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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

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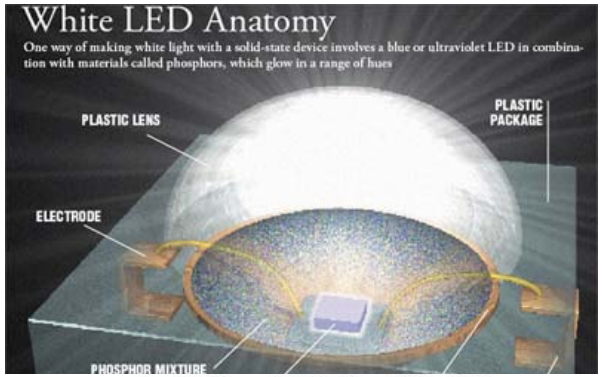
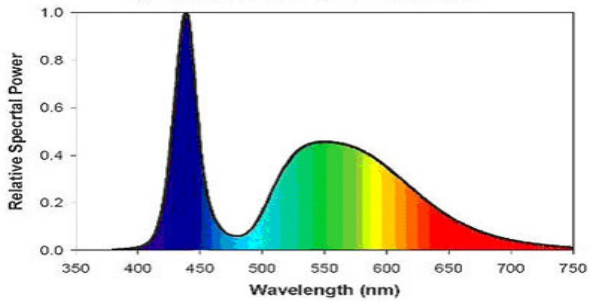
Contents

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

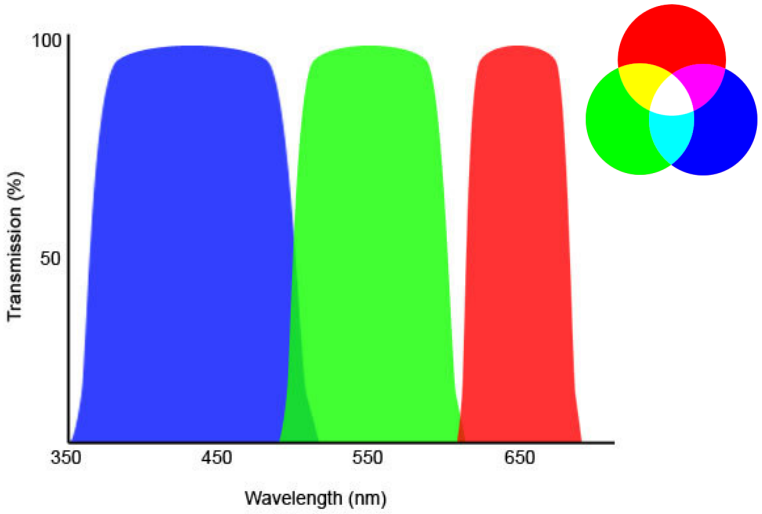
Sources

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



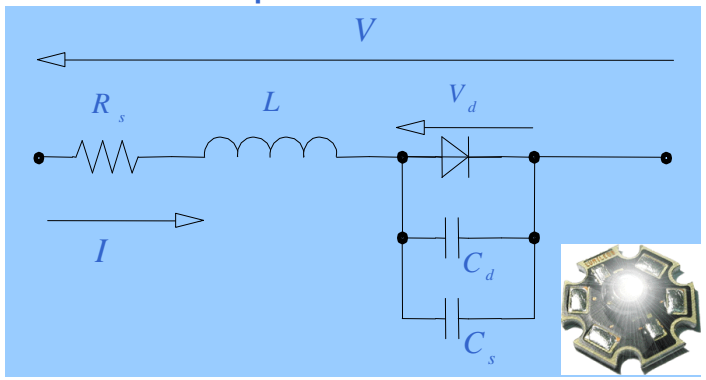


- RGB triplet
  - Higher cost
  - Potentially higher bandwidth
  - Potential for WDM



