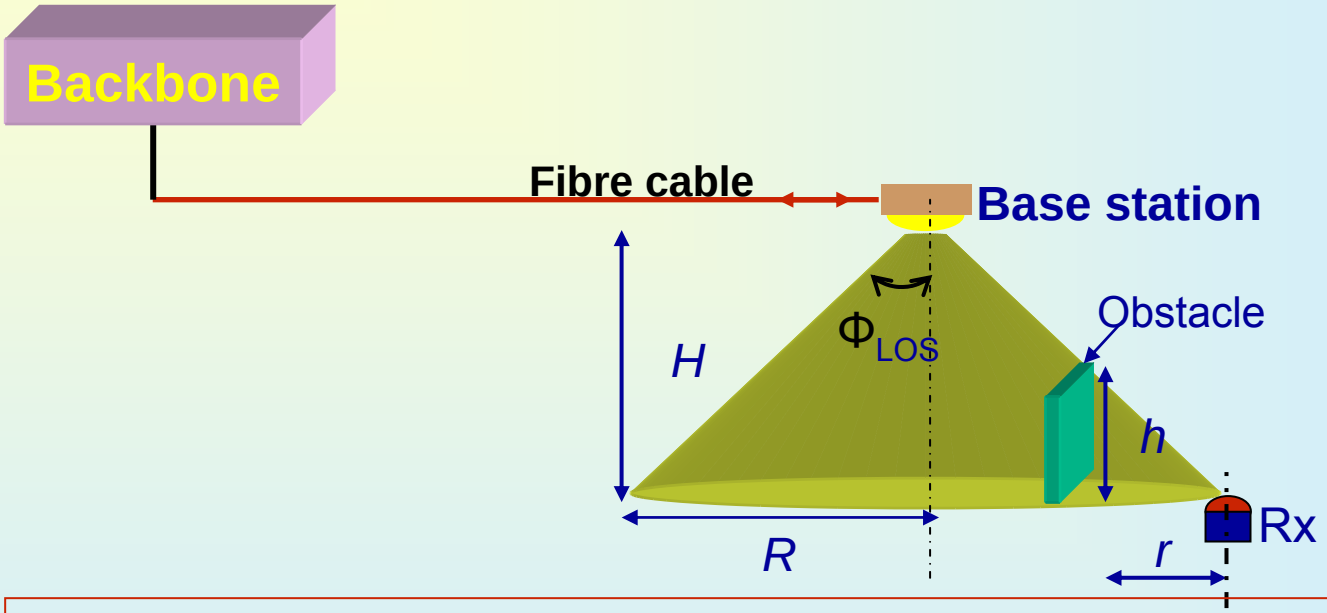
In both cellular and MSD architectures,

- large coverage area is desired. Thus the need for:
  - Wide receiver field-of-view for Tx and Rx
  - Large emission angle

  Which are not routinely achieved.

- There is a need to increase the coverage area beyond certain size because of the increased probability of link blockage by people on the move [*An area needs further investigation*]. Thus need to determine:
  - *Transmitter radiation angle*
  - *Receiver acceptance angle*

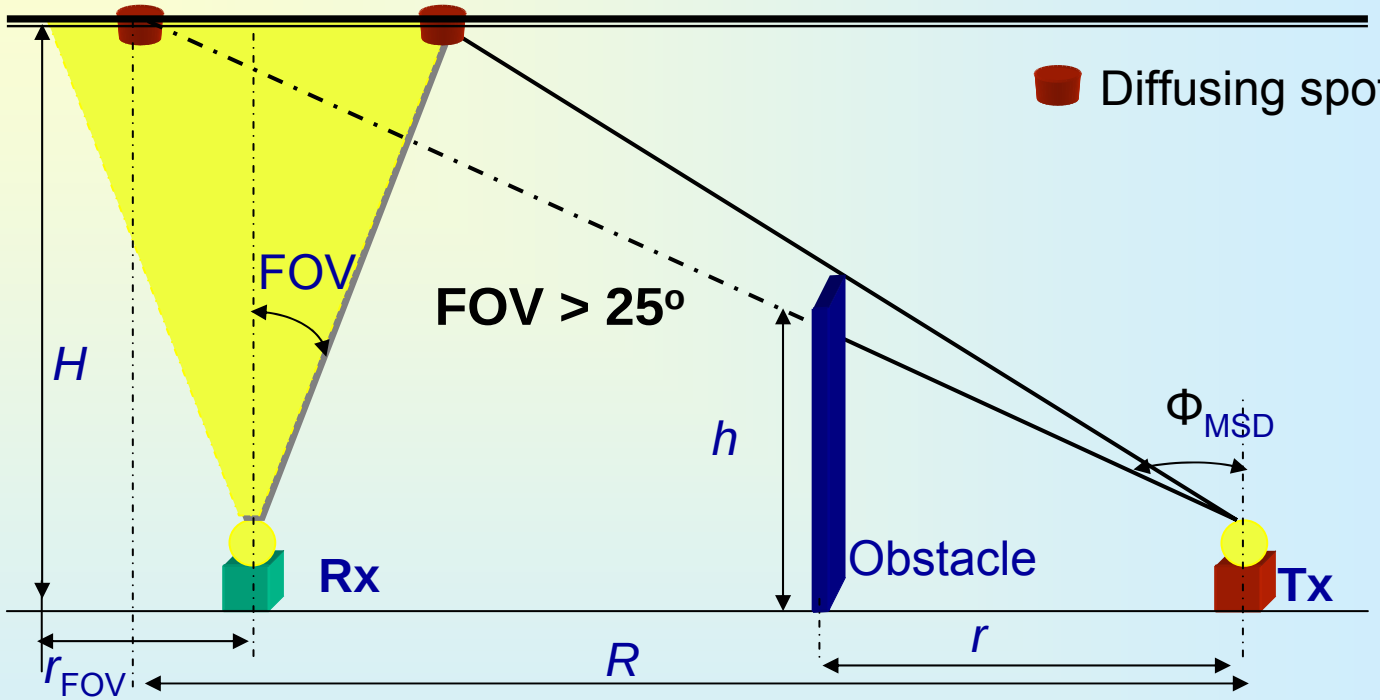
LOS – Transmitter Radiation Angle



For full connection, the maximum semi-angle
Φ = arctan (r/*h*)

Rx field-of-view (half acceptance angle) ≥ $\Phi_{LOS} = 27°$.

Quasi Diffuse (MSD) – Receiver Acceptance Angle

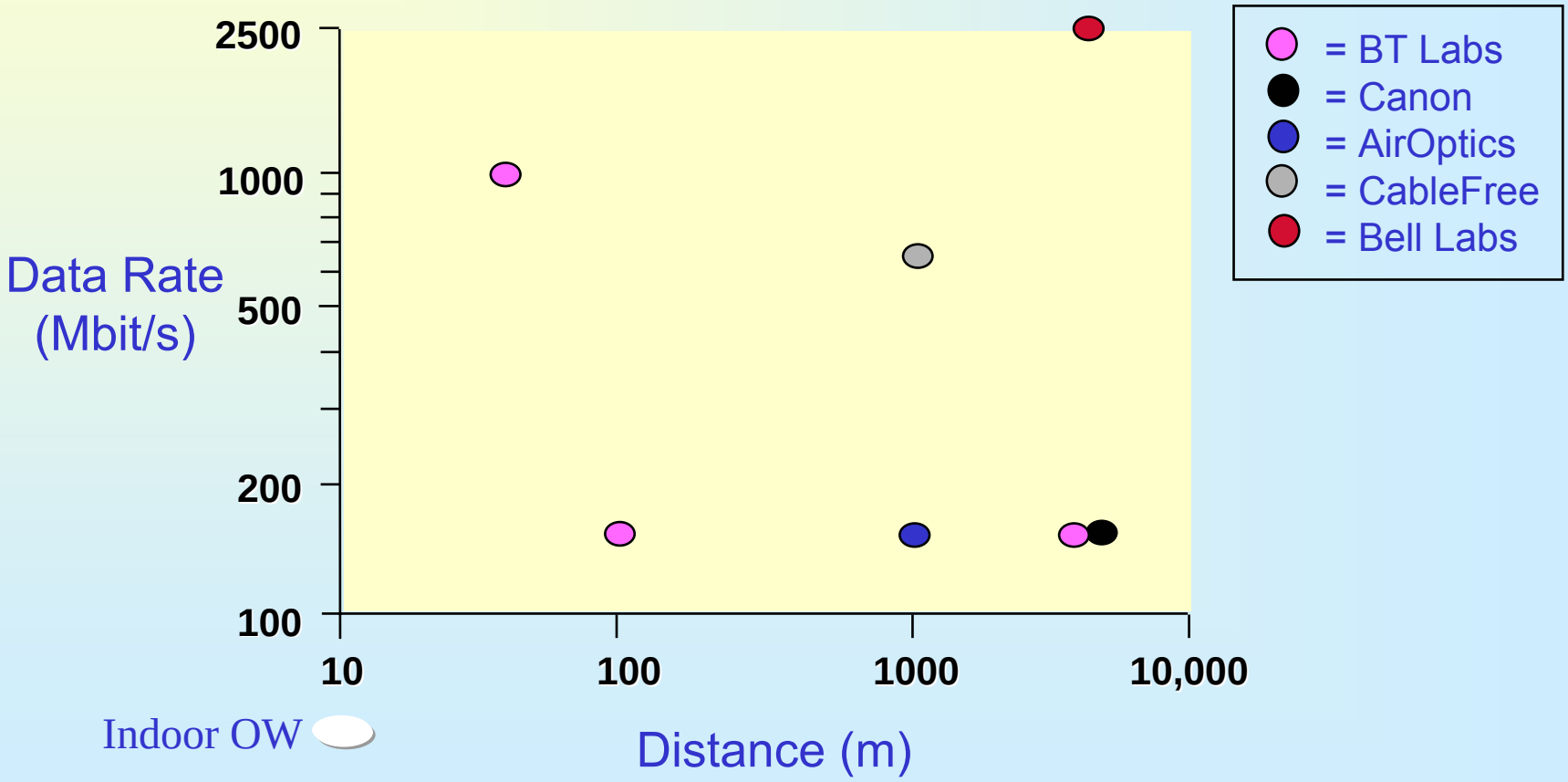


- Reflection pattern for diffusing spot is Lambertian for the angle of incidence Φ_{MSD} <= 60°, but
  - Maximum Φ_{MSD} < 45° (due to link blockages and shadowing)
- Power penalty due to shadowing = not exceeding 0.1 dB in 99% of the cases.

Reported Working Systems

Year	Type	Data rate (b/s)	Range (m)
1978-Gfeller	Non-directed, Non-LOS	125 k	20
1985 - C S Yun *et al*	1st LOS	1 M	50
1987 - T S Chu *et al*	LOS	50 M	30
1992- G Berline *et al*	LOS	4 M	24
1993- JOLT Ltd.	LOS	125 M	30
1995- J R Barry, *et al*	Non-direct LOS	100 M	4
1996 - D R Wisely	LOS Tracked	1G	
1997- J M Kahn, *et al*	Diffused	50 M	10x10
1999- D J Heatley, *et al*	LOS	1 G	a few
2000- D. M. Holburn	LOS LAN	155 -310M	a few
2000- Bell lab	LOS	10 G	~5 km Free space
2001 (IrDA)	LOS	16 M	a few
2005 (JM Garrido et al)	Non-LOS	50 M	a few

Long Distance Systems



(Bell Labs: 4 x 2.5Gb/s over 4.4km, OFC'99)

Optical Wireless LAN & WAN

System	Capacity Mb/s	Range (m)	Tx/Rx	NW Interface	λ (nm)/ P_o (mW)	Error rate
Simplex (LAN)	10	Up 1500	LED/PD	Ethernet 10Base-T	870/400	10^{-9}
	100			Fast Ethernet 100Base-T		
Duplex (WAN)	2	Up 3000	LED/PD	V35, G703	870/400	10^{-9}
	34					
Optical Access	1-1000	Up 4000	Laser/PD	T1/E1, 10/100/ 1000 Ethernet, OC-3, and OC-12		

Optical Vs. Radio LANs

Medium	System	Capacity	Cell size	Roaming
Optical	JVC Spectrix	10Mb/s 4Mbit/s	10m 10m	No Yes
Radio	WaveLAN HiperLAN Bluetooth	11Mbit/s 26Mbit/s 1Mbits/s	100m 50m 10m	Yes Yes Yes

- Similar capacities today
- Radio gives larger cell and supports roaming
- Radio is omni-directional and unaffected by obstacles

OW Systems Today - Summary

- Bandwidth
  - A few Gbit/s in the lab
  - 10 Mbit/s commercially
- Cell size
  - Up to 10m
- Roaming within the cell
  - No for telepoint, *unless tracking architecture used or multiple cells*
  - Yes for diffuse

OW Systems - Issues

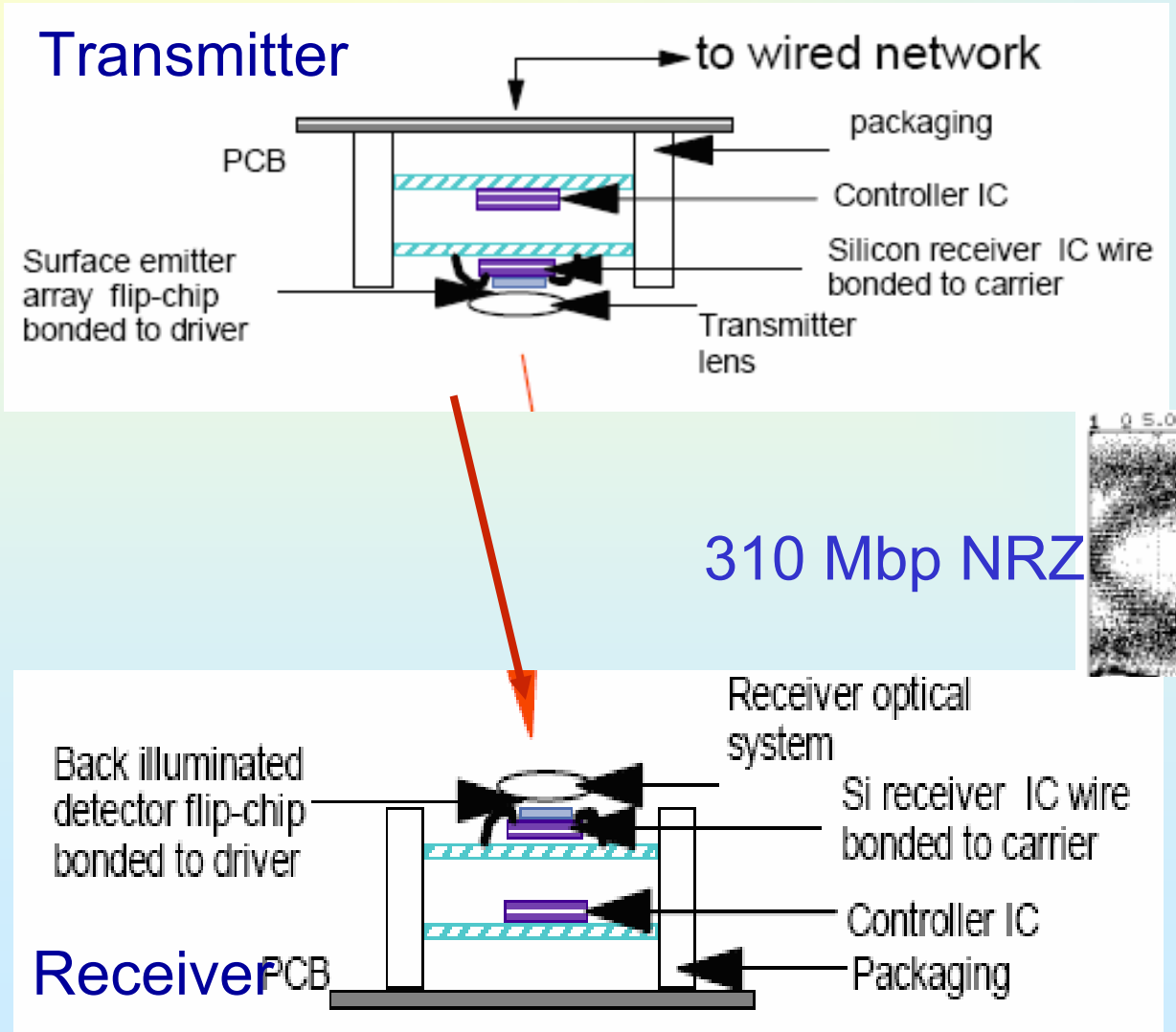
Issues

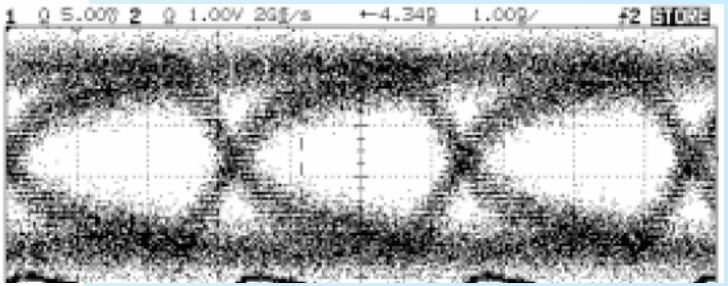
- **Multipath:** *Result in inter-symbol interference*
- **Ambient noise:** *Signal degradation*
- **Limited transmission power:**
  At ~850nm due to eye safety considerations
- **Limited bandwidth:**
  Due to large capacitance of the large area detectors

How to Combat Noise and Dispersion?

