

Visible light communications: achieving high data rates

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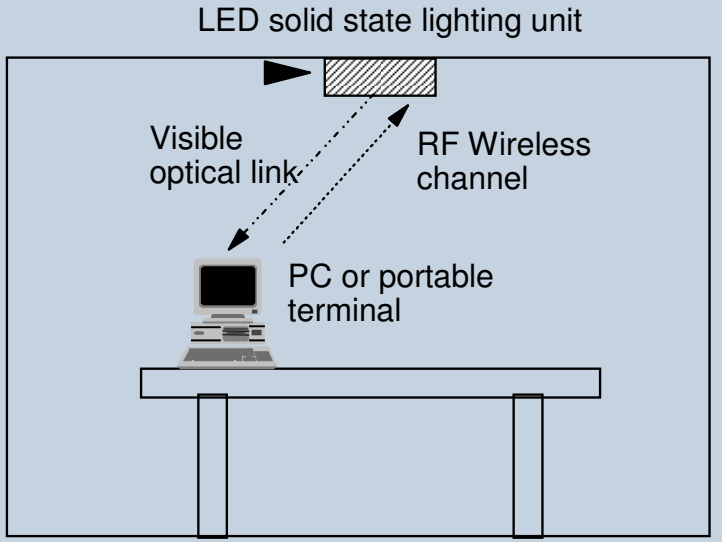
Introduction

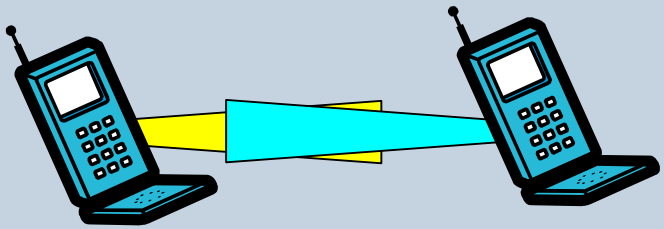
- Overview and applications
- The Visible Light Communications Channel
- Approaches to high data rates
  - Complex modulation
  - Equalisation
  - Multi-input multi-output systems
    - Parallel communication
    - MIMO
    - Spatial modulation
  - High-speed sources
- Future directions
  - Cooperative systems
- Conclusions

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Visible Light Communications: Introduction

- Two major applications areas
  - Augmenting existing functions
    - Illumination and data transmission
    - University of Edinburgh/Jacobs university
    - OMEGA: Gigabit Home Networks (www.ict-omega.eu)
    - University of Oxford
  - Using visible light as it has advantages
    - Plastic optical fibre (not considered)
    - Visible data links
      - Alignment/safety
      - Wavelength well suited to CMOS detection
      - University of Strathclyde/University of Glasgow





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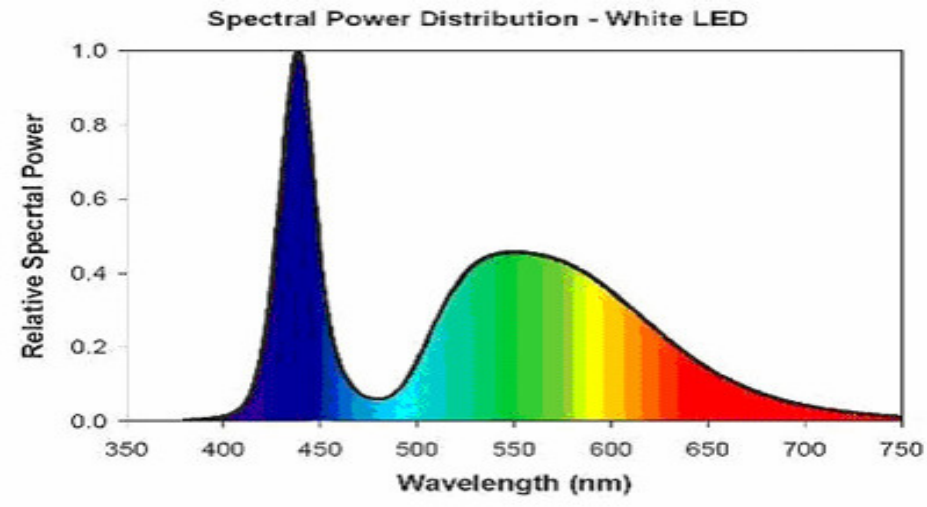
THE VLC CHANNEL

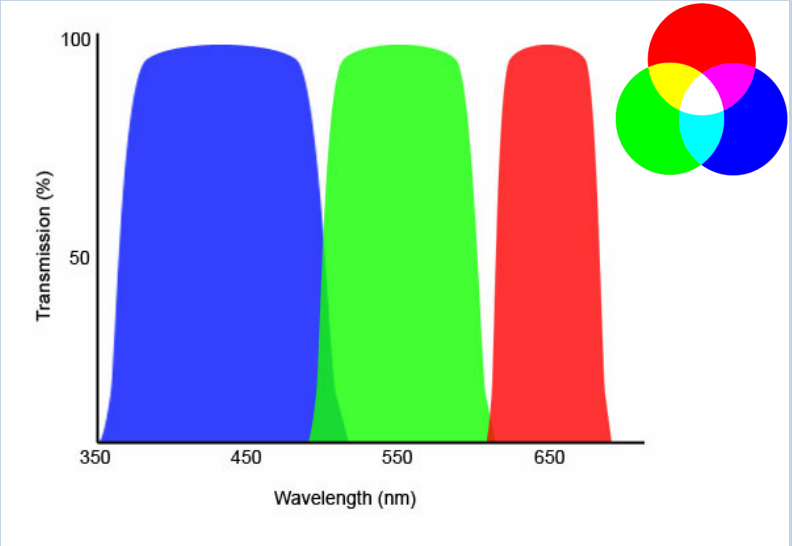


VLC: Sources (1)

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

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

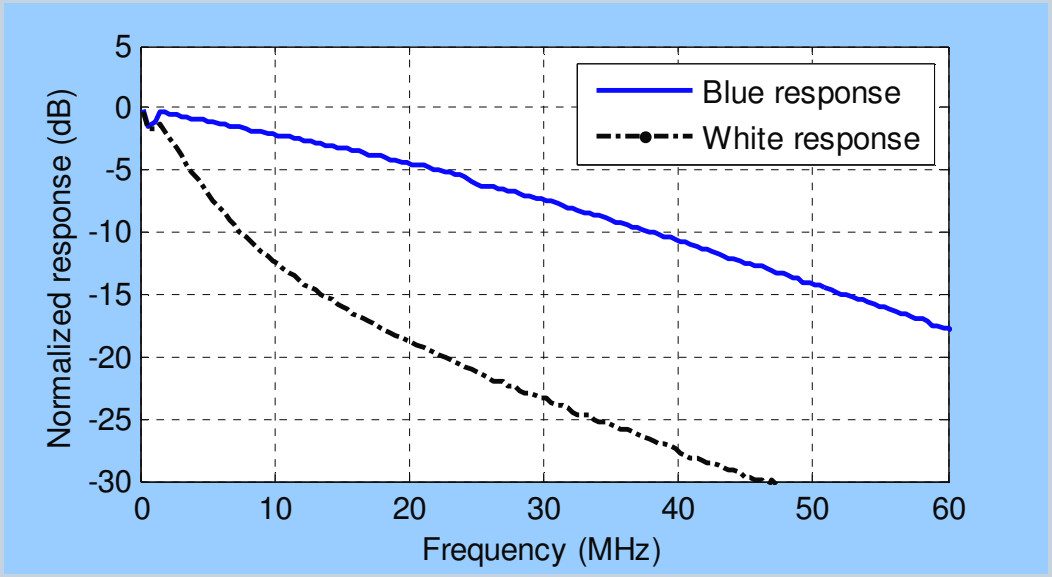




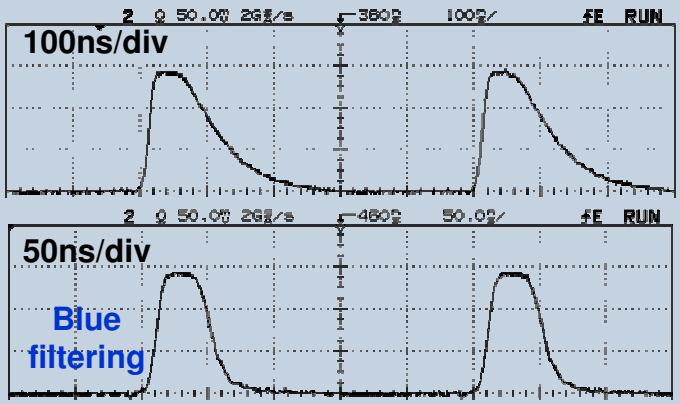
Consider phosphor sources here as more likely to be used in general illumination

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VLC: Sources (2)



