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Submission Title: [VLC with white-light LEDs: strategies to increase data rate]
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Source: [D C O'Brien] Company [University of Oxford]
Address [Department of Engineering Science, Parks Road, Oxford, OX1 3PJ,UK]
Voice:[+441865273916], FAX: [+441865273906], E-Mail:[dominic.obrien@eng.ox.ac.uk]

Abstract: [Presentation on techniques to improve transmission data-rate for VLC systems that use white-light LEDs]

Purpose: [Information]

VLC with white-light LEDs: strategies to increase data rate

Dominic O'Brien
Hoa Le Minh
Lubin Zeng
Grahame Faulkner

University of Oxford

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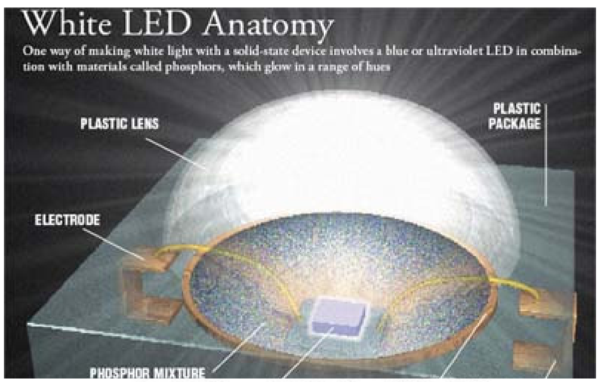
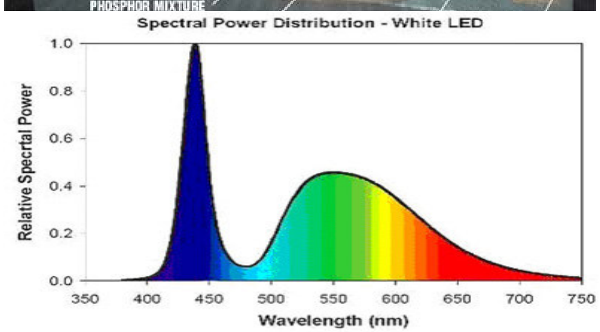
- The VLC link
  - Sources
  - Propagation
  - Receiver
- Strategies to increase data rate
  - Pre-equalisation
  - Post-equalisation
  - Complex modulation
  - Parallel transmission (optical MIMO)
- Conclusions

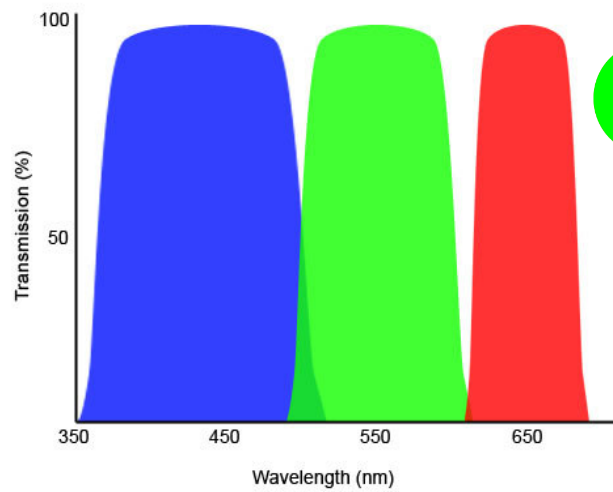
Sources

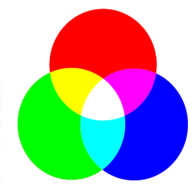
- Blue LED & Phosphor
  - Low cost
  - Phosphor limits bandwidth





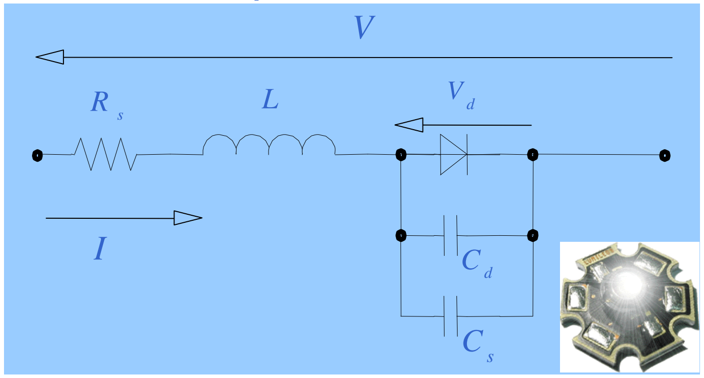
- RGB triplet
  - Higher cost
  - Potentially higher bandwidth
  - Potential for WDM