- Noise Filtering: Optical or Electrical
- Match Filtering:
  - Maximises signal-to-noise ratio,
- Modulation: Z. Ghassemlooy et al
- Coding: Block codes, Convolutional and Turbo codes.
- Spread Spectrum
- Tracking Transmitters: D. Wisely et al, 1997
- Imaging Receivers: J.M. Kahn et al, 1998
- Integrated Optical Wireless Transceivers: D.C. O'Brien, 2000
- Equalisation
- Diversity: S. H. Khoo et al 2001
- Wavelet and AI based equalisers: Z. Ghassemlooy et al, 2004

Integrated Optical Wireless Transceivers



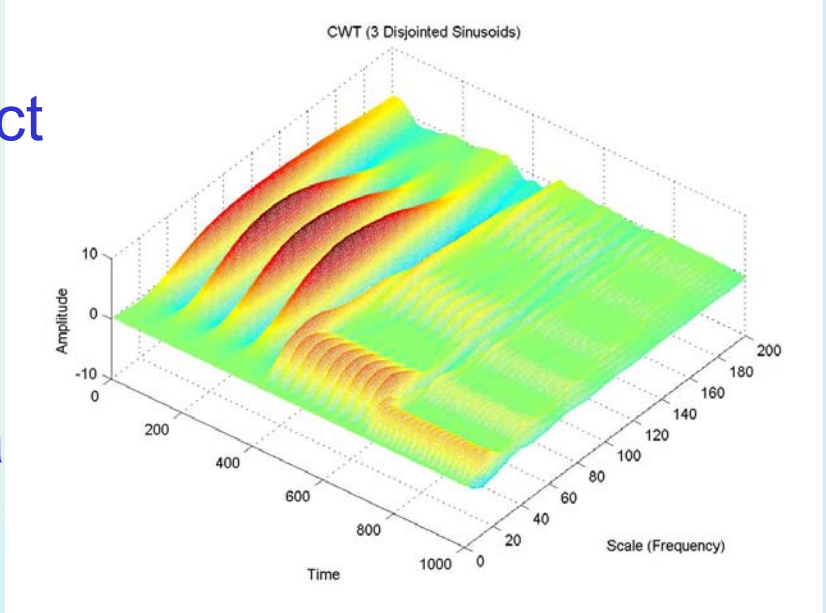


D.C.O'Brien, et al 2000

Z. Ghassemlooy 2006

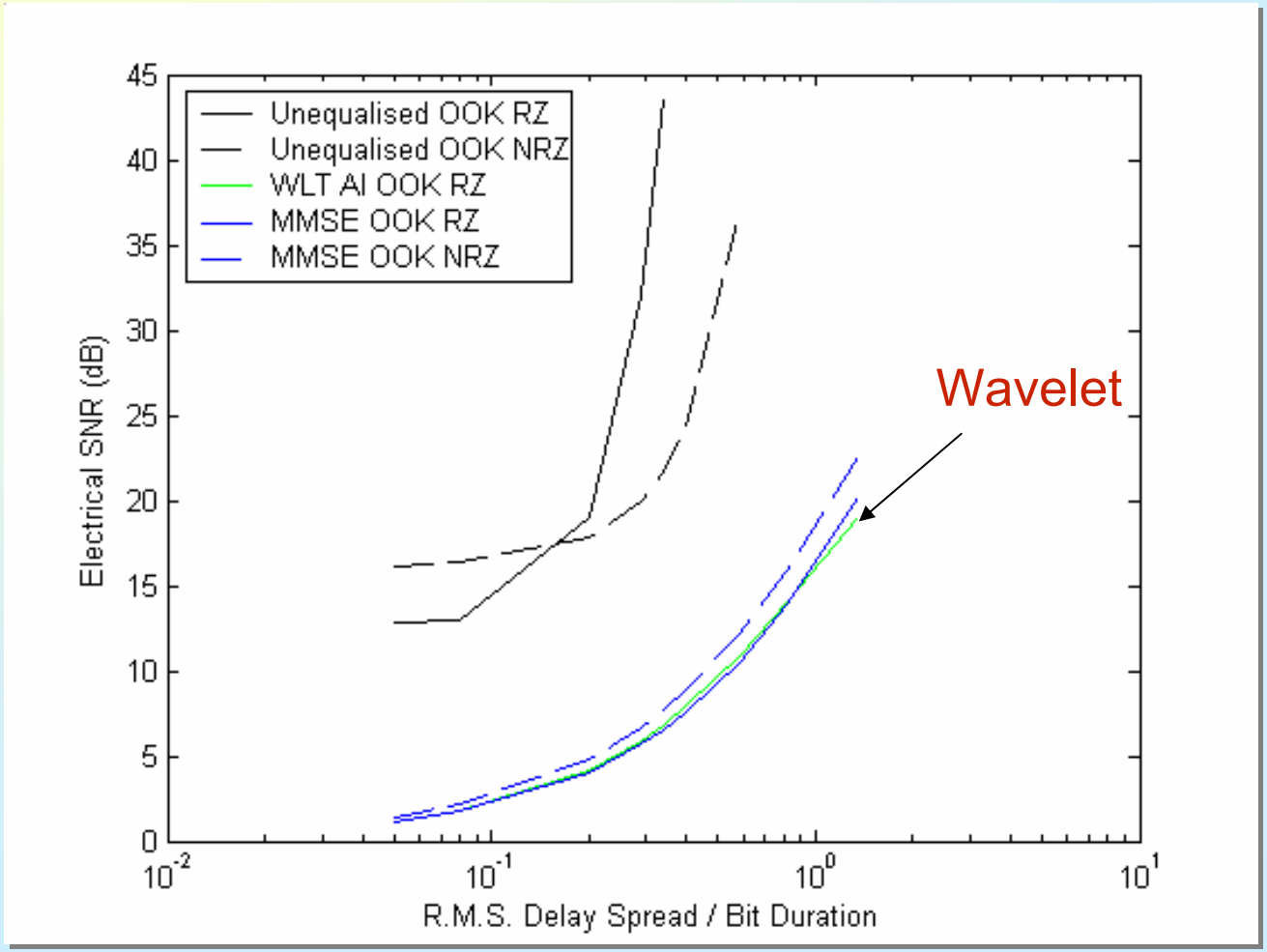
Wavelet Transform

- Scaling and translating (shifting) the **'Mother Wavelet'** with respect to the signal under analysis.
- Coefficient produced can be thought of as the goodness of fit between a particular wavelet at a particular scale and time.
- Wavelets are:
  - best at analysing waveforms that are similar to themselves.
  - also good for detecting discontinuities within a waveform.



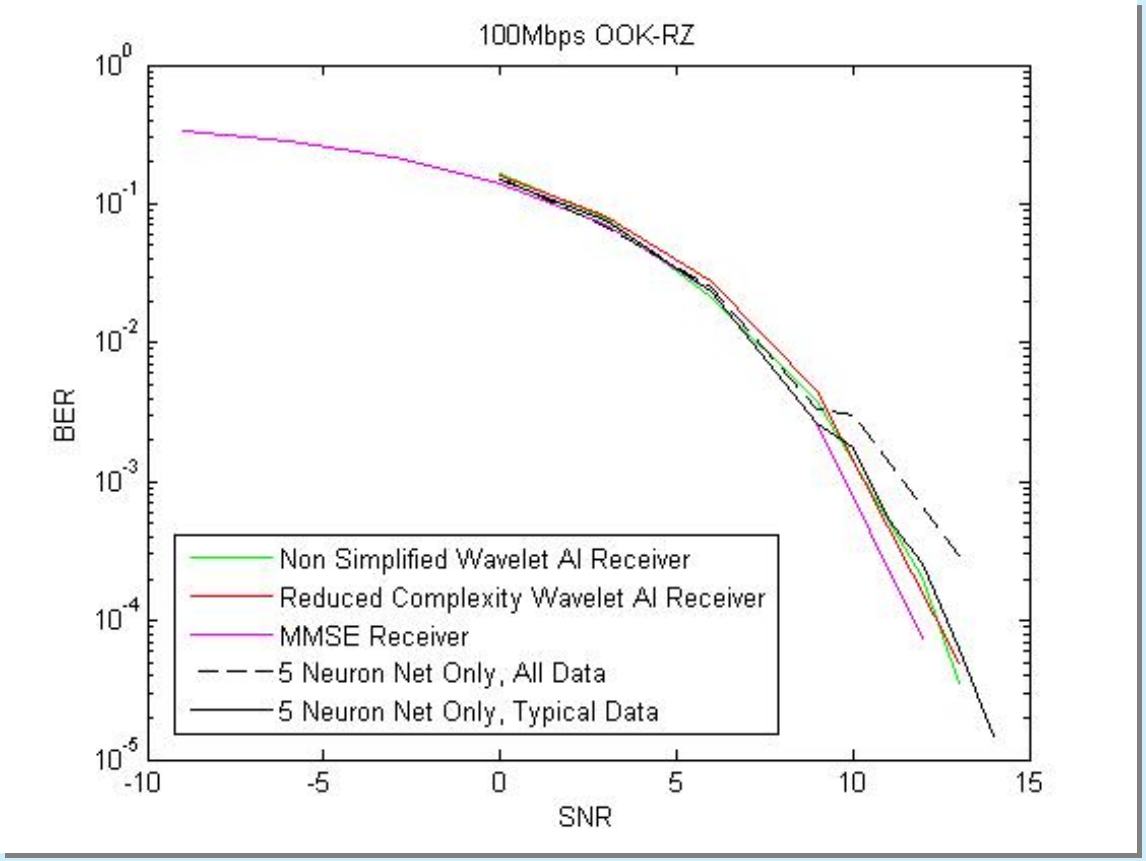
$$CWT(a,\tau) = \frac{1}{\sqrt{a}} \int s(t) \Psi \left(\frac{t-\tau}{a} \right) dt$$

Wavelet-AI Receiver - Results



SNR Vs. the RMS delay spread/bit duration

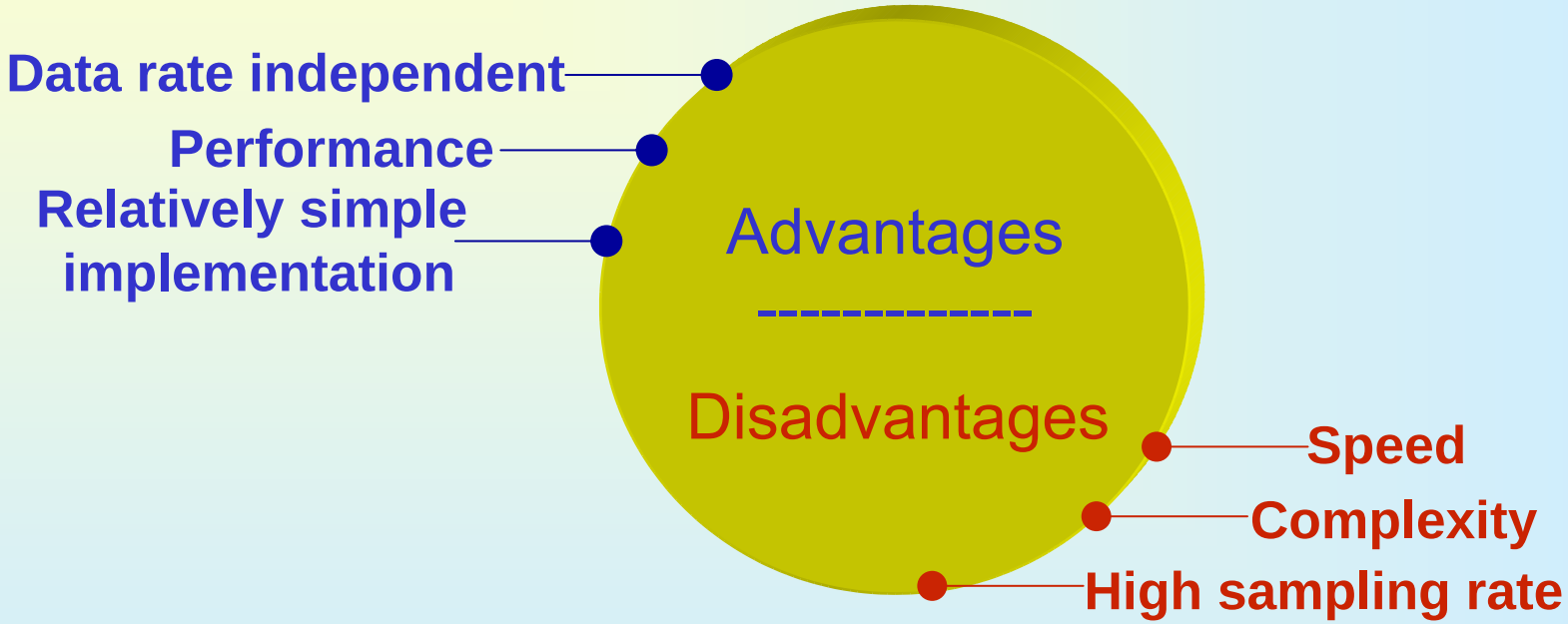
Comparisons of Different Schemes



- Reduced complexity performance almost identical to original curve and close to MMSE.
- 6 Neuron Net (5 in layer 1) is almost as good as Wavelet AI, Sometimes!