Sources: Phosphor-based LED Emitter

Spice model

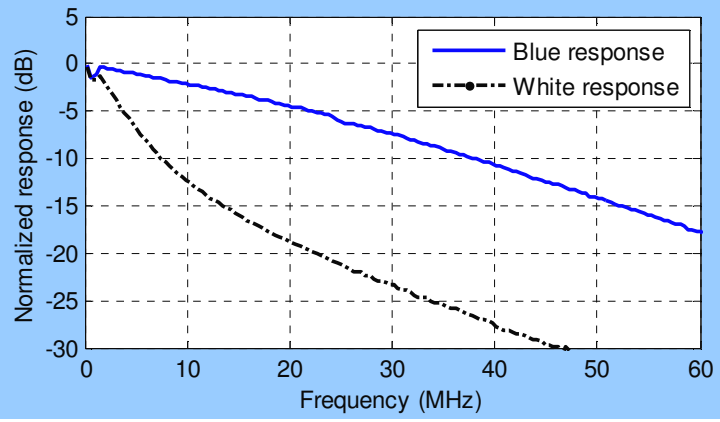


R_s = 0.9727 Ω, L = 33.342 nH
C_s = 2.8 nF, C_d = 2.567 nF, tt = 1.09 ns

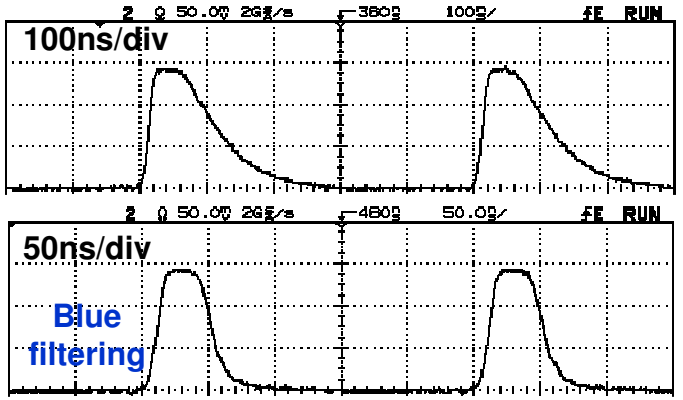
(1) Intrinsic LED modulation bandwidth is narrow

