Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Some challenges for visible light communications]
Date Submitted: [Revised version July 24th 2008]
Source: [Dominic O'Brien] Company [University of Oxford]
Address [Parks Road, Oxford, OX1 3PJ UK]
Voice:[+441865273916], FAX: [+441865273906], E-Mail:[dominic.obrien@eng.ox.ac.uk]

Abstract: [VLC has a number of technical challenges, which are discussed in the presentation]
Purpose: [Informing those interested in VLC of some of the technical challenges faced

Some Challenges for Visible Light Communications

Dominic O'Brien
Lubin Zeng
Hoa Le Minh
Grahame Faulkner
Department of Engineering Science, University of Oxford

Introduction

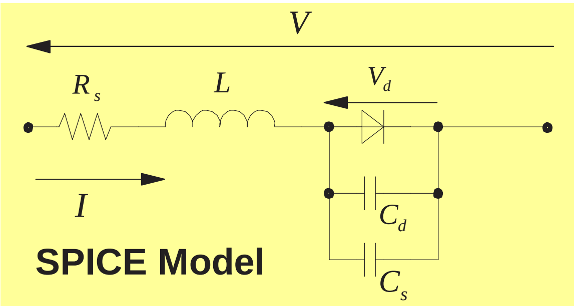
- Typical VLC link characteristics
- Challenges
  - Technical
    - Bandwidth limitations
    - Providing an uplink
  - Regulatory
    - Compatibility with Lighting Control systems
    - Illumination systems
- Conclusions

Typical link characteristics

- Source
- Channel
- Receiver

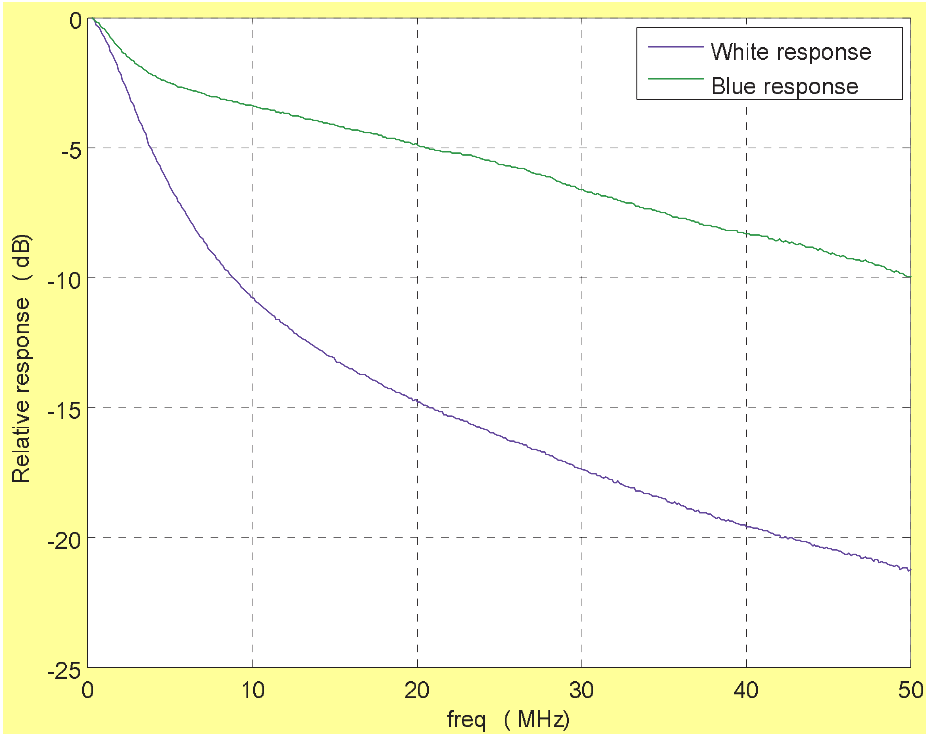
LED Modulation

- Opto-electronic response



Luxeon LED

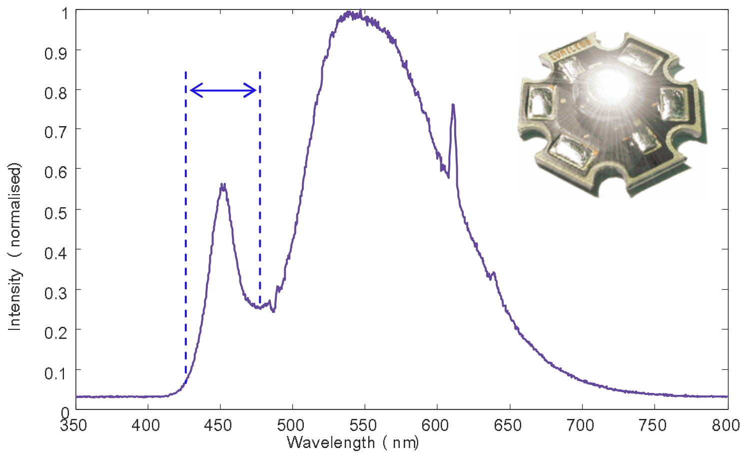
R_s = 0.9727 Ω
L = 33.342 nH
C_s = 2.8 nF
C_d = 2.567 nF
tt = 1.09 ns



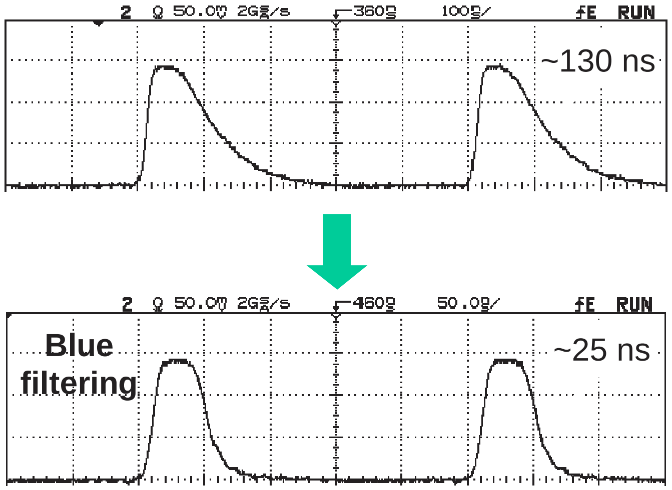
Measured LED small-signal bandwidth

Improvement of LED Response

- Using blue-response only (blue filtering)