Z. Ghassemlooy 2006

Wavelet-AI Receiver



Optical Channel

Optical Wireless Channel Model

- Electromagnetic waves at optical frequencies exhibit different propagation behaviour than those at RF frequencies.
- At optical frequencies,
  - Most building surfaces are opaque: - limiting the propagation of light to the transmitter's room.
  - For most surfaces the reflected light wave is diffusely reflected (as from a matte surface) rather than specularly reflected (as from a mirrored surface).

Optical Wireless Channel Model

- High-quality access is achieved via links with:
  - low delay,
  - high data rates,
  - reliableperformance,
  - **accurate characterization of the channel**
- Channel simulation and modelling are required to predict the link losses and multipath dispersion within these systems.

Optical Wireless - Channel Model

- Basic system models – *F. R. Gfeller et al 1979, J. M. Kahn et al 1995,*
- Measurement studies - *H. Hashemi et al 1994, J. M. Kahn et al 1995,*
  - Diffuse + shadowing
- Statistical models - *J.B. Carruthers et al 1997*
- Ray tracing techniques (to obtain simulated channel responses) - *J.R. Barry, J.R., et al. 1995, F.J. Lopez-Hernandez, et al, 2000*
- Segmentation of reflecting surfaces + ray tracing techniques to calculate the intensity and temporal distributions - *S. H. Khoo et al 2001*
- Fast multi-receiver channel estimation - *J.B. Carruthers et al 2002*

Optical Channel Model

- Channel impulse response $h(t)$:
  - Fixed
  - Vary significantly (many bit period) due to movements
- Power penalty due to channel:
  - Path loss
  - Multipath dispersion
- RMS Delay spread is used to determine the power penalty due to multipath dispersion:

$$D_{RMS} = \left[\frac{\int (t-\mu)^2 h^2(t)\,dt}{\int h^2(t)\,dt} \right]^{1/2}$$

where mean delay

$$u = \frac{\int t h^2(t)\,dt}{\int h^2(t)\,dt}$$

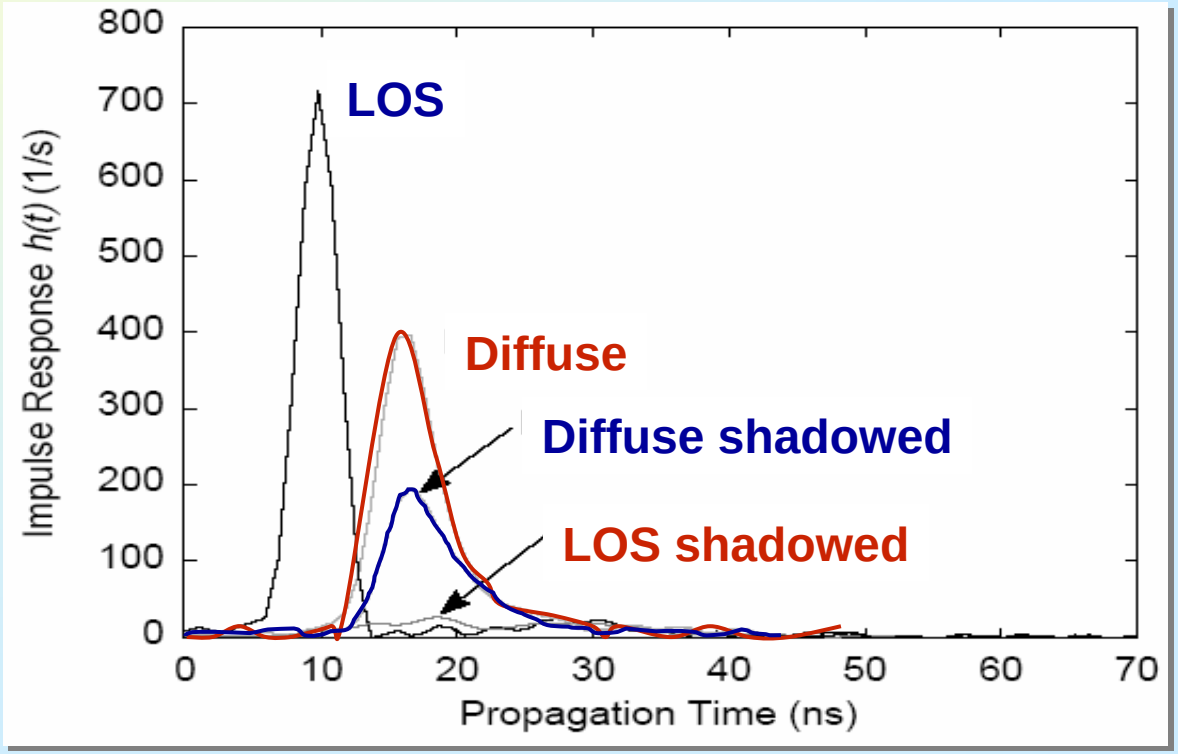
Channel Model - Ceiling Bounce Model

- Developed by *Carruthers* and *Kahn*.
- Impulse response is:

$$h(t,a) = \frac{6a^6}{(t+a)^7}u(t)$$

where $u(t)$ is the unit step function and a is related to the RMS delay spread D

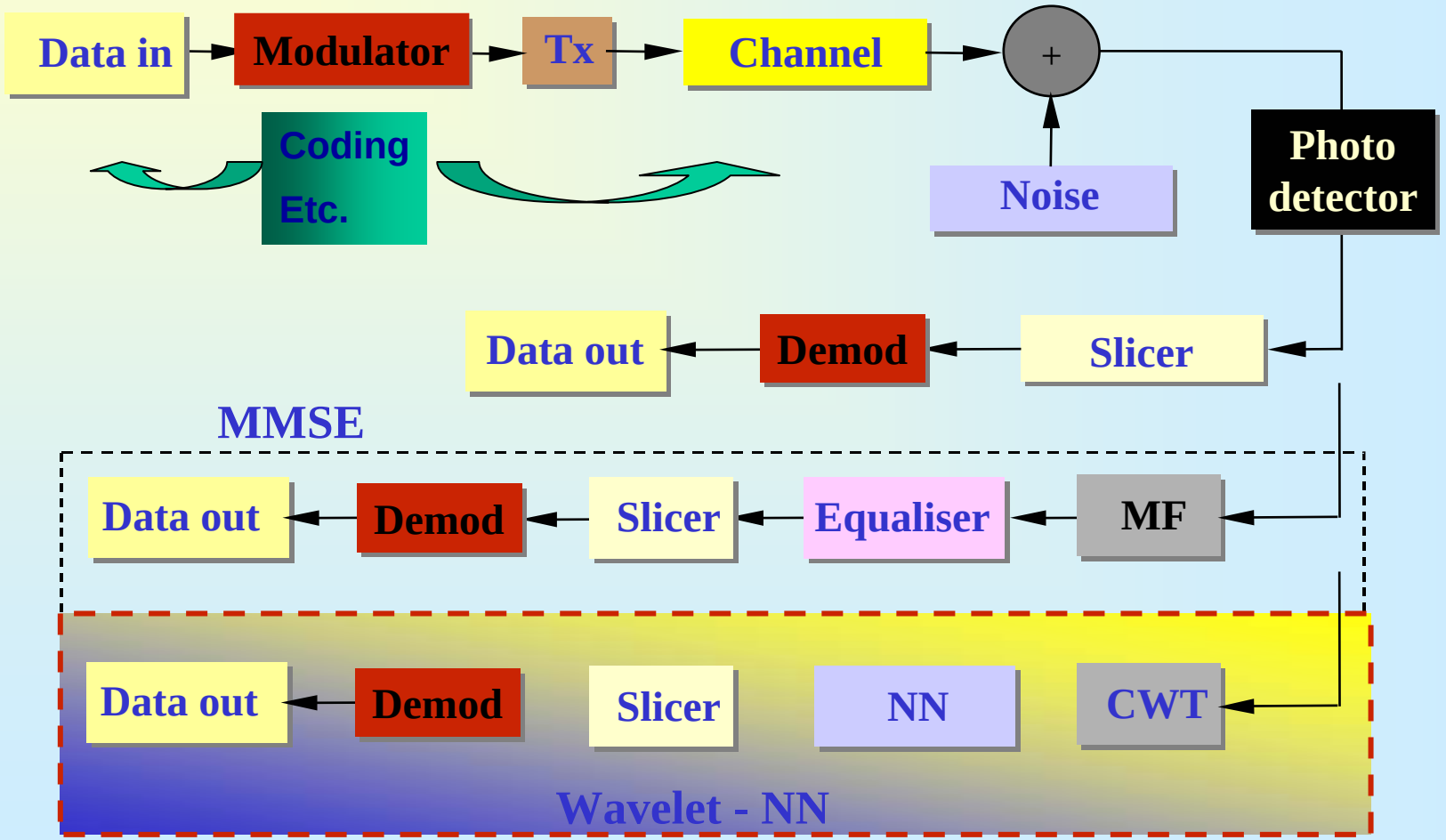
$$D = \frac{a}{12}\sqrt{\frac{13}{11}}$$



Modulation Schemes for Optical Wireless Systems

Z. Ghassemlooy 2006

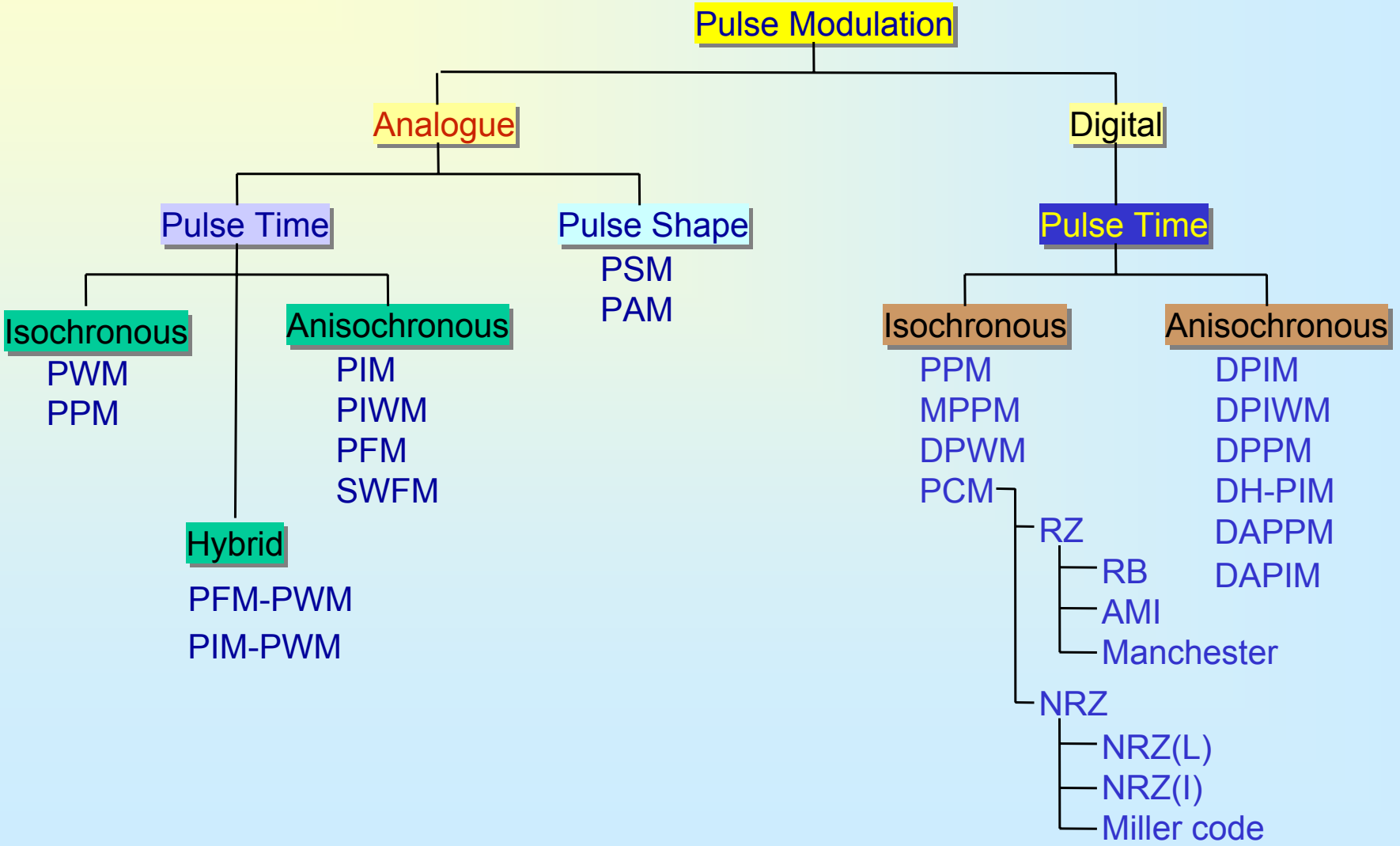
OWC System Block Diagram



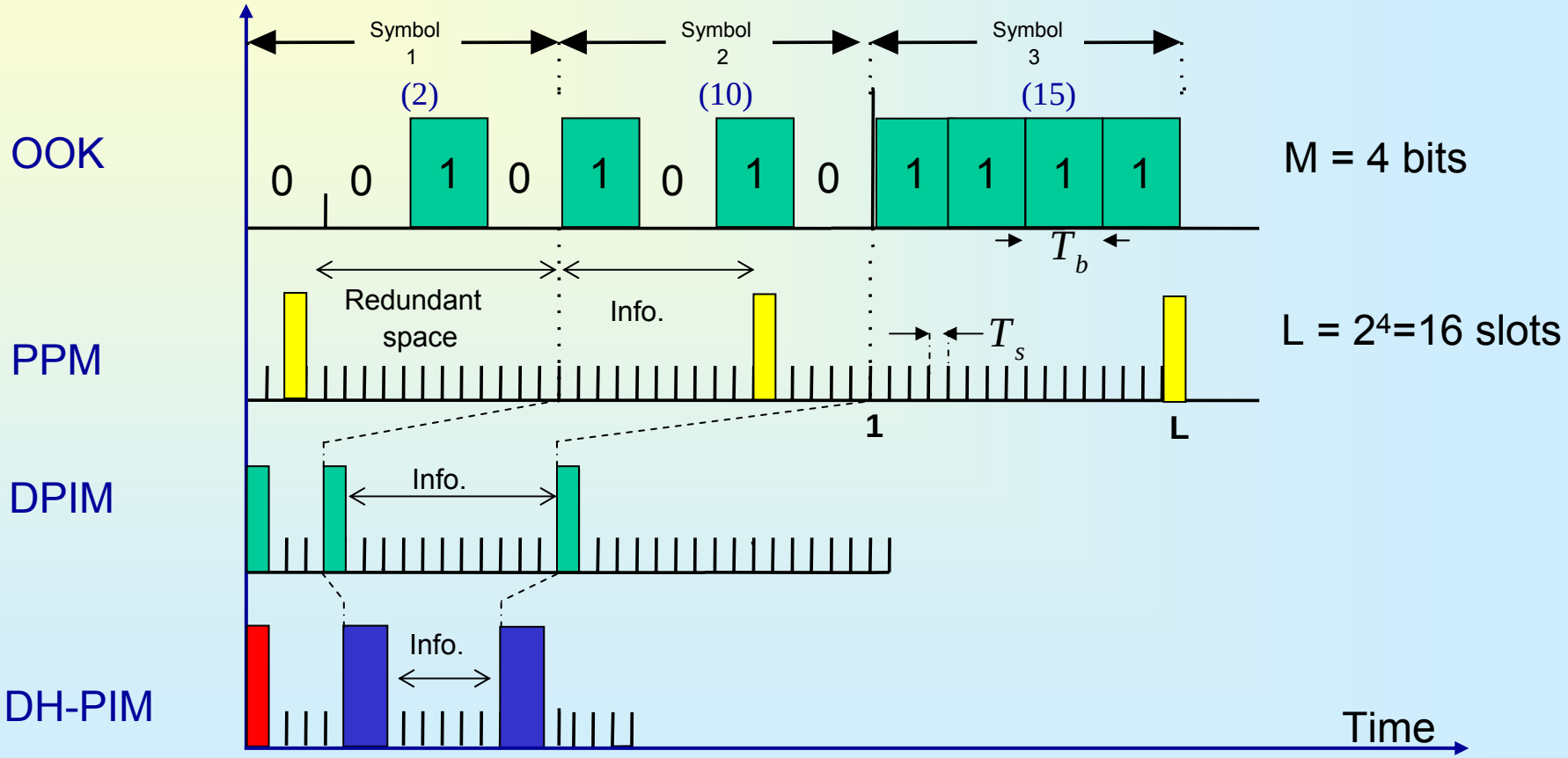
Modulation Schemes - Selection Criteria

- Average optical power emitted:
  - limited by eye safety regulations, and therefore, modulation techniques are compared in terms of the average received optical power required to achieve a desired BER at a given data rate. This favours modulation schemes with a high peak to average power ratio.
- Bandwidth efficiency:
  - typical infrared receivers use large area photodetectors (eg. 1 cm^2) which limits the receiver bandwidth.
- Resistance to multipath dispersion effects
- Amenability to multiple access
  - the last two are best achieved by subcarrier multiplexing, but at the cost of increased power.