LED frequency response



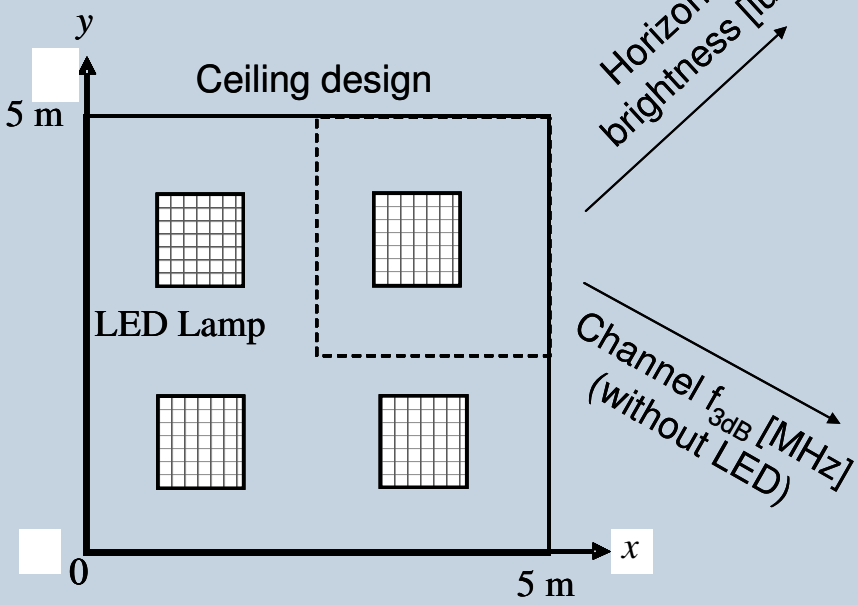
LED temporal (impulse) response

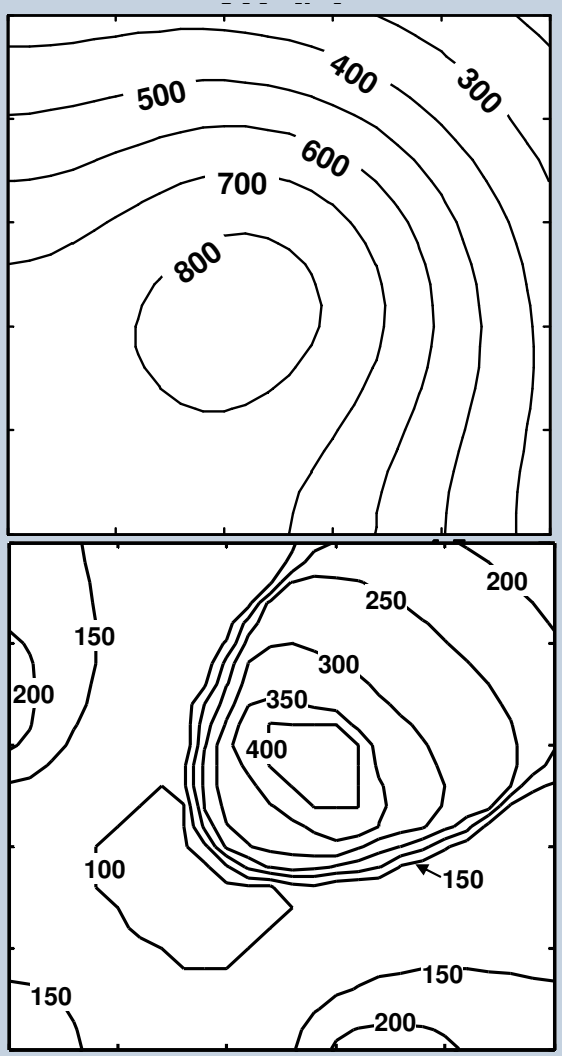
(1) Intrinsic LED modulation bandwidth is narrow (~2-3 MHz)

(2) Blue component offers wider bandwidth (~12MHz)

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VLC: Channel





J. Grubor, S. Randel, K. D. Langer, and J. W. Walewski, "Broadband information broadcasting using LED-based interior lighting," *Journal of Lightwave Technology,* vol. 26, no, 24, pp. 3883-3892 2008.

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OMEGA

SEVENTH FRAMEWORK PROGRAMME

work from HHI, Siemens

VLC: Receiver and summary

- Straightforward to build receivers with 10s-100MHz of bandwidth
- Resulting communications channel
  - Bandwidth limited by the LED
    - Few MHz for the white LED
    - 10 MHz for the blue part of the spectrum
  - Very high signal to noise ratio (>50dB for typical illumination/configurations)

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VLC: Increasing information rate

- Channel
  - Bandwidth limited by LED (~10s of MHz)
  - Very high signal to noise ratio
- Increasing information rate
    - Complex modulation
    - Equalisation
    - Parallel (MIMO) communication
- Other considerations
  - Dimming and control

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Complex modulation

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VLC: Complex modulation

- Orthogonal Frequency Division Multiplexing (OFDM)
- 'Standard' used in copper broadband (DSL), and most wireless communications
- Pursued by (not an exhaustive list)
  - OMEGA project
    - HHI, Siemens
    - 100 Mbit/s multimedia streaming (online)[1]
    - 513Mbit/s achieved[2] at 1000 lux (offline processing)
  - "D-Light" project Edinburgh University
    - Commercial transceiver module – target 100 Mb/s
- University of Oxford
  - MIMO-OFDM
  - Monash University and others

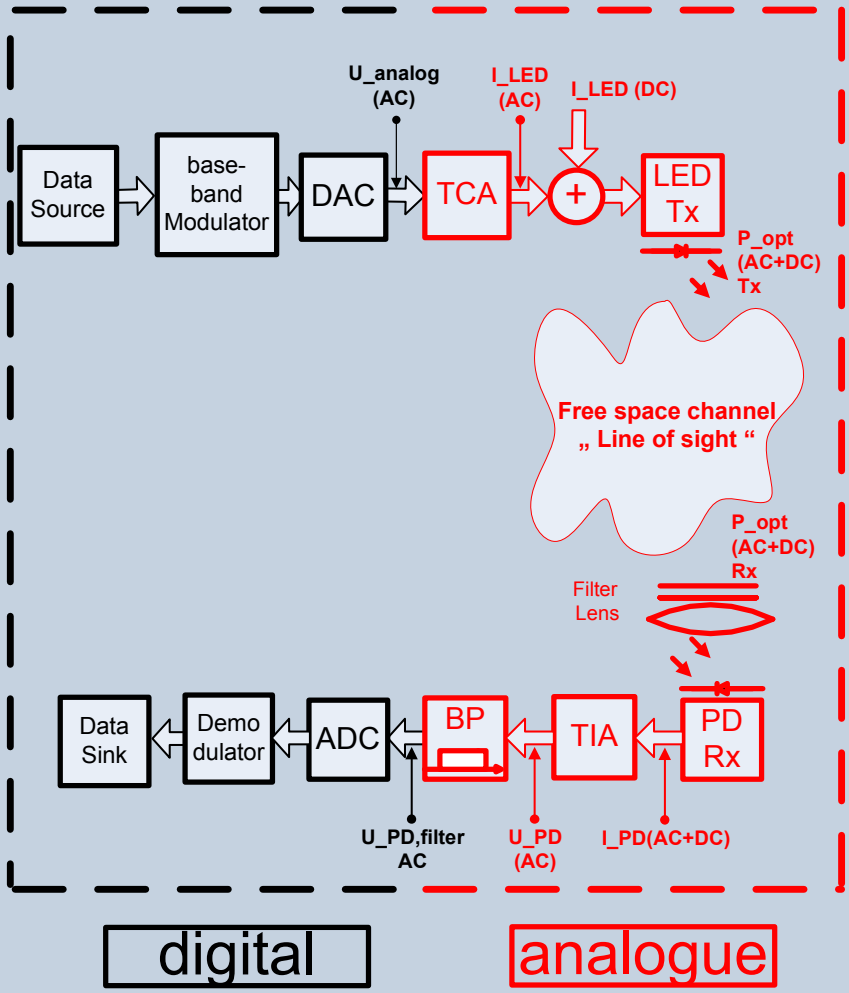
[1] Visible-light communication system enabling 73 Mb/s data streaming
Olivier Bouchet Mike Wolf Thomas Kamalakis Klaus-Dieter Langer (Heinrich-Hertz-Institut, Germany); Stefan Nerreter (Joachim W. Walewski Liane Grobe Pascal Porcon Georgia Ntogari Luz Fernández Eric Gueutier Jelena Vucic (Fraunhofer
[2] J. Vucic, C. Kottke, S. Nerreter, K.-D. Langer, and J. W. Walewski, "513 Mbit/s Visible Light Communications Link Based on DMT-modulation of a White LED" Journal of Lightwave Technology 2010.

