Visible Light Communications

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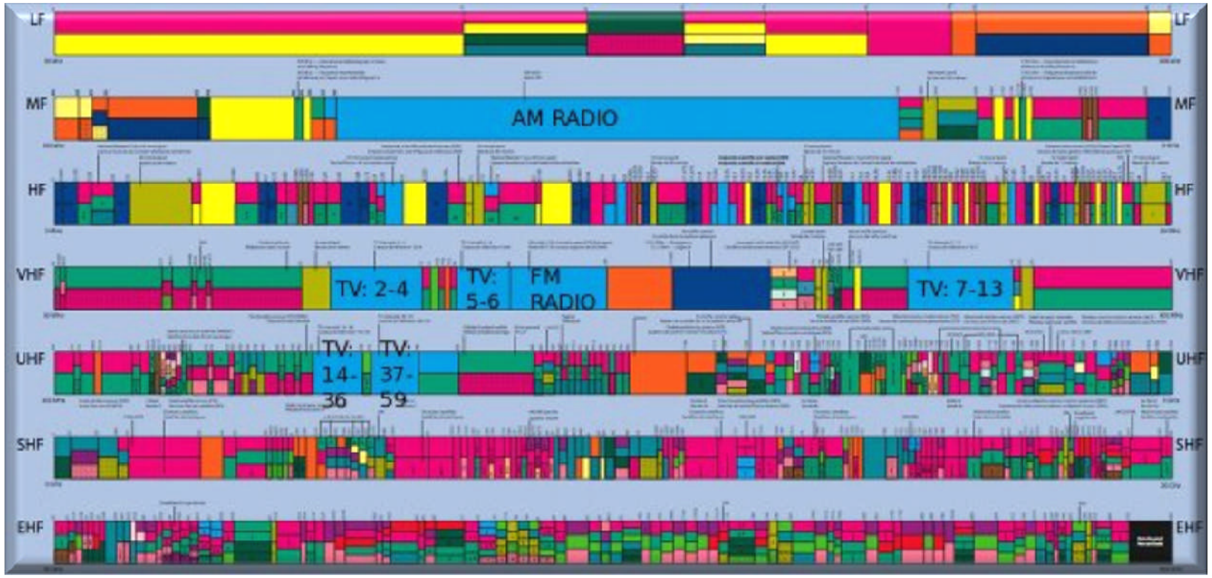
http://soe.northumbria.ac.uk/ocr/

Presentation Outline

- Visible Light Communications
- Light Sources
  - Light Emitting Diode
  - Organic Light Emitting Diode
- Equalisation
- Results
- Summary

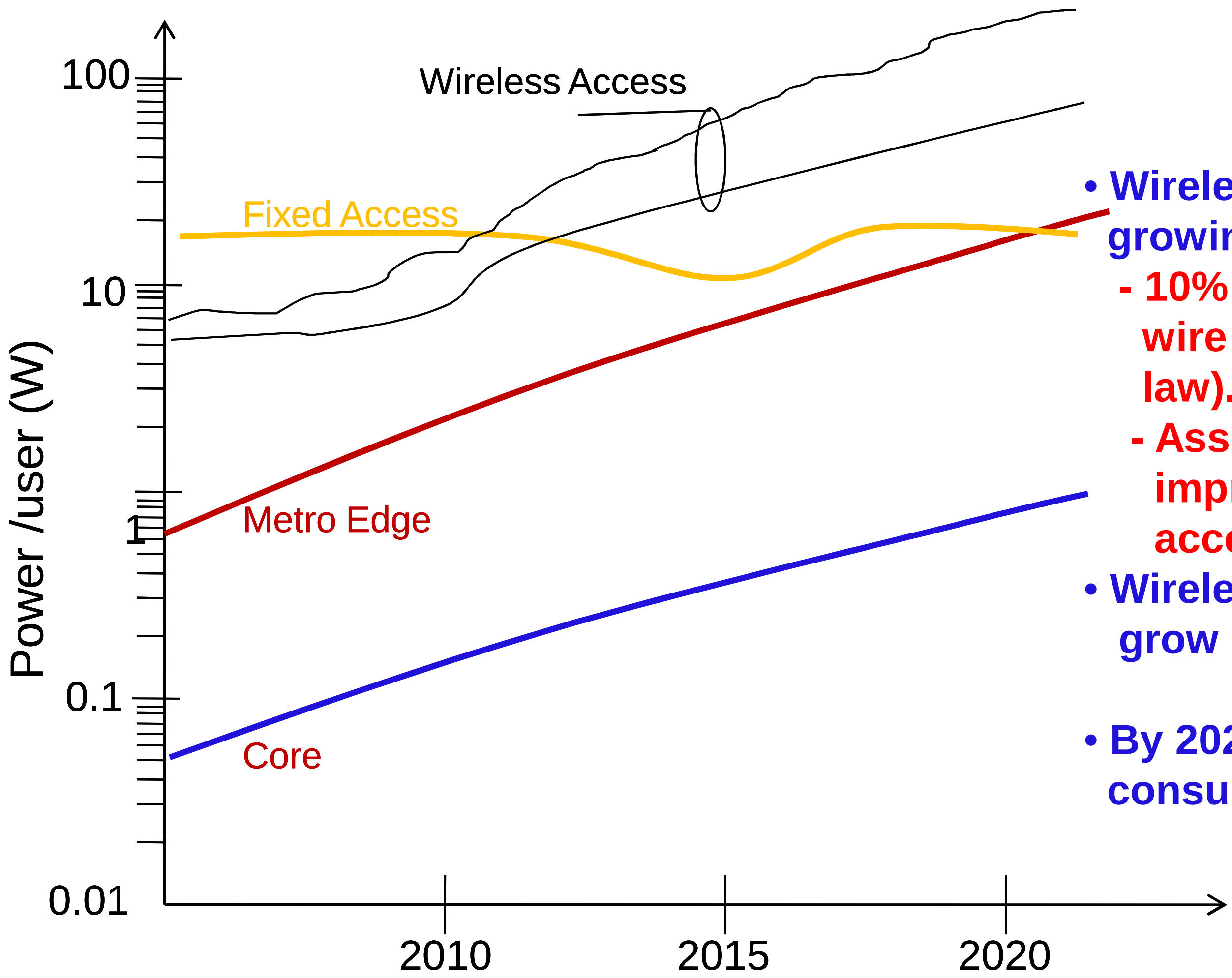
What is the Problem? Radio Spectrum Famine



- Smart phones - we used them to:
  - Stream YouTube, Facebook videos
  - watch TV
  - download and store music and movies
  - photos
  - books
  - games
  - and sometimes talk to each other

- Consume radio bandwidth
- We are already feeling the pinch

What is the Problem? Network Power Usage



Bell Labs Analysis

- **Wireless (RF) data is a rapidly growing problem:**
  - **10% per year improvement in wire line equip. efficiency (Moore's law).**
  - **Assumes 9% per year improvement in wireless (RF) access.**
- **Wireless RF access power could grow by a factor of 100 in 10 years.**
- **By 2020 wireless RF access power consumption dominates network.**

northumbria UNIVERSITY

OCRG

Access Network Technology

xDSL

- Copper based (**limited bandwidth**) - Phone and data combine
- Availability, quality and data rate depend on service provider

RF

- Spectrum congestion (license needed to reduce interference)
- Security worries (encryption?)
- Lower bandwidth than optical bandwidth
- At higher frequencies atmospheric conditions attenuation (rain) /absorption (oxygen gas) limits link to ~1km

frequency bands: 7, 18, 23, 35, 60, 66 GHz

Cable

- Shared network resulting in quality and security issues
- Low data rate during peak times