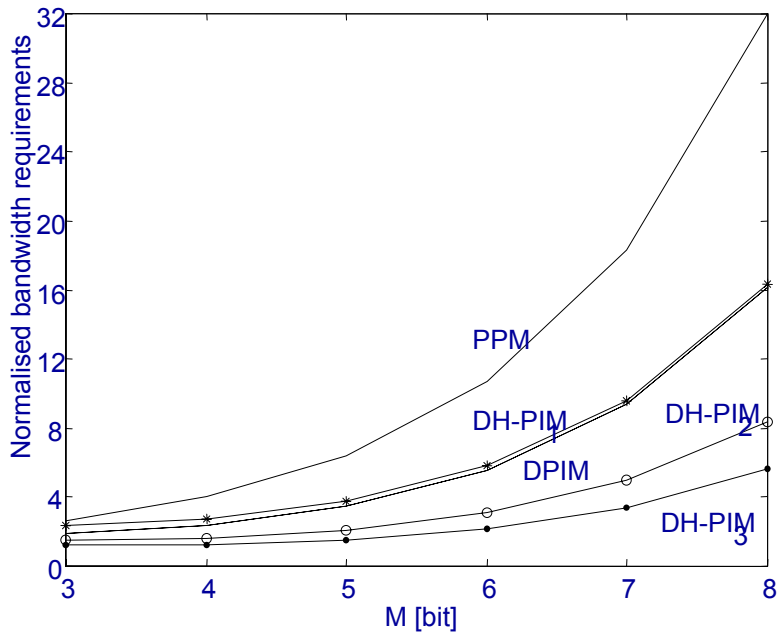
Modulation Tree



Digital Pulse Time Modulation Schemes

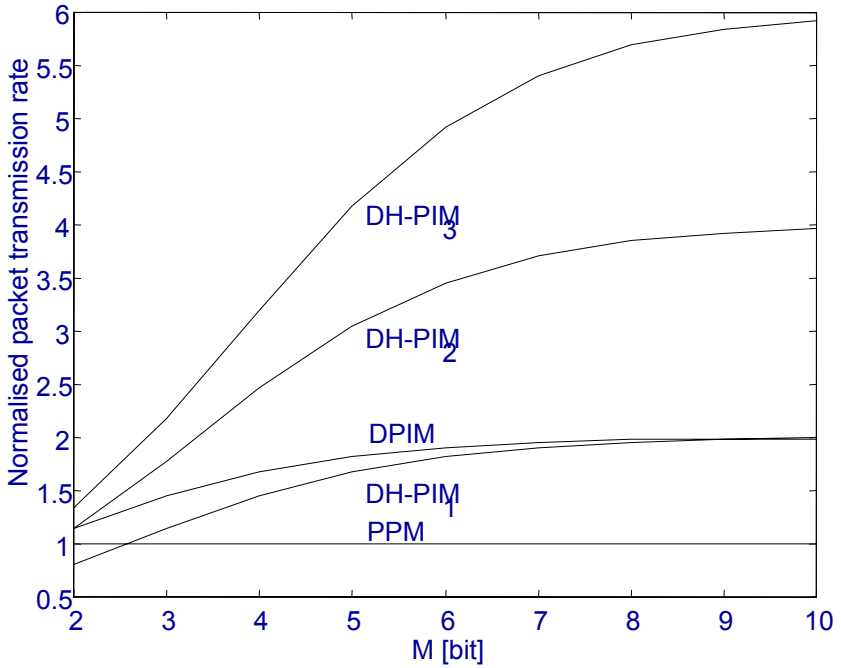


Bandwidth and Packet Transmission



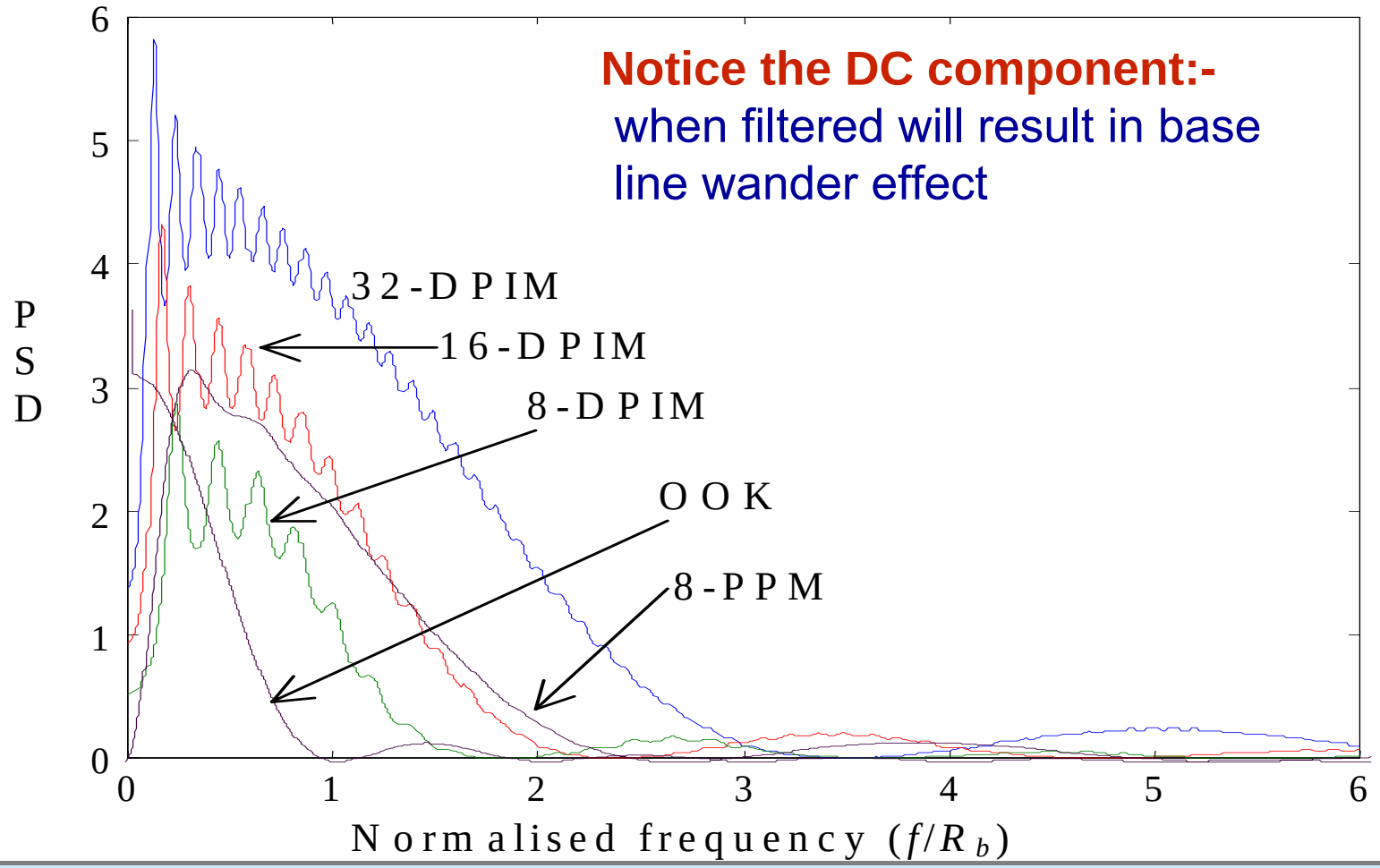
Normalised bandwidth

Normalised packet transmission



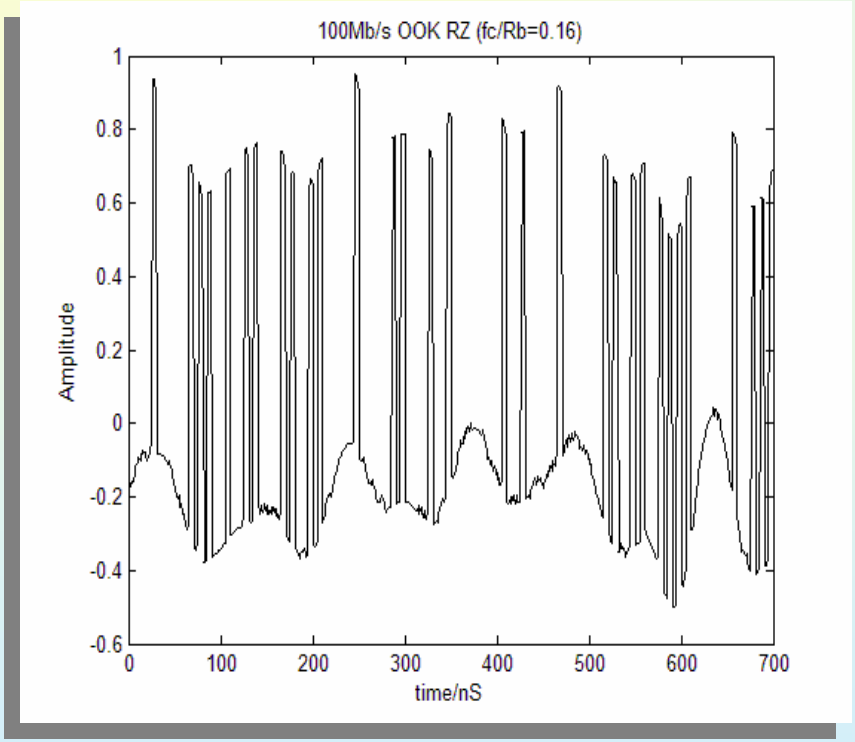
Z. Ghassemlooy 2006

Power Spectral Density

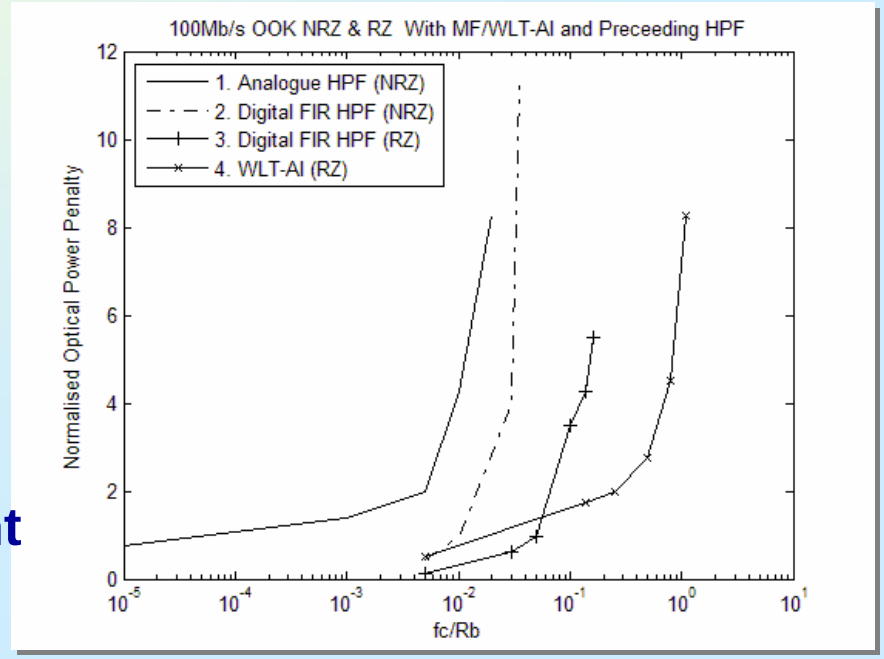


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Baseline Wander Effect



High pass filtering of ambient light Results in baseline wander



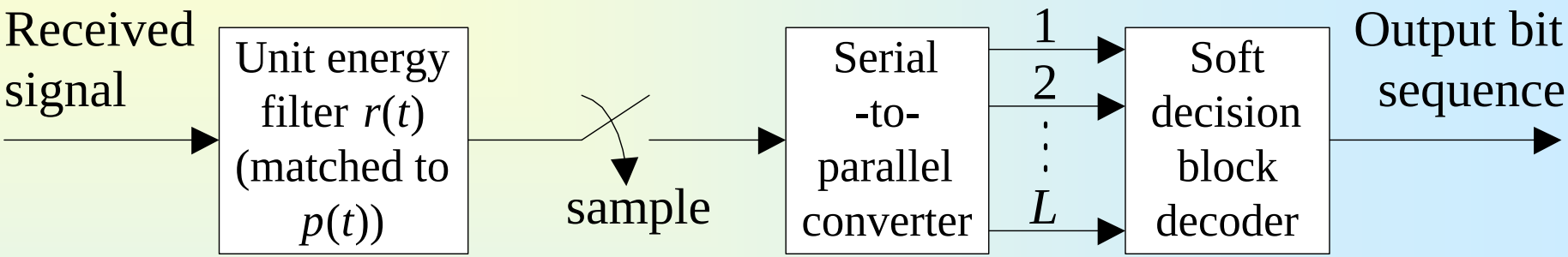
Power penalty using different filtering schemes

Z. Ghassemlooy 2006

Decoding

- Threshold Detection
- Soft Decision: maximum *a posteriori* (MAP) or maximum likelihood detector
- Hard Decision:

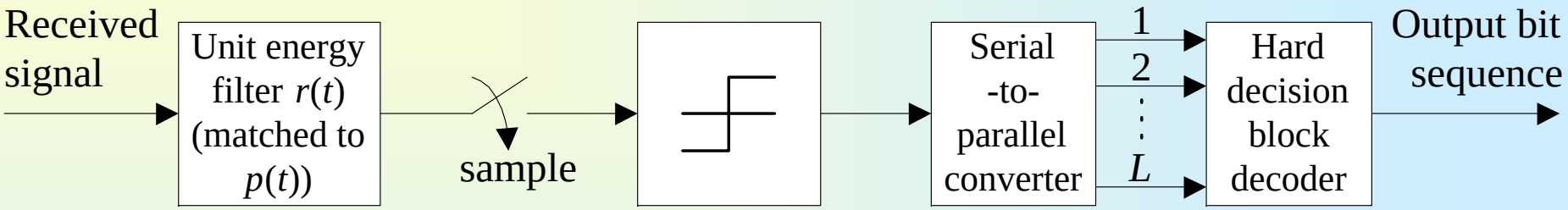
Maximum A *Posteriori* (MAP) or Maximum Likelihood Detector



- Compares the values of all *L* samples within a symbol
- Assigns a one to the slot containing the sample with the highest value.
- The remaining *L*-1 slots are then assigned as zeros.