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VLC: Complex modulation

- System configuration
  - Transmitter
    - Multi-symbol modulation (OFDM)
  - Receiver
    - Use blue component of LED emission (filter)
    - Amplifier
    - Demodulator

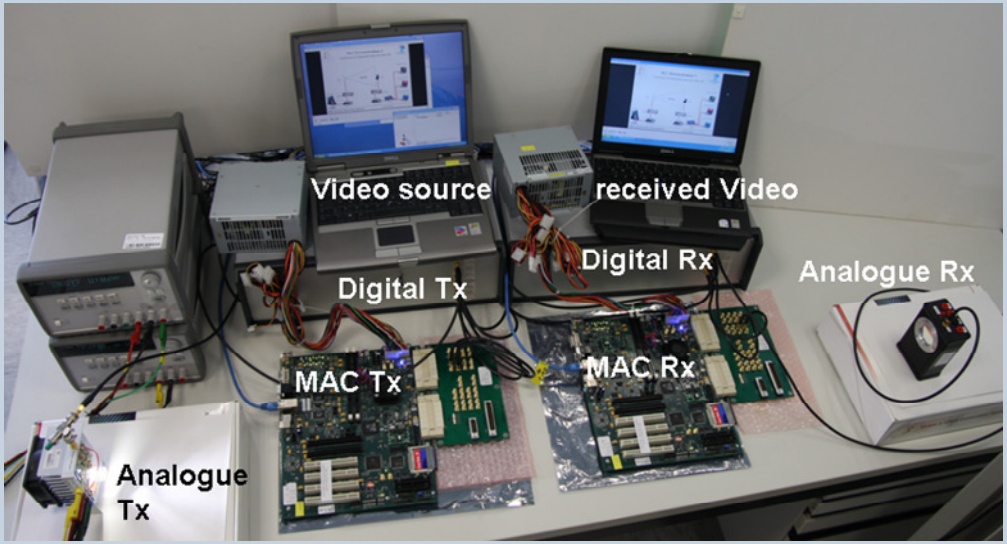
- DAC : Digital Analog Converter
- ADC : AnalogDigital Converter
- TCA : Trans Conductance Amplifer
- TIA : Trans Impedance Amplifer
- PD : Photo Diode
- LED : Light Emitting Diode
- BP : Band Pass



work by HHI, Siemens, University of Athens, France Telecom, Apside

VLC Video Streaming @ 100 Mbit/s

- Off-the-shelf LEDs & PIN-PD
- DMT using 31 el. subcarriers w. 16-QAM (BW 30.6 MHz)
- FPGA implementation: FEC Mod./Demod, Ethernet MAC
- 1.4 m reach @ 500 lux
- Demo setup using low-cost key components



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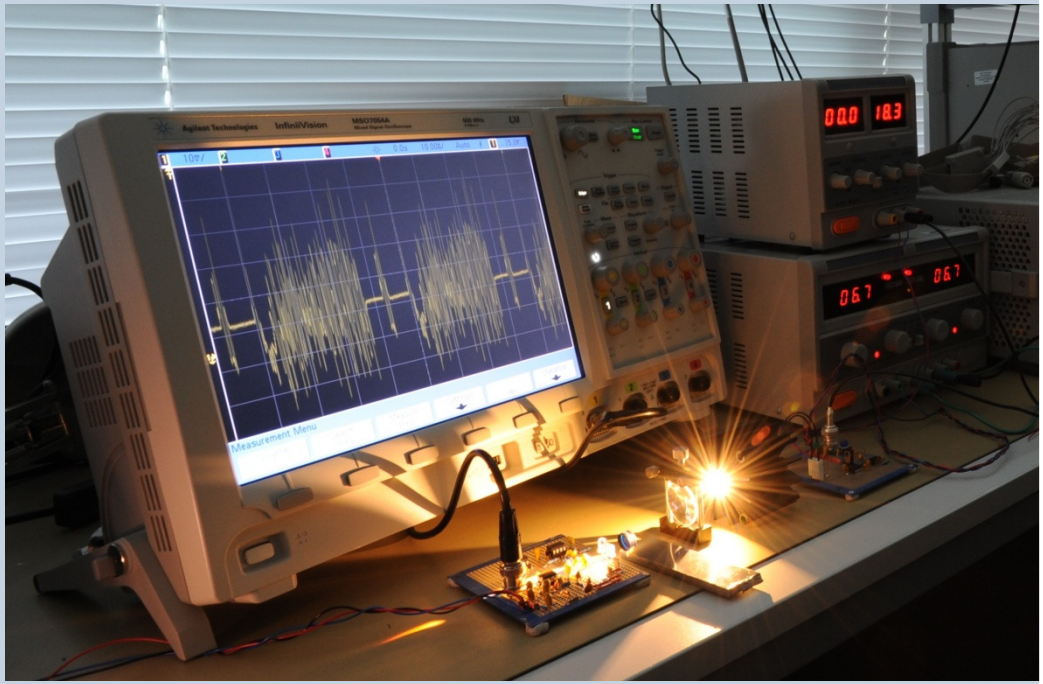
OMEGA

SEVENTH FRAMEWORK PROGRAMME

work by HHI, Siemens, University of Athens, France Telecom, Apside

D-Light (Edinburgh University): Optical wireless transceiver module

- Subcarrier index modulation (SIM) – OFDM
  - Reduced PAPR (peak-to-average power ratio)
  - Less non-linear distortions
  - Reduced power backoff
  - Good trade-offs between coverage, power efficiency and spectral efficiency
- Off-the-self components
- Ongoing demonstrator development developed based on Xilinx Vertex 6
- Target rates: 100 Mbps at 5 m



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work by the University of Edinburgh

Complex modulation: challenges

- Implementation complexity
  - Similar to widely used standards
- LED nonlinearity
- Peak to average power ratio
- Work to address this
  - Edinburgh/Jacobs University[1]
  - OMEGA project [2]

[1] H Elgala, R Mesleh , H Haas, “Modeling for Predistortion of LEDs in Optical Wireless Transmission using OFDM“, Proc. of the IEEE International Conference on Hybrid Intelligent Systems (HIS), 2009
[2]. Thomas Kamalakis, Joachim W. Walewski, Georgia Ntogari, and Gerasimos Mileounis. Empirical Volterra-Kernel Modeling of Commercial Light-Emitting Diodes. *Submitted to JLT.*

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Equalisation

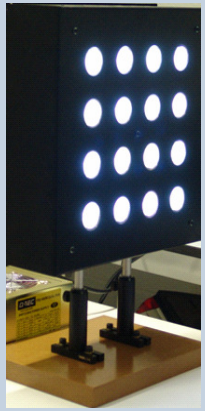


Equalisation

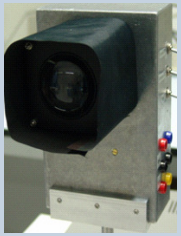
- OFDM schemes use equalisation in digital domain
- Analogue circuit equalisation
  - More compatible with simple On-Off Keying Schemes
  - Can use simple analogue transmitter and receiver designs
- Transmitter (pre) equalisation
- Receiver (post) equalisation

VLC: pre-equalisation

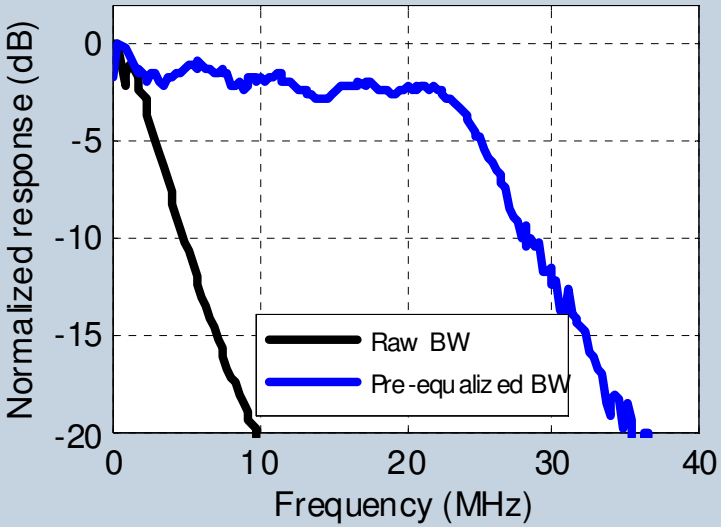
- Equalise each emitter in array separately
- Aggregate bandwidth increase
- 40Mbit/s NRZ-OOK over several metres