(2) Blue component offers wider bandwidth

LED frequency response



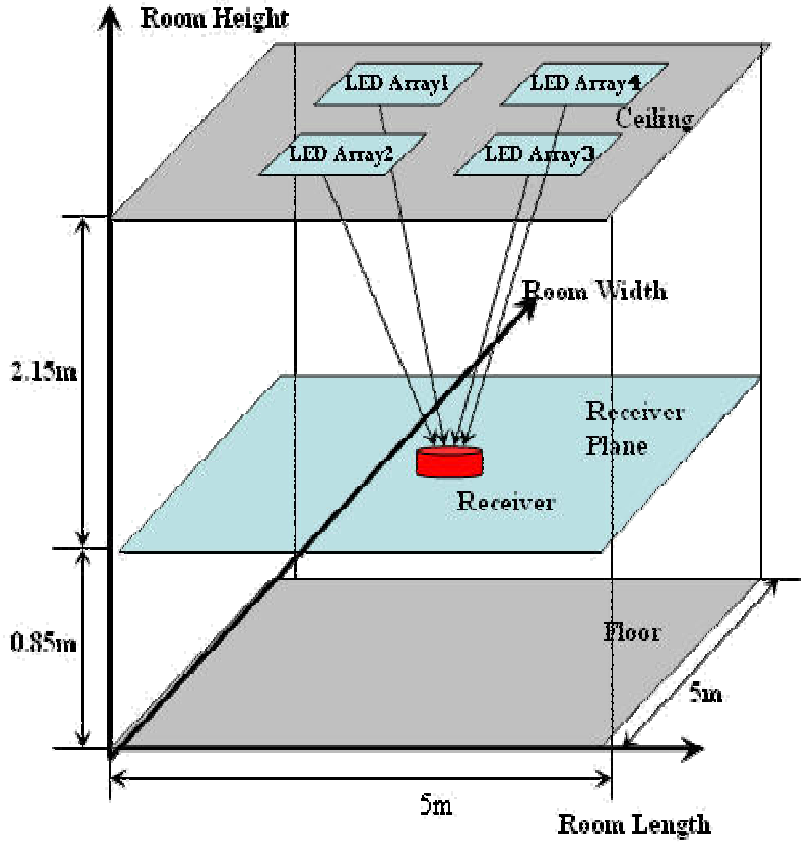
LED temporal impulse response



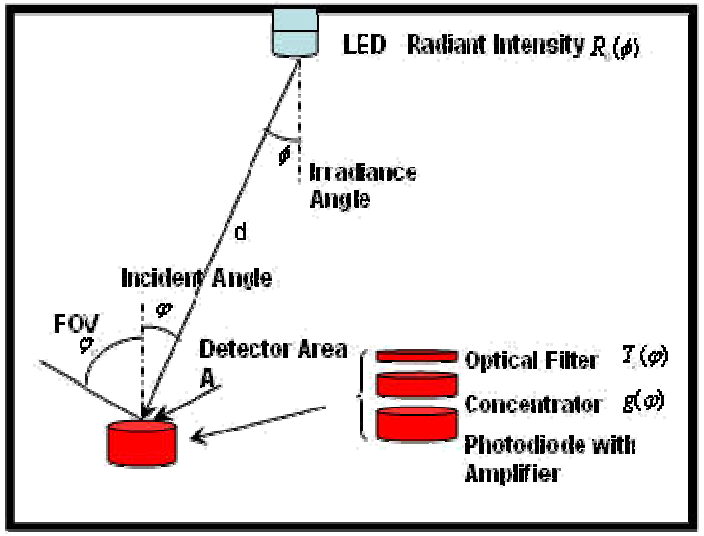
Sources: typical bandwidths

- **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 >~90MHz within ‘typical’ room
    - (results from Heinrich Herz Institute)

Propagation: conclusions

- Very high SNR available
- Bandwidth of channel >~90MHz

Receiver

- Bandwidth set by photo-detector and preamplifier combination
  - Capacitance and transit time of photo-detector
  - Impedance of front end of amplifier
- Constraints
  - Increasing area increases collected power
    - Increased capacitance therefore reduced bandwidth
- Examples
  - 20mm^2 bootstrapped APD receiver (155Mb/s -40dBm OOK 1E-9)[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

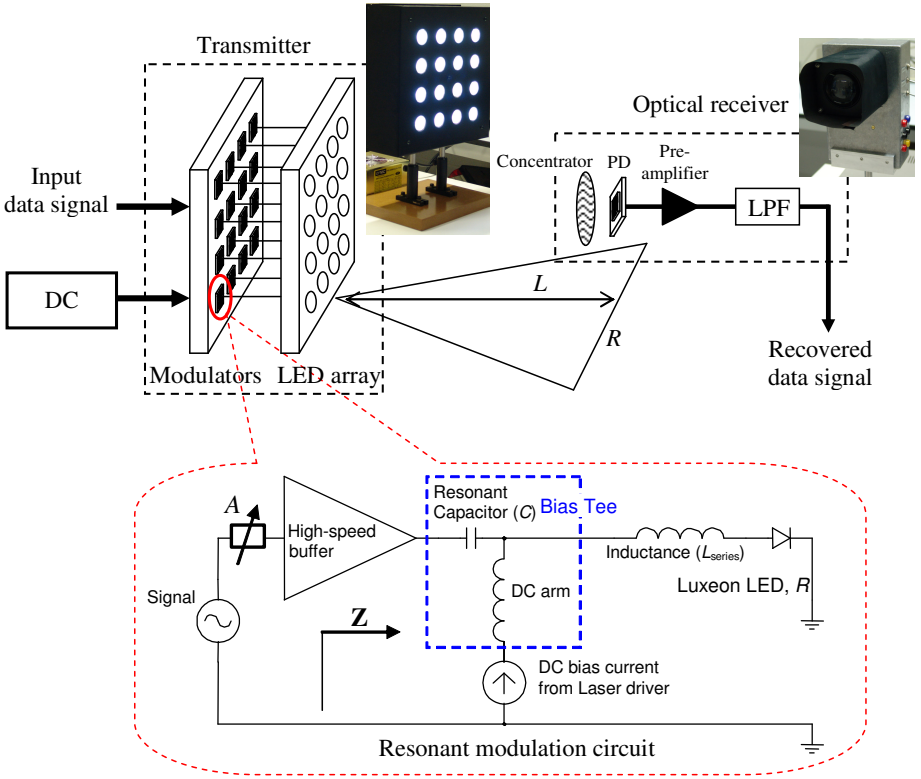
- If required bandwidth<~100MHz
  - LED provides constraints
- Channel and receiver constraints need consideration if required bandwidth >~100MHz