Sources: Phosphor-based LED Emitter

Spice model

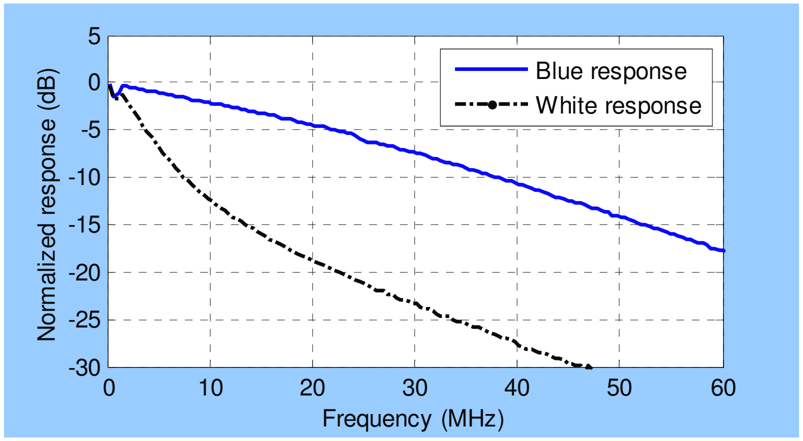


R_s = 0.9727 Ω, L = 33.342 nH
C_s = 2.8 nF, C_d = 2.567 nF, tt = 1.09 ns

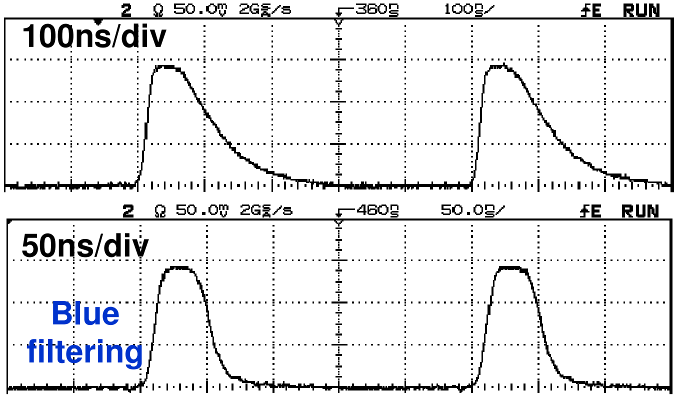
(1) **Intrinsic LED modulation bandwidth is narrow**