In this method, it is not the actual values of the samples which are important, but rather, their value relative to each other. This method of decoding is optimal for systems in which AWGN is the dominant noise source and there is no channel distortion

Hard Decision Decoding



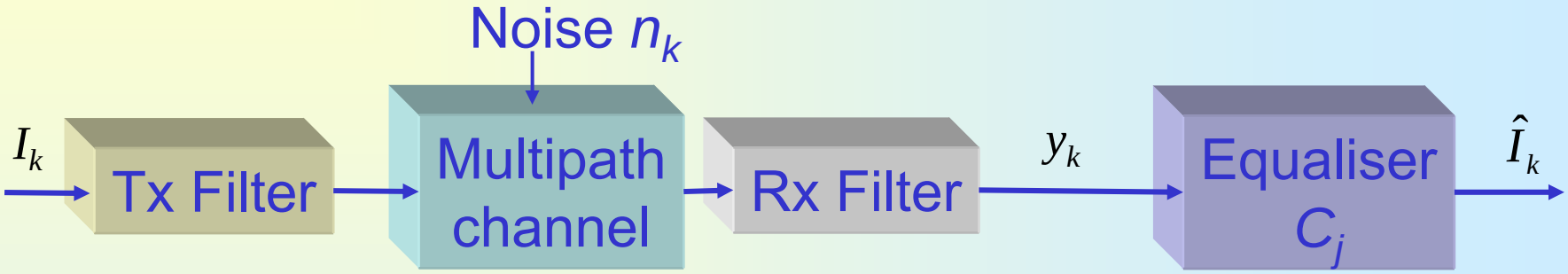
- Samples the incoming signal at the slot rate
- Assigns a one or zero to each slot depending on whether the sample is above or below the threshold level.
- The output is then determined by which of the *L* samples in the symbol is a one.
- If the block of *L* samples consists entirely of zeros, or two or more ones, then clearly an error has occurred and the receiver must mediate

OWC – Equalisation

- **Linear**
  - Lattice
  - Transversal
    - **Zero Forcing**
    - **LMS**
    - Fast RLS
    - Square-root RLS
- **Non-Linear**
  - DFE
  - ML Symbol detector
  - MLS

Linear Equaliser: *Traversal filter structure that has a computational complexity which is a linear function of the channel dispersion length.*

OWC - Equalisation – contd.



- Discrete equivalent of the convolution of the Tx filter, channel and Rx filter with the information sequence I_k

$$y_k = I_k + \sum_{\substack{n=0 \\ n \neq k}}^{\infty} I_n f_{k-n} + n_k \qquad k = 0,1,2,3....$$

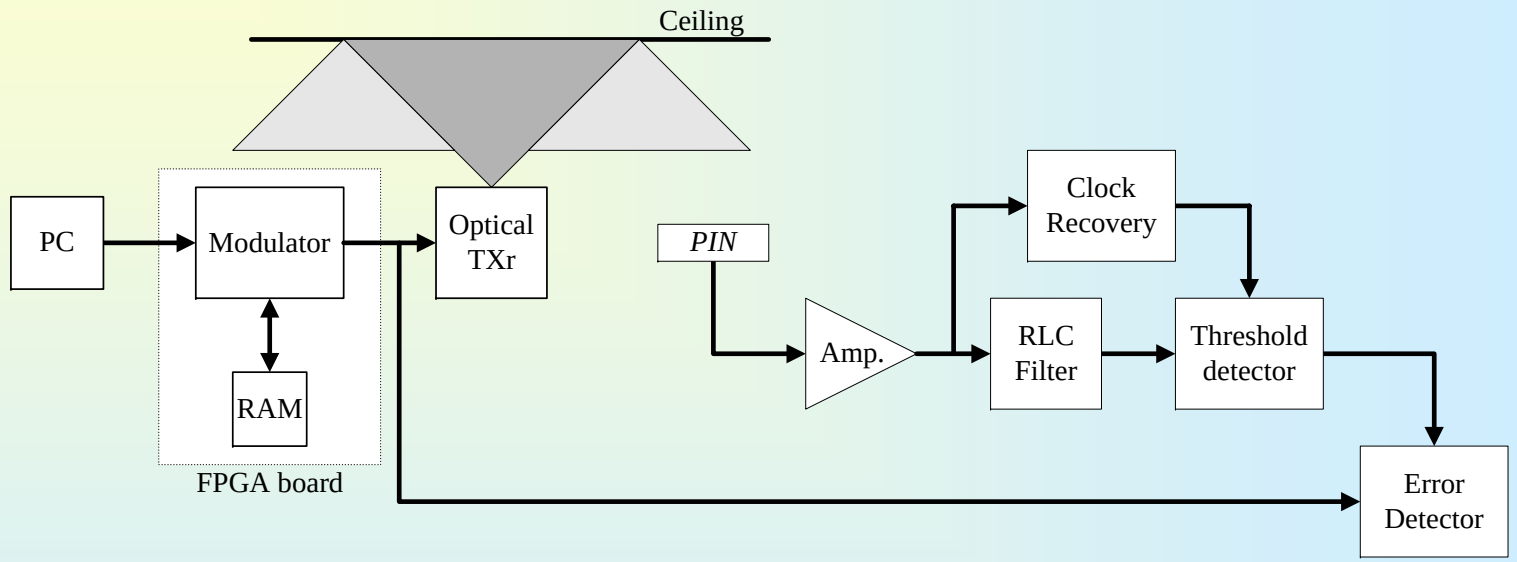
ISI Noise

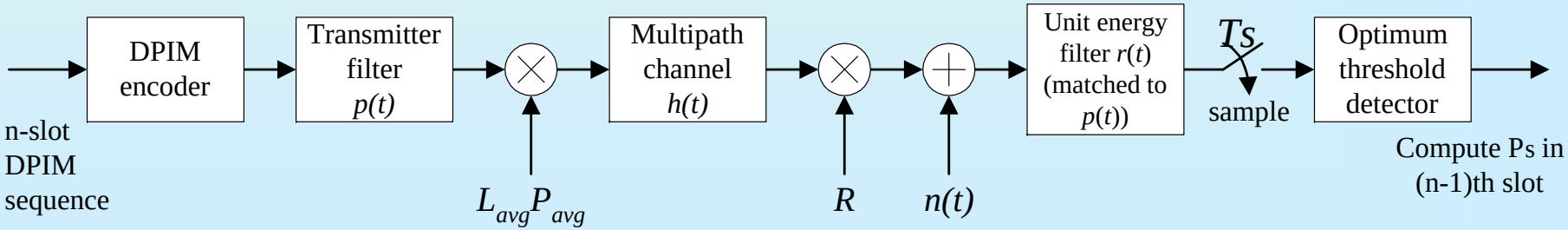
- Equaliser output (estimate) $$\hat{I}_k = \sum_{j=-k}^{k} c_j y_{k-j}$$

Where $\{c_j\}$ are the $2K+1$ complex-valued tap weight/coefficients of the filter.

System Implementation

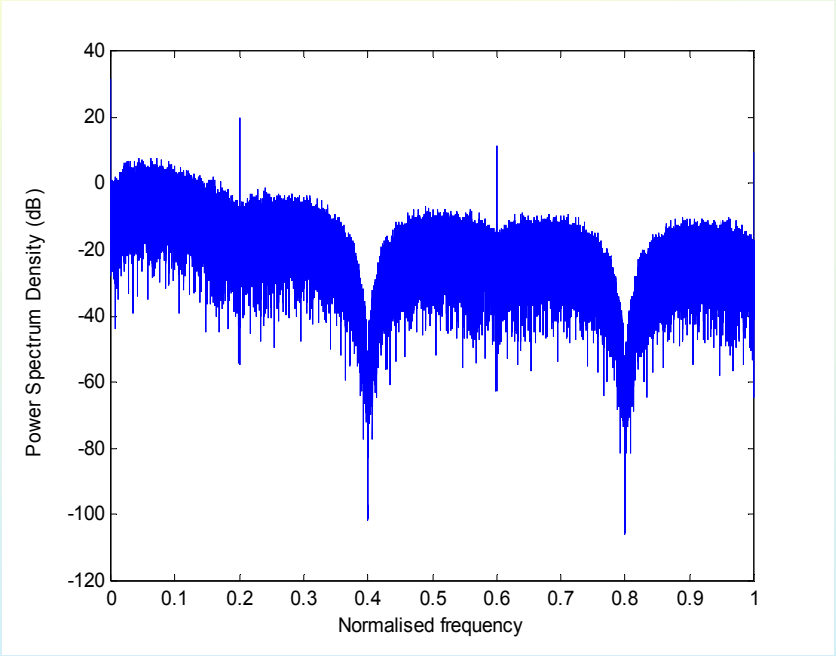
System Implementation - Unequalised DPIM(NGB)