Strategies for High-speed VLC

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

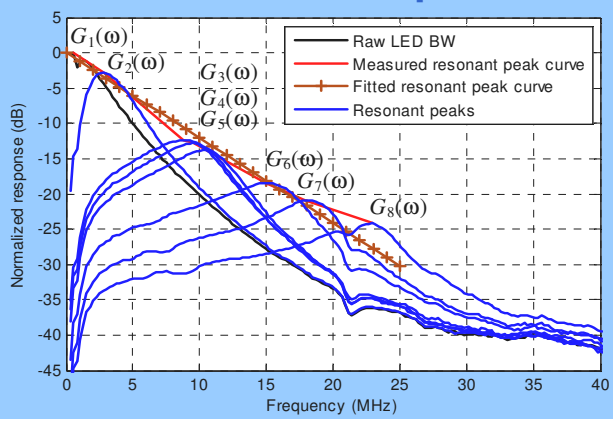
(Pre-) Equalization: Multiple Resonant LEDs

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

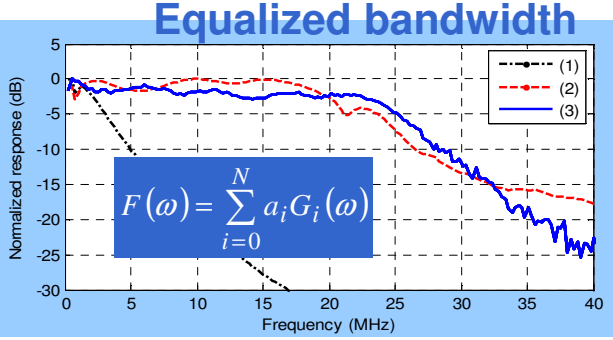


Multiple-resonant 16-LED VLC demonstration system

Resonant responses

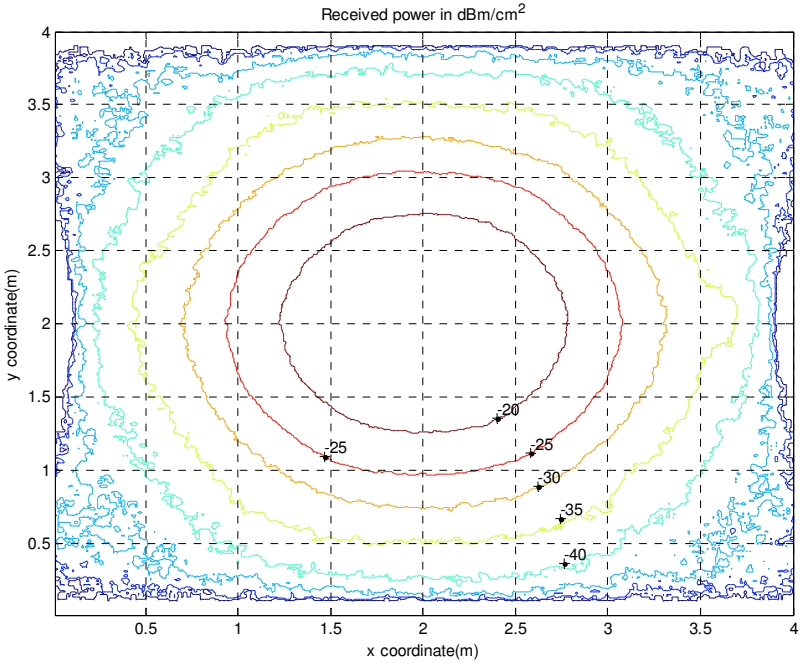


Equalized bandwidth

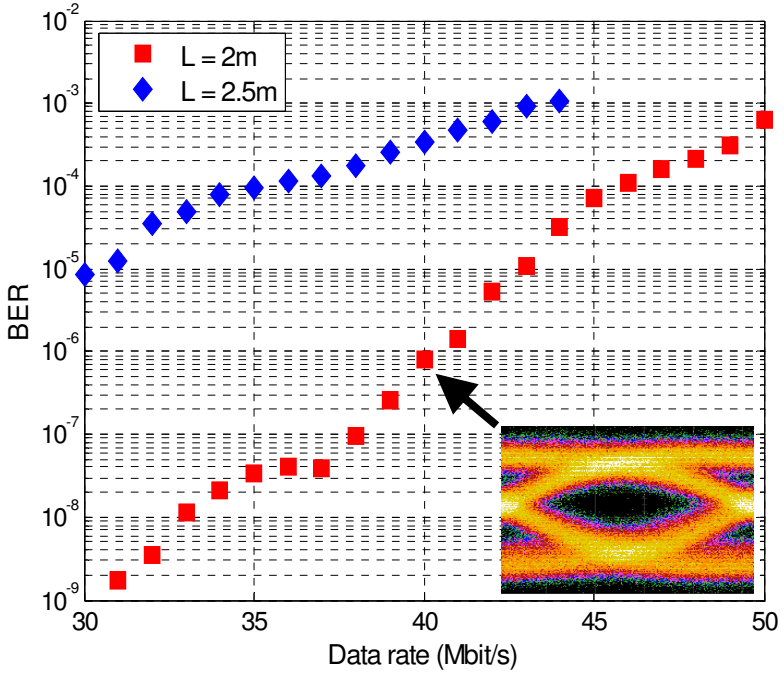