Measured optical spectrum

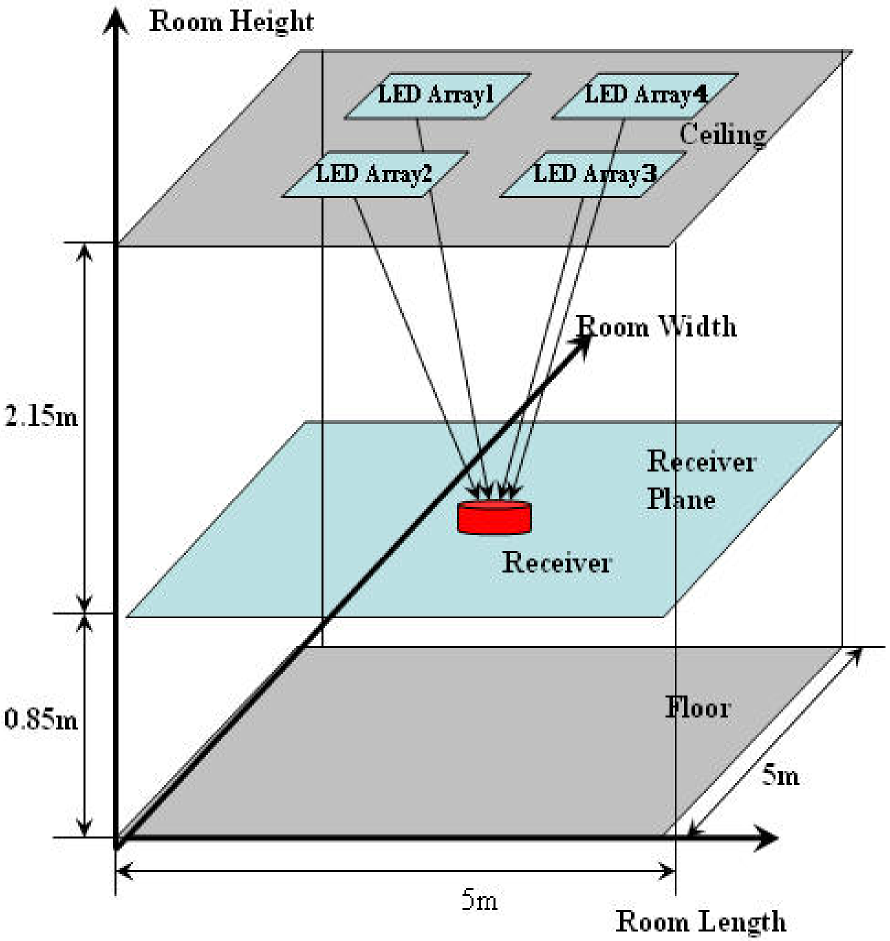


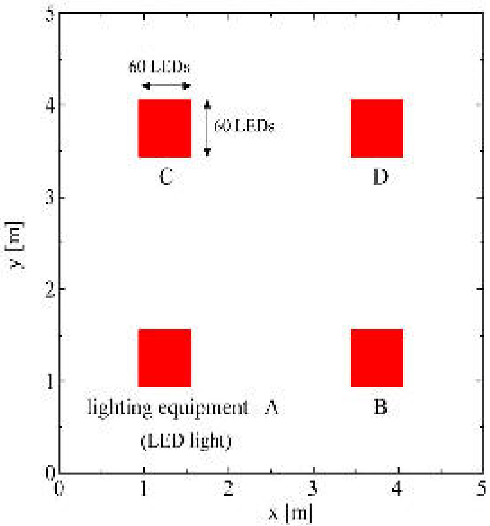
Measured impulse response

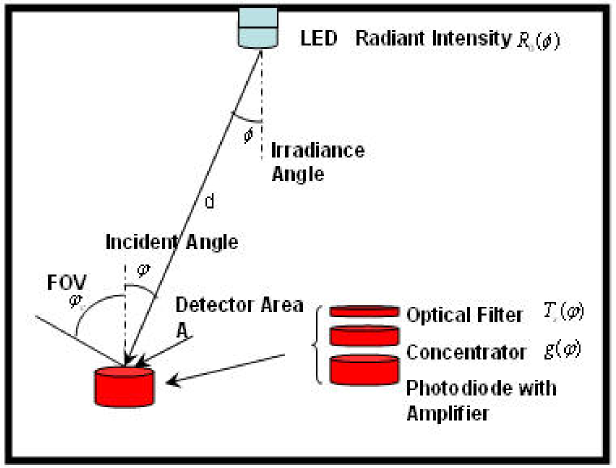
- Issue: Only 10% of signal power is recovered
  ⇒ Reducing SNR, link distance
- LEDs with more blue energy [1] could be used to gain more filtered power, however the balance of white colour is shifted

[1] Grubor, J., et al., "Wireless high-speed data transmission with phosphorescent white-light LEDs", Proc. ECOC 07 (PDS 3.6), pp. 1-2. ECO [06.11], 16-20 Sep. 2007, Berlin, Germany