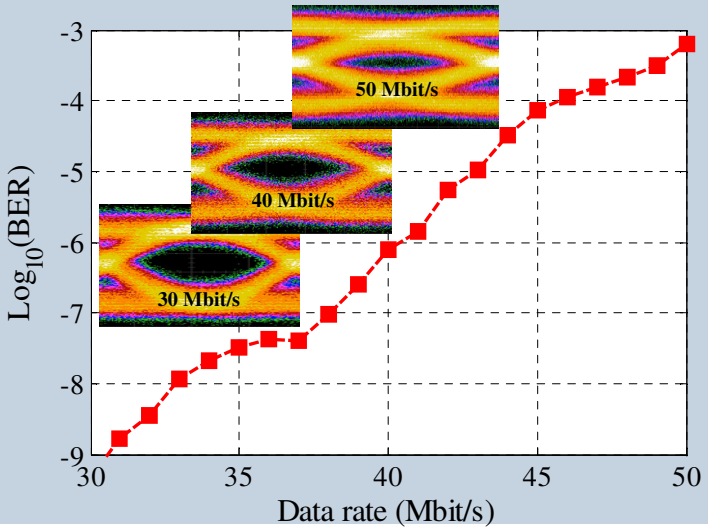


Transmitter



Receiver



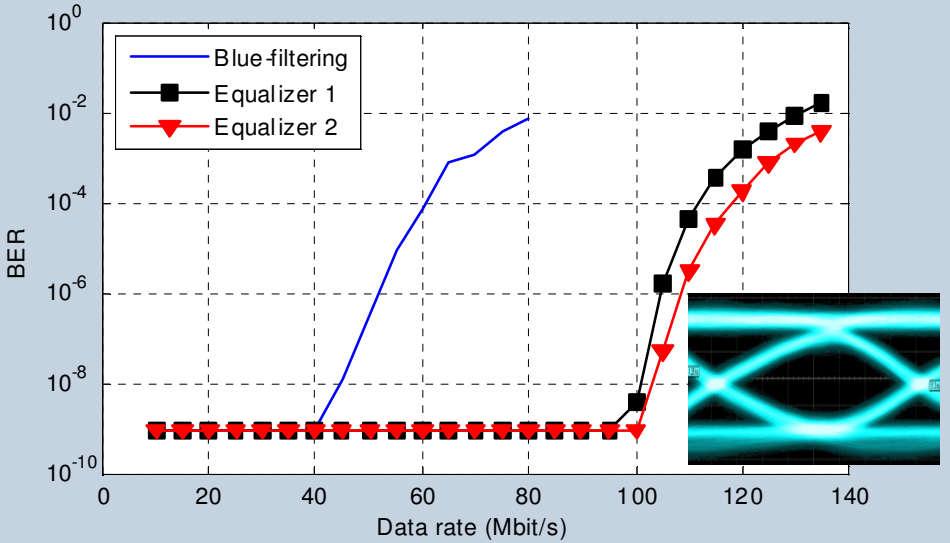


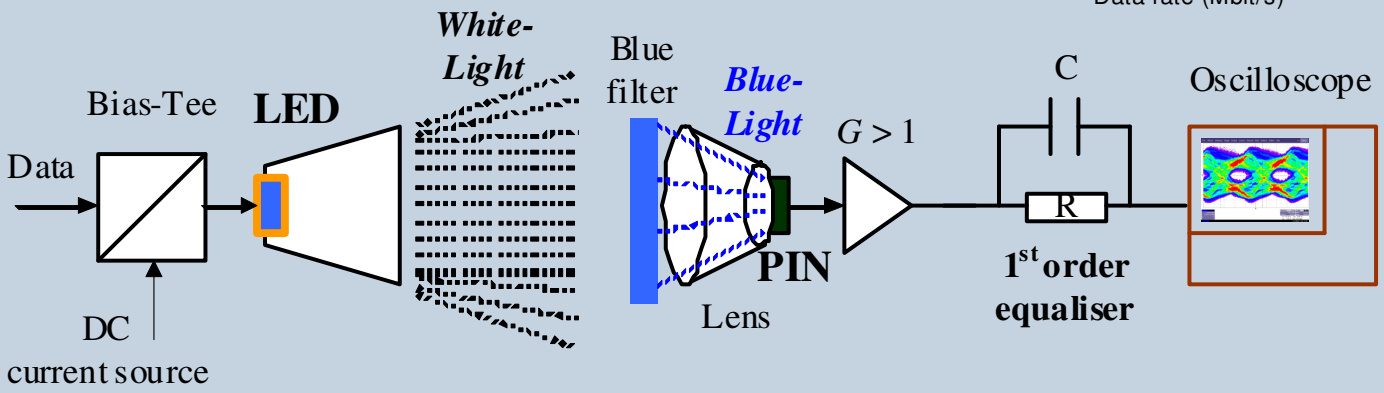
H. Le-Minh, O'Brien-Dc, G. Faulkner, L. Zeng, K. Lee, D. Jung, and Y. Oh, "High-Speed Visible Light Communications Using Multiple-Resonant Equalization," *Photonics Technology Letters,* vol. 20, pp. 1243-1245, 2008.

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VLC: post-equalisation

- Blue-filtering removes slow yellow component
- Simple receiver equalisation
- 100Mbit/s NRZ-OOK
- High illumination levels required





Le Minh, H., et al., 100-Mb/s NRZ Visible Light Communications Using a Postequalized White LED. Ieee Photonics Technology Letters, 2009. 21(15): p. 1063-1065.

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Optical MIMO

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MIMO: VLC based systems

- Many sources offers the potential for parallel data transmission
  - 1Gb/s parallel ‘proof-of concept’ by Keio University
    - 576LED array @5Mbit/s
    - 256 Element receiver array
- Using Multi-Input Multi-Output techniques from radio communications removes need for alignment

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Indoor MIMO: investigations

- Multi-spot configurations
  - Penn State[1]
- Diffuse
  - Drexel University[2]
  - Edinburgh University [3]-spatial modulation
- Line of sight
  - McMaster University[4]- liquid crystal display and camera
  - Monash University [5]- spatial OFDM
  - Oxford[6]

[1] S. T. Jivkova and M. Kavehrad, IEEE Transactions on Communications, vol. 48, pp. 970-978, 2000

[2] Garfield-M, Chao-Liang, Kurzweg-Tp, and Dandekar-Kr, *Microwave and Optical Technology Letters,* vol. 48, pp. 1108-10, June 2006.

[3] Mesleh, R.; Elgala, H.; Mehmood., R.; Haas, H. IEEE Communications Letters, vol.: 15, 2011, pp.: 79 – 81.

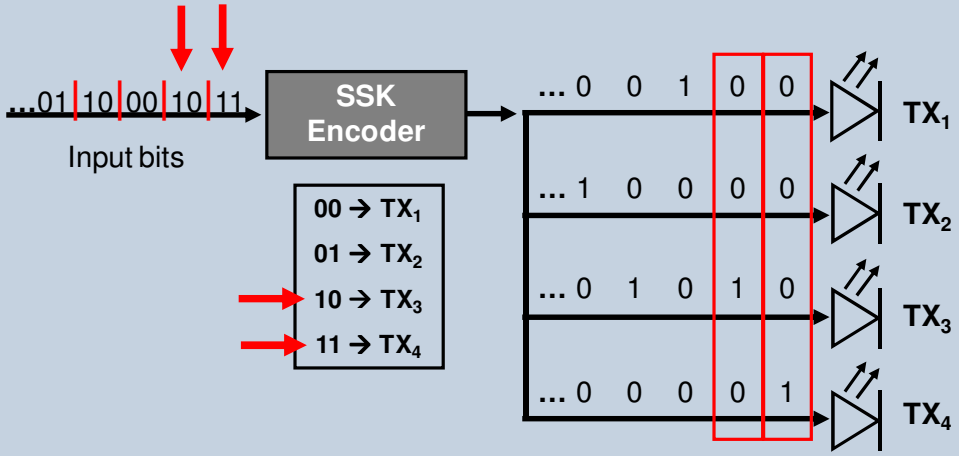
[4] S. Hranilovic and F. R. Kschischang, presented at 2004 IEEE International Conference on Communications. Vol.2 20 24 June 2004 Paris, France, 2004.

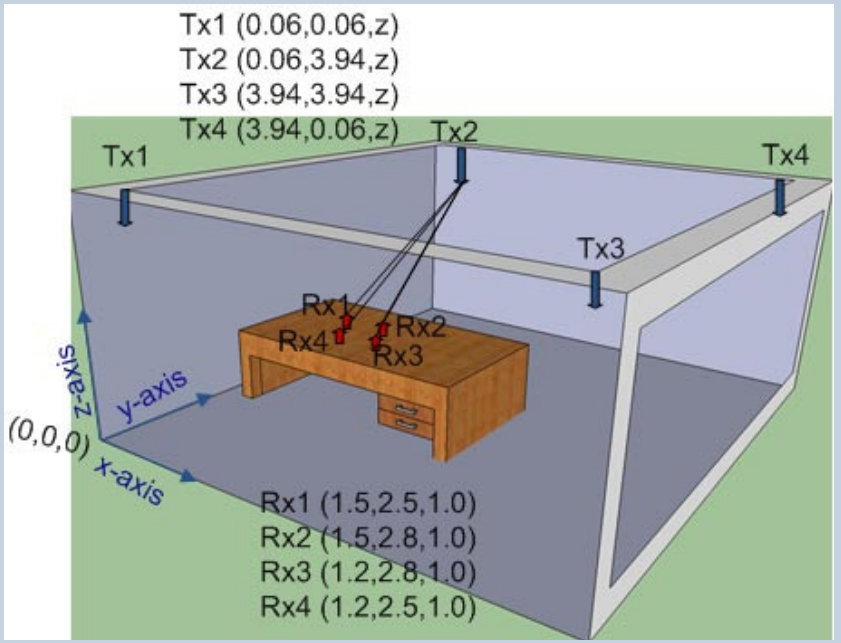
[5] R. Mondal, J. Armstrong, K. Panta. Performance of Two Dimensional Asymmetrically Clipped Optical OFDM, in Globecom 2010.

[6] D. C. O'Brien, S. Quasem, S. Zikic, and G. E. Faulkner, in *Free-Space Laser Communications VI*, 2006, p. 630416.