(Pre-) Equalization: Multiple Resonant LEDs

- Link performance



Receiving power plane-distribution



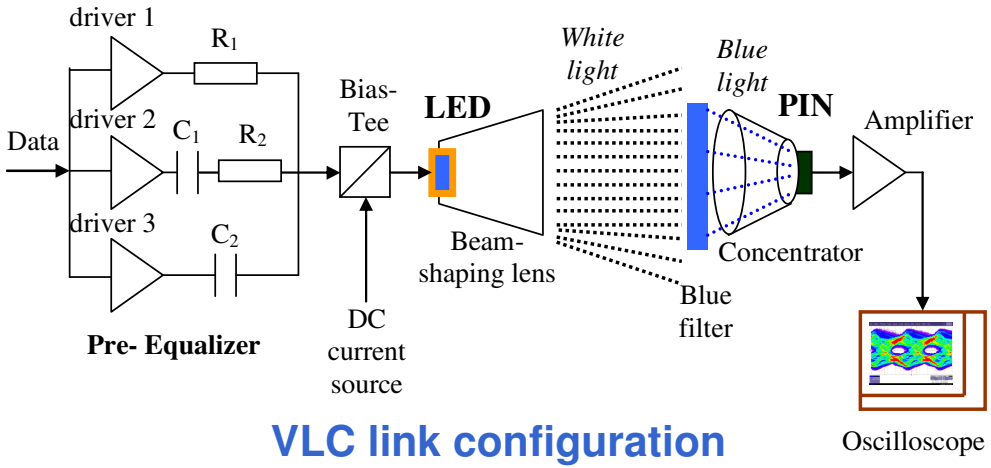
BER performance

40 Mbit/s OOK-NRZ in standard room lighting condition [3]

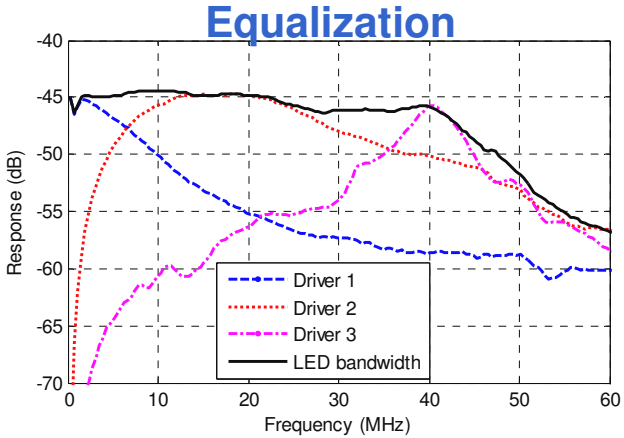
[3]Le-Minh, H., O'Brien-Dc, Faulkner, G., Zeng, L., and Lee, K.: 'High-Speed Visible Light Communications Using Multiple-Resonant Equalization', Photonics Technology Letters, 2008, 20, (15), pp. 1243-1245