VLC Channel

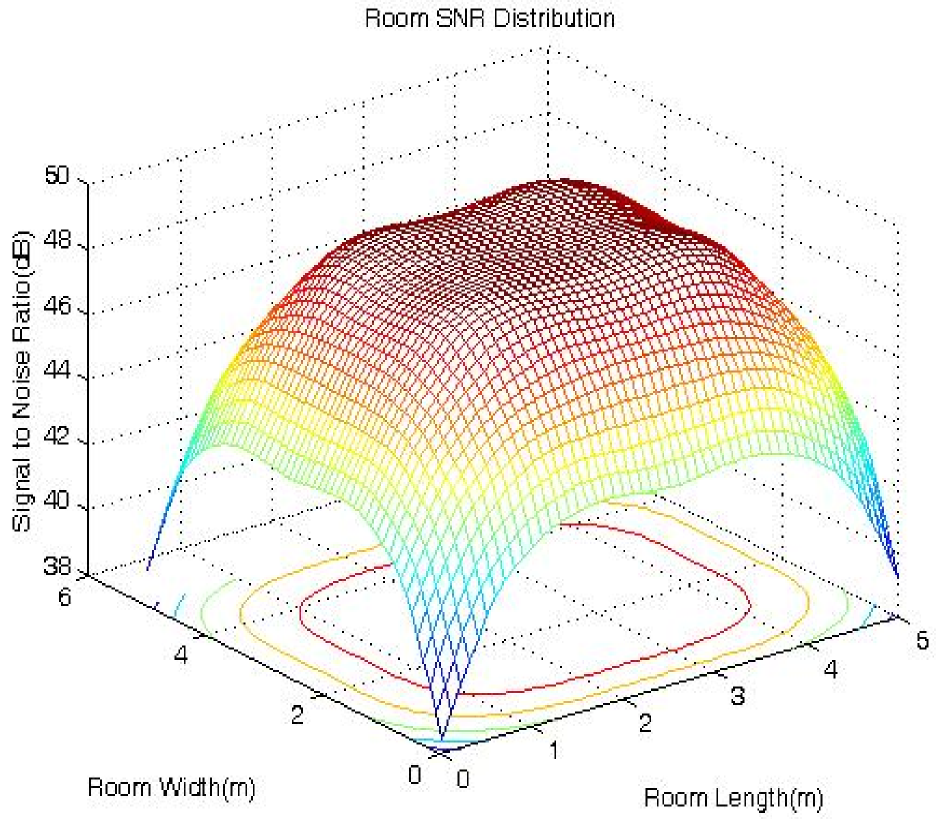

Room Height
LED Array1
LED Array4
Ceiling
LED Array2
LED Array3
Room Width
2.15m
Receiver
Plane
Receiver
0.85m
Floor
5m
5m
Room Length


60 LEDs
60 LEDs
C
D
lighting equipment A
(LED light)
B
y [m]
x [m]
0
1
2
3
4
5


LED Radiant Intensity $R_0(\phi)$
ϕ
Irradiance
Angle
d
Incident Angle
φ
FOV
Detector Area
A
Optical Filter $T_s(\varphi)$
Concentrator $g(\varphi)$
Photodiode with
Amplifier

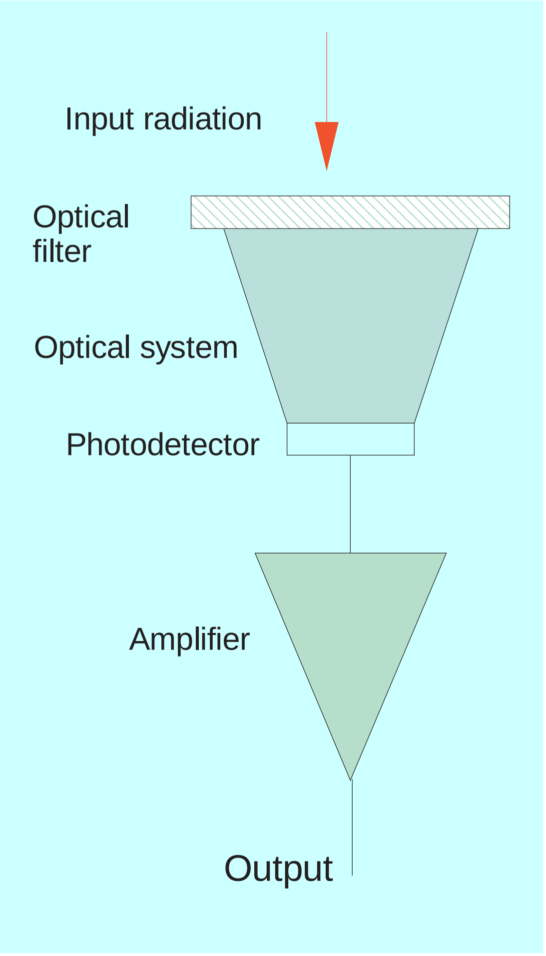
Room Power Distribution

- Assume
  - 1% modulation of typical illumination power
  - Typical receiver performance
- Conclusions
  - Very high SNR available
    - SNRmin = 38.50dB
    - SNRmax = 49.41dB
  - Modulation limited by source bandwidth



Optical Receiver

- Receiver consists of
  - Optical filter
    - Rejects ‘out-of-band’ ambient illumination noise
  - Lens system or concentrator
    - Collects and focuses radiation
  - Photodetector (or array of detectors)
    - Converts optical *power* to *photocurrent*
      - Incoherent detection
  - Preamplifier (or number of preamplifiers)
    - Determines system noise performance
  - Post-amplifier and subsequent processing