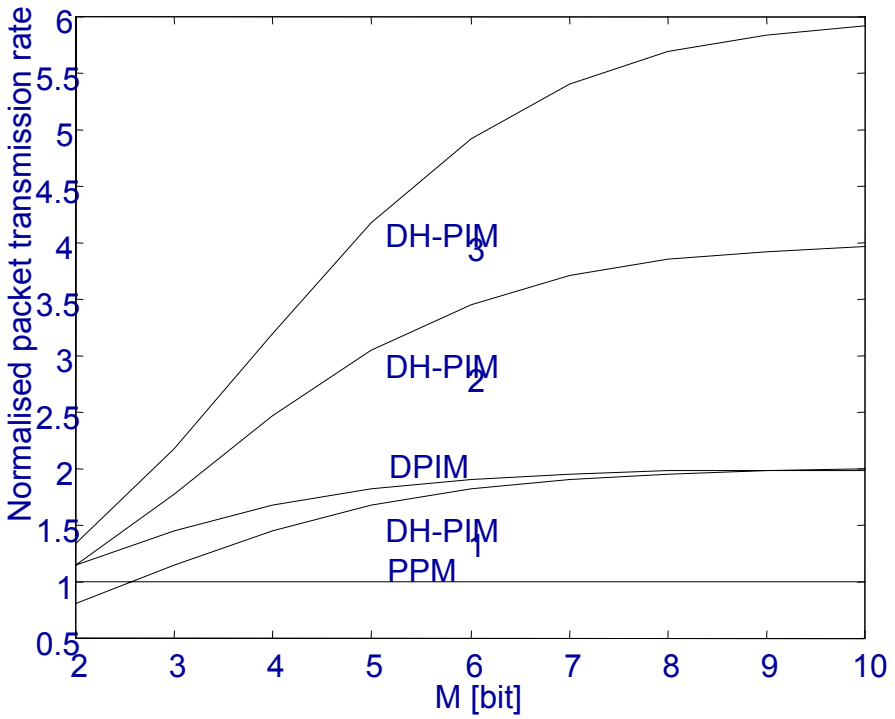


DPIM – Characteristics

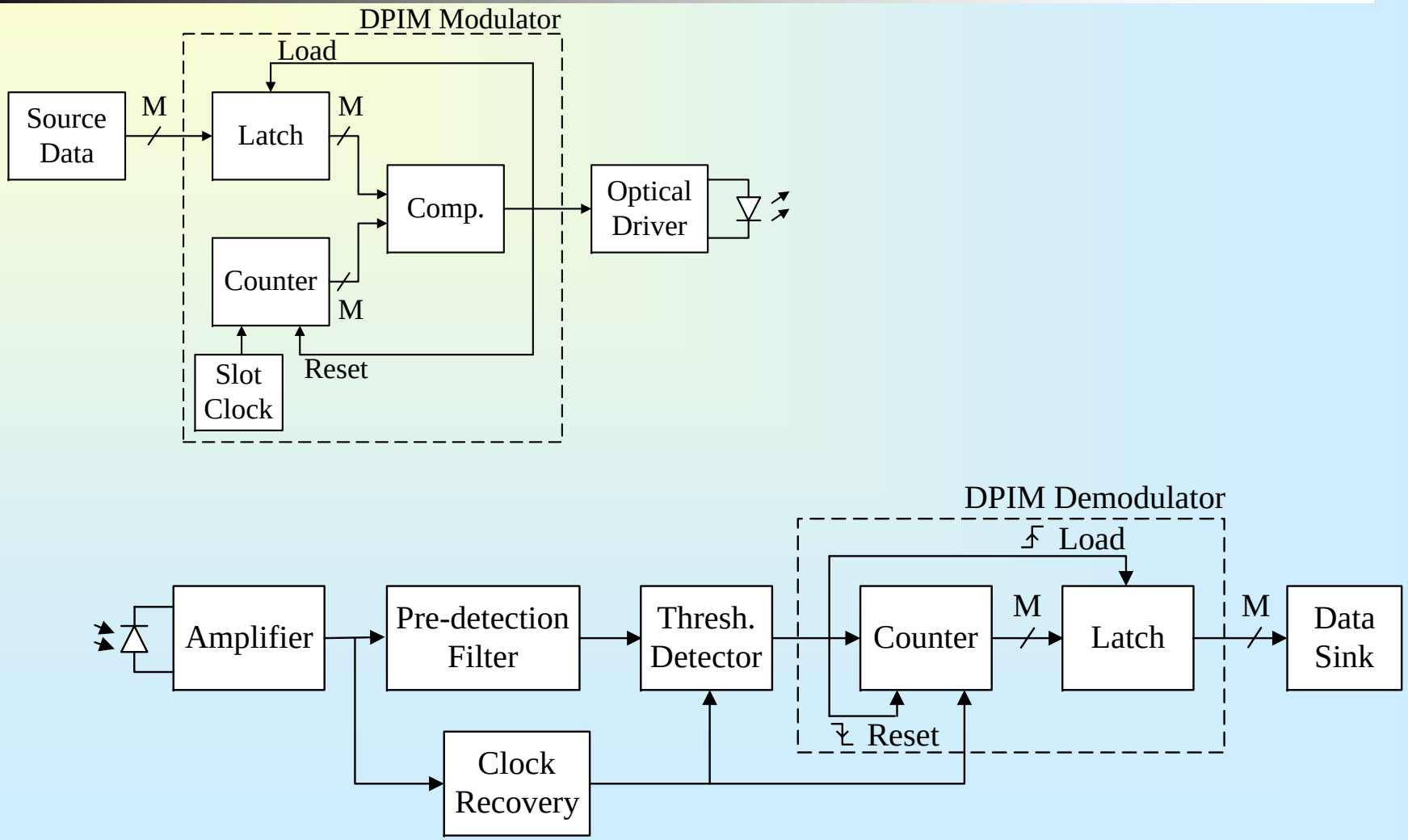
Synchronisation



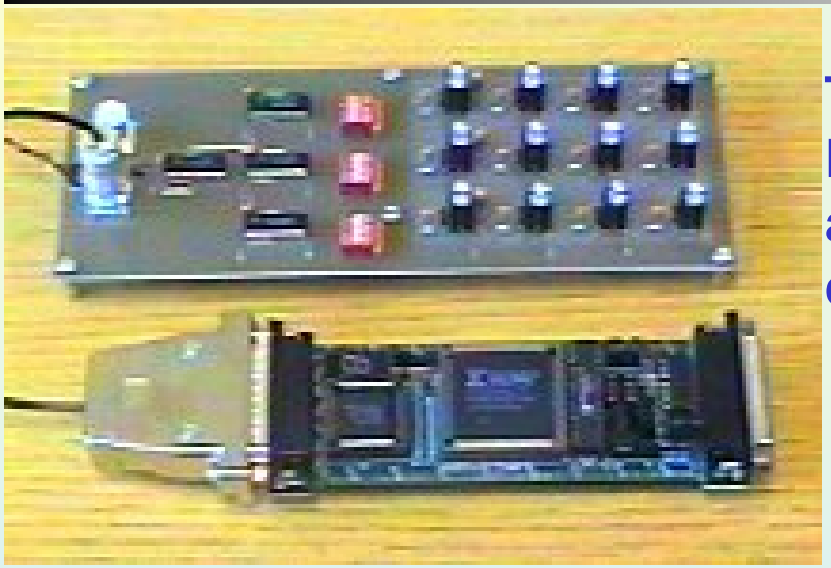
Higher packet transmission throughput



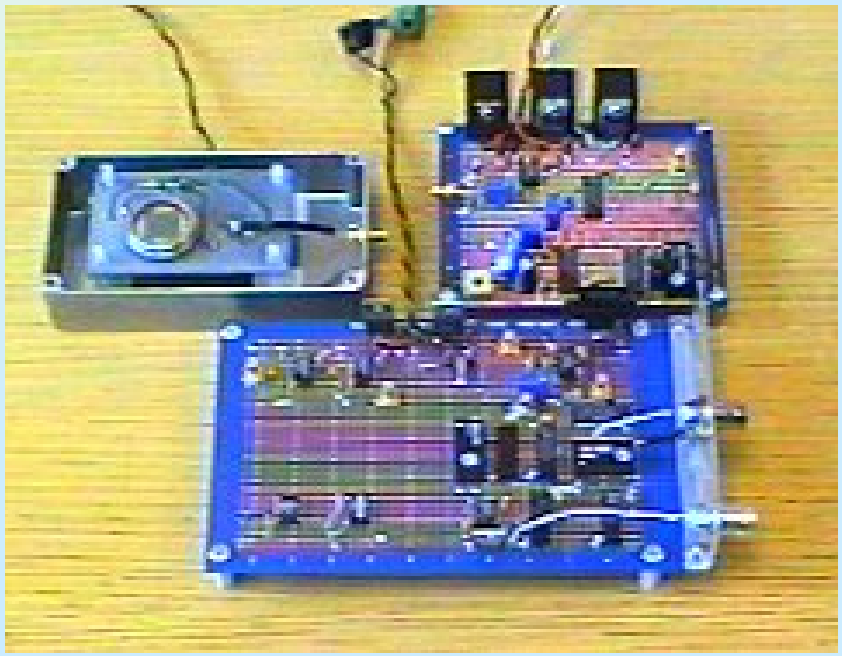
DPIM - Transmitter



DPIM Experimental System



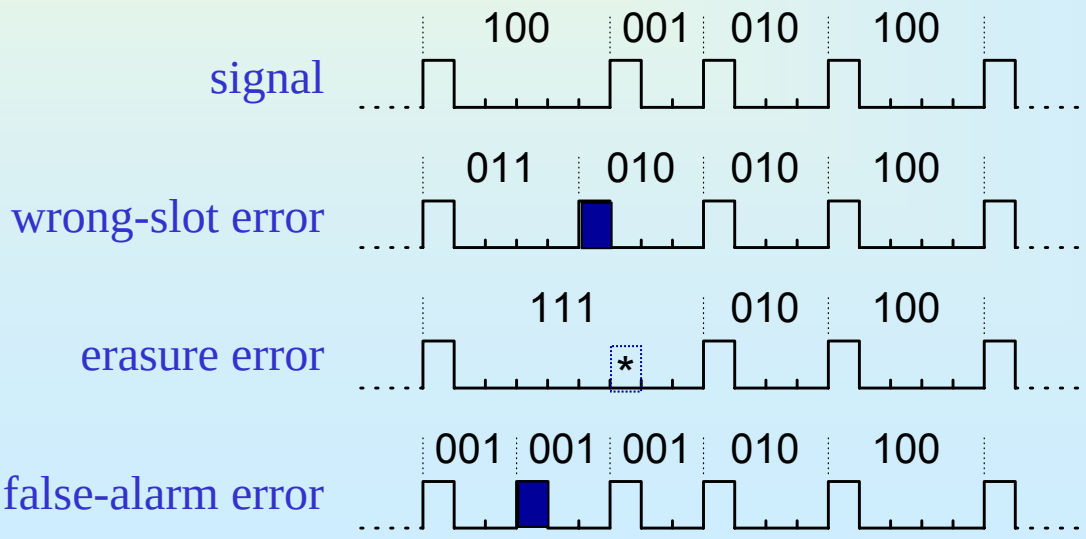
Transmitter :- comprising of an FPGA development board and an array of 12 infrared LEDs with the corresponding drive circuitry.



Receiver :- comprising of an optical front-end (with some amplification stages), a clock recovery circuit and signal regeneration circuitry.

Error Performance

- In fixed length symbols an error is confined to the symbol in which the error occurs. Thus it is possible to convert from the probability of symbol error to bit error rate.
- In variable length symbols errors are not confined to one symbol, therefore the slot and packet error rates are used

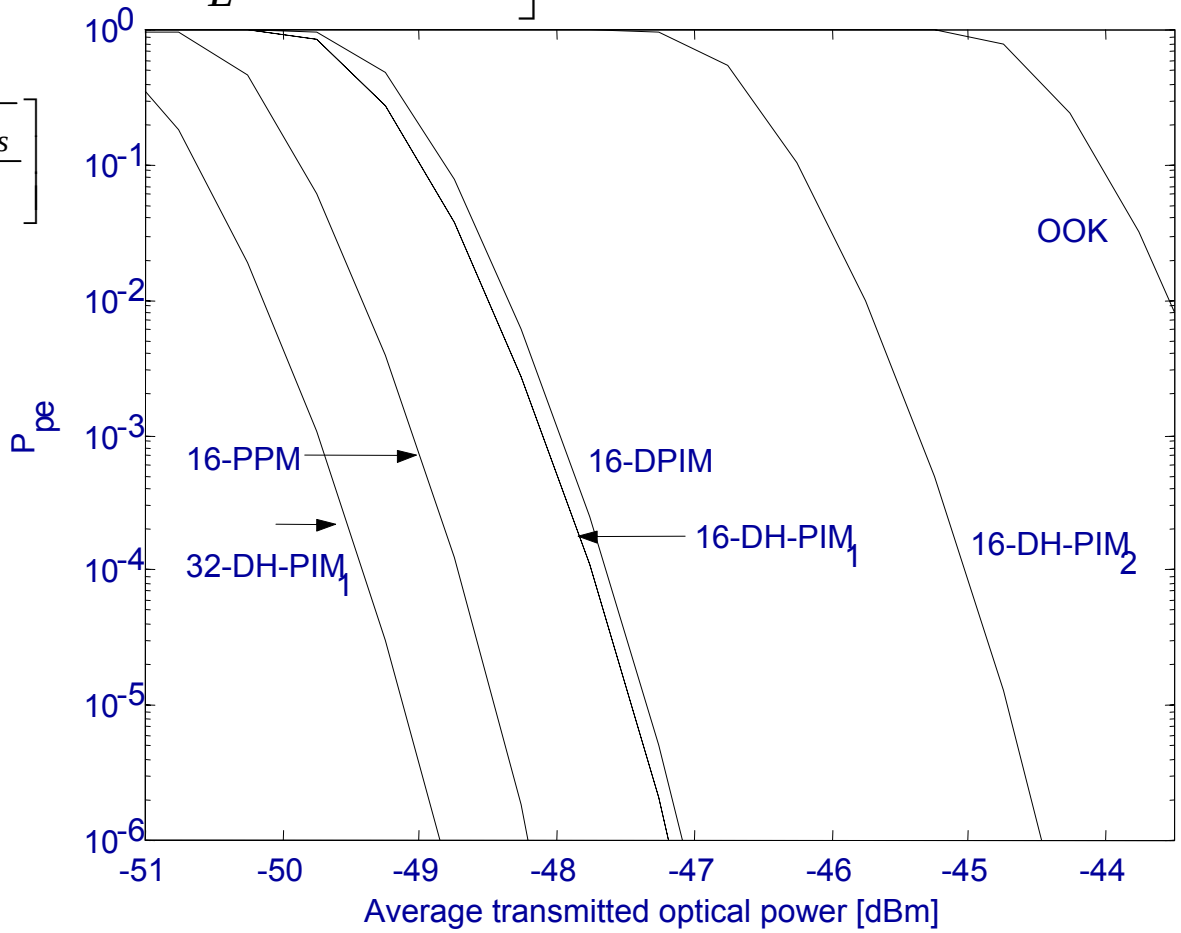


Packet Error Rate – Eg. DPIM

$$P_{SE_{DPIM}} = 1 - \left[\frac{1}{L} \sum_{n=0}^{L-1} (1 - P_{01})(1 - P_{10})^n + \frac{1}{L} P_{01} (1 - P_{10})^{L-1} \right]$$

$$P_{01} = P_{10} = \frac{1}{2} Erfc \left[\frac{(L+3) P_{ave} R \sqrt{T_s}}{4\sqrt{2qI_b}} \right]$$

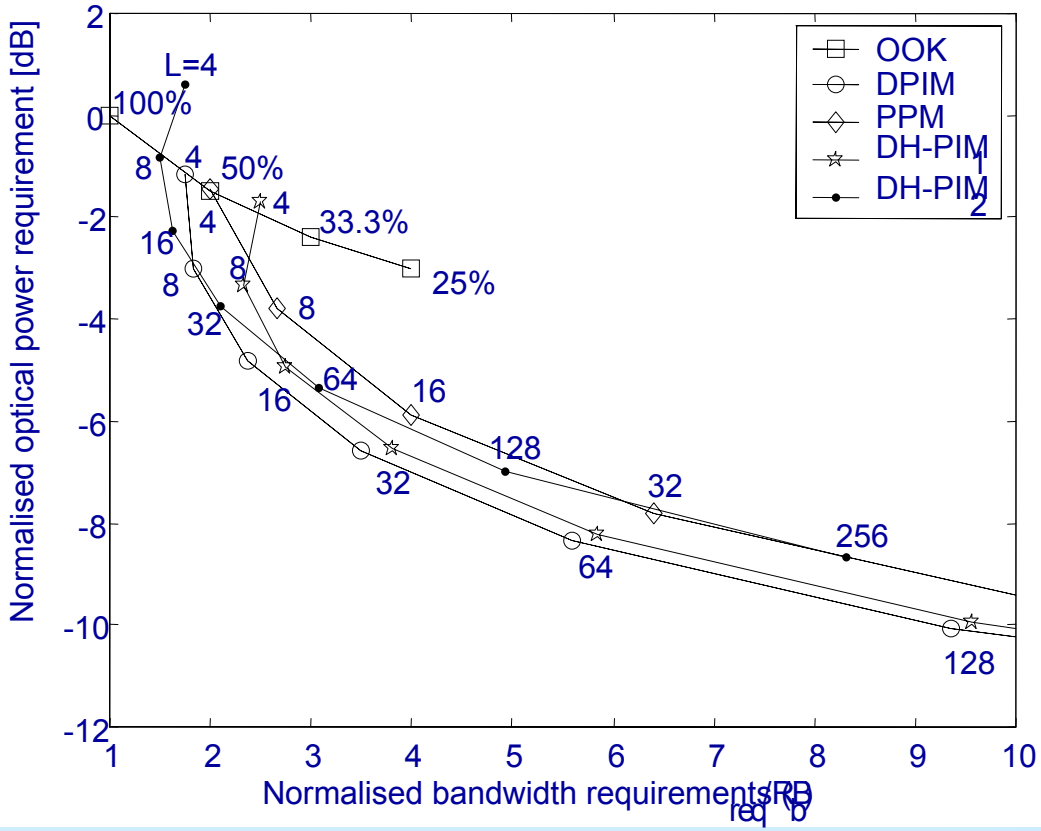
$$PER = 1 - \left(1 - P_{e,s(NGS)}\right)^{L_{avg} D / \log_2}$$



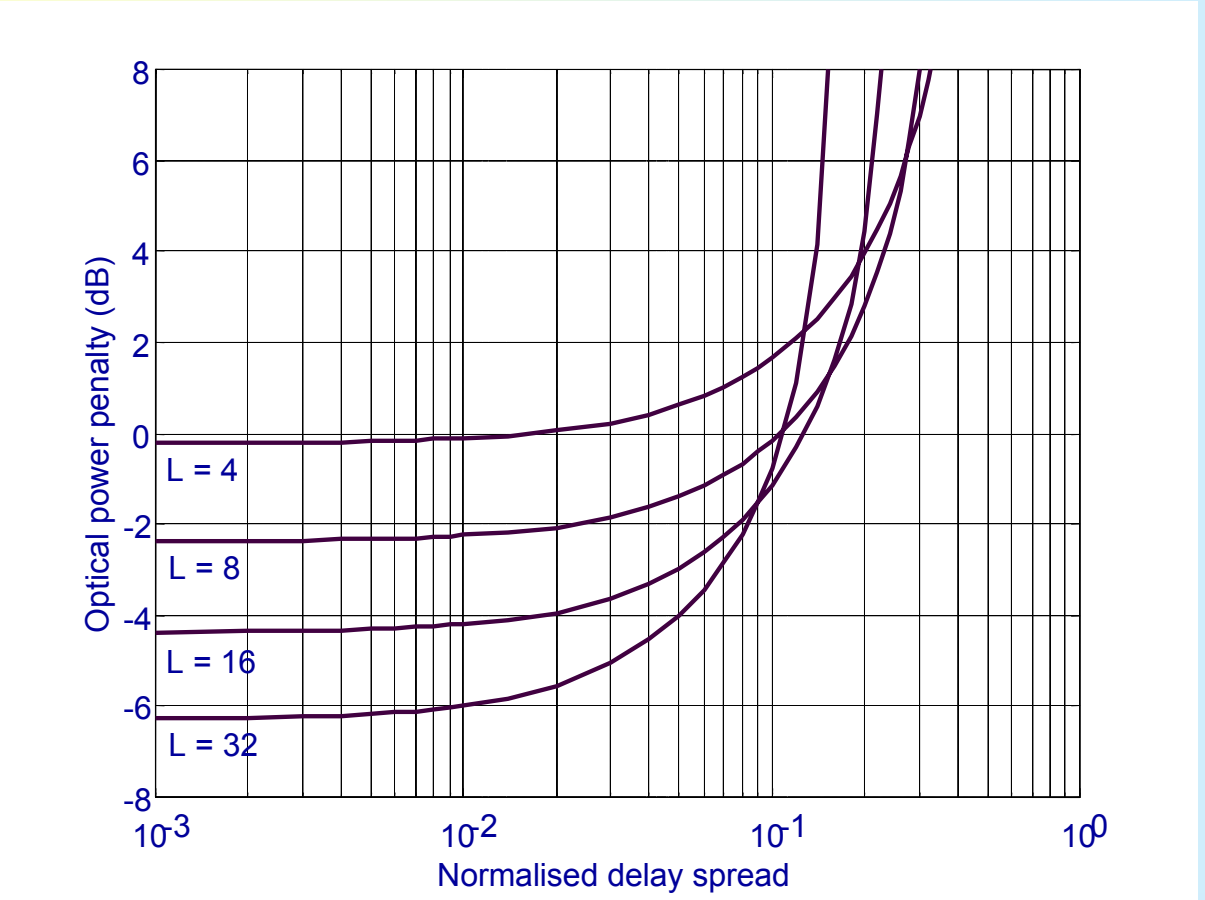
Z. Ghassemlooy 2006

Optical Power Requirement Vs. Bandwidth

- Average optical power requirement normalised to that required by OOK-NRZ to achieve a PER of 10^{-6} for packet lengths of 1 kbyte, on a channel limited by AWGN.
- Bandwidth requirement normalised to OOK-NRZ.