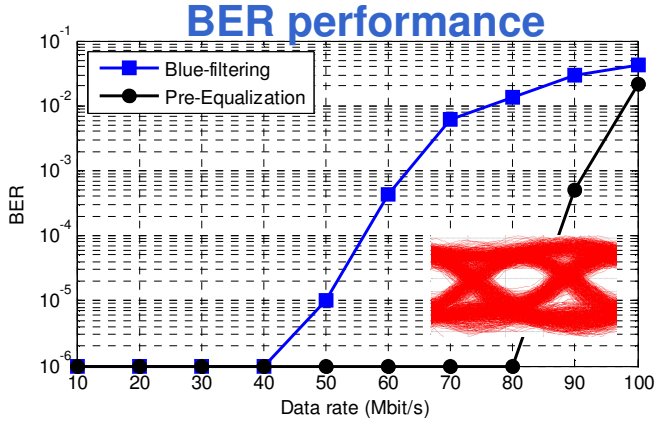
(Pre-) Equalization: Single LED Link

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



VLC link configuration



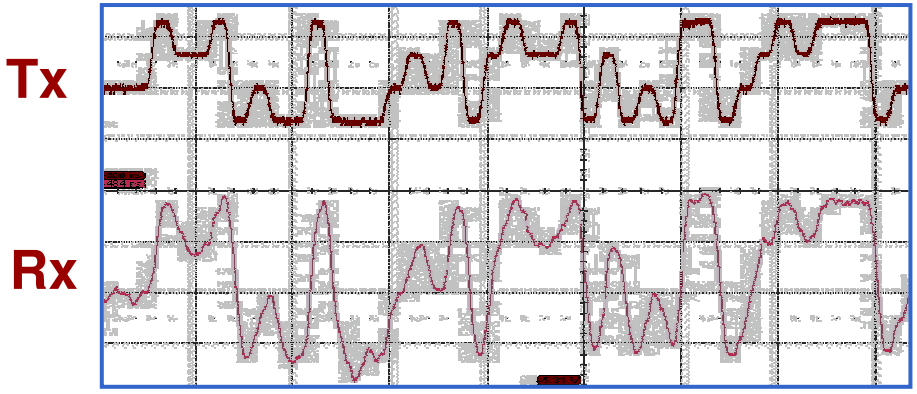


- **45 MHz equalized bandwidth achieved (3 drivers)**
- **80 Mbit/s OOK-NRZ transmission [4]**

[4] 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", accepted for poster presentation at *European Conference on Optical Communications* (ECOC 2008)

Complex Modulation

- **High optical SNR (OSNR)**
  - **Potential for complex modulation**
  - **But**
    - **Driving devices potentially challenging**
- **DMT/OFDM**
  - Link of (equivalent data-rate) 101-Mbit/s is demonstrated using 20-MHz bandwidth [5]
- **M-PAM**
  - Potential (OSNR is high)



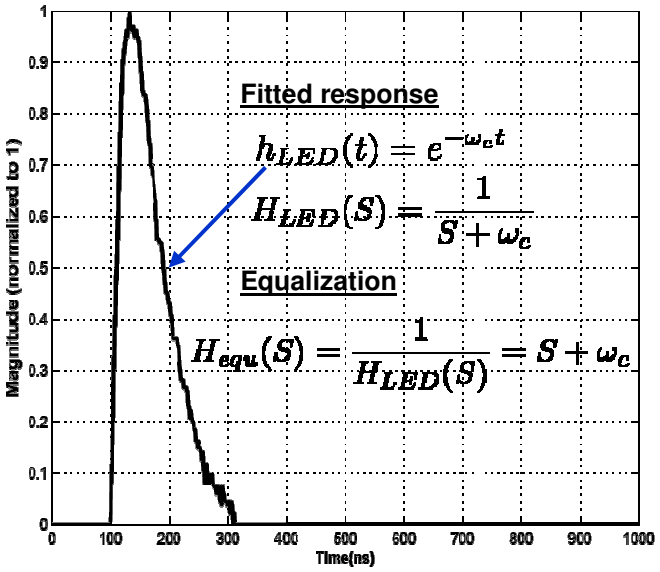
50 Mbit/s 4-PAM VLC link (from [4])