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Optical Spatial Modulation (OSM)

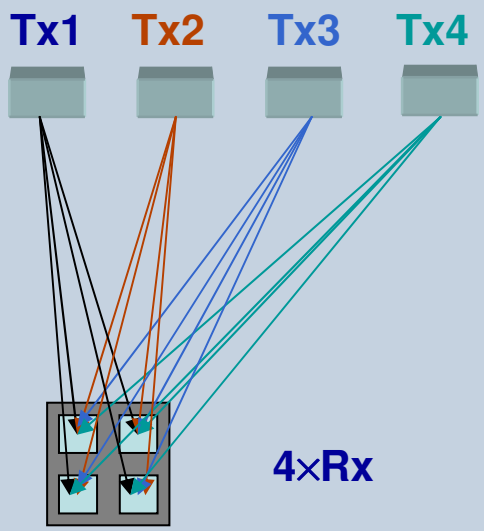




4x4 OSM achieves same BER performance as OOK, but at **double** data rate

work by the University of Edinburgh

MIMO: Principle of operation



$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H_{21} & H_{22} & H_{23} & H_{24} \\ H_{31} & H_{32} & H_{33} & H_{34} \\ H_{41} & H_{42} & H_{43} & H_{44} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}$$

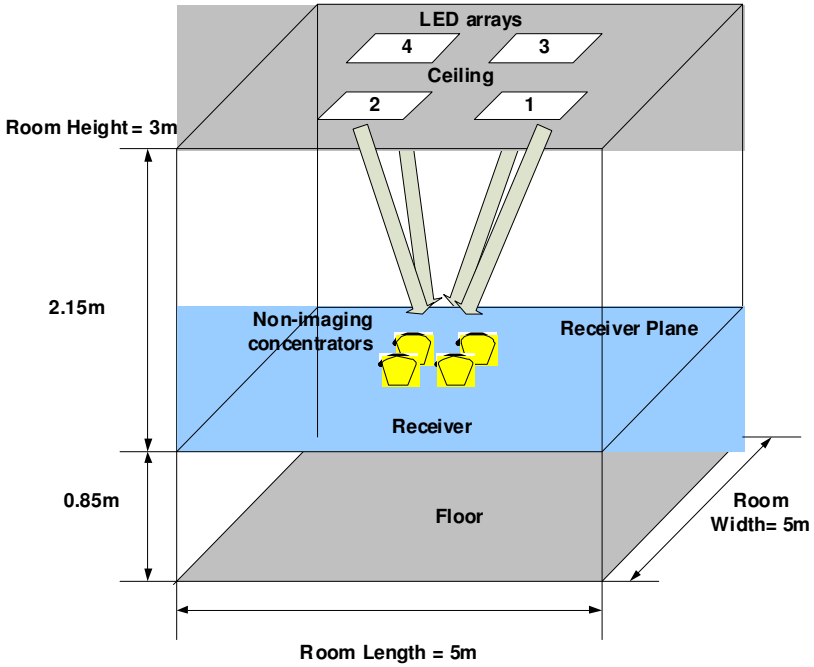
$$\mathbf{R} = \mathbf{HT}$$

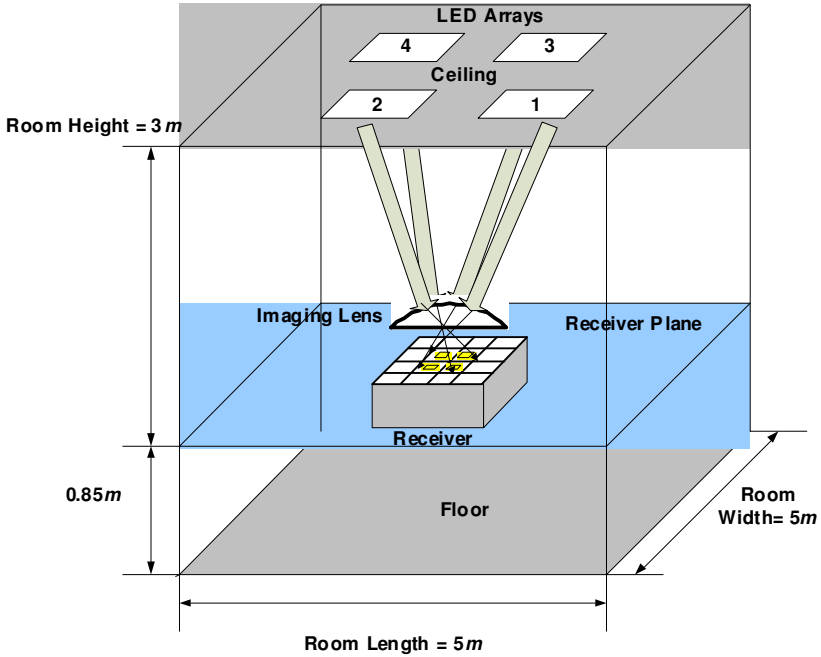
$$\mathbf{T}' = \mathbf{H}^{-1}\mathbf{R}$$

- Step 1
  - Determine H by training
- Step 2
  - Determine estimate on transmitted signal T’ by H^{-1} or equivalent

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MIMO System different geometries

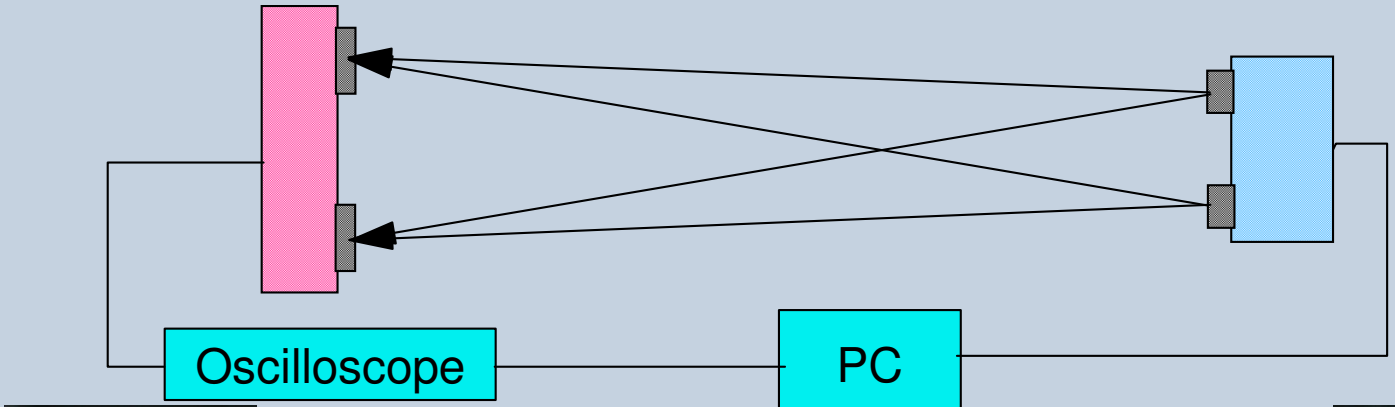


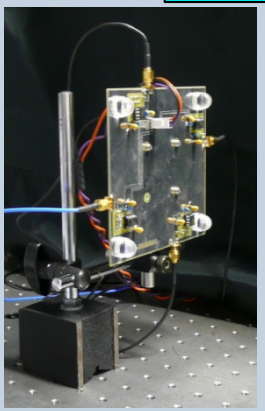


- Non imaging geometry
  - Receivers simple ‘photon buckets’
  - Robust to alignment
  - Channel matrix ill conditioned
- Imaging geometry
  - Receiver
  - Imaging lens
  - Array of detectors
  - Channel matrix well conditioned

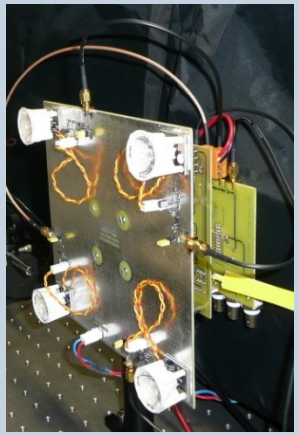
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MIMO system: Non imaging demonstration