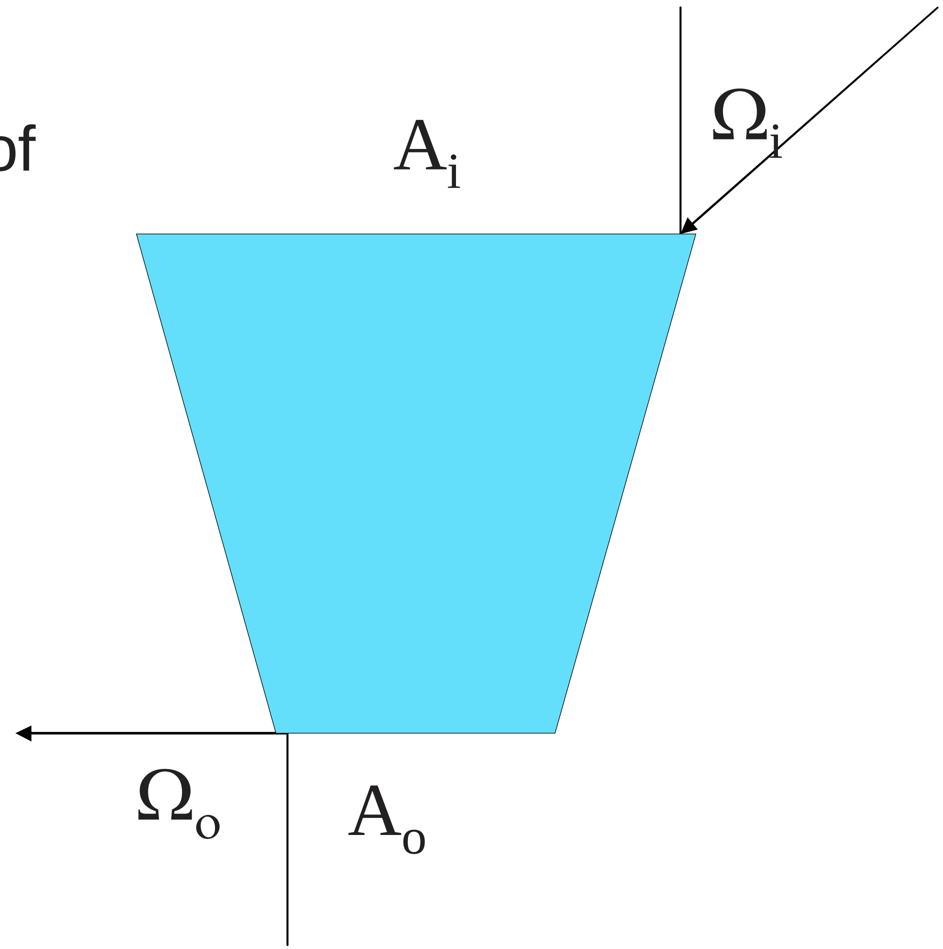


Optical Receiver: Constant Radiance Theorem

- Optical ‘gain’ of receiver limited by required field of view

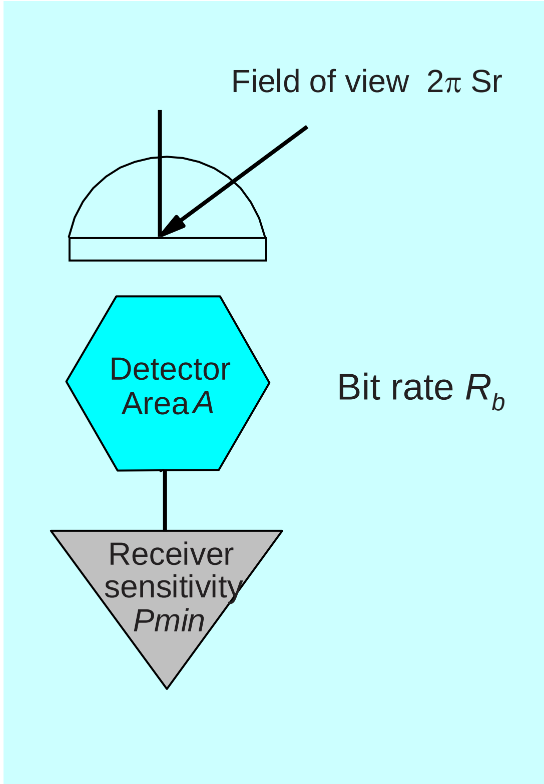
$A_i\Omega_i <= A_o\Omega_o$

$A_i\Omega_i <= A_o 2\pi$



Receiver Performance: Figure of Merit

- Receiver Figure of Merit (FOM)
  - Fibre systems
    - Performance determined by sensitivity (given sufficient detector area)
    - FOV usually not relevant
  - Free space systems
    - Etendue crucial determinant