(2) **Blue component offers wider bandwidth**

LED frequency response



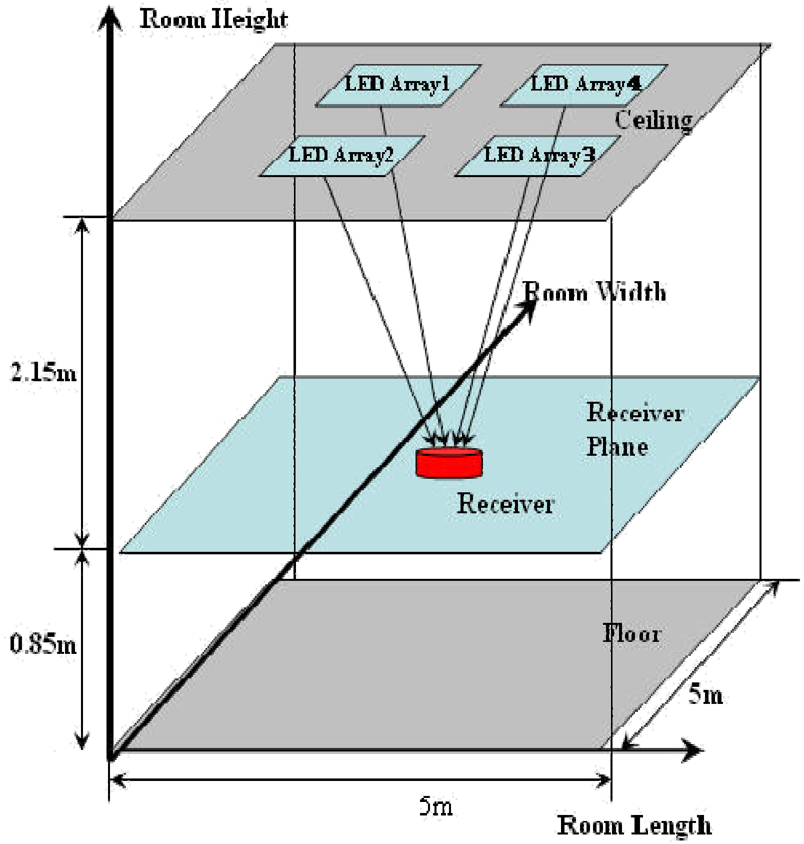
LED temporal impulse response



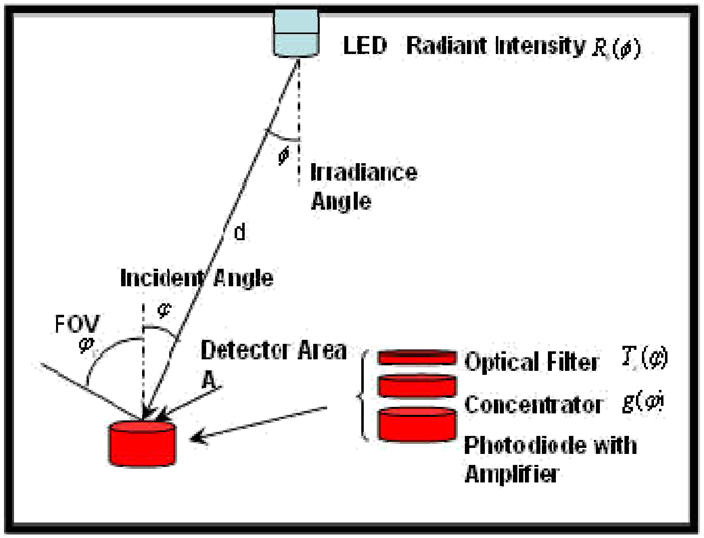
Sources: typical bandwidths

- **Available bandwidth**
  - LED modulation bandwidth is narrow ~3 MHz
  - Blue-part has wider bandwidth ~12-20 MHz (dependent on devices)

Propagation: modelling



A typical geometry for indoor VLC



- **Transmitter**: LEDs, lens and driver
- **Channel**: LOS and diffuse paths
- **Receiver**: Optics, PD and amplifiers

Propagation: summary

- Power
  - Illumination levels ensure strong communications signal
  - Typical signal to noise ratio of >40dB
- Bandwidth
  - Channel bandwidth potentially affected by
    - Inter-symbol interference from multiple line of sight paths
    - Diffuse reflections from surfaces
  - Modelling indicates bandwidth >88MHz[1] within ‘typical’ room

[1]J. Grubor et al., High-speed wireless indoor communication via visible light, ITG Fachbericht, Vol. 198 (2007), pp. 203-208.

Propagation: conclusions

- Very high SNR available
- Bandwidth of channel >~88MHz

Receiver

- Bandwidth set by photo-detector and preamplifier combination
- Constraints
  - Increasing area increases collected power
    - Increased capacitance therefore reduced bandwidth
- Examples
  - 20mm^2 bootstrapped APD receiver (155Mb/s -40dBm OOK 1E-9 BER)[1]
  - 14.4mm^2 PIN diode receiver using commercial transimpedance amplifer- bandwidth of 77MHz (100Mb/s -27dBm OOK 1E-9 BER)[2]
- Conclusion
  - Receiver bandwidths of up to 100MHz available with ‘reasonable’ collection areas
  - Greater bandwidths more challenging

[1] McCullagh-Mj and Wisely-Dr, "155 Mbit/s optical wireless link using a bootstrapped silicon APD receiver," *Electronics Letters,* vol. 30, pp. 430-2, 3 March 1994.
[2] Khoo-SH (DPhil Thesis, University of Oxford)

Summary of VLC link properties

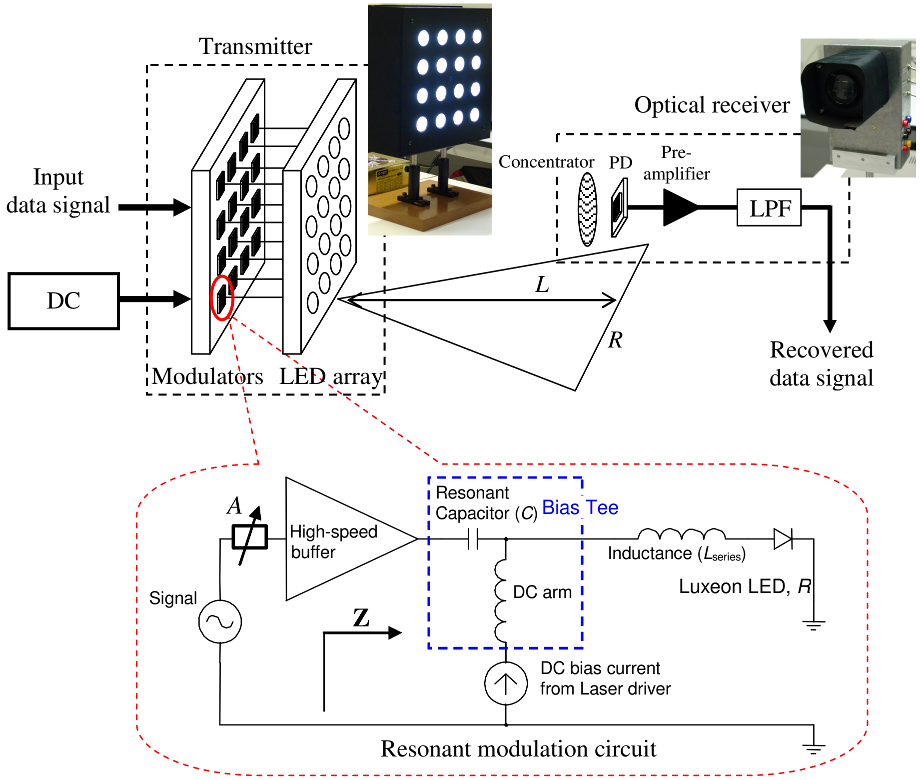
- Data rates limited by LED characteristics for bandwidths <100MHz
- Channel and receiver constraints need consideration for bandwidths>100MHz