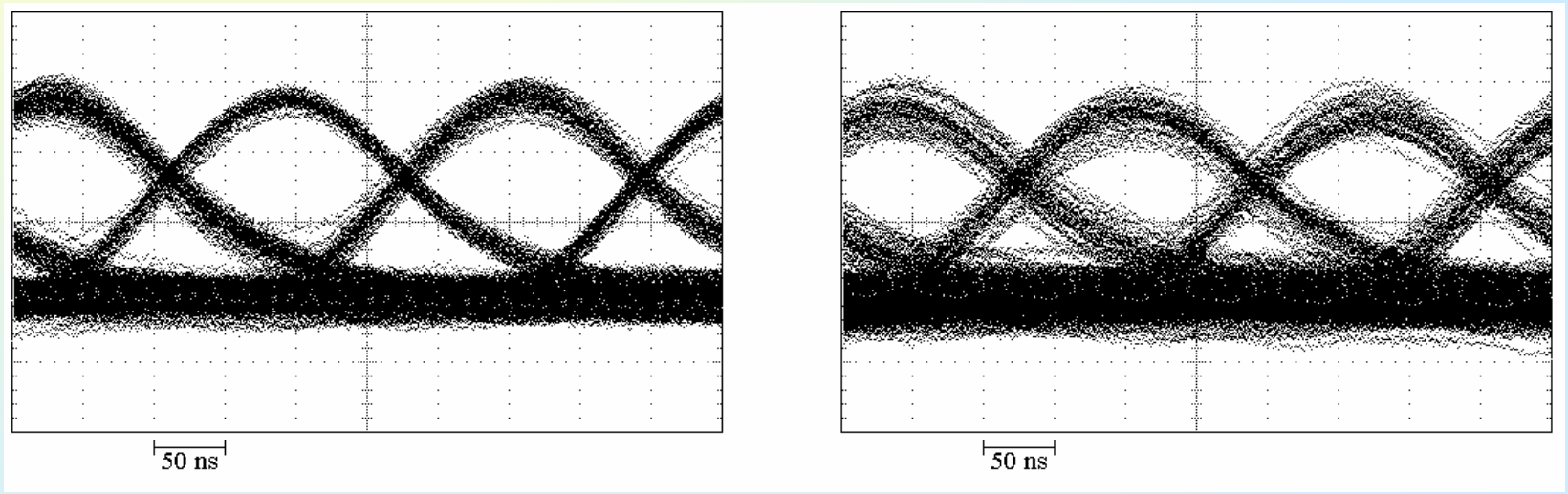
Optical Power Penalty vs. Normalised Delay



Average optical power penalty versus normalised delay spread for DPIM with no guard band

Z. Ghassemlooy 2006

Eye Diagram - Input to threshold Detector



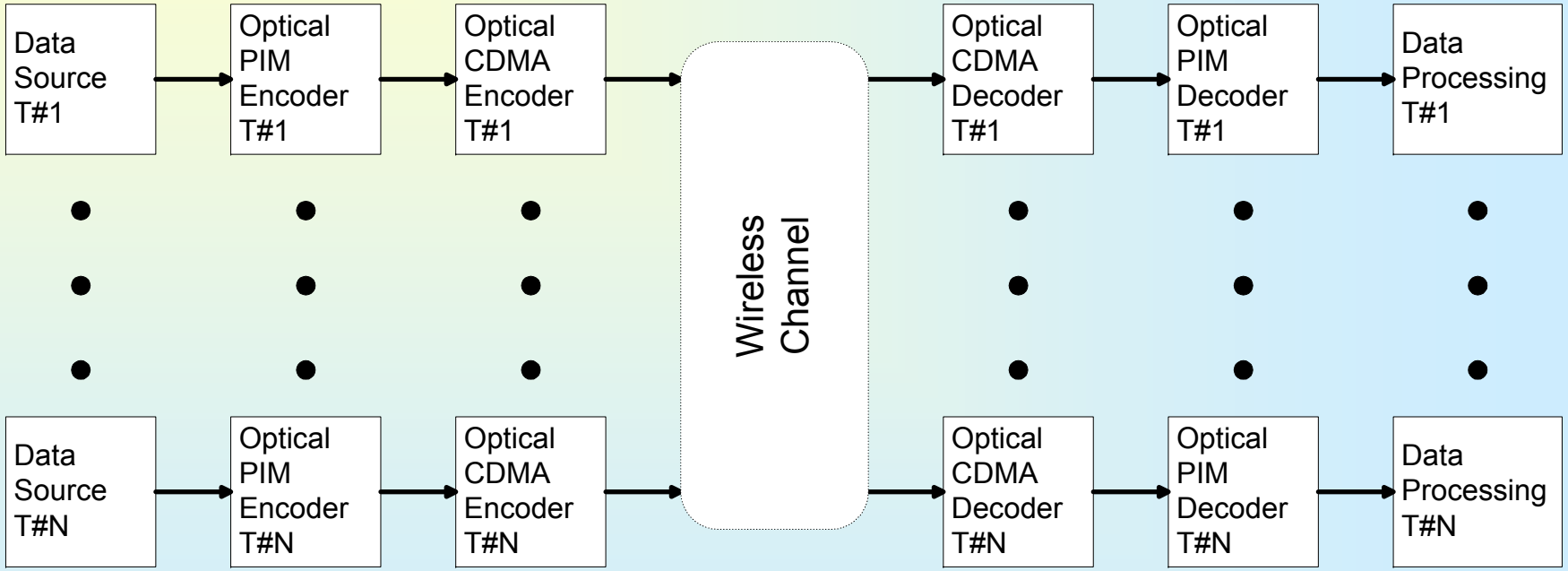
- 42 dBm/cm^2 - 49 dBm/cm^2

Ambient power = - 10 dBm/cm^2

Hybrid PTM-CDMA Schemes

Z. Ghassemlooy 2006

PIM-CDMA Optical Wireless Systems

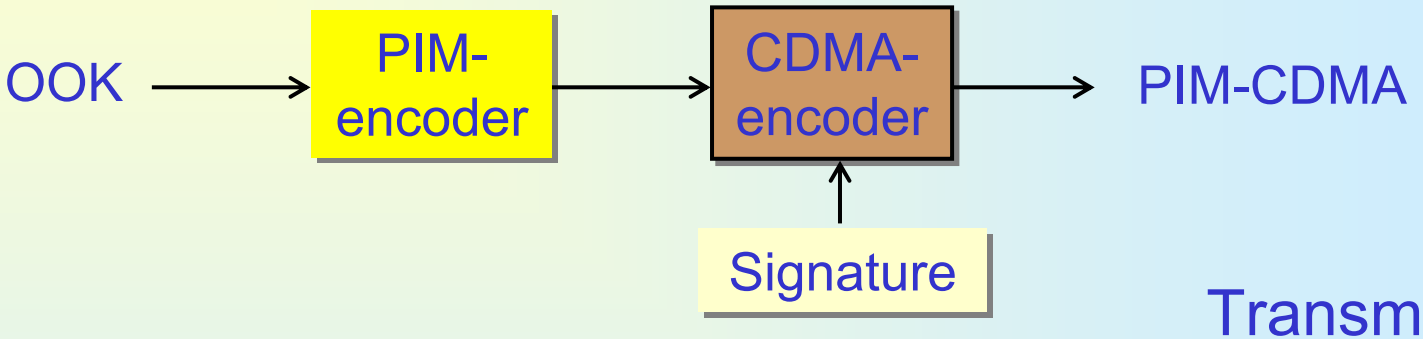


Advantages:

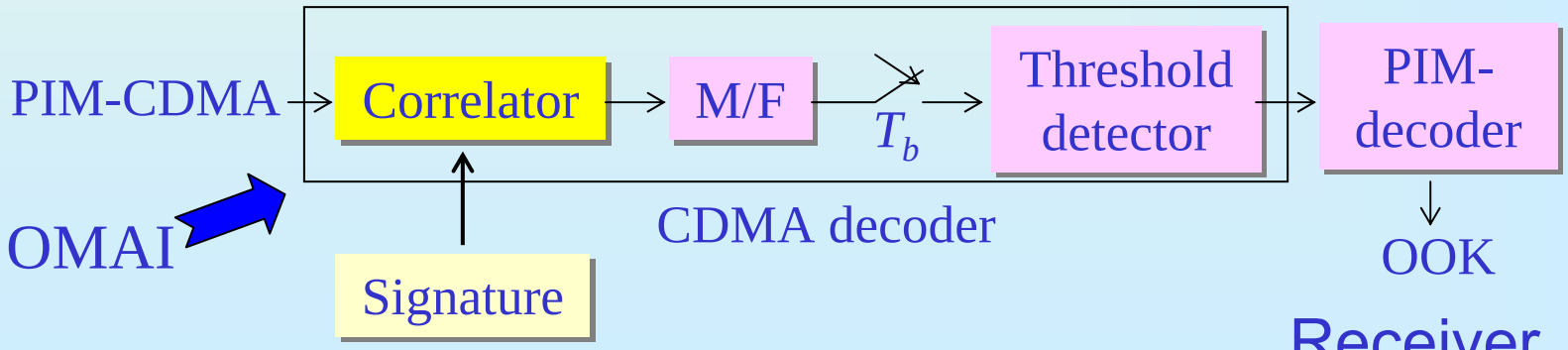
vs. TDMA: no “t” sync.

vs. WDMA: no “λ” management.