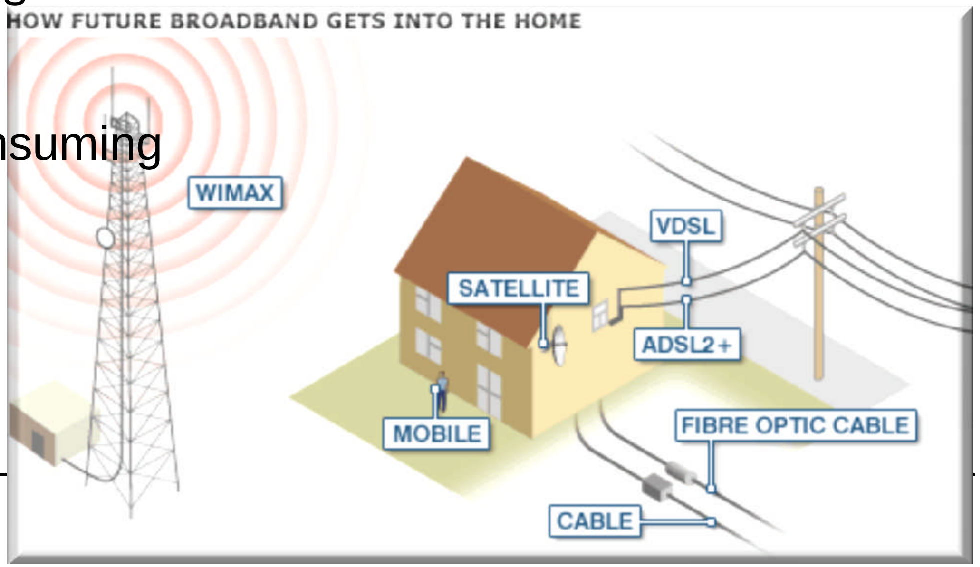
FTTH

- 100 Mb/s, but Costly
- Right of way required - time consuming

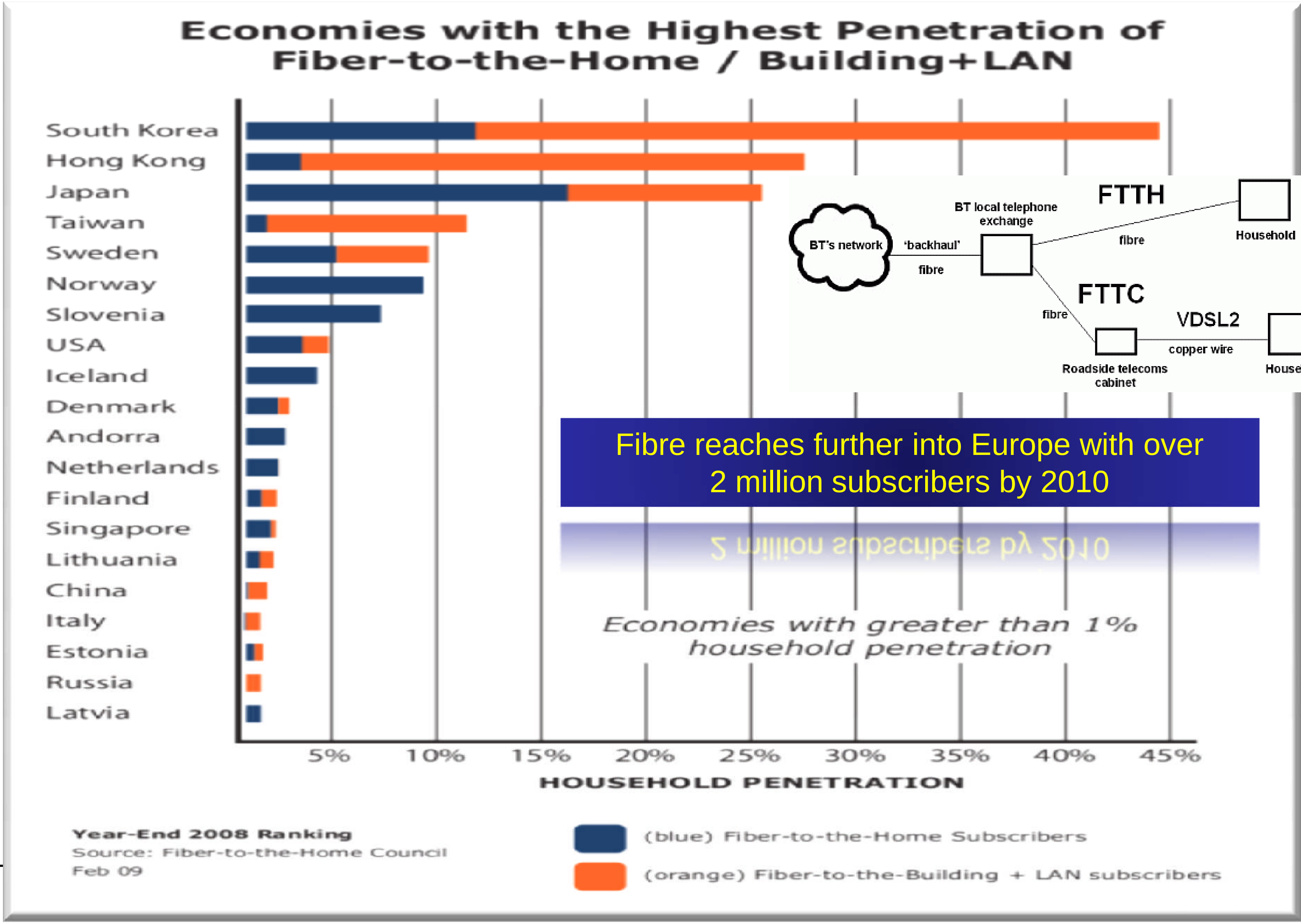
Satellite

- Expensive
- Limited bandwidth

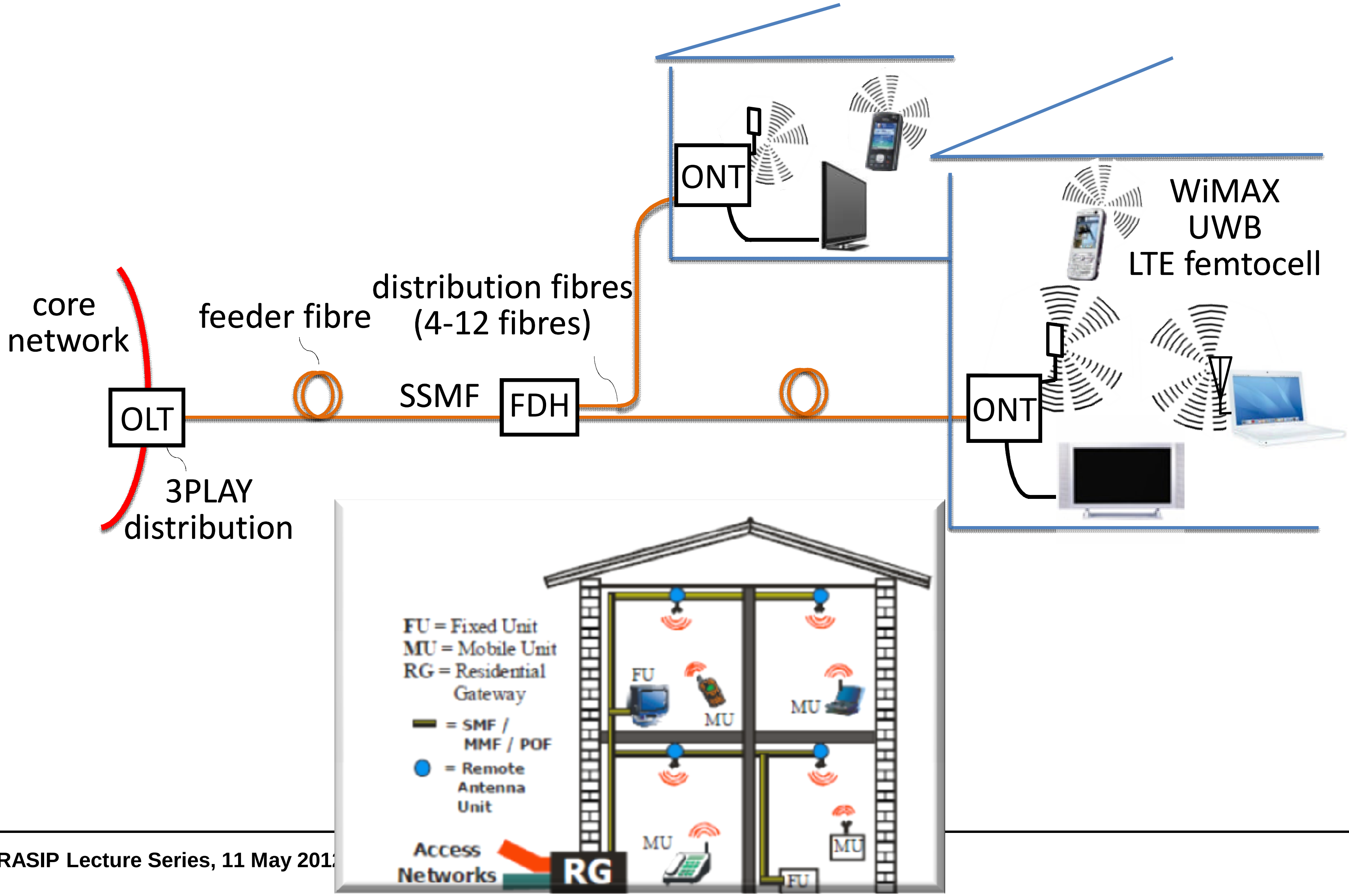
OWC



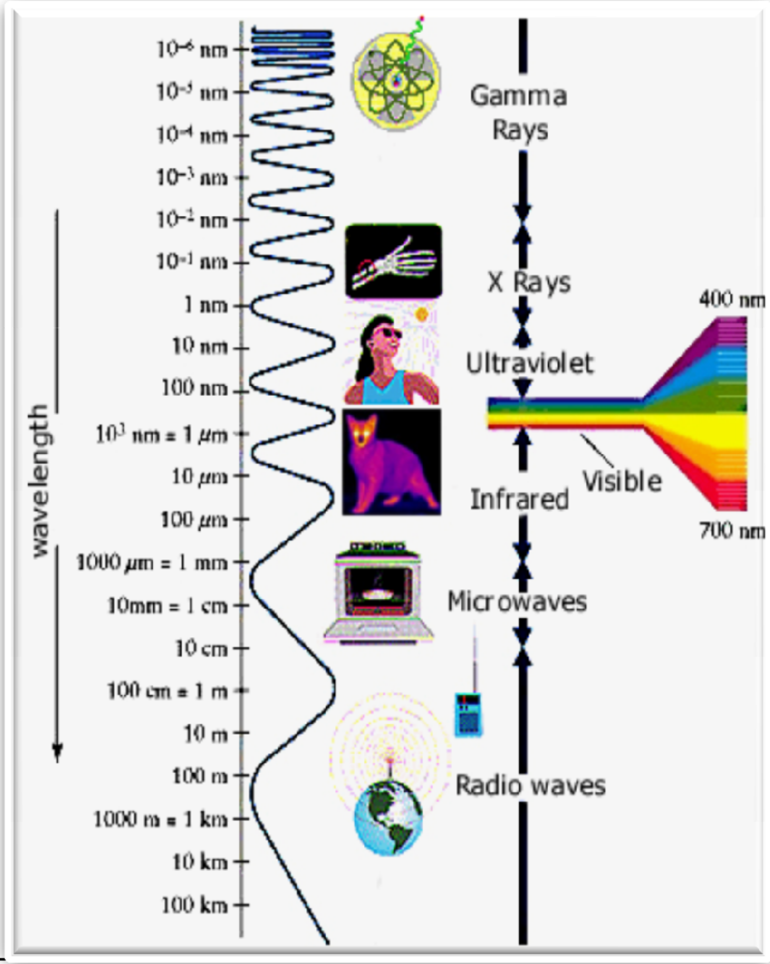
Access Network Technology - FTTH



Access Network Technology – Radio over Fibre



What is the Solution? Transmission by Light



- **Unregulated bandwidth (>540 THz), when and where needed.**
- **Over the last 20 years deployment of optical fibre cables in the backbone and metro networks have made huge bandwidth readily available to within one mile of businesses/home in most places.**