(100 Mbit/s equivalent NRZ rate)

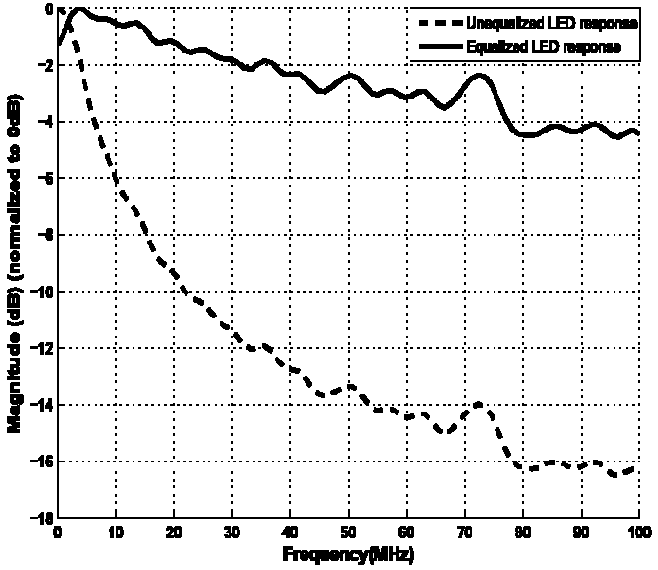
[5] Grubor, J., et al., "Wireless high-speed data transmission with phosphorescent white-light LEDs", Proc. *European Conference on Optical Communications* (ECOC 2007) (PDS 3.6), pp. 1-2. ECO [06.11], Sep. 2007, Berlin, Germany

(Post-) Equalization: LED Impulse Response

- Fall time of devices >> Rise time
  - Equalization of exponential decay



Equalization process



Bandwidth improvement

Equalisation

- Post-equalisation
  - Simulation of 1st order equaliser
  - OOK-NRZ data rate is increased from 16 Mbit/s to 32 Mbit/s [6]
- Pre and post equalisation
  - Resonant LED array+1st order equaliser (simulation)
    - 42Mb/s to 73 Mb/s (using 25MHz bandwidth)

[6] 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

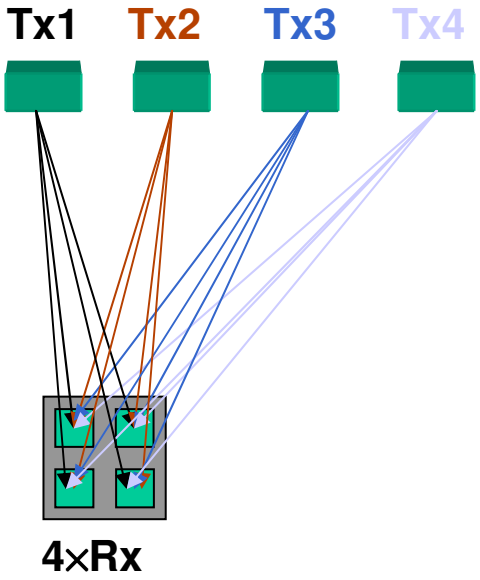
Equalisation summary

- 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
  - Combination of pre-and post offers substantial improvements (in simulation)