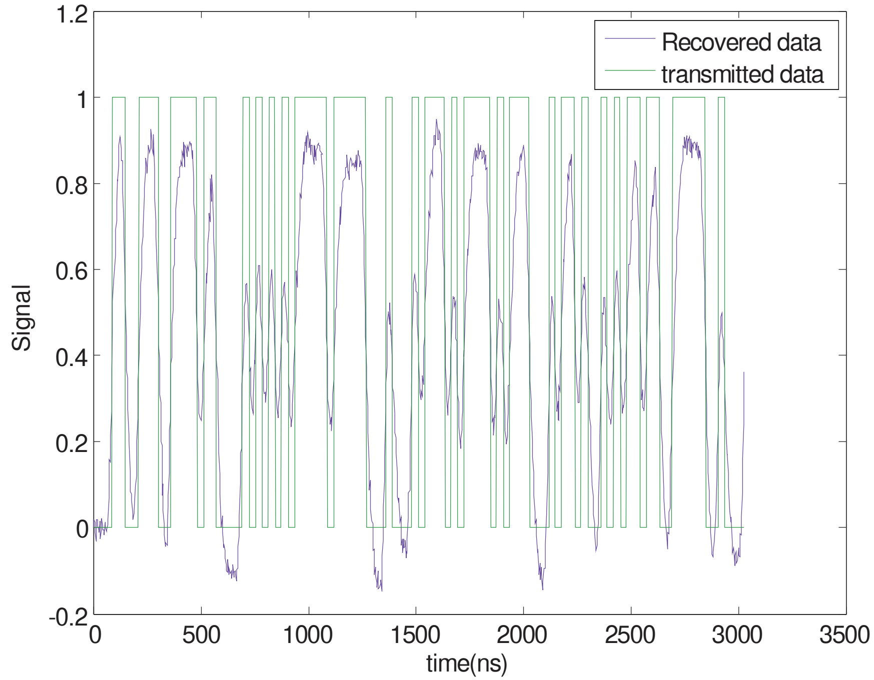


$$FOM = \frac{2\pi R_b A}{P_{\min}}$$

Improving data rate: equalisation

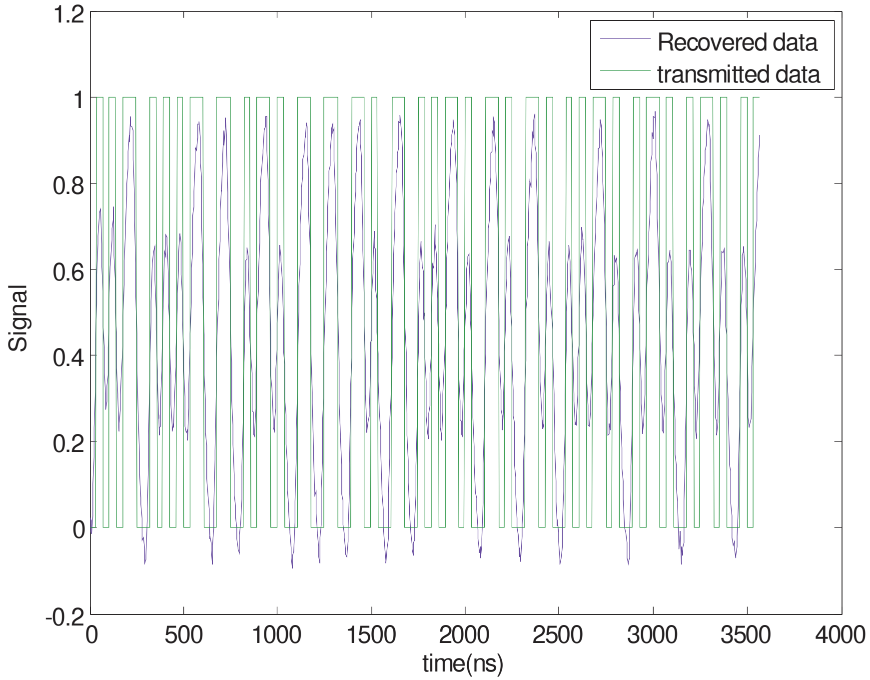
- Transmitter equalisation
  - High bandwidth
  - Energy efficiency
- Blue filtering
  - Lose low frequency energy from phosphor
- Receiver
  - Simple analogue equalisation
  - More complex also