***But*, HUGE BANDWIDTH IS STILL NOT AVAILABLE TO THE END USERS.**

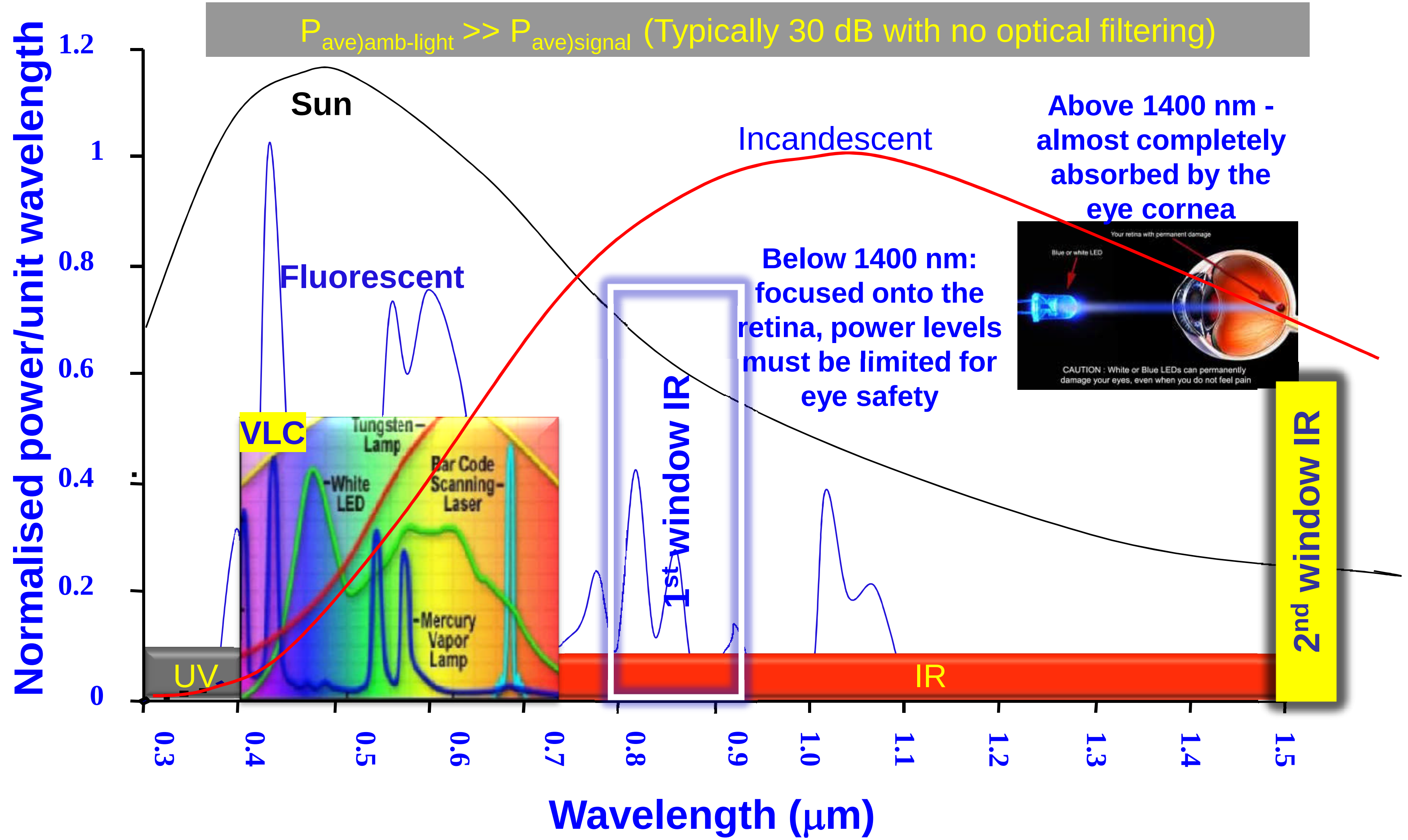
Optical Wireless Communications

Sunlight reflection

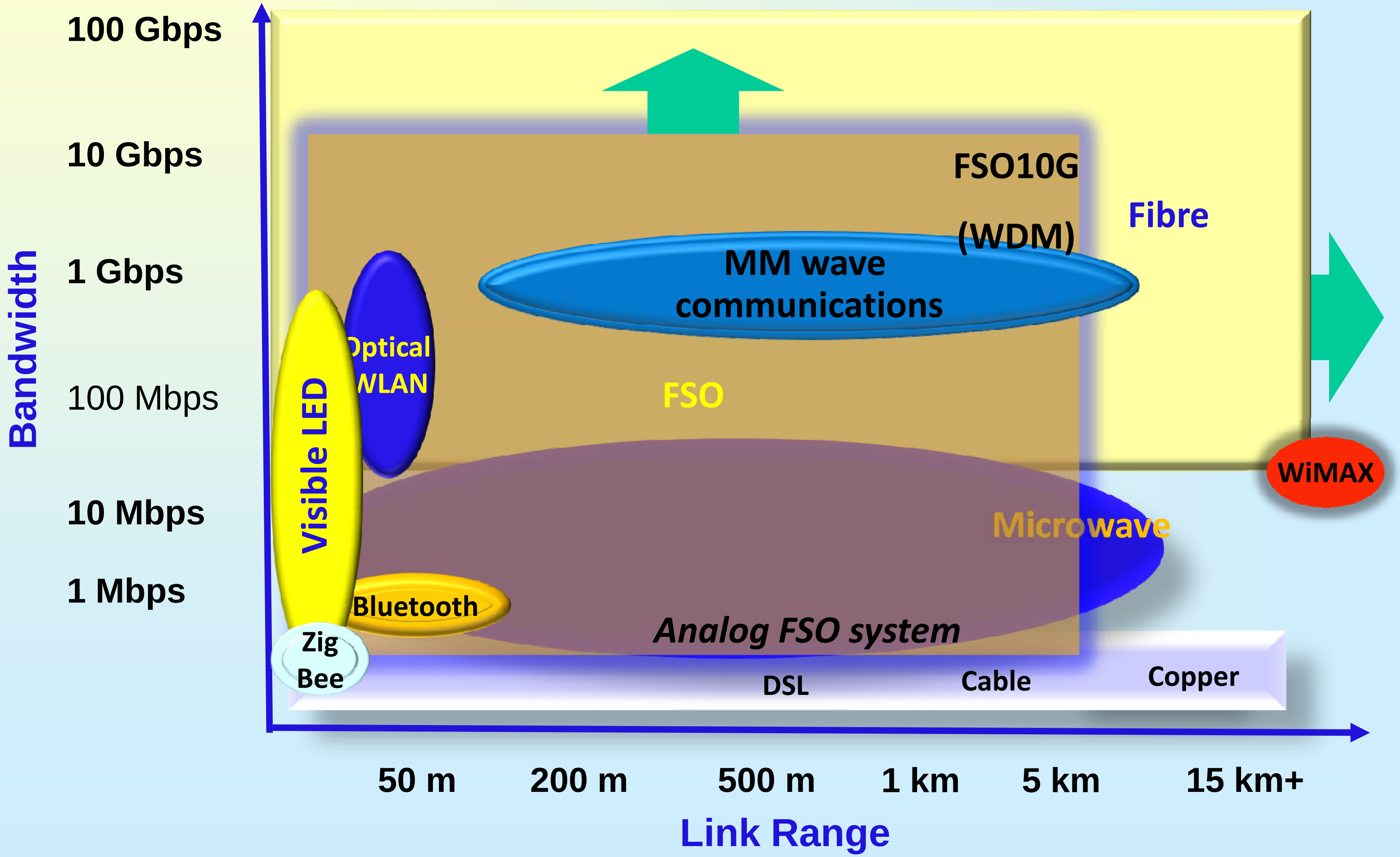
Flame

Source: Discovery Channel

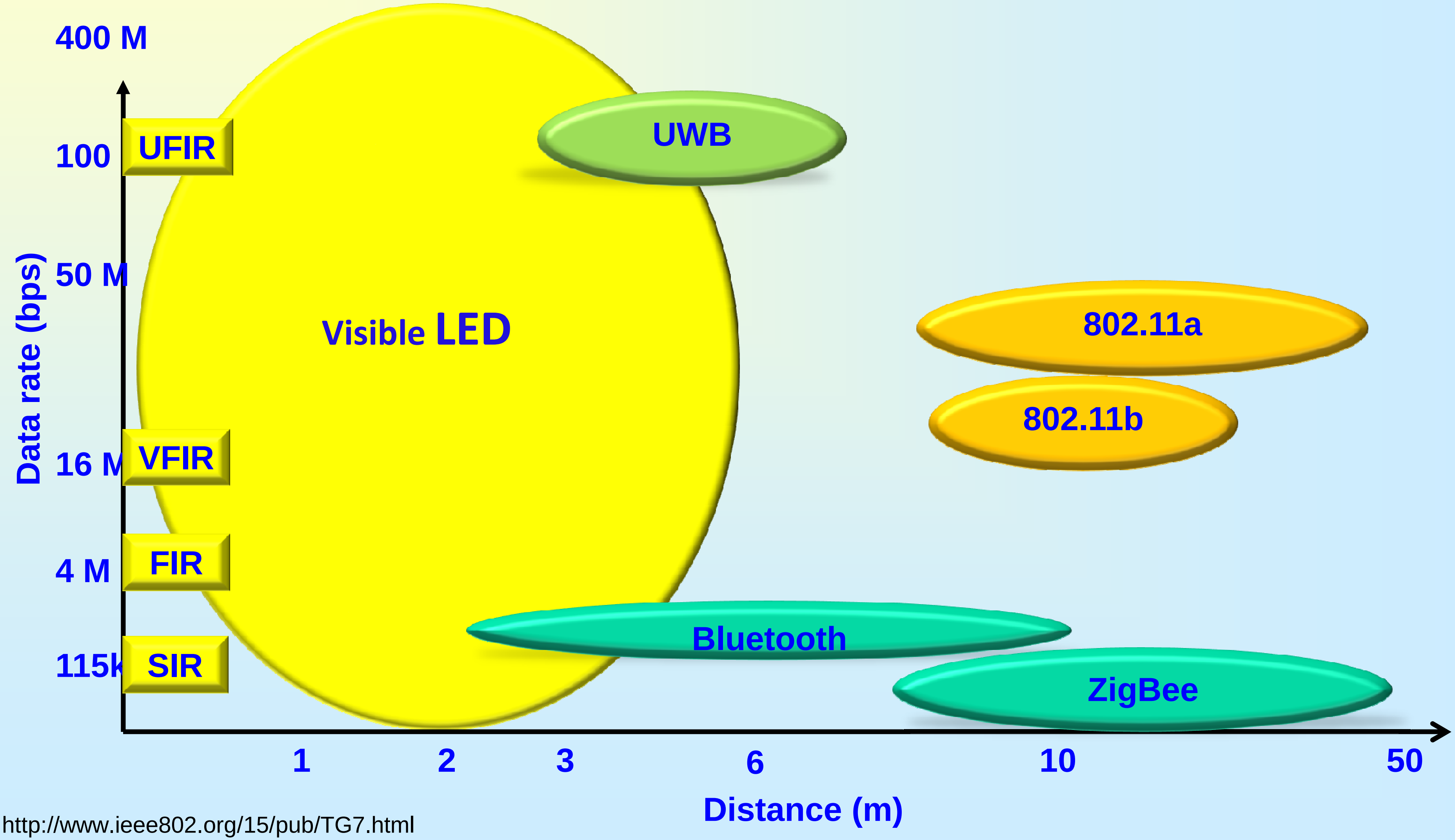
OWC - Transmission Windows



Wireless – Technology and Standards



Wireless – Technology and Standards



http://www.ieee802.org/15/pub/TG7.html

Visible Light Communications

- Features
  - Energy efficiency
  - Secured data communications
  - No electromagnetic interference
  - Beam radiation directivity
  - Green communications
- Added Value: Communications

VLC- When Did It All Start?

2003 The Visible Light Communications Consortium (VLCC) – *Japan*

2008 "hOME Gigabit Access" (OMEGA) Project – *EU -* **Develop global standards for home networking (infrared and VLC technologies).**

2009 IEEE802.15.7 - *Call for Contributions on IEEE802.15.7 VLC.*

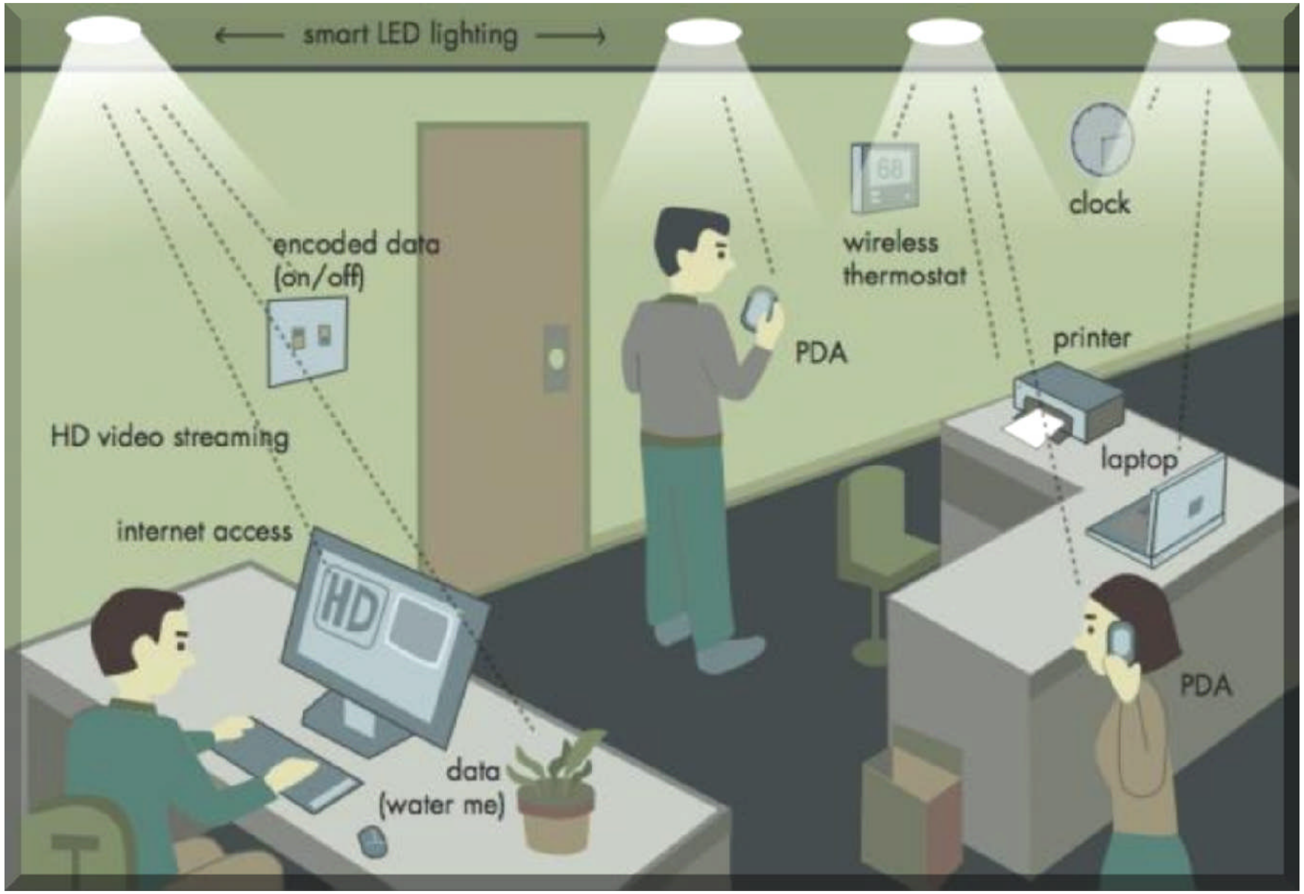
2011 Organic VLC – *Northumbria University*