Strategies for High-speed VLC

- Equalization
  - Transmitter (pre-) equalization
  - Receiver (post-) equalization
- Complex modulation
- Multiple-Input-Multiple-Output (MIMO)

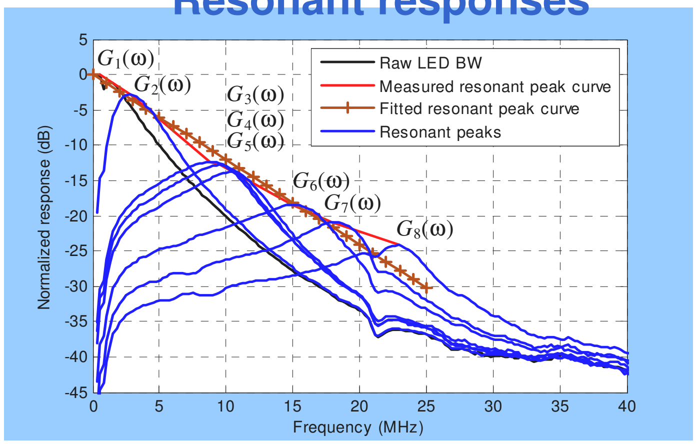
(Pre-) Equalization: Multiple Resonant LEDs

- Combination of the responses from multiple LED devices being driven at different resonant frequencies → larger VLC bandwidth