Up to 1m



Four channel receiver

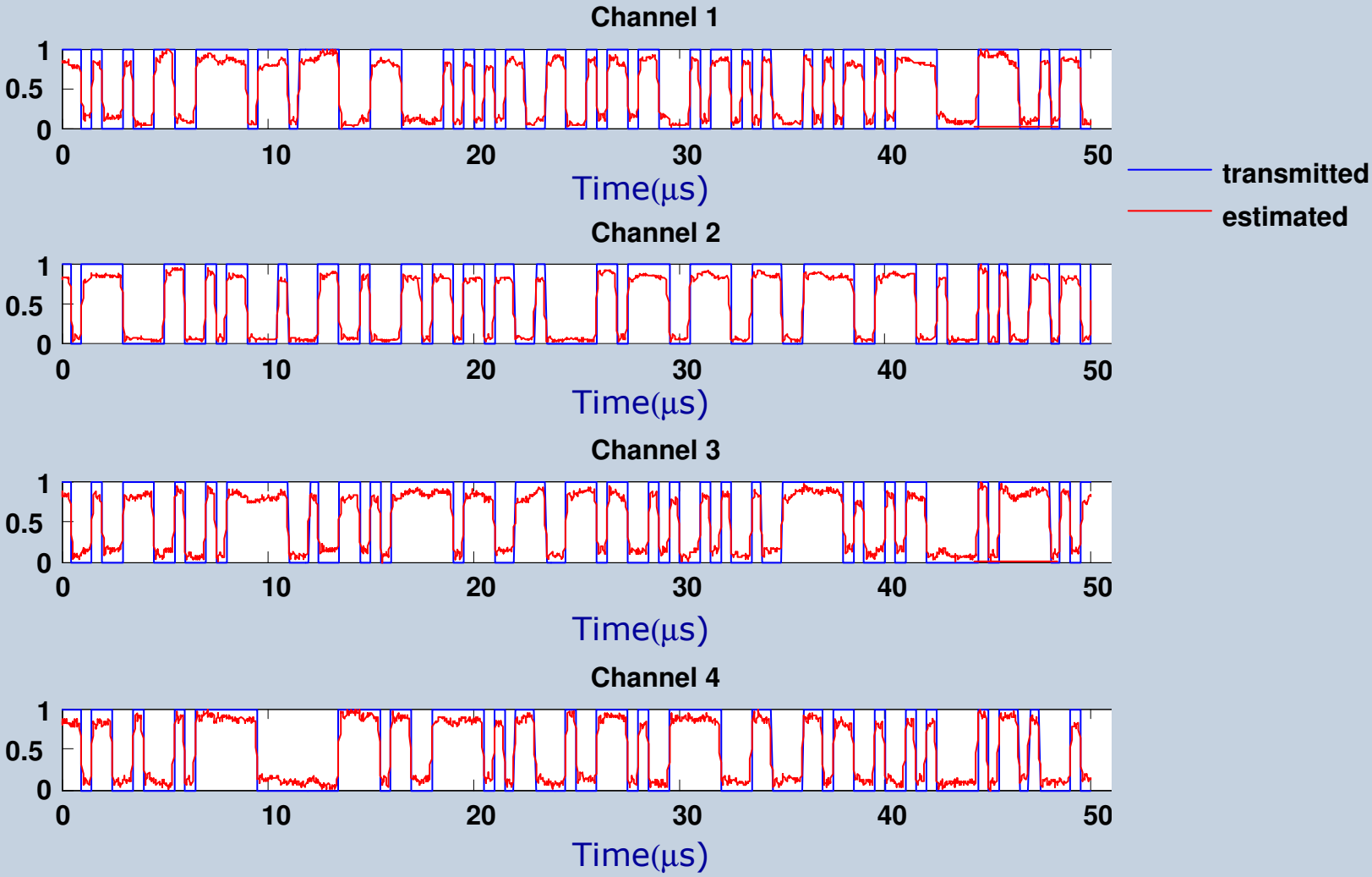
White-Light LEDs

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MIMO: data processing

- *H*-matrix
  - Each LED emits training sequence in turn
  - Signal strength at each receiver measured
  - No channel decorrelation
  - Stable as power detection
- Estimating the data
  - Send data sequence on all transmitters simultaneously
  - Record data on oscilloscope
  - Obtain estimates by simple matrix inversion
    - Much more sophisticated techniques available

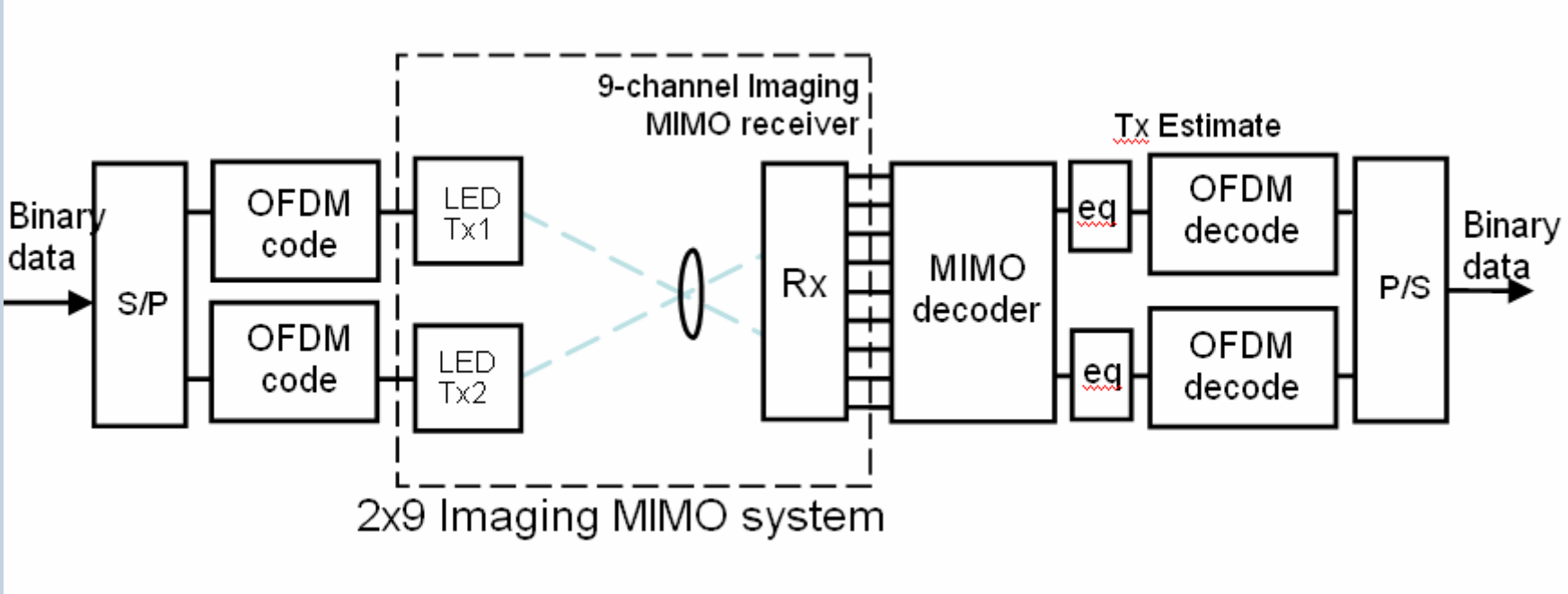
MIMO system: results



Estimated and transmitted waveforms for 2Mbit/s/channel data

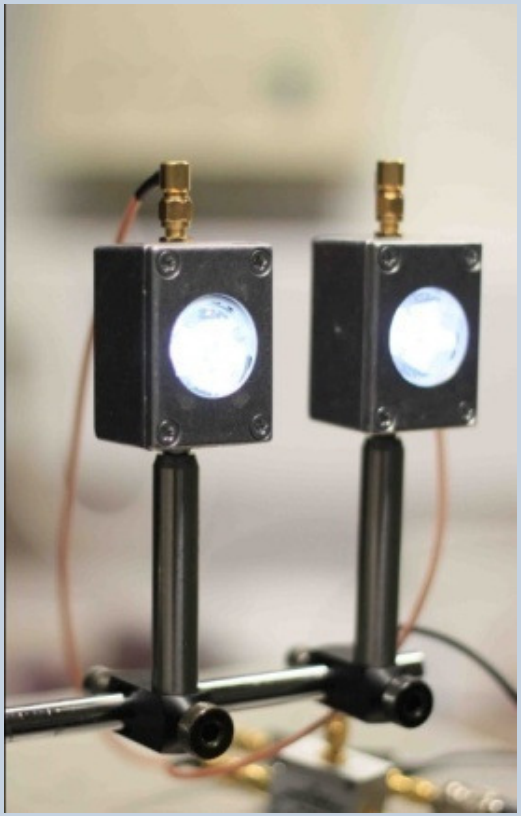
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MIMO system: imaging demonstration