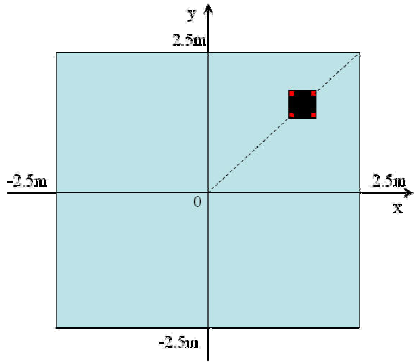
MIMO using VLC

- 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

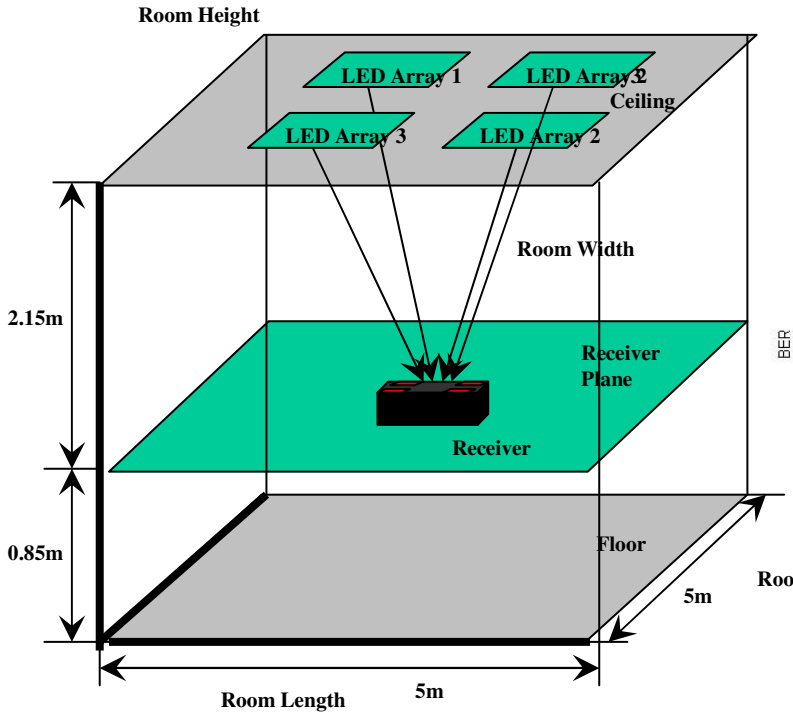


$$H = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H_{21} & H_{22} & H_{23} & H_{24} \\ H_{31} & H_{32} & H_{33} & H_{34} \\ H_{41} & H_{42} & H_{43} & H_{44} \end{bmatrix}$$

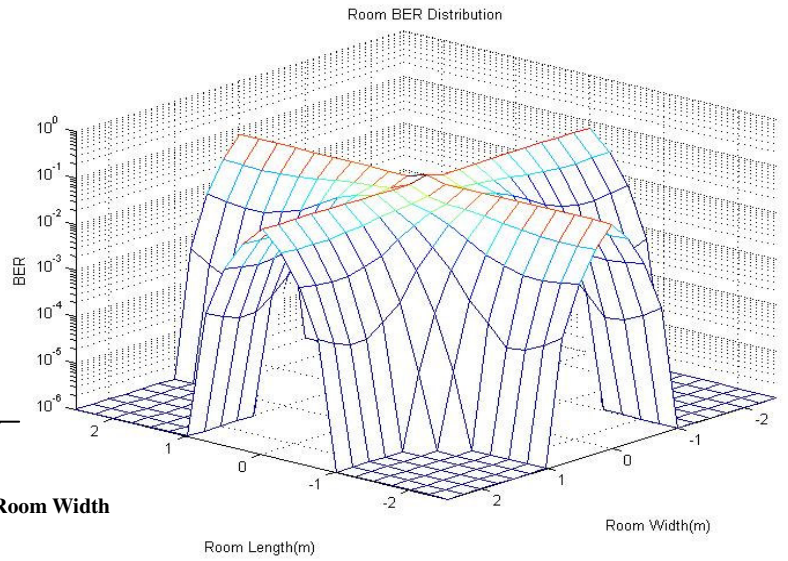


- **Channel matrix *H* needs to be estimated at different receiver positions**
- **Simulation shows that data rate is linearly increased if *H* is full rank**
- **Geometric symmetry can reduce rank-MIMO does not work**

MIMO System: Room Test Performance



(a)



(b)

- 4 x 20 Mb/s channels
- Aggregate 80Mb/s transmission
- Low BER except ‘lines of symmetry’

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
  - Comparison of alternatives