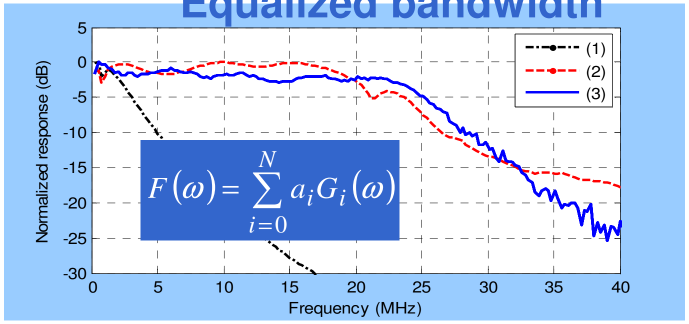


Multiple-resonant 16-LED VLC demonstration system

Resonant responses



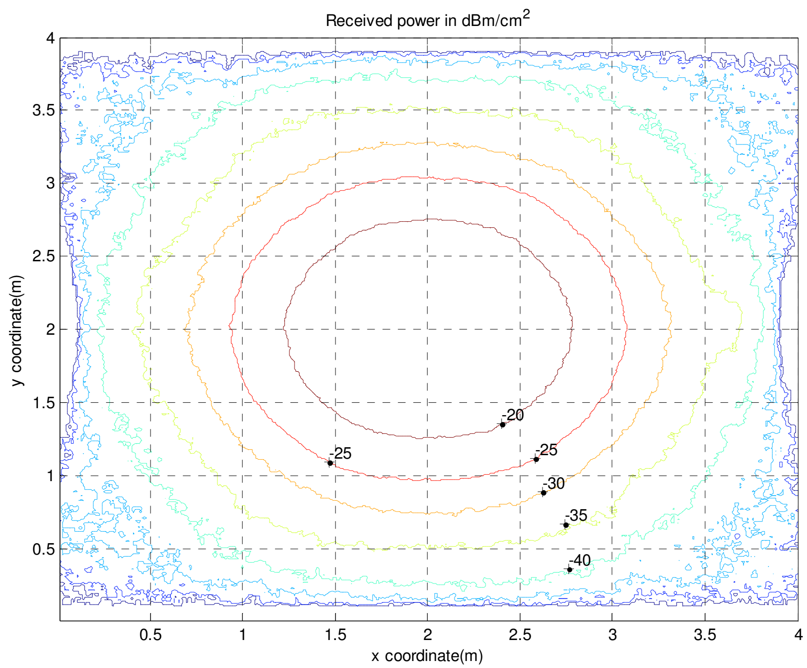
Equalized bandwidth

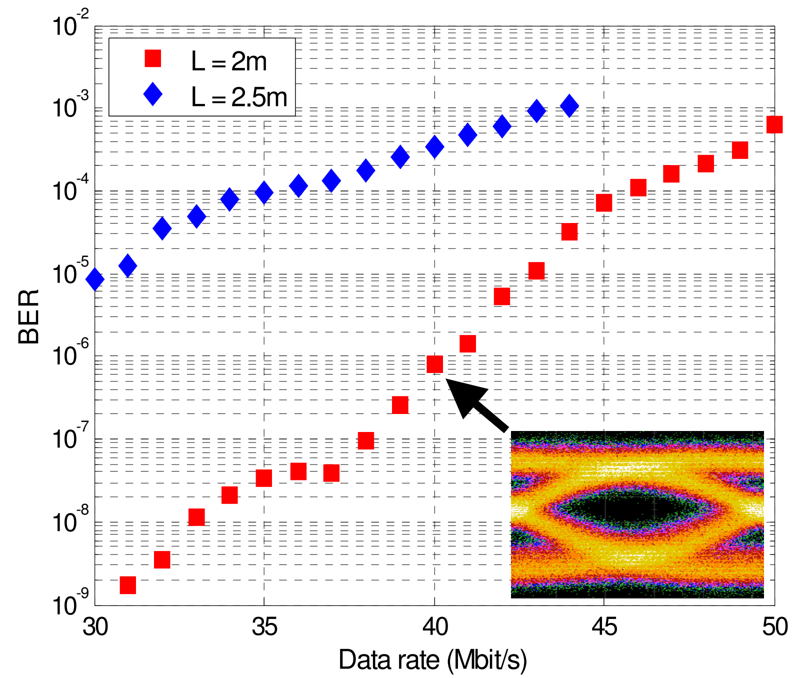


$$F(\omega) = \sum_{i=0}^{N} a_i G_i(\omega)$$

(Pre-) Equalization: Multiple Resonant LEDs

- Link performance





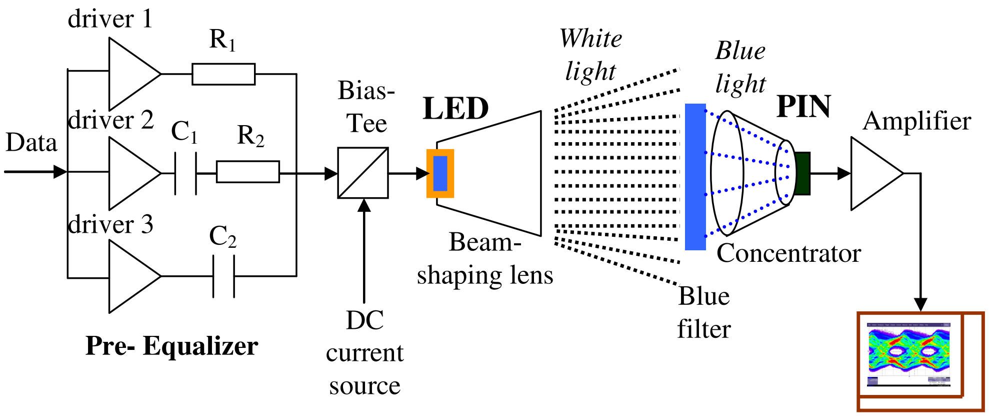
Receiving power plane-distribution **BER performance**

40 Mbit/s OOK-NRZ in standard room lighting condition [2]

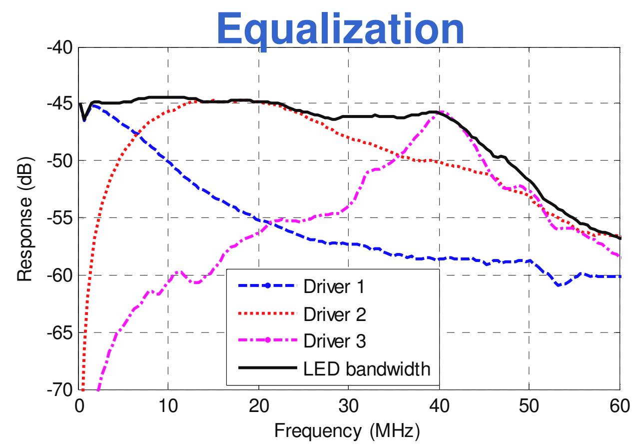
[2] H. Le-Minh, D. C. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung and Y. Oh, "High-Speed Visible Light Communications Using Multiple-Resonant Equalization", accepted for publication in *IEEE Photonics Technology Letters*.