VLC Applications

- **Airport & Station**
  - Information for departure and arrival
  - signalling among, lighting infrastructure, ground vehicles and aircraft
- **Store Arcade**
  - Advertisement, electrical coupon
- **Signboard for illumination**
  - Active advertisement, Menu
- **Signal Lamp & Mobile**
  - Transportation information
- **Cafe/Home/Office**
  - Internet, Home A/V network
- **Aircraft & Hospital**
  - Non-RF communication, Video

OW Apps: Broadband VLC

Indoor broadband broadcasting in Hospital / Supermarket / University / Office



Source:
Boston University

VLC: Consortium (1/2)

- Established in 2003 by Japanese companies
- Aims to standardize VLC Technology
- Two standards proposed
  - JEITA CP-1221
    - VLC systems (380 – 750 nm)
    - Range accuracy of 1 nm
    - Subcarrier modulation
    - Range 1: 15 kHz- 40 kHz – Data communications
    - Range 2: 40 kHz – 1 MHz – Fluorescent light cannot use this range, too slow and generate too much noise
    - Range 3: > 1 MHz – only for data transmission with special LEDs

Japan Electronics and Information Technology Industries Association

VLC: Consortium (2/2)

- Two standards proposed
  - JEITA CP-1222 – VL ID systems
    - Subcarrier frequency: 28.8 kHz
    - Transmission rate: 4.8 kbps
    - Modulation: SC-4PPM
    - Cyclic redundancy checks (CRC) for error detection/correction
- IEEE 802.15, Task Group 7 – Physical and media access layer

VLC: Technology

- Every kind of light source could be used
- LEDs are the preferred option

  - Up to 40 Mbps - Phosphorus LEDs can achieve up to 40 Mbps
  - Up to 100 Mbps - RGB LEDs
  - Up to 500 Mbps – Resonant cavity LEDs
    - *Use Bragg reflector (serving as a mirrors) to enhance the emitted light*
    - *Offer spectral purity compared to conventional LEDs*
  - Are energy efficient

- Receivers:
  - Photodiodes
  - CCD and CMOS sensors

Research in VLC

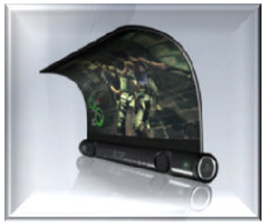
- VLCC - Casio, NEC, Panasonic Electric Works, Samsung, Sharp, Toshiba, NTT, Docomo
- OMEGA - EU Framework 7
- IEEE 802.15 Wireless Personal Area Network standards
- Many Universities: Boston (USA), Oxford, Edinburgh, Northumbria, Keio (JP), Wonkwang & Chosun (SK), H H Inst. (GER) + others
- Siemens
- France Telecom
- EU COST Action 1101 (2011 – 2015) – more than 20 countries

General Lighting Sources

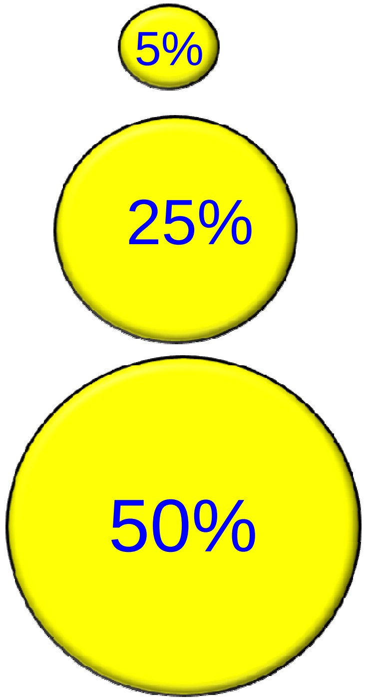
- Incandescent bulb
  - First industrial light source
  - 5% light, **95% heat**
  - Few thousand hours of life

- Fluorescent lamp
  - White light
  - 25% light
  - Lifetime ~10,000s hours

- Solid-state light emitting diode (LED)
  - Compact
  - 50% light
  - More than 50,000 hours lifespan

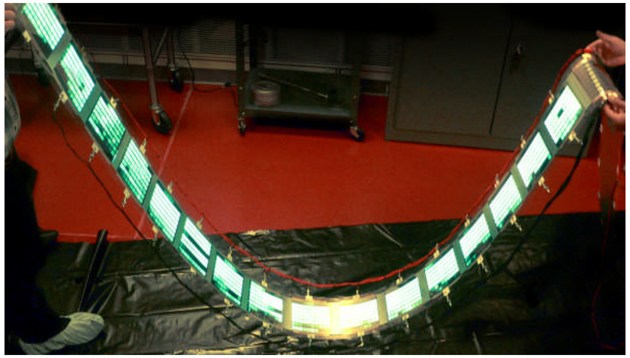


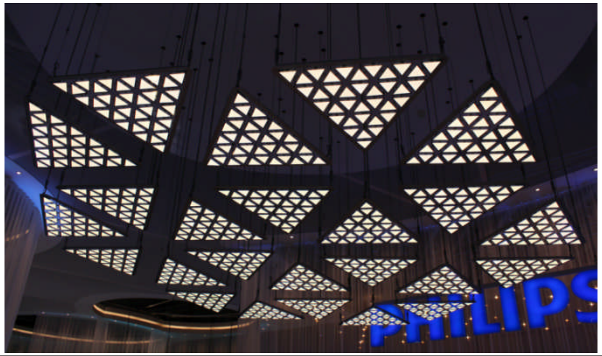
- Organic light emitting diode (OLED)



Organic LED – State of the Art

- Invented by **Kodak** in the 1980s
- Intended for use in screens (brighter, thinner, faster, lighter and less power consumption than LCDs)
- Produced in large panels that illuminate a broad area.
- Can be flexible with the relevant plastic substrate (create different shape)
- 100% internal quantum efficiency (Fraunhofer IPMS – COMEDD, 2012)
- Brightness 2.000 cd/m², 5mm thickness (Verbatim Velve, 2012)
- 120 lumen (~table lamp) (Philip Lumiblade GL350, 2012)
- 80 lumen/watt with 20.000 hours of lifetime (LG, 2012)





Organic LED – Applications

High end **smartphone** display products: Super-AMOLED) (Samsung Galaxy S3 phone, 2012)

55 inch OLED HDTV (Samsung Electronics, 2012)

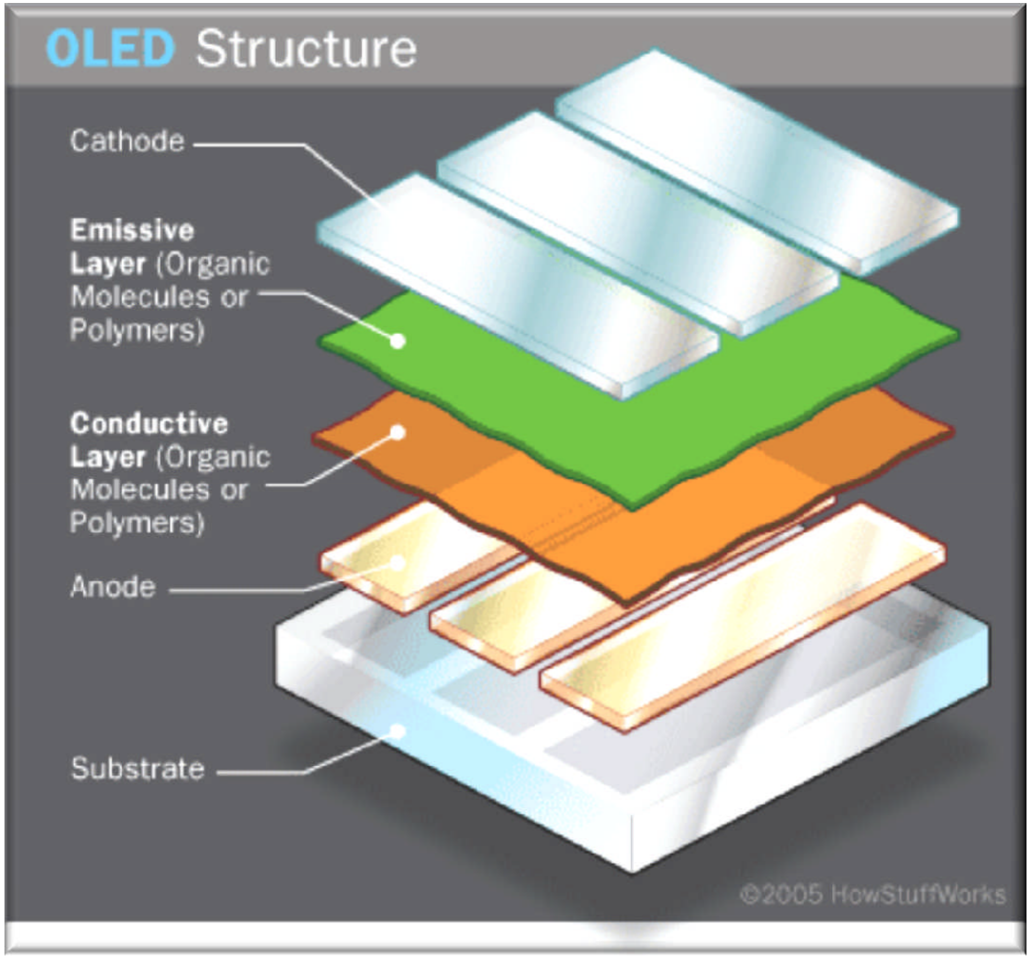
6 inch E-paper on plastic (XGA, 14 gram, 0.7mm thickness), (LG, 2012)

Solar OLED car (BASF, 2012)

Flexible AMOLED display (Samsung patent, 2012)