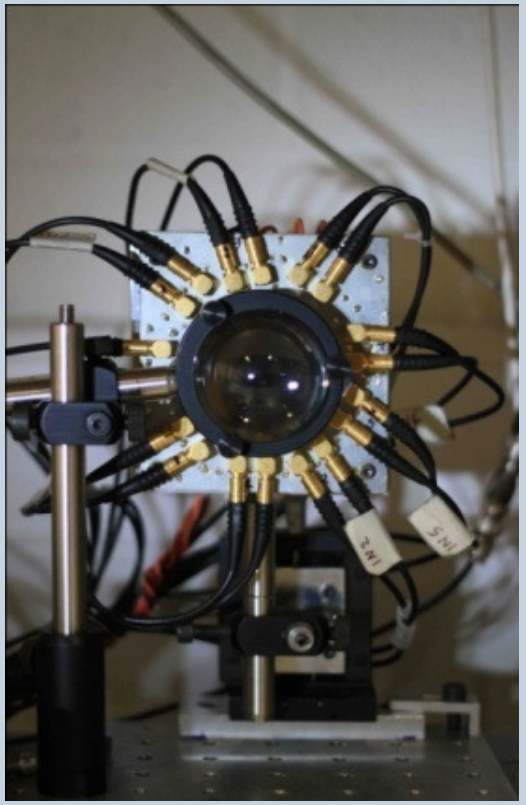


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Experimental apparatus



2 channel transmitter

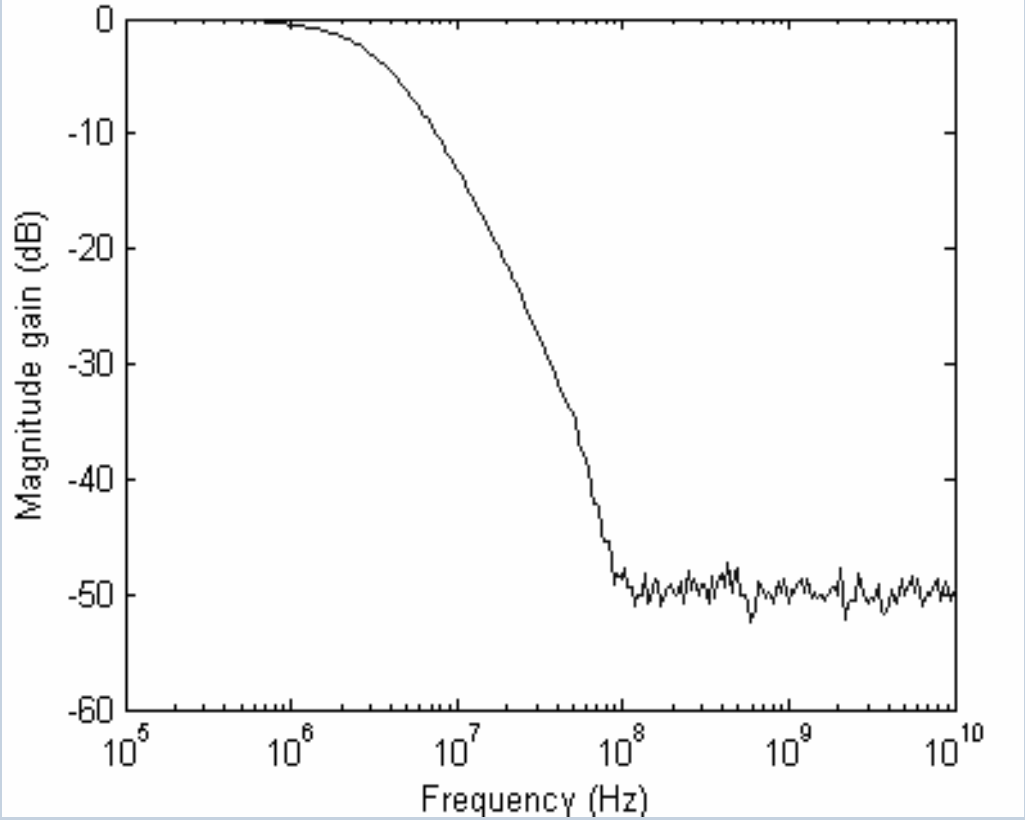


9 channel receiver

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Channel Characteristics

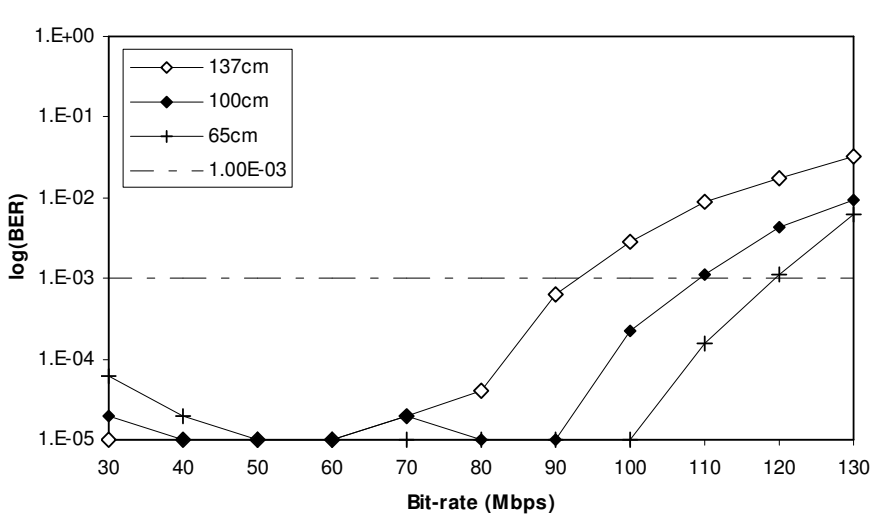
- White channel used
- Luxeon star emitter
  - 2MHz bandwidth
- Receiver
  - ~40MHz bandwidth
- Signal to noise ratio
  - 400 lux illumination at receiver
  - ~88dB SNR over lowest 2MHz
  - ~30-40dB SNR at 70MHz
- Not limited by SNR



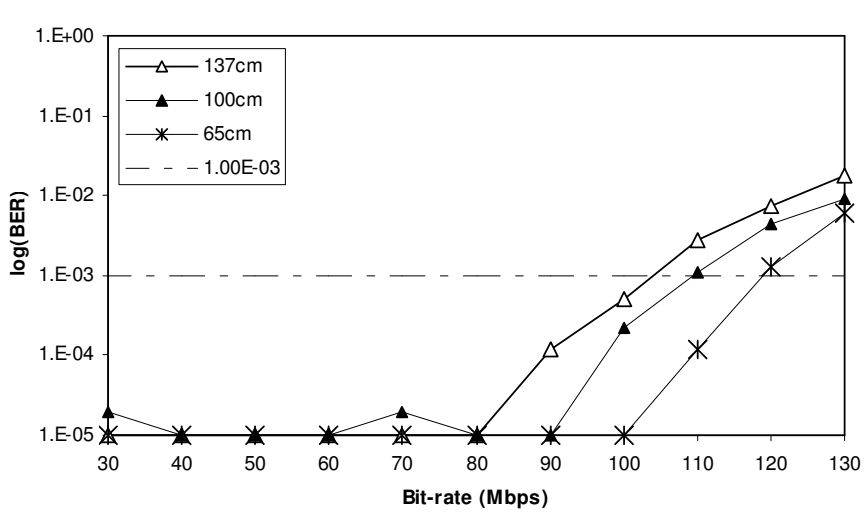
Channel frequency response

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Results – Transmission rate



Channel 1



Channel 2

Aggregate data rate of 220Mbit/s@1m achieved

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High speed sources

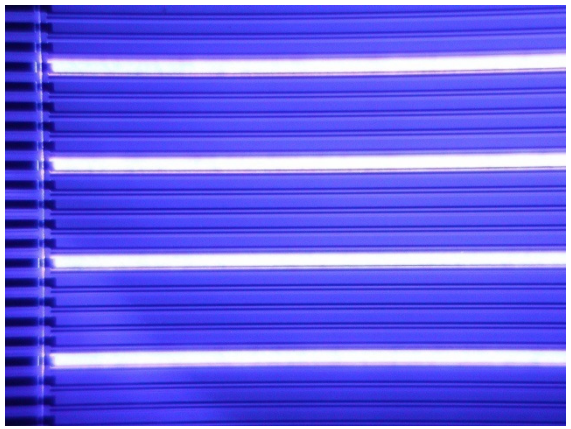
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High speed visible sources

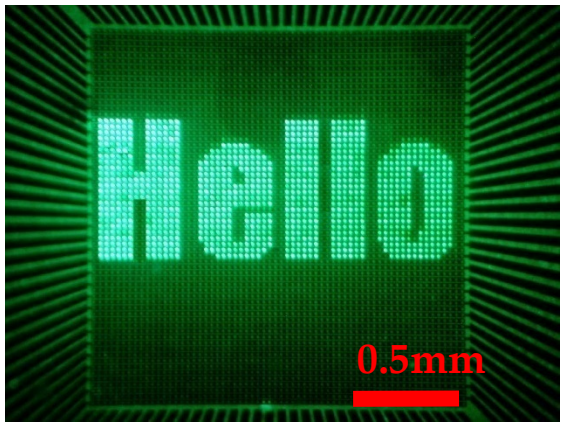
- Lighting focuses on small number of large high power Gallium Nitride (GaN) LEDs
  - Low bandwidth,high power
- Alternative approach
  - Arrays of small devices
    - Low power, high bandwidth devices
    - Power from aggregation
- Pursued by University of Strathclyde (Institute of Photonics) and University of Glasgow

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Micro-LED design



Micro-stripes

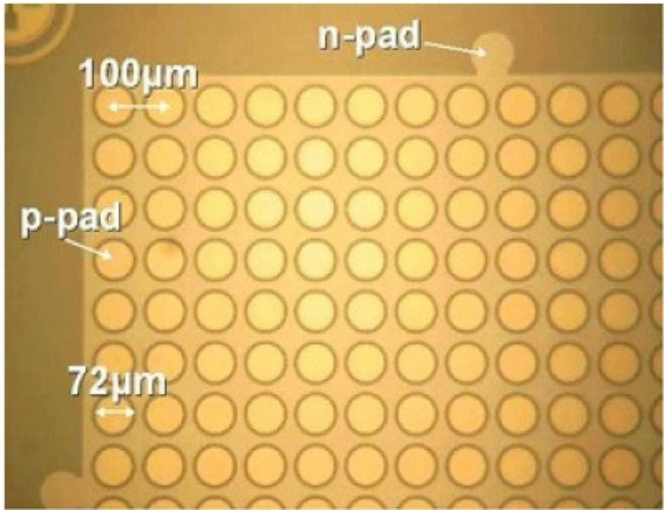


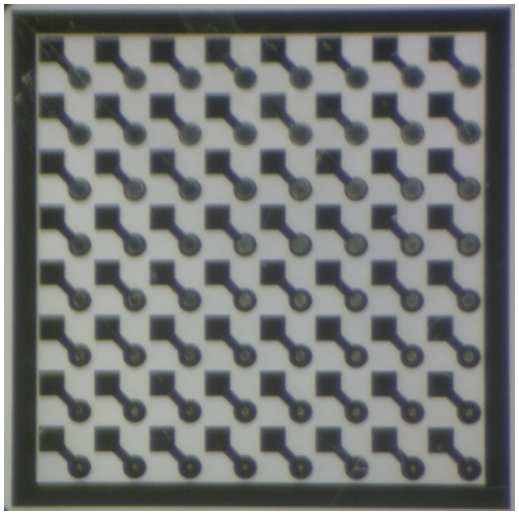
Matrix-addressable

- III-nitride based
- Commercial wafers grown on sapphire
- **UV** (370nm), **violet** (405nm) **blue** (450 and 470nm) and **green** (520nm)
- Patterned by photolithography