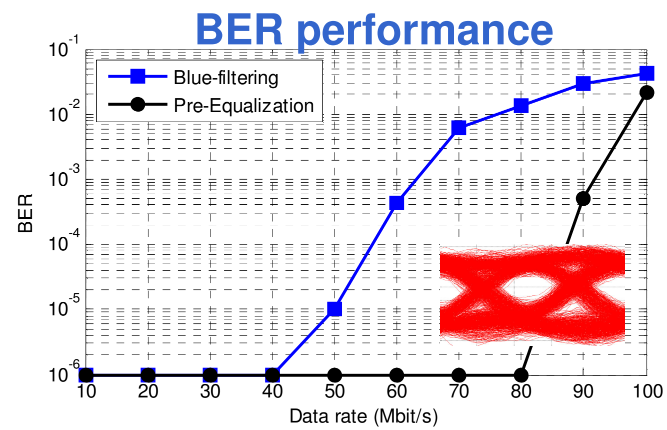
(Pre-) Equalization: Single LED Link

- Single LED is driven by multiple resonant driver branches + blue-filtering at receiver



VLC link configuration



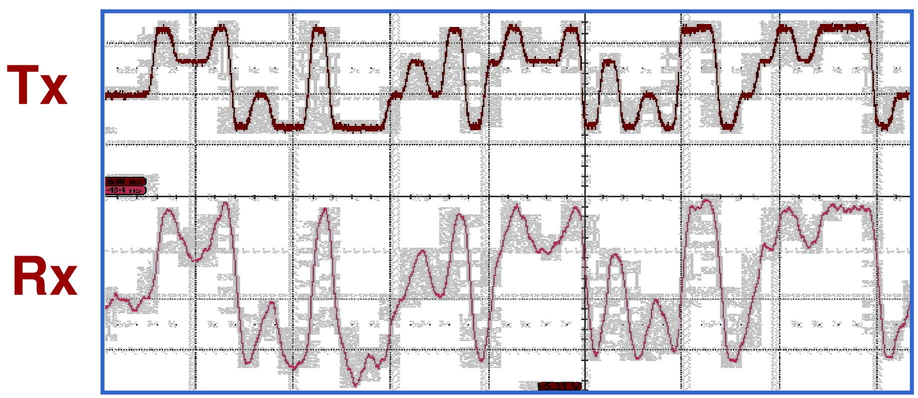


- **45 MHz equalized bandwidth achieved (3 drivers)**
- **80 Mbit/s OOK-NRZ transmission [3]**

[3] H. Le-Minh, D. C. O'Brien, G. Faulkner, L. Zeng, K. Lee, D. Jung and Y. Oh, " 80 Mbit/s Visible Light Communications Using Pre-Equalized White LED", submitted to *European Conference on Optical Communications* (ECOC 2008)

Complex Modulation

- **High SNR**
  - **Potential for complex modulation**
  - **Driving devices potentially challenging**
- **DMT/OFDM**
  - Link of (equivalent data-rate) 101-Mbit/s is demonstrated using 20-MHz bandwidth [4]
- **M-PAM**
  - Initial demonstrations



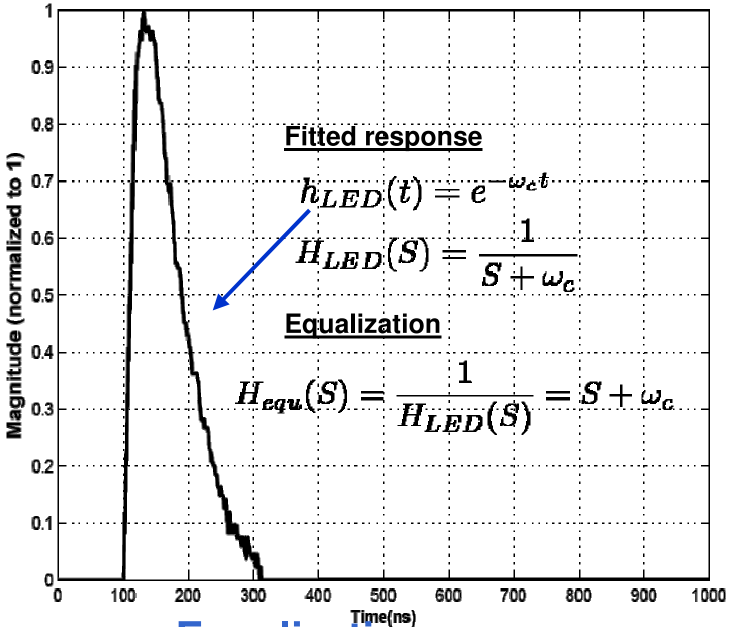
50 Msymbol/s 4-PAM VLC link (from [3])

(100 Mbit/s equivalent NRZ rate)