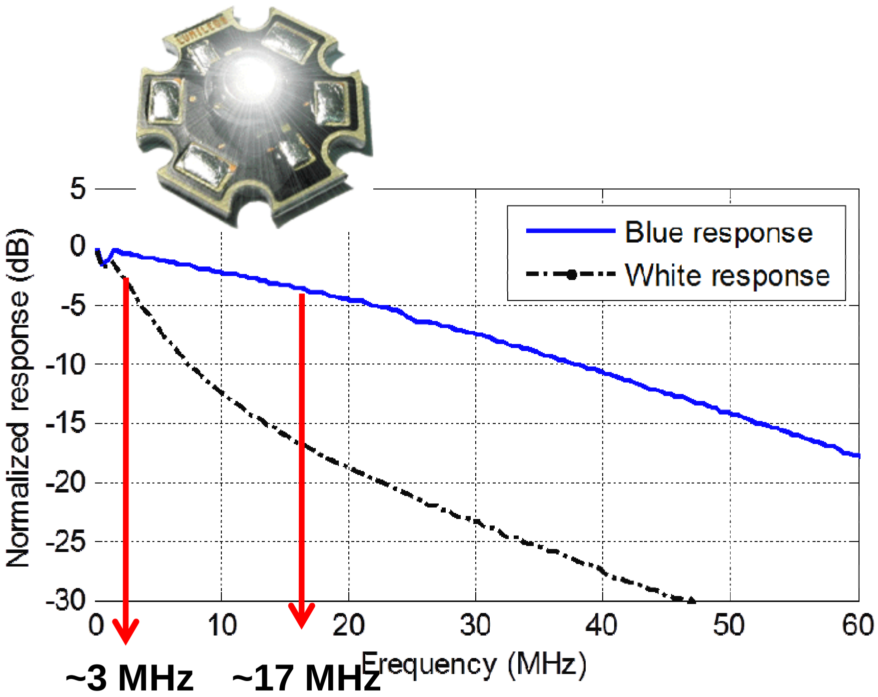
None of the commercial applications is for communications!

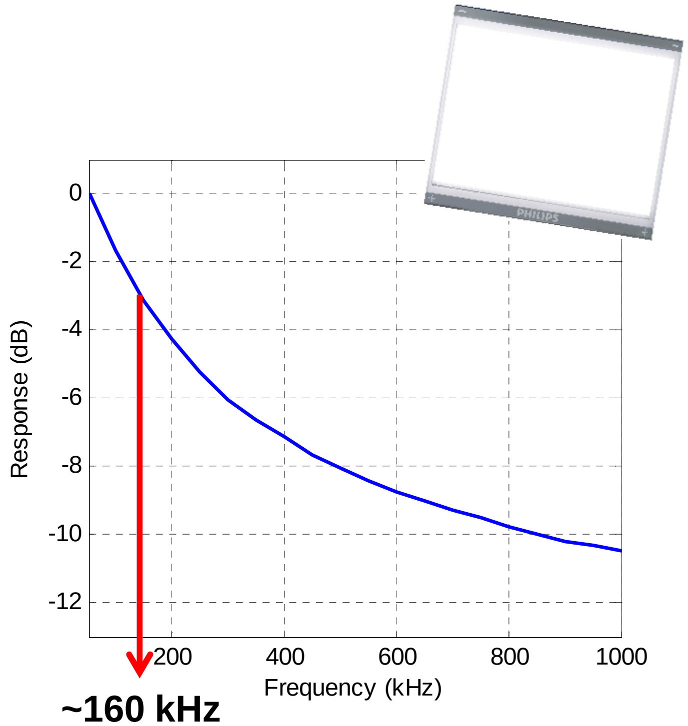
Device Structure - OLED



New technology, expensive and short life time. It is, however, has high potentials

Device Frequency Response





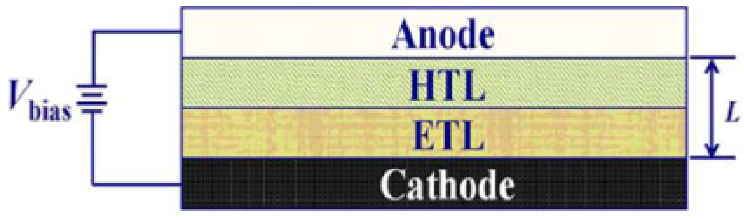
Measured frequency response of (Philips) Luxeon-star white LED

Measured frequency response of (Philips) Lumiblade white OLED

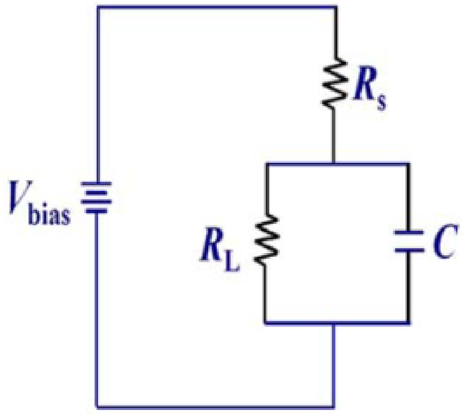
But OLED modulation bandwidth is much smaller than LED, due to the device size

How to improve the OLED bandwidth?

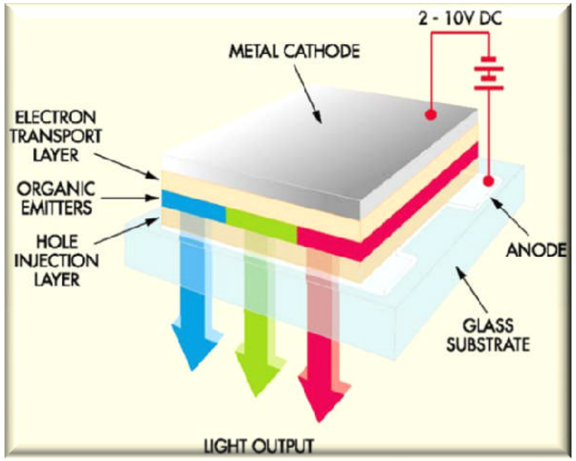
OLED - Electrical Characterisation



(a)



(b)



For lighting
Large panel → **better** for illumination
→ **larger capacitance**

$$C = \varepsilon_0 \varepsilon_r \frac{S}{L}$$

For communications
Larger capacitor value → **slow response**

ε_0 and ε_r are the permittivity of free space and dielectric constant of an organic molecule
L is the distance between two electrodes
S is the emitting area

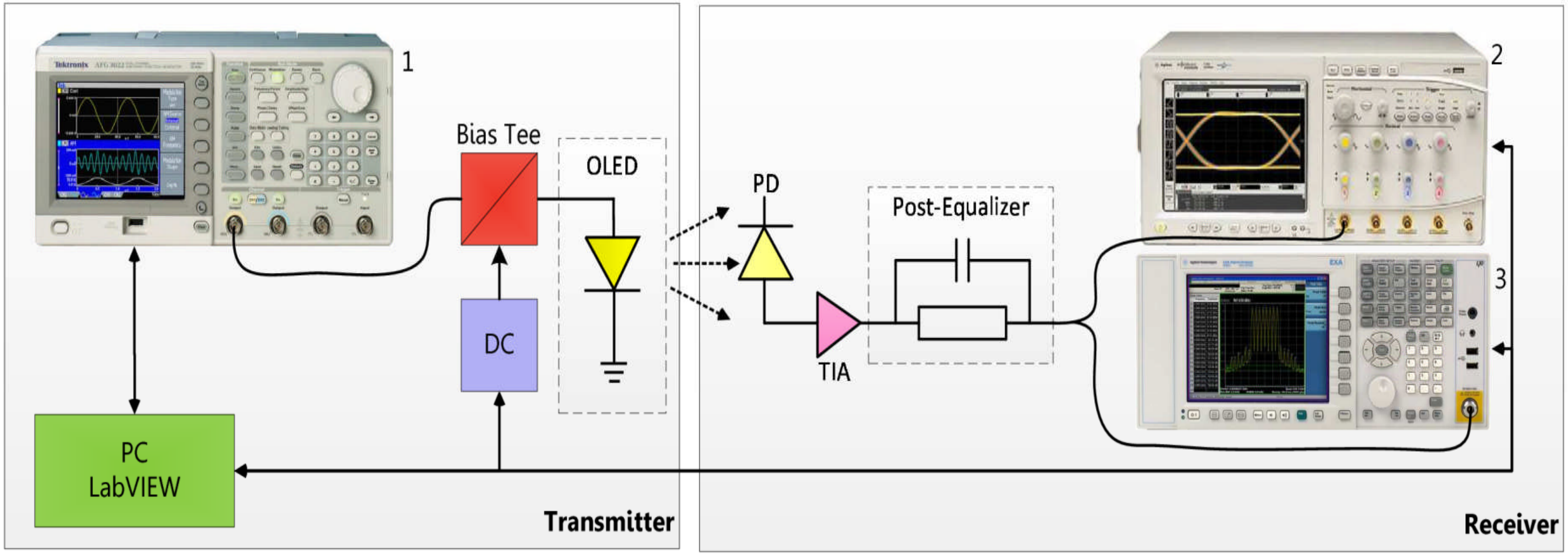
Source: Lumiblade, Korea Institute of Industrial Technology

OLED – Bandwidth Improvement

- Bandwidth equalisation (Analogue)
- Digital filtering
- Complex modulation

$P_r(t) = tx_{opt}(t)H$

OLED – Bandwidth (5) Improvement



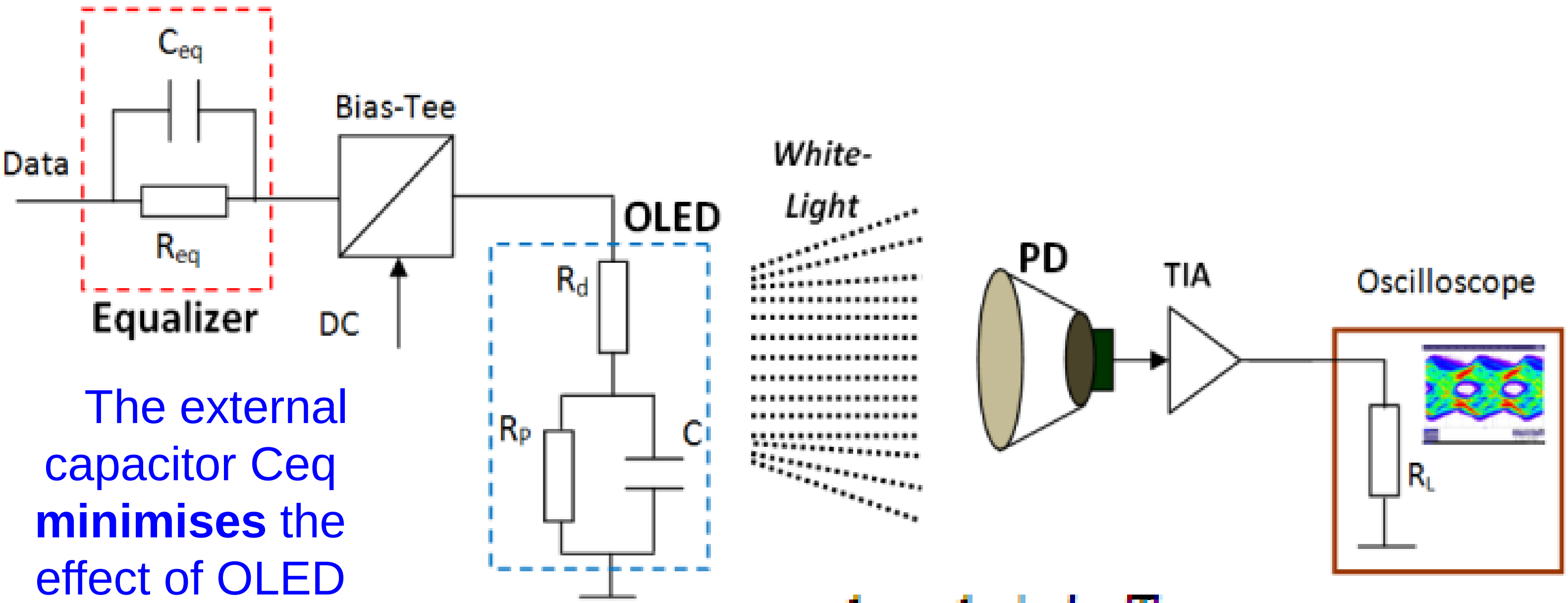
Therefore the received optical signal $P_r(t) = tx_{opt}(t)H(0)$

$$tx_{opt}(t) = [x(t) \otimes h_{Bias\ Tee}(t) \otimes h_{OLED}(t)]P_{Tx}$$

The DC gain (Lambertain)

$$H(0) = \begin{cases} \dfrac{(m+1)A_{det}}{2\pi\ell^2} cos^m(\phi)\cos(\psi), 0 \le \psi \le \psi_c \\ 0 \qquad , \psi > \psi_c \end{cases}$$