Typical waveforms for RX equalisation



Data rate 33Mb/s

NRZ data

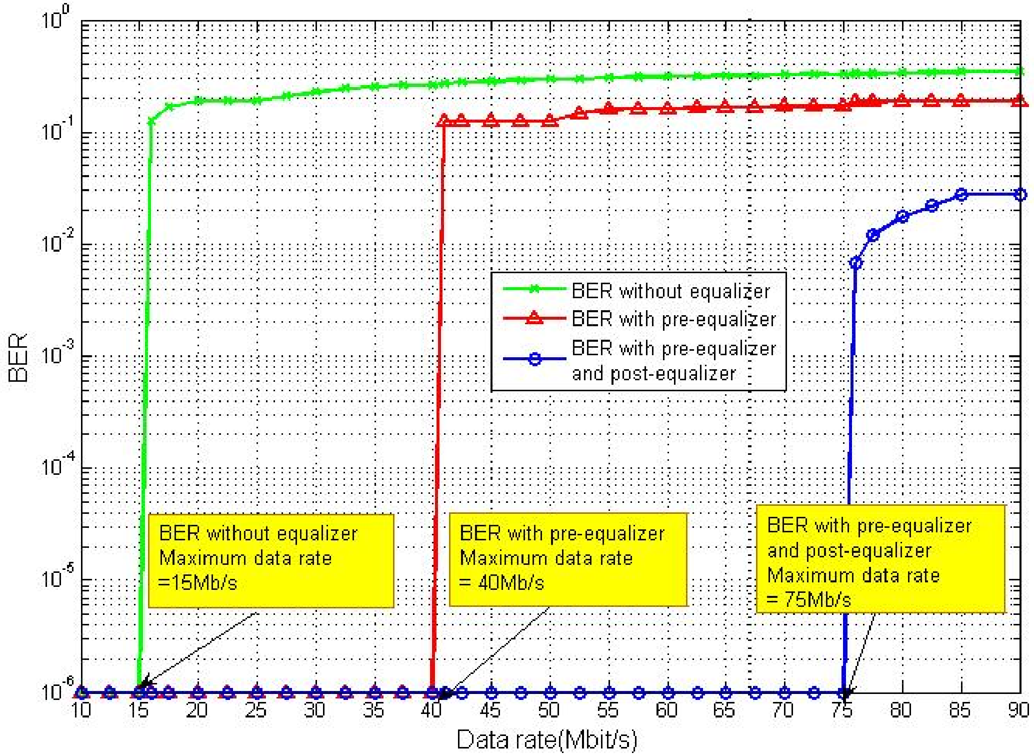


Data rate 14Mb/s

Manchester data

Bandwidth Improvement: Post Equalisation

- Pre- and post-equalization: single LED link



Pre-equalisation: experiment

Post-equalisation: simulation

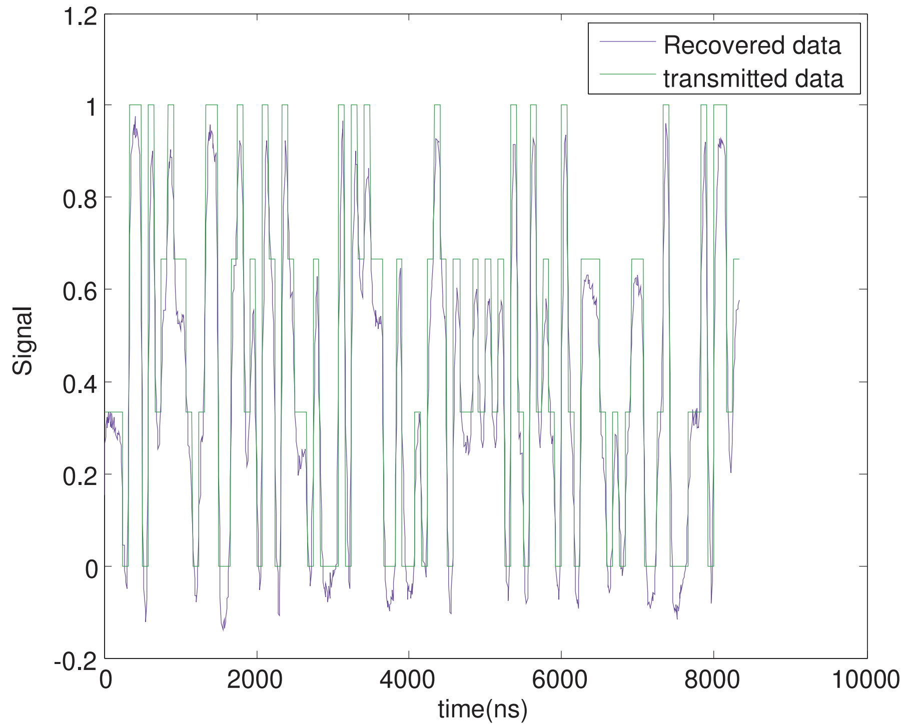
Improving data rate: complex modulation

- High SNR channel
  - Complex modulation attractive
- OFDM
  - 100Mb/s over 20MHz channel [1]
- PAM
  - Simulations show LED characteristics not optimal

[1] Grubor, J., et al., "Wireless high-speed data transmission with phosphorescent white-light LEDs", Proc. ECOC 07 (PDS 3.6), pp. 1-2. ECO [06.11], 16-20 Sep. 2007, Berlin, Germany

Improving data rate: PAM

- Simulation uses measured LED impulse response
- Simple 1st order RX equaliser
- 4-PAM
- 24Mb/s (33Mb/s NRZ)



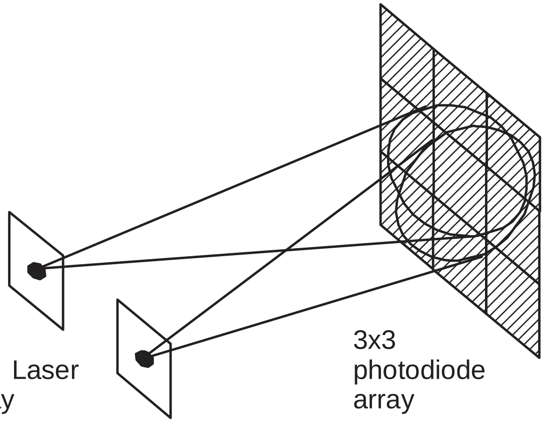
Data rate 24Mb/s (4-PAM)