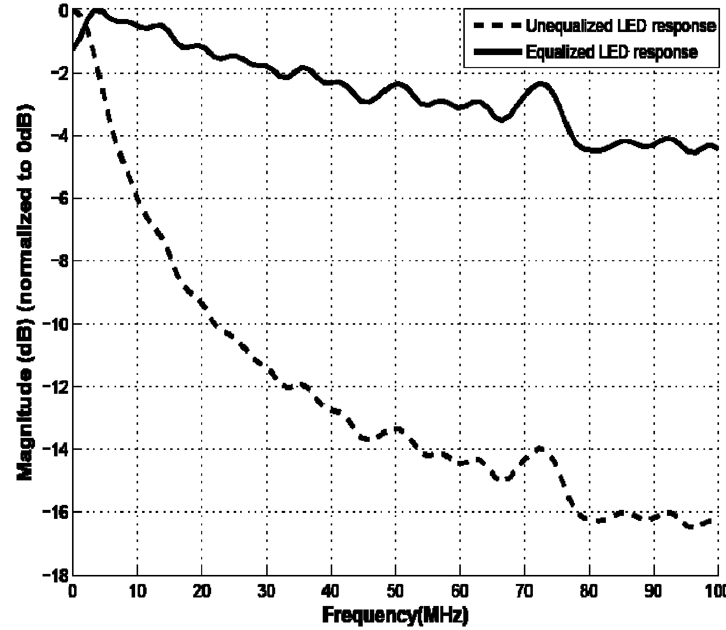
[4] Grubor, J., et al., "Wireless high-speed data transmission with phosphorescent white-light LEDs", Proc. *European Conference on Optical Communications* (ECOC 2007) (PDS 3.6), pp. 1-2. ECO [06.11], Sep. 2007, Berlin, Germany

(Post-) Equalization

- LED Impulse response measured
  - Fall time of devices >> Rise time
  - Equalization of exponential decay



Equalization process



Bandwidth performance

OOK-NRZ data rate is increased from 16 Mbit/s to 35 Mbit/s [1]

[1] L. Zeng, D. C. O'Brien, H. Le-Minh, K. Lee, D. Jung and Y. Oh, "Improvement of Data Rate by Using Equalization in an Indoor VLC System", *IEEE International Conference on Circuits and Systems for Communications 2008* (IEEE ICCSC 2008), Shanghai, China, May 2008

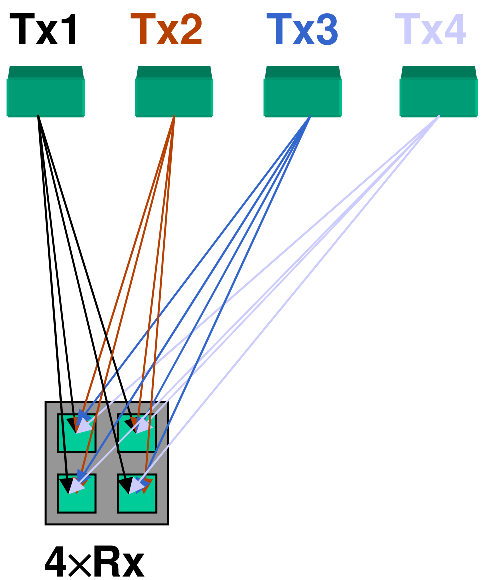
Equalisation summary

- Pre-equalisation
  - Possible with single or multiple LEDs
  - Substantial bandwidth improvement
  - Issues
    - Energy efficiency
    - Driver complexity
    - Effect of device variation
- Post-equalisation
  - Simulations indicate substantial improvement
  - Preliminary experimental results promising
  - Attractive as no complex LED drive circuitry
- Post-equalisation preferable from complexity point of view
  - Unclear as to which offers best performance
  - Combination of pre-and post offers substantial improvements (in simulation)

MIMO using VLC

- Many sources offers the potential for parallel data transmission
  - 1Gb/s parallel ‘proof-of concept’ by VLCC
- Would normally require careful alignment of sources and detectors
- MIMO processing allows signals to be recovered without precise alignment