OLED – 1st Order Equalisation



The external capacitor Ceq **minimises** the effect of OLED capacitance

$$H(\omega) = \frac{1}{k} \times \frac{1 + j\omega T}{1 + j\omega \frac{T}{k}}$$

$$\frac{1}{k} = \frac{R_d}{R_{eq} + R_d}$$

$$|H(\omega)| = \frac{1}{k} \times \sqrt{\frac{1 + \omega^2 T^2}{1 + \omega^2 \left(\frac{T}{k}\right)^2}}$$

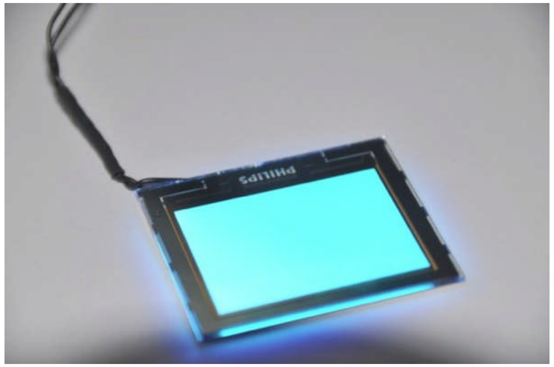
$$T = R_{eq} C_{eq}$$

H. Le-Minh, D. C. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung and Y. Oh, "100-Mbit/s NRZ Visible Light Communications Using a Post-Equalized White LED", *IEEE Photonics Technology Letters*, vol. 21, no. 15, pp. 1063-1065, 2009

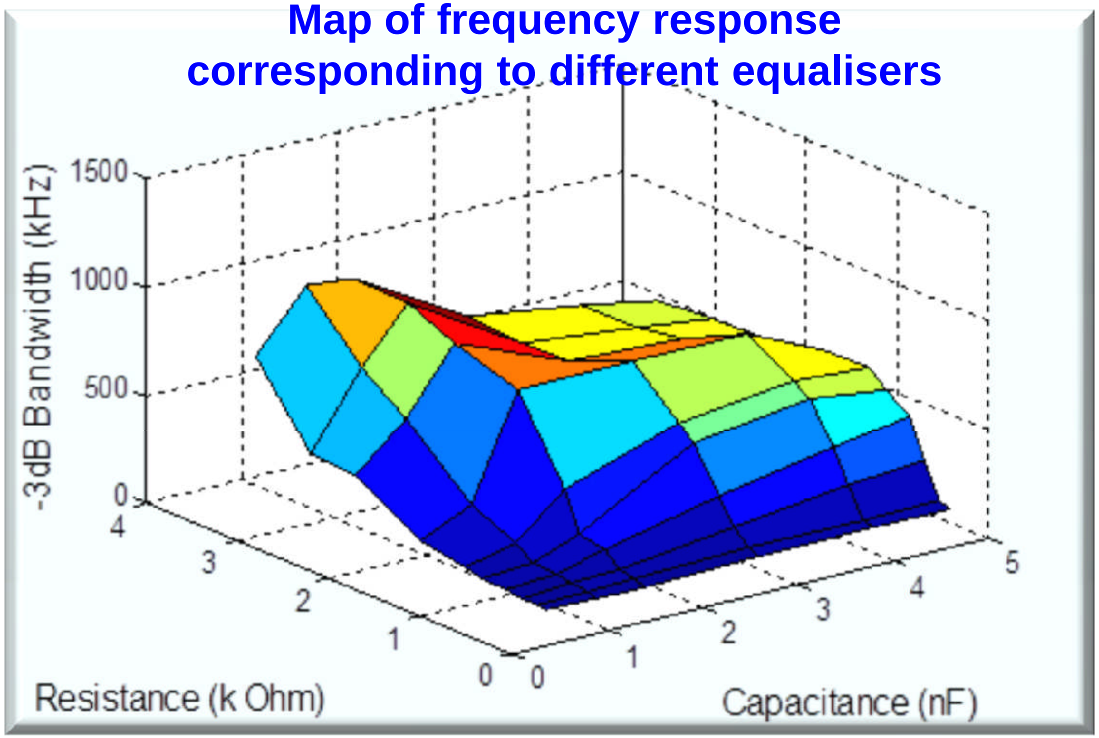
OLED – 1st Order Equalisation

Parameter	Value
OLED half angle ϕ_{hp}	36^o
Angle of irradiance	0^o
Drive current (600 lux for illumination)	80 mA
Angle of acceptance	0^o
Half angle field of view of the receiver	85^o
Transmission distance	5 cm
Optical power	1 W
PIN responsivity	0.2 A/W

OLED – 1^{st} Order Equalisation



Philip Lumiblade OLED
~£70



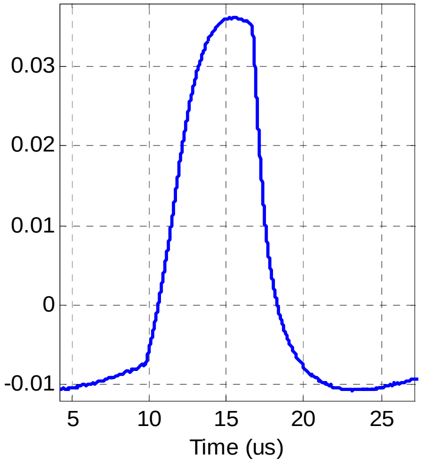
The equalized bandwidth is maximum when C_{eq}~1.5 nF over the wide range value of R_{eq}.

H. Le Minh, Z. Ghassemlooy, A. Burton and P. A. Haigh, "Equalization for Organic Light Emitting Diodes in Visible Light Communications" *IEEE GLOBECOM*, *Workshop on Optical Wireless Communications* in Houston, USA, 5-9 December, 2011

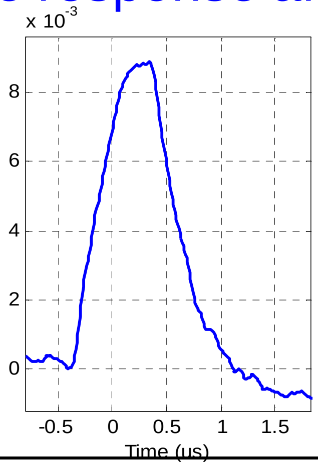
H. Le Minh, Z. Ghassemlooy, A. Burton, P. A. Haigh, and S.-K. Liaw, "Bandwidth Improvement for Organic Light Emitting Diodes Based Visible Light Communications", *IEEE Communications Letters*, 2012 (submited)

OLED – 1st Order Equalisation

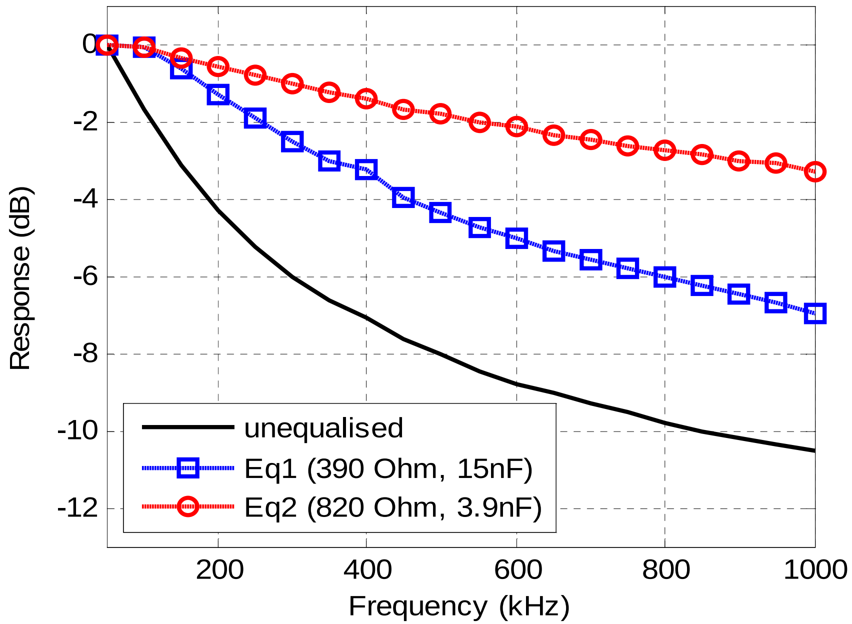
Impulse response before equalisation



Impulse response after equalisation



OLED frequency response before/after equalisation



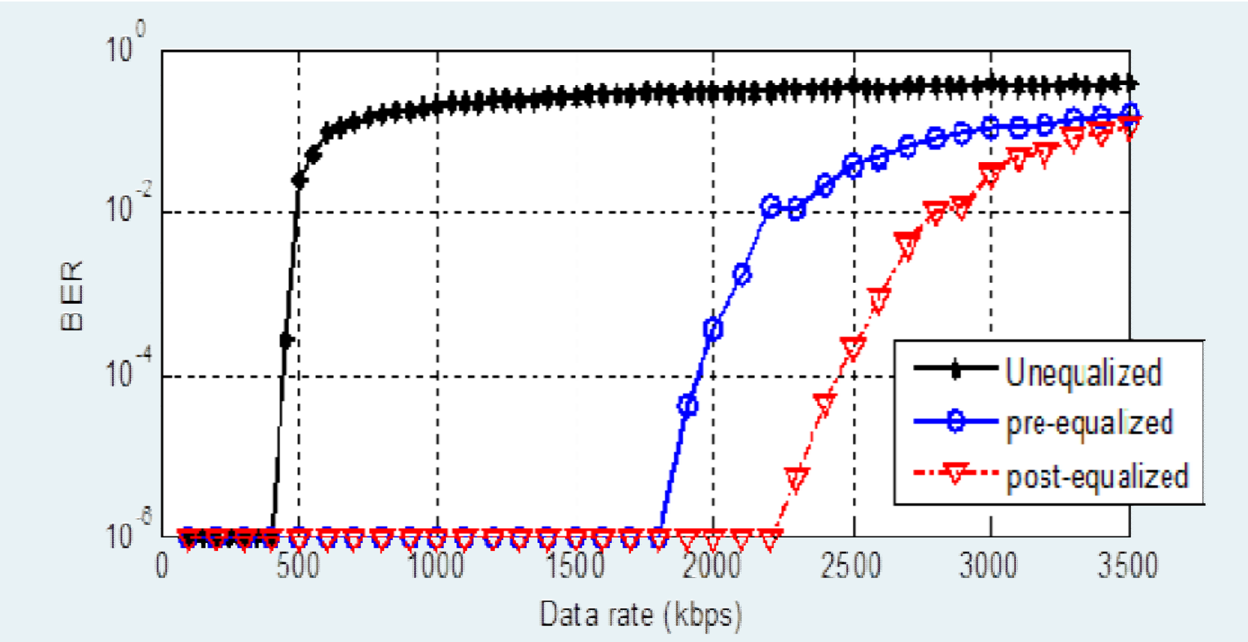
Equalised bandwidth can be increased up to 6 times Loss due to equalisation is ~ 8.5 dB