Further work required

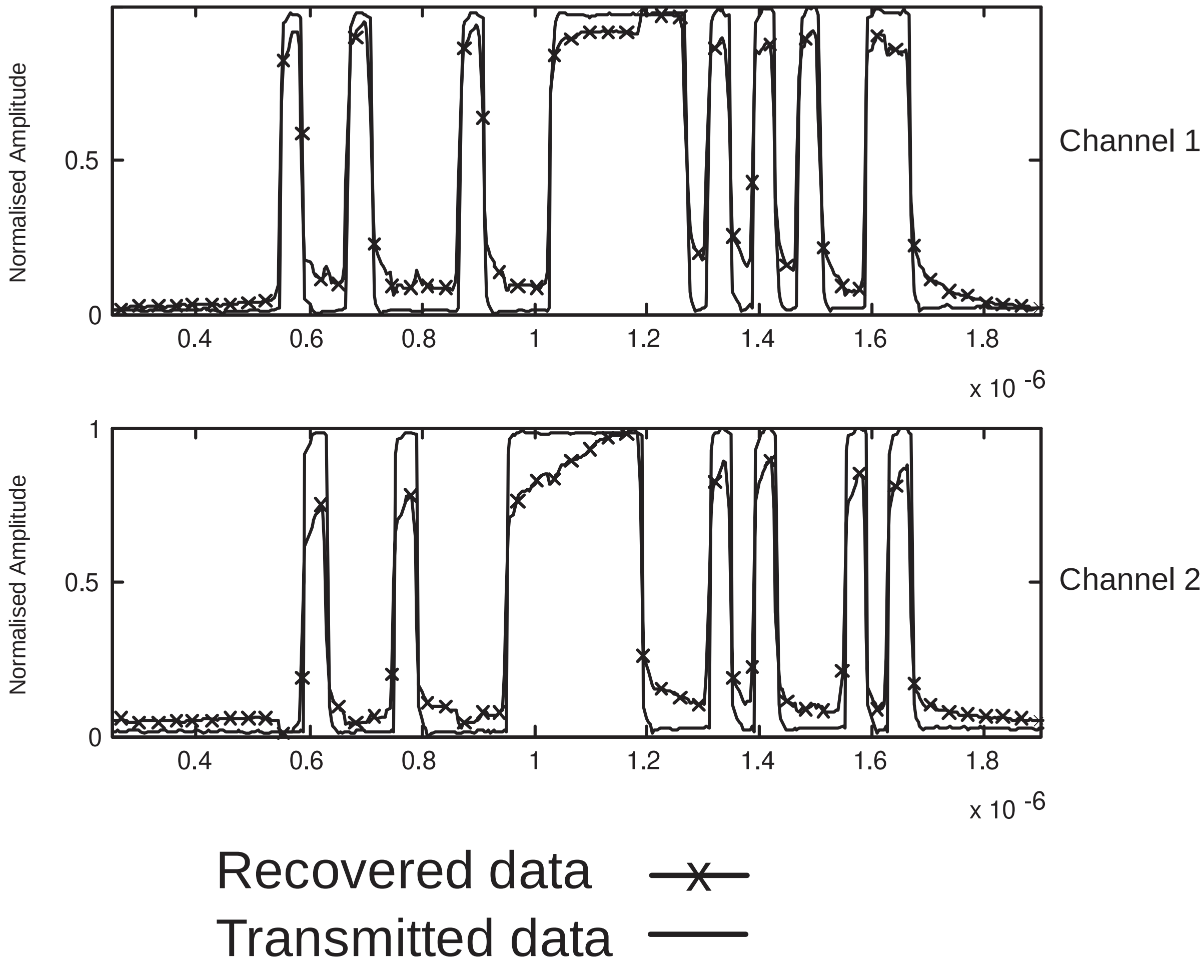
Improving data rate: MIMO

- Parallel ‘alignment free’ data links
- Simulations show linear capacity growth
- Experimental results for a simple IR system
- Simulations of in-room VLC system