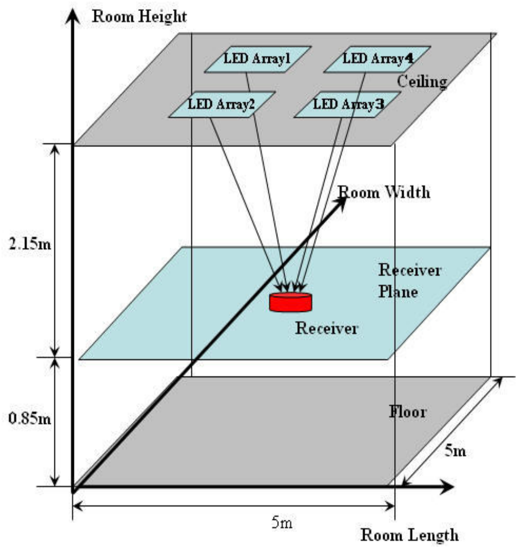
Multiple-Input-Multiple-Output System



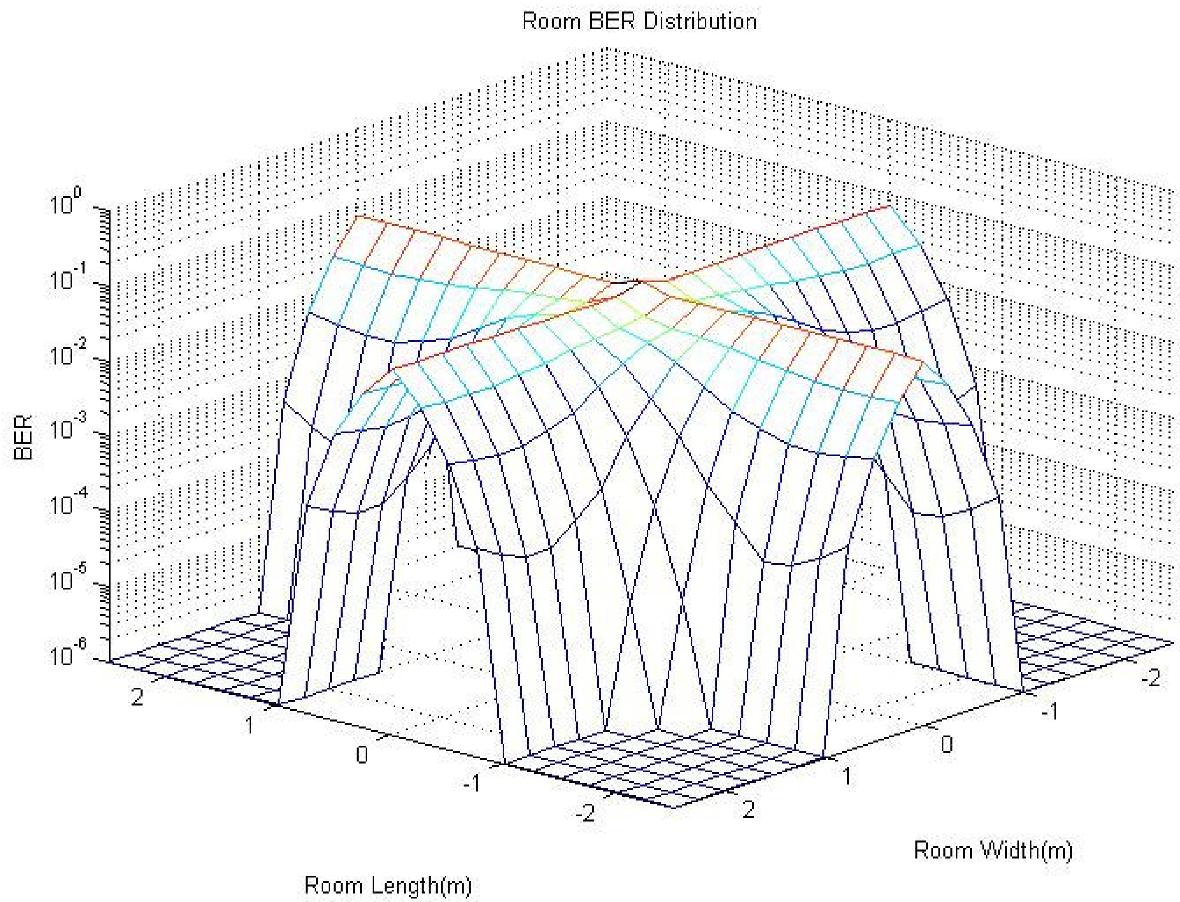
$$H = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H_{21} & H_{22} & H_{23} & H_{24} \\ H_{31} & H_{32} & H_{33} & H_{34} \\ H_{41} & H_{42} & H_{43} & H_{44} \end{bmatrix}$$

- **Channel matrix *H* needs to be estimated at different receiver positions**
- **Simulation shows that data rate is linearly increased with the rank of *H***
- **Geometric symmetry reduces the rank**

MIMO System: Room Test Performance



(Aggregate) 80 Mbit/s parallel transmission



Challenges:

- **Non-geometric symmetry**
- **Channel estimation**

MIMO summary

- Initial results show linear capacity growth
- Possibility of increasing capacity by transmitting data
- Not possible at all locations due to symmetry of H-matrix
  - Work to develop a receiver optical system that addresses this issue underway

Conclusions

- VLC has the potential to offer high data rates
  - 100Mb/s either demonstrated or simulated using a number of different techniques
- Data rates of Gbit/s possible with more advanced techniques
- Further work required on
  - Development of each technique
  - Comparison of alternatives