Work from Universities of Strathclyde and Glasgow

Micro LED arrays





16 × 16 array

- 72µm diameter
- 100µm pitch
- 370, 405, 450nm emission

8 × 8 array

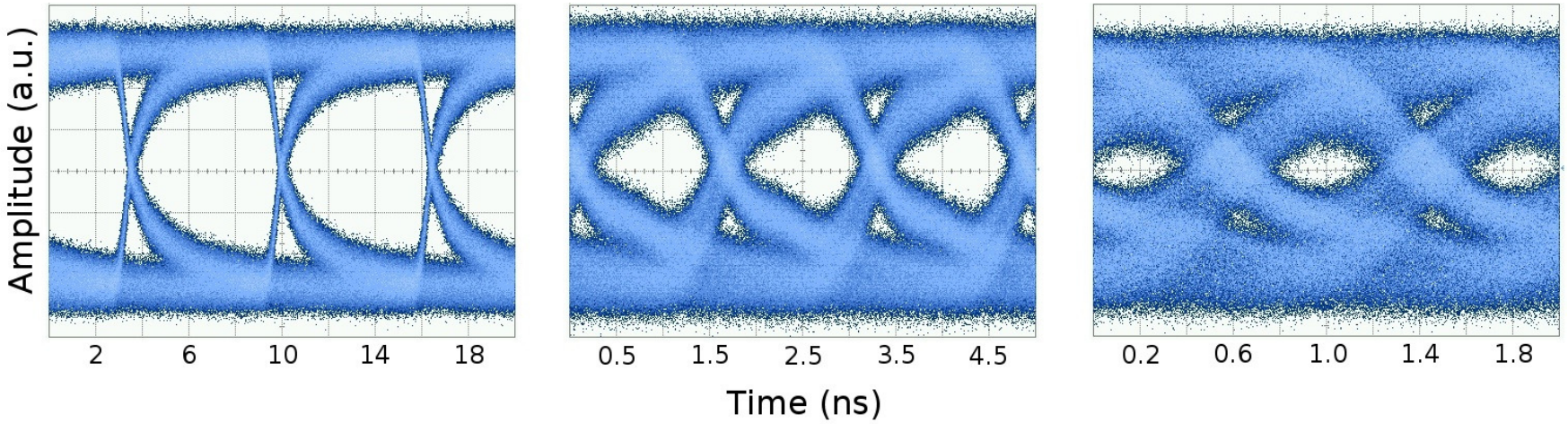
- 10, 20…80µm diameter
- 200µm pitch
- 370, 405, 450, 520, 560nm emission

Maximum DC output powers of up to 6 mW per (72µm diameter) pixel

Work from Universities of Strathclyde and Glasgow

Data transmission

- Non return to zero data transmission
- 520nm, 34µm diameter micro-LED
- Data rates of 1.2Gbit/s (with some eye closure)
- Error free data transmission achieved for 1.1 Gbit/s (for pattern lengths of 2^7-1 and 2^9-1).



155 Mbit/s 622 Mbit/s 1.2 Gbit/s

J McKendry *et al. "High Speed Visible Light Communications Using Individual Pixels in a Micro Light-Emitting Diode Array,* IEEE PTL, **21**, 1346 – 1348.

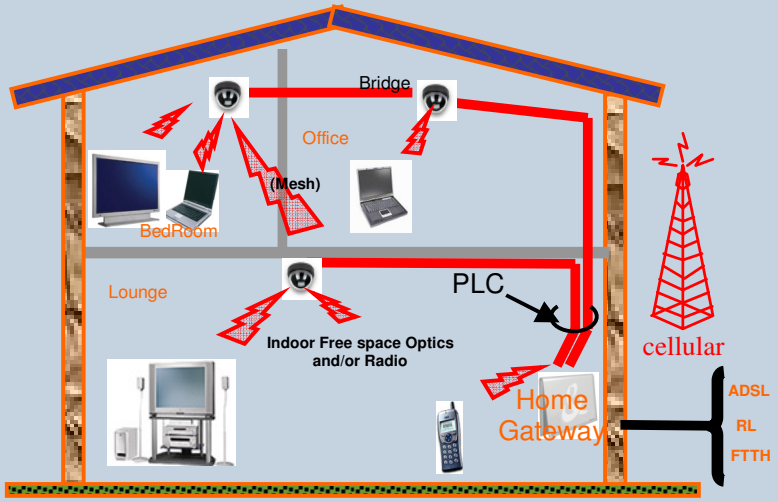
Work from Universities of Strathclyde and Glasgow

Future directions and conclusions

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Cooperative wireless: Omega project

- Increasing interest in Fibre to the Home, Passive Optical Networks
  - Data rates of 100Mbit/s and above
  - Requirement for a Home Access Network (HAN) with Gbit/s order data rates
  - HAN should be
    - Wireless
    - 'Invisible to the user'
  - OMEGA project
    - Different wireless standards (RF and Optical)
    - Intelligent 'InterMAC' to control
    - 21 partners
    - Finishing March 2011
  - Optical wireless
    - Visible Light Communications broadcast
    - Infra-red networking





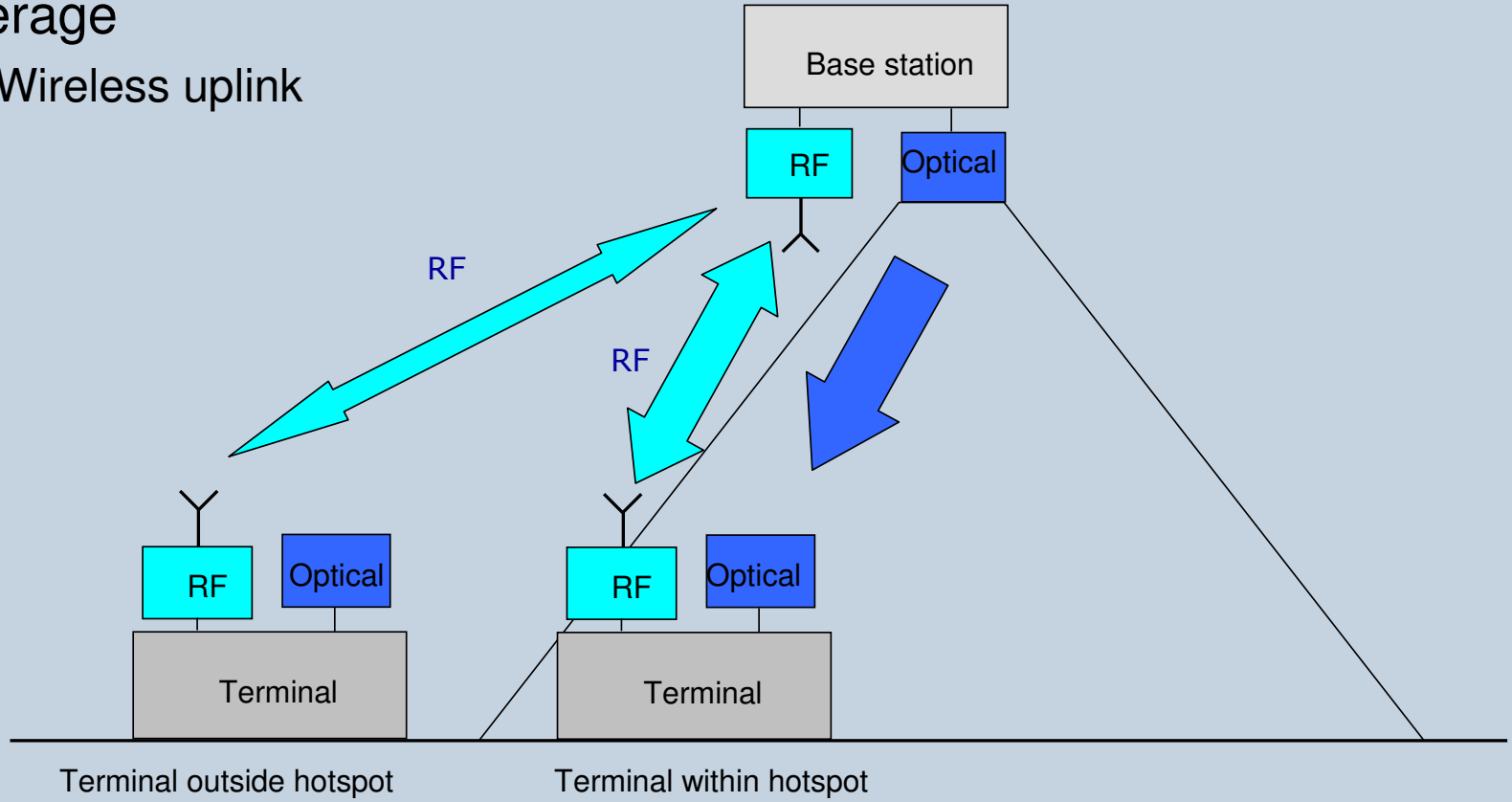
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OMEGA

SEVENTH FRAMEWORK PROGRAMME

Cooperative wireless: optical hotspots

- VLC downlink only
- Most areas have WiFi or other coverage
  - Wireless uplink



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Future directions and conclusions

- High data rates definitely feasible
  - 100s-1000s Mbit/s using ‘normal to bright’ levels of illumination
- Challenges
  - Technological
    - Modification of sources to make it easier
    - Providing an uplink
    - Dimming
    - Efficiency penalties
  - Other
    - ‘It’s not our channel’ problem
    - How to integrate them in the wireless infrastructure
    - ‘Careful use of photons’

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