OLED – 1st Order Equalisation

Measurement condition:

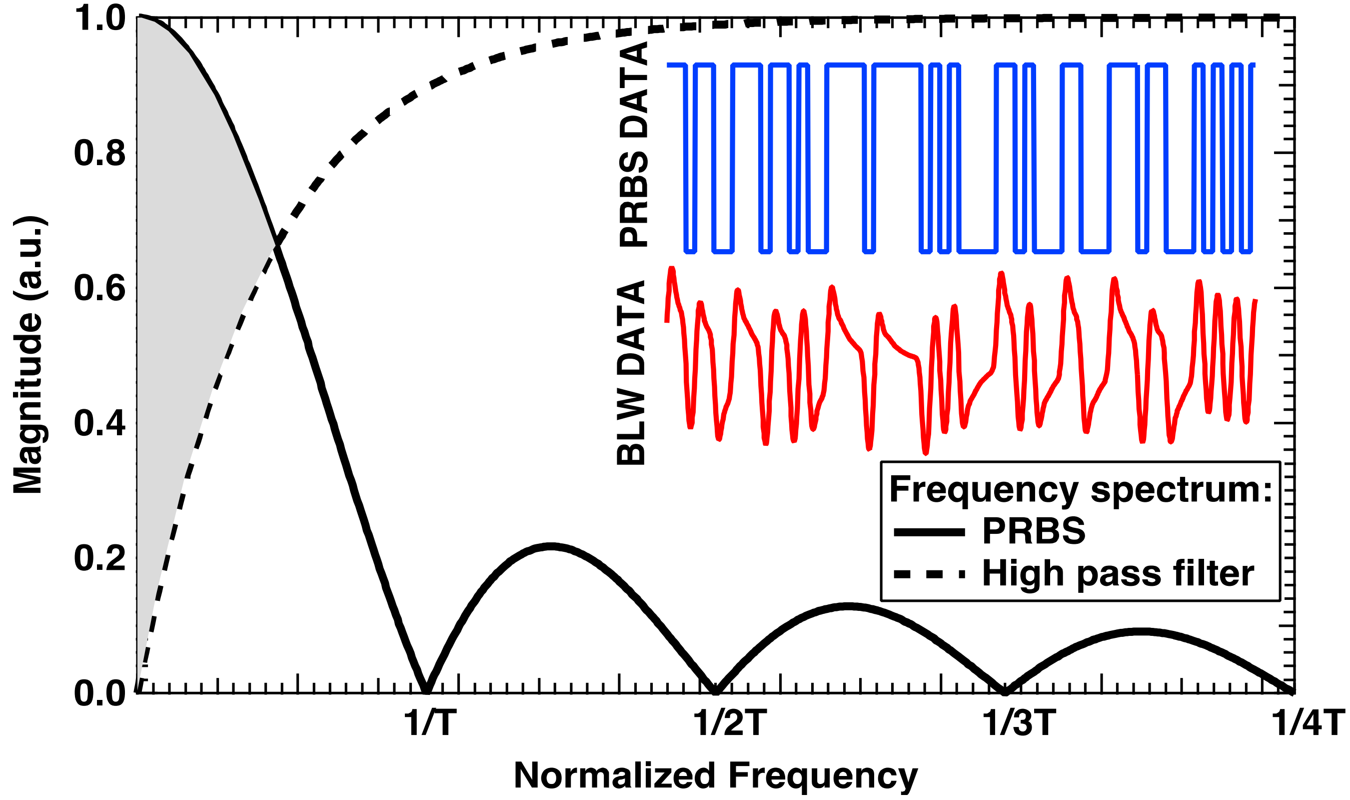
- Data NRZ PRBS, 2^10 – 1
- OLED DC current 80mA
- Link distance 5cm (at that point the luminous level is 600 lux (standard for office illumination)
- PIN PD, 15cm^2 + AD8015 TIA
- Electrical bandwidth 0.8xDataRate

BER performance



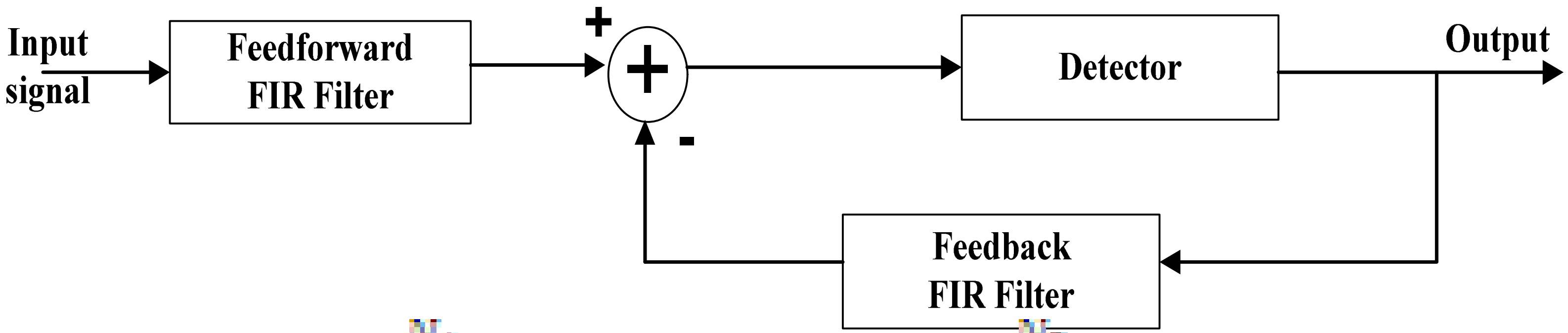
OLED – 1st Order Equalisation

Baseline wander



OLED – Decision Feedback Equalization

- Widely used in digital systems transmitting through BW-limited AWGN channels
- Better performance than ZF and MMSE-based filter



$$z_m = \sum_{n=0}^{N_1} c_n y(\mu T - n\tau) - \sum_{n=1}^{N_2} b_n \tilde{a}_{m-n}$$

sampled incoming signal $y(\mu T - n\tau)$

μT is the μ^{th} sample of the bit period, T.

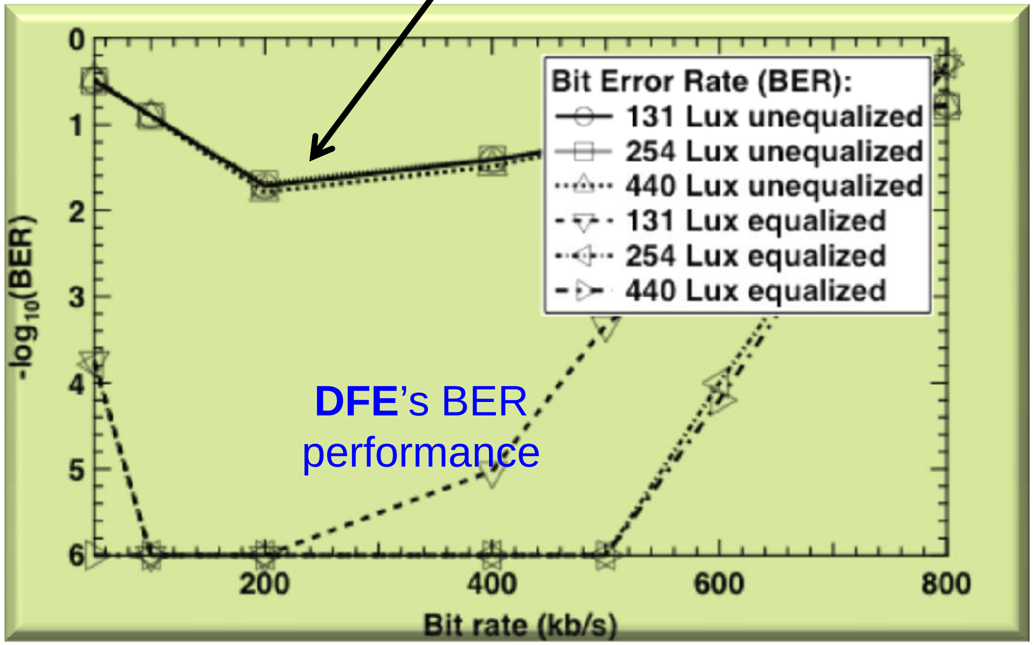
The number of filter taps is given by n and τ is the oversampling rate typically τ ≥ T/2; we selected τ = T/2 for this test. cn and bn are the adjustable coefficients

OLED – DFE

Measured BER vs. Bandwidth at different illumination level (lux)

Unequalised and baseline-wandered **RC equaliser's** BER performance

Parameter	Value
Data format	OOK-NRZ
PRBS length	2^10 - 1
Number of feed-forward taps	18
Number of feed-back taps	9
Algorithm	Least Mean Square (LMS)
Algorithm step size	0.03



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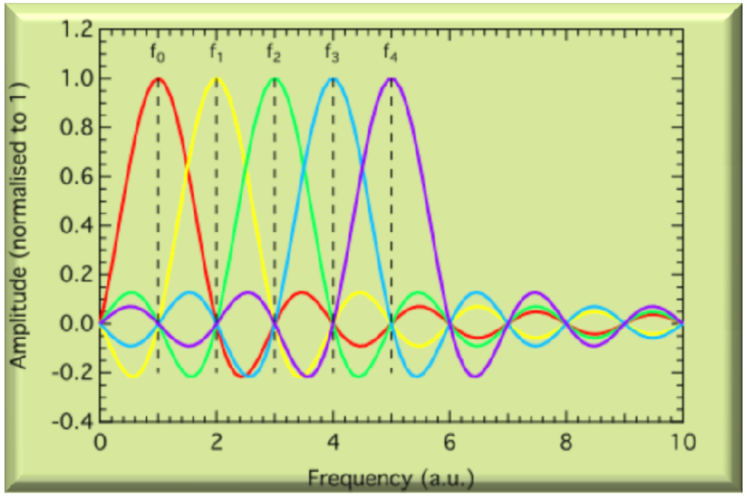
OLED – Complex Modulation

Multiple carrier modulation: Orthogonal Frequency Division Multiplexing

- Carriers are orthogonal to each others
- Each carrier is modulated by QAM, PSK etc.
- Equalisation in small band of modulation bandwidth is feasible



Discrete Multi-Tone Modulation

- The subcarriers used must fulfill the orthogonality condition, such that:

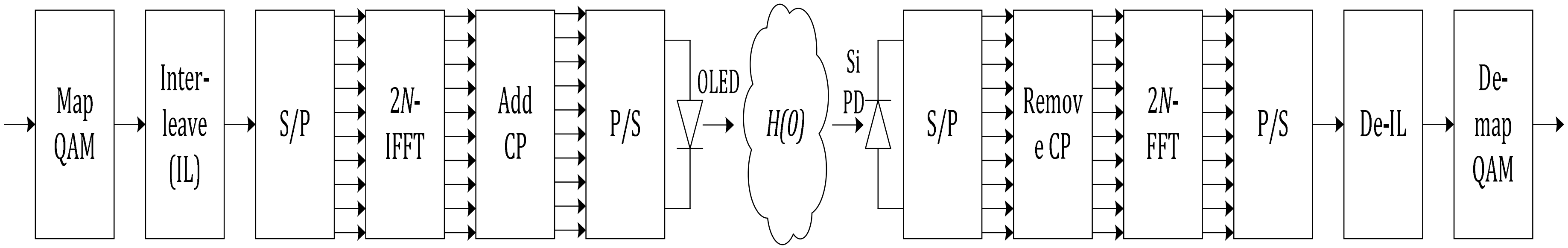
$$\frac{1}{T_{sym}} \int_{0}^{T_{sym}} e^{j2\pi f_k t} e^{-2\pi f_i t}\, dt = \begin{cases} 1, & \forall\, k = i \\ 0, & \text{otherwise} \end{cases}$$

where T_{sym} is the time domain DMT symbol time and the complex exponential frequency domain data is given by

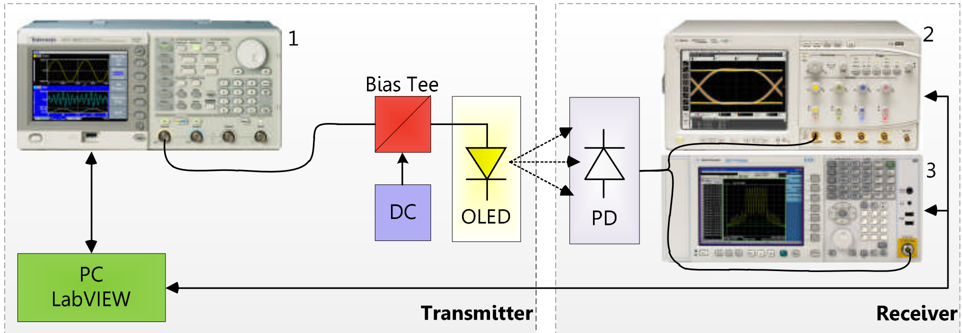
$$X_k = \{e^{j2\pi f_k t}\}_{k=0}^{N-1}$$

N is the number of subcarriers and *k* is the subcarrier under inspection.

OLED + DMT – Experimental



- M = 16 QAM
- Number of useful subcarriers = 64
- The distance over which the symbols are transmitted is set appropriately to fix the luminance level to 440 lux (for office environment)
- A simple one-tap frequency domain equalizer



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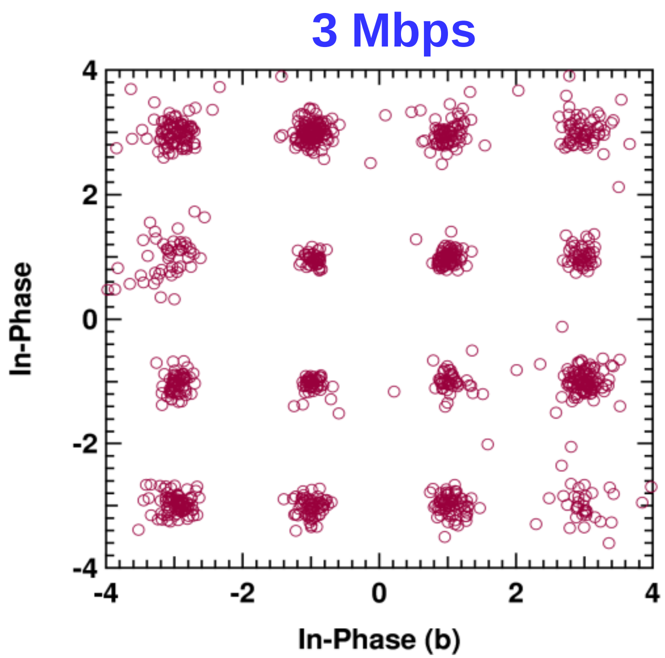
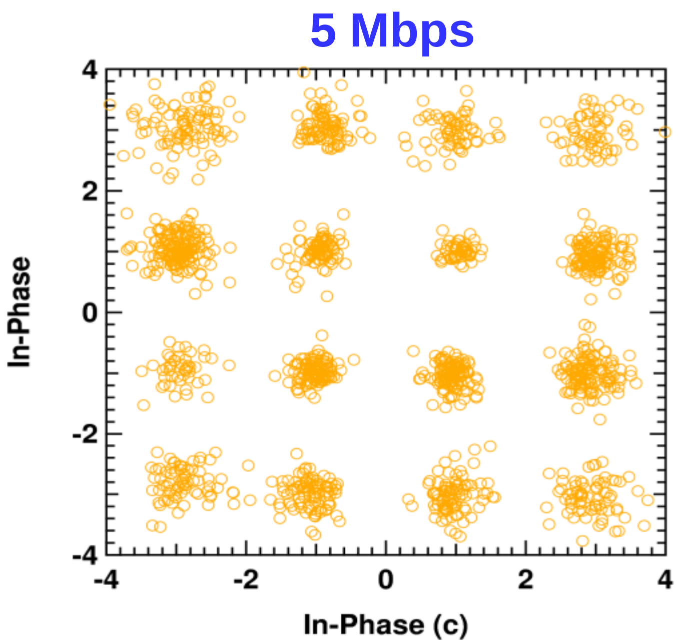
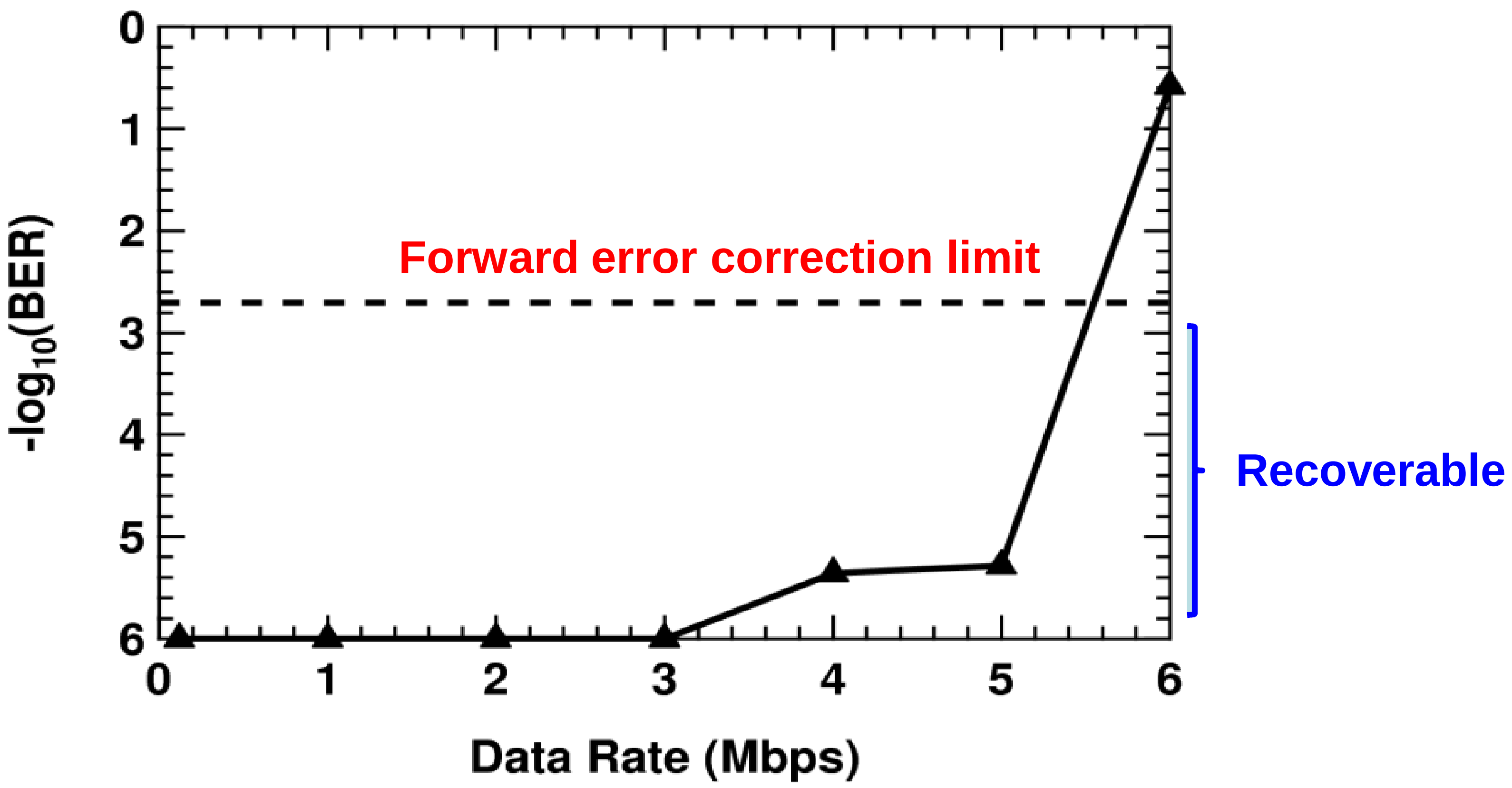
OLED + DMT- Received Constellations





- To improve the equalizer and achieve higher bit rates, a longer pilot symbol should be transmitted to provide a better representation of the memoryless channel.
- Since the noise is additive and Gaussian, the transmission of an abundance of pilot symbols would reduce the effect of noise by simple averaging.

OLED + DMT- BER


0
1
2
3
4
5
6
-log10(BER)
Forward error correction limit
Recoverable
0
1
2
3
4
5
6
Data Rate (Mbps)

OLED - Challenges

- **OLED is under development, therefore challenges**
  - Materials and device structures
  - Heavily calibrated for display purpose (unlike LED used for signalling and illumination)
  - Expensive (~10/20 times costlier than the same performing LED)
  - Lack of a wide range of commercially available products

- **Communications aspects**
  - Light efficiency is low → large illumination panels are typically fabricated → high capacitance thus limiting the device modulation bandwidth (100's kHz)
  - Limited researches in data communications
  - Not yet being standardised

OLED – Possibilities & Potential

- **Possibilities and Future Work**
  - Higher data rate - 0-15 Mbit/s for standard 10BASE-T Ethernet communications
  - Working with the manufacturers to improve the device response time (newer display has faster response and wider dynamic contrast range)
  - Device modelling and characterisation to optimise the performance
  - Possible to adopt the existing VLC standard (IEEE 802.15/16)
  - FEC inclusion

- **Potentials and Opportunity**
  - OLED is available in many displays, tablets and phones → new areas of short-range and personal VLC applications and researches
  - Toward mobile and flexible VLC
  - Environmental friendly → potentially to be adopted in wide range of VLC

Acknowledgment

- OCRG's OLED / VLC team, *Northumbria University*
- EURASIP
- Prof. Erich Leitgeb - *TU Graz*
- EU Cost Action IC 1101

Thank you!

3rd Colloquium on Optical Wireless Communications

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