Hybrid PIM-CDMA

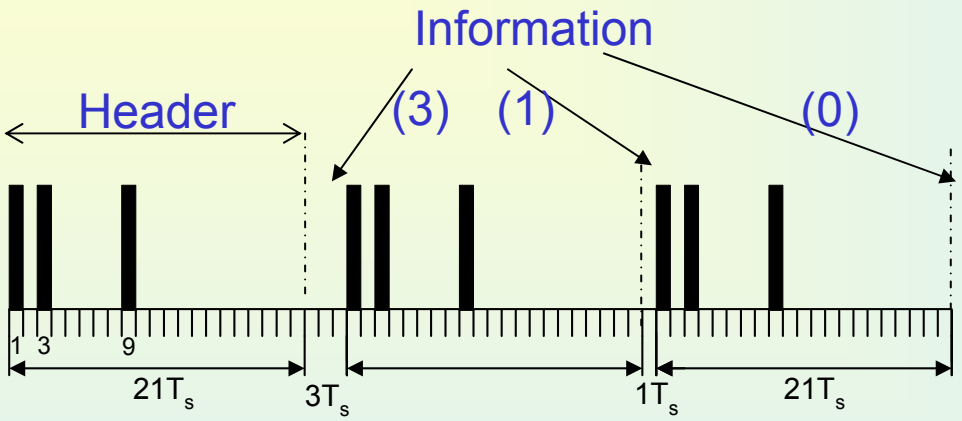


Transmitter

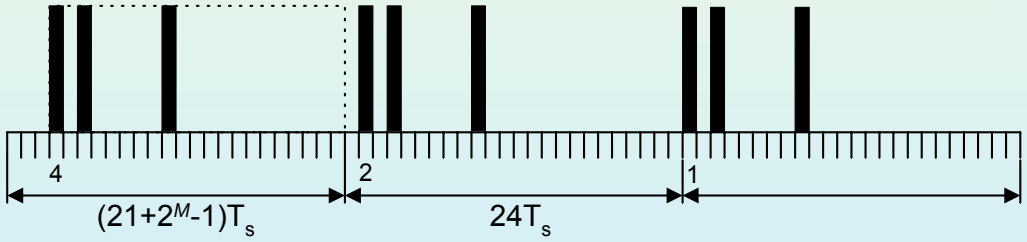


Receiver

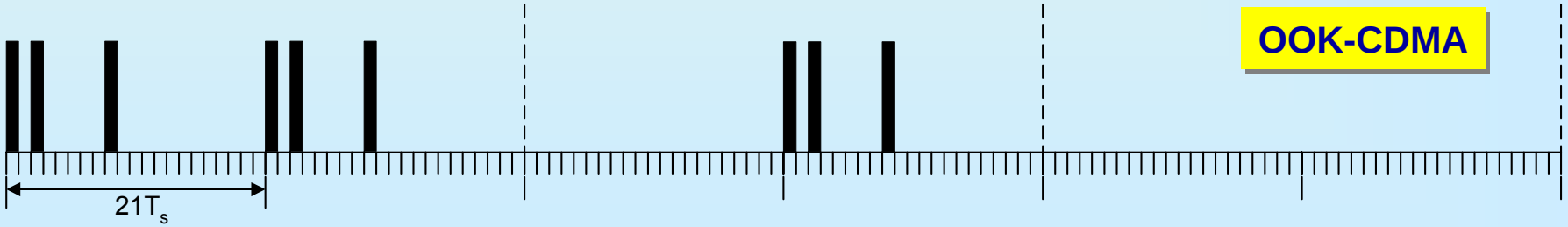
PIM-CDMA - Frame structures



Hybrid PIM-CDMA



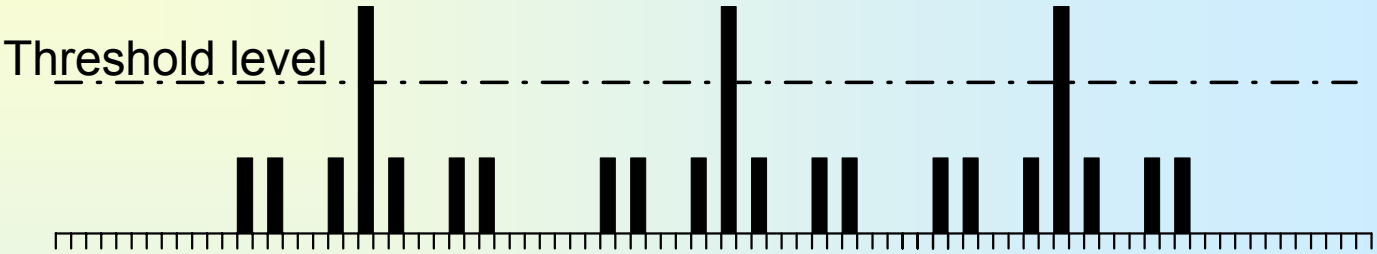
Hybrid PPM-CDMA



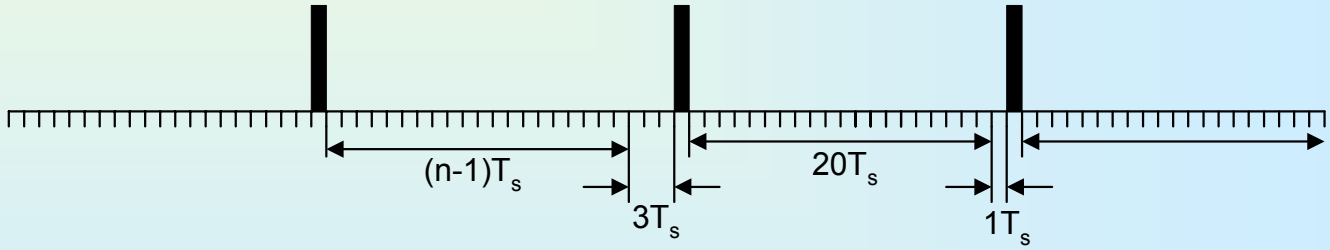
OOK-CDMA

PIM-CDMA - Decoder

Matched detector



PIM decoder



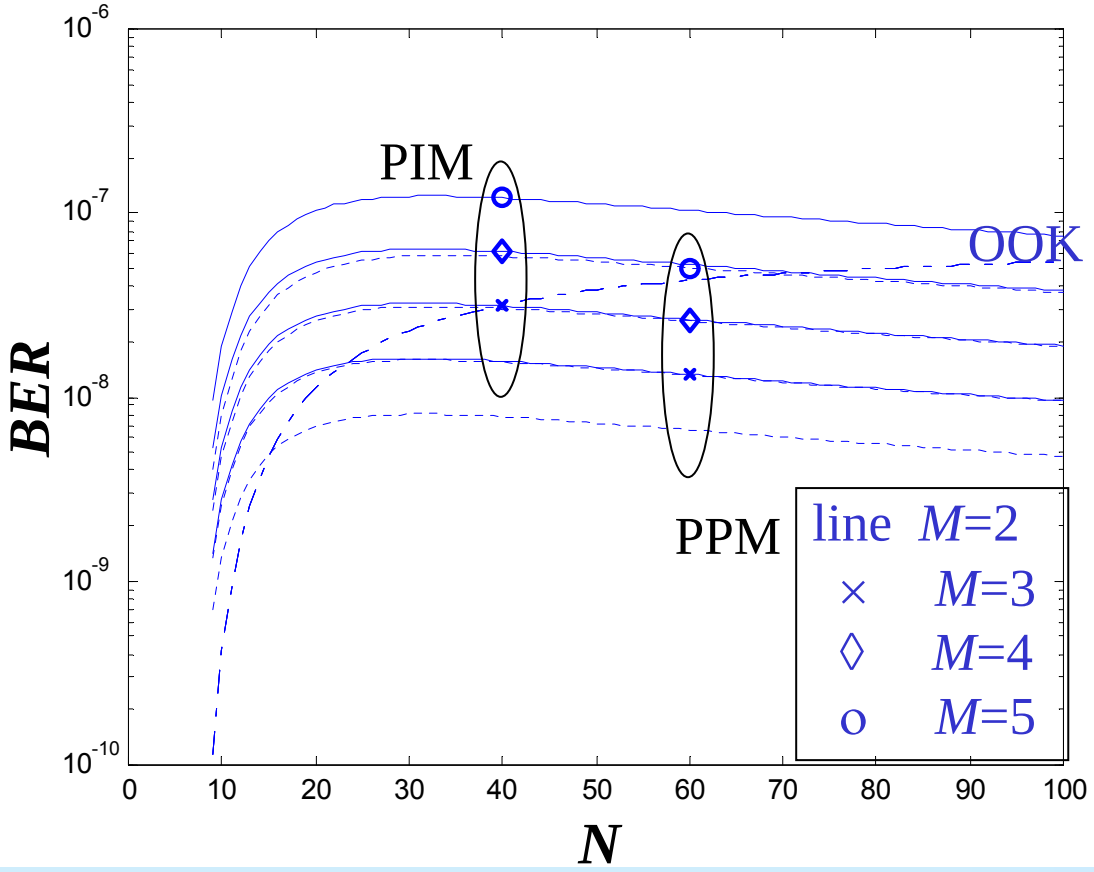
Decoding is done by:

- *Detect the pulse*
- *Ignore n-1time slots*
- *Count time slots until the next pulse*

PIM-CDMA - BER Performance

$$P_{f|PIM} = P_{self} + P_{OMAI}$$

$$P_b = \left(2^M / 2\left(2^M - 1\right)\right) P_{f|PIM}$$



Final Remarks

- Could the promise of optical wireless live up to reality?
  - **Yes!!**
- But
  - Optical wireless must complement radio, not compete
  - Industry must be bold in research and development
  - Lower component cost, and single technology based deviced
  - Integration with existing systems
  - Lover receiver sensitivity
  - *Of course* **more research and development at all levels**

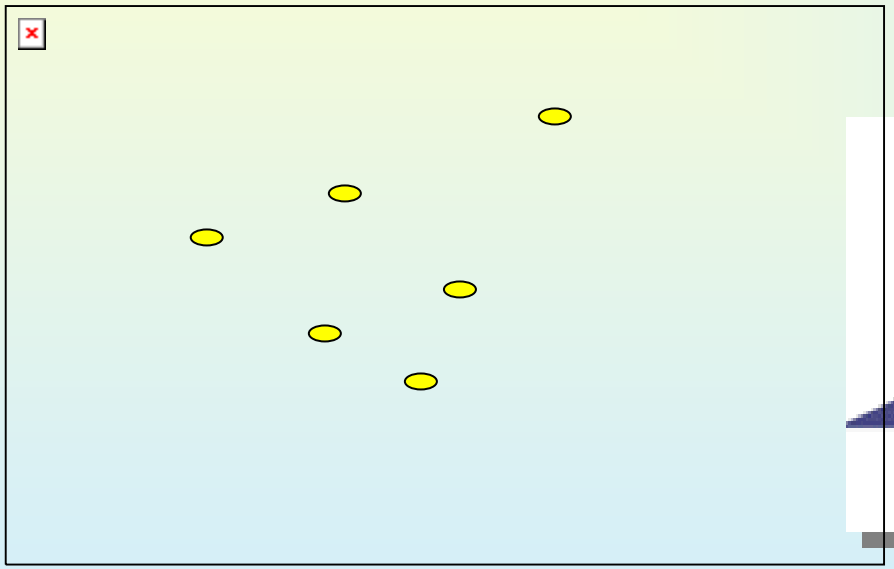
Acknowledgements

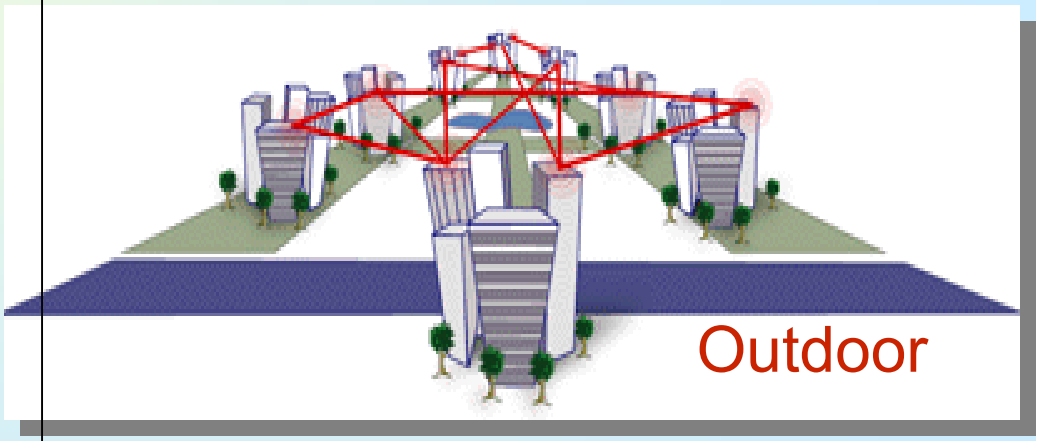
- To many colleagues national and international and in particular to all my MSc and PhD students (past and present) and post-doctoral research fellows

Thank you.

Solution to the Last Mile & Indoor– Optical Wireless

- RF Wireless
- **Optical (Infrared) Wireless**

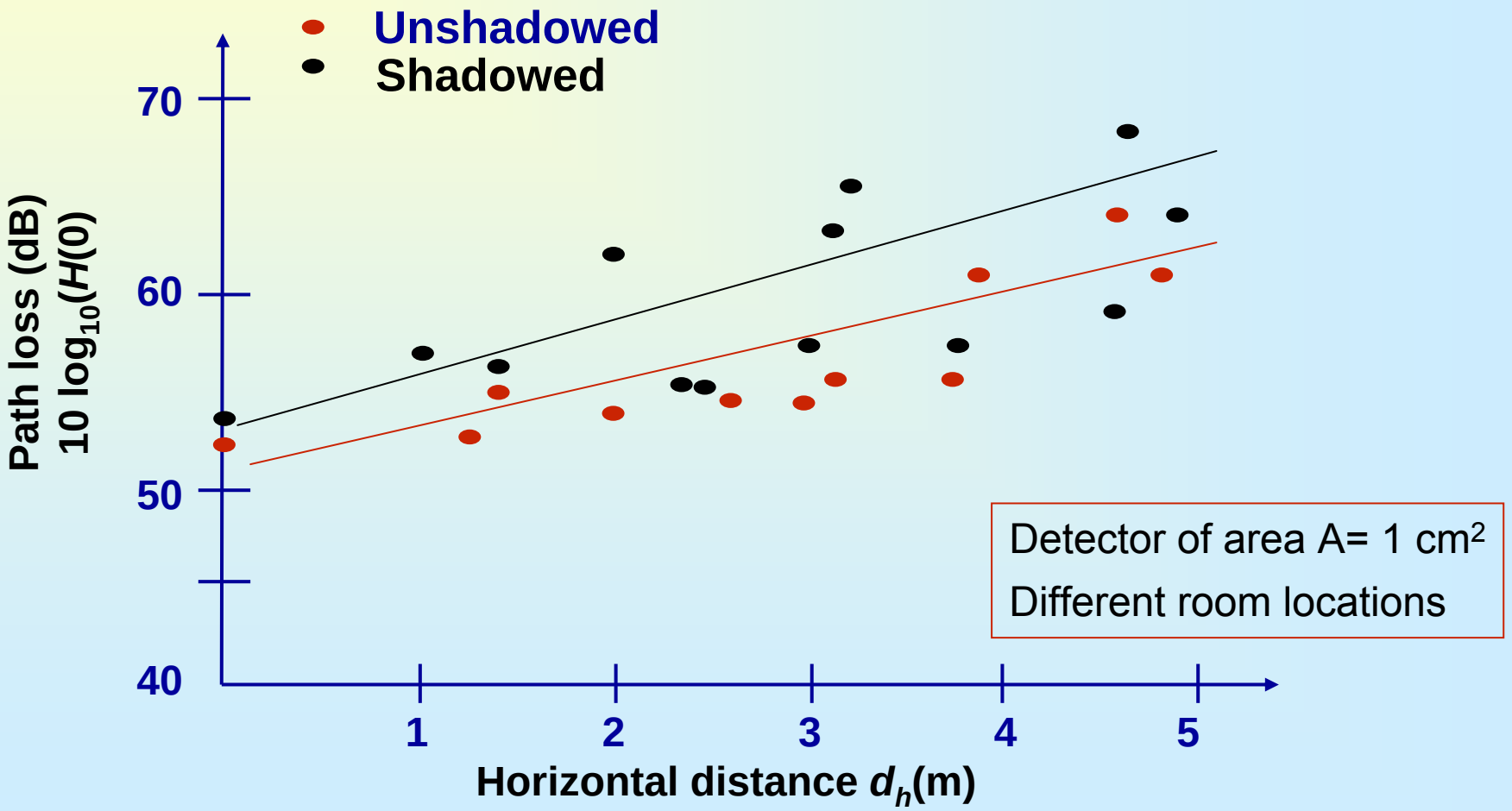




- To replace existing copper cables
- Well suited for dense urban environments
- Rapid insulation
- Low cost

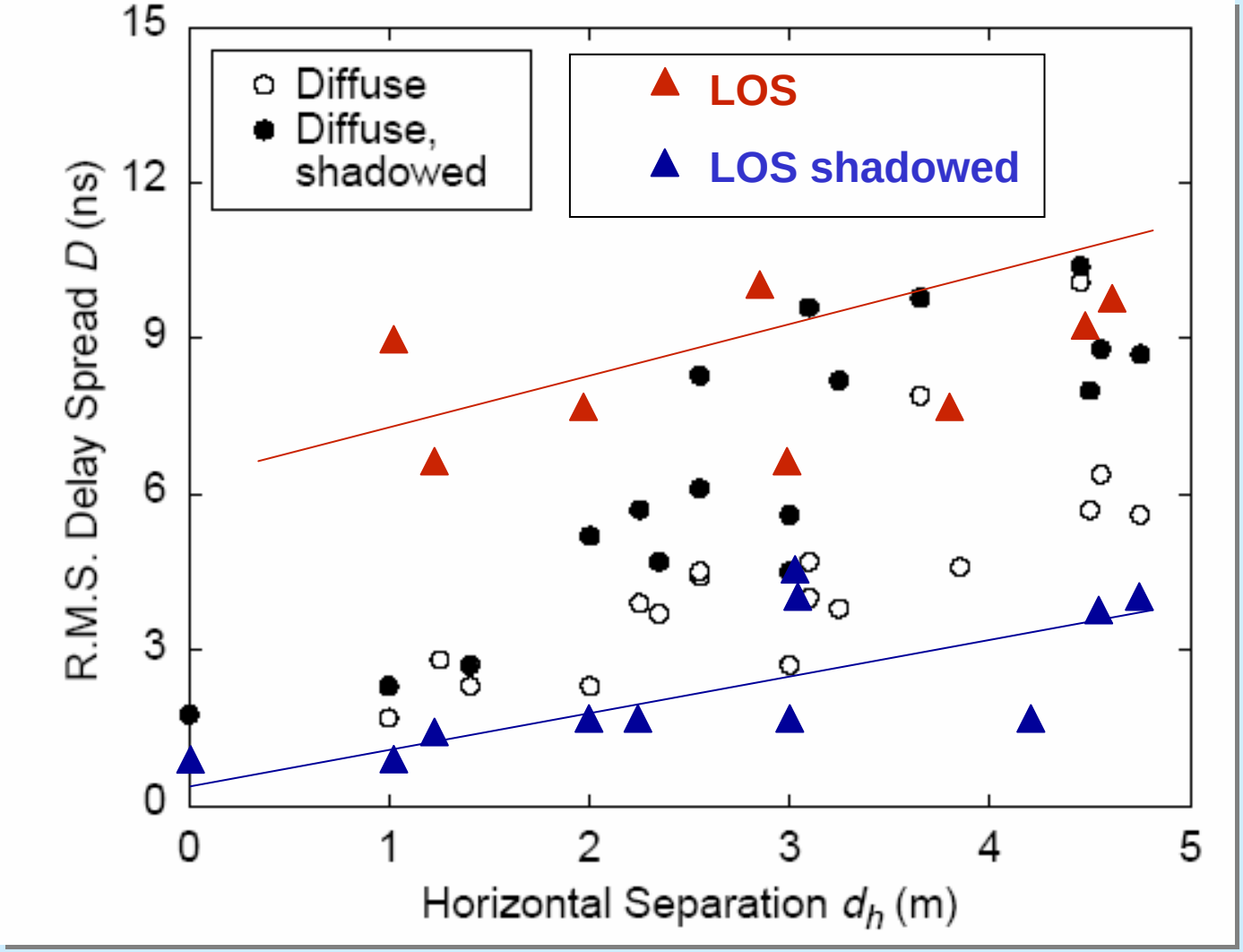
Z. Ghassemlooy 2006

Optical Path Loss of a Diffuse Links



Z. Ghassemlooy 2006

Root-Mean-Square Delay Spreads



Z. Ghassemlooy 2006

OWC System Block Diagram