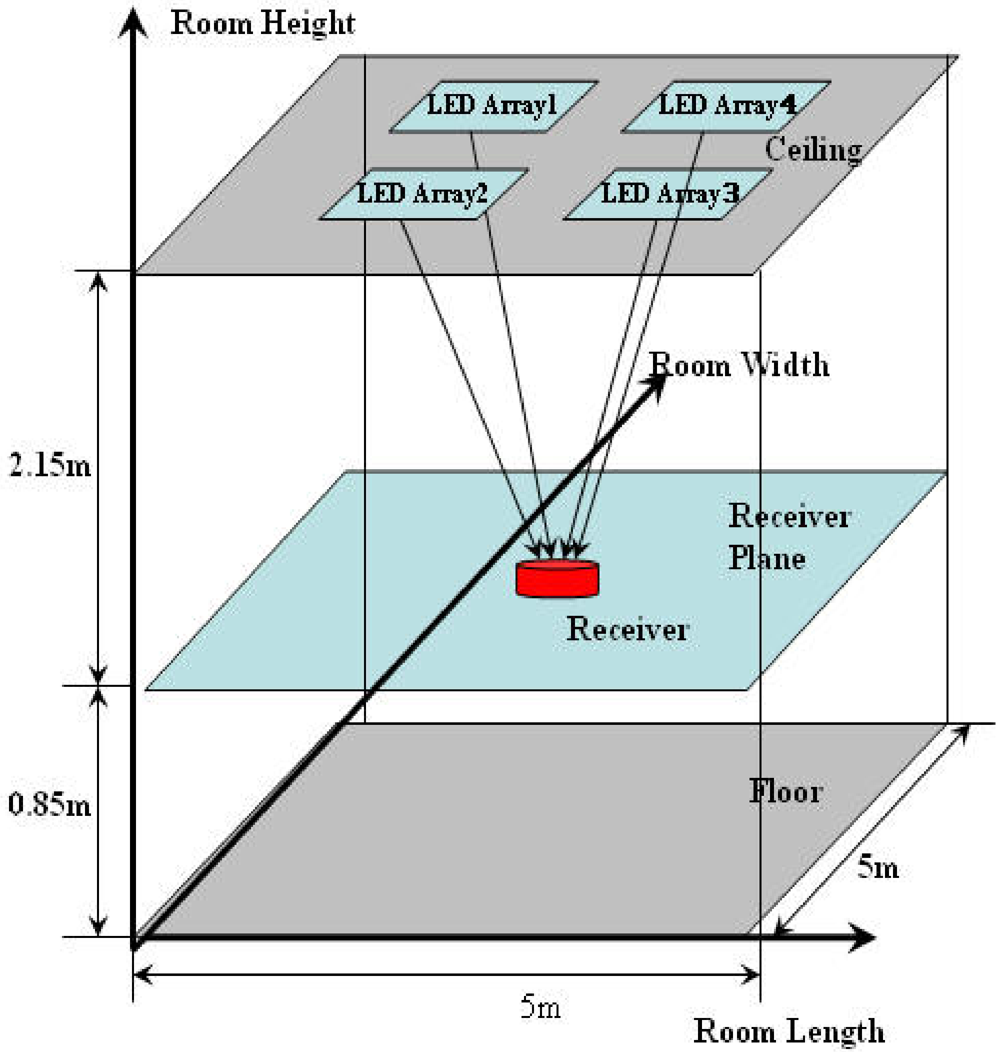
Simple IR system



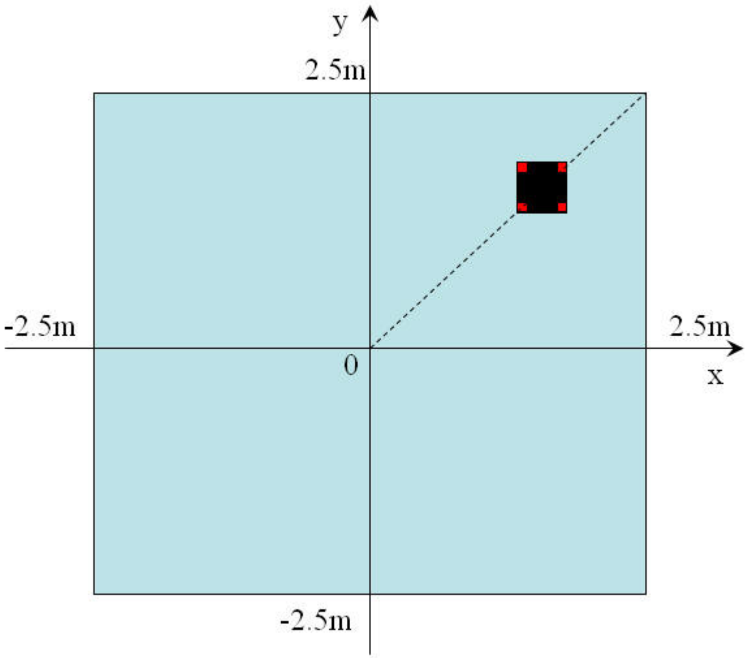
Experimental system



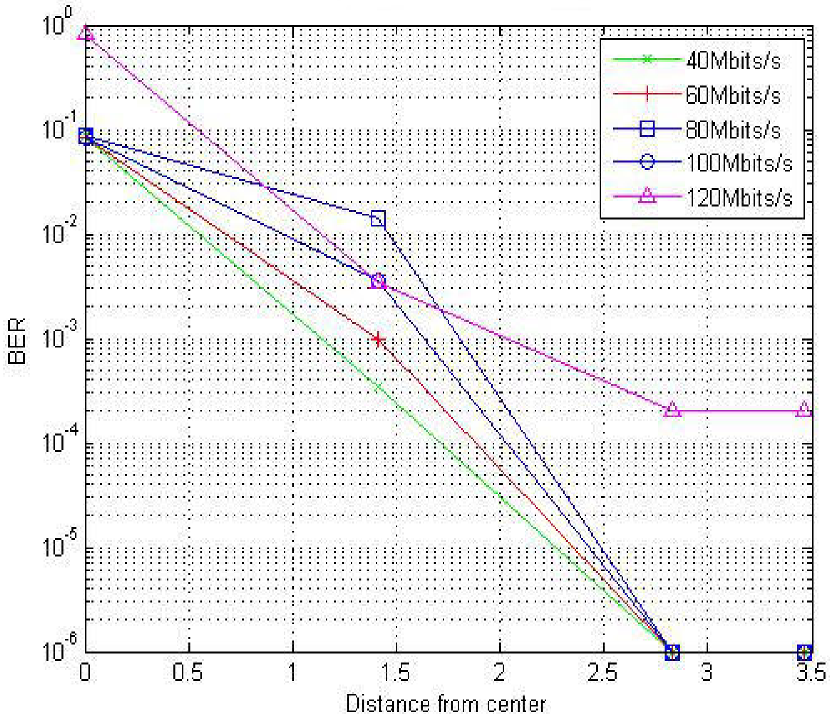
MIMO VLC: Simulation System



MIMO VLC: Preliminary Results



Position of the receiver



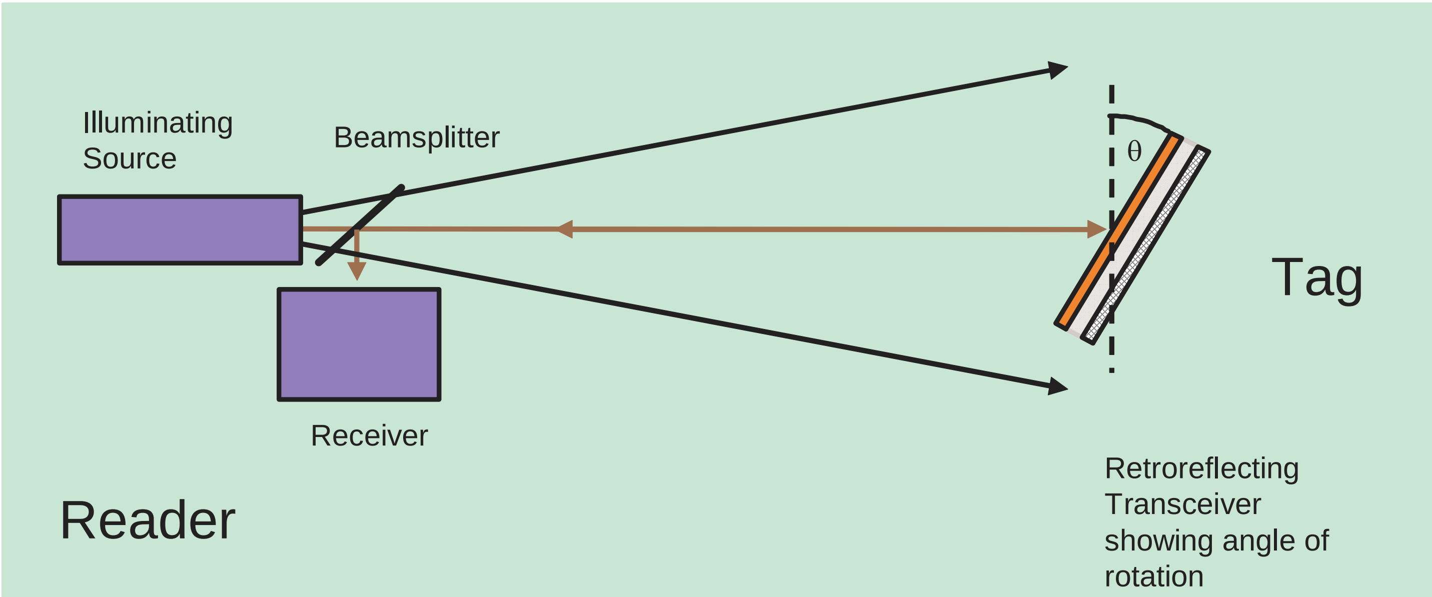
Aggregate data rate is linearly proportional to the number of channels and channel rate

Providing an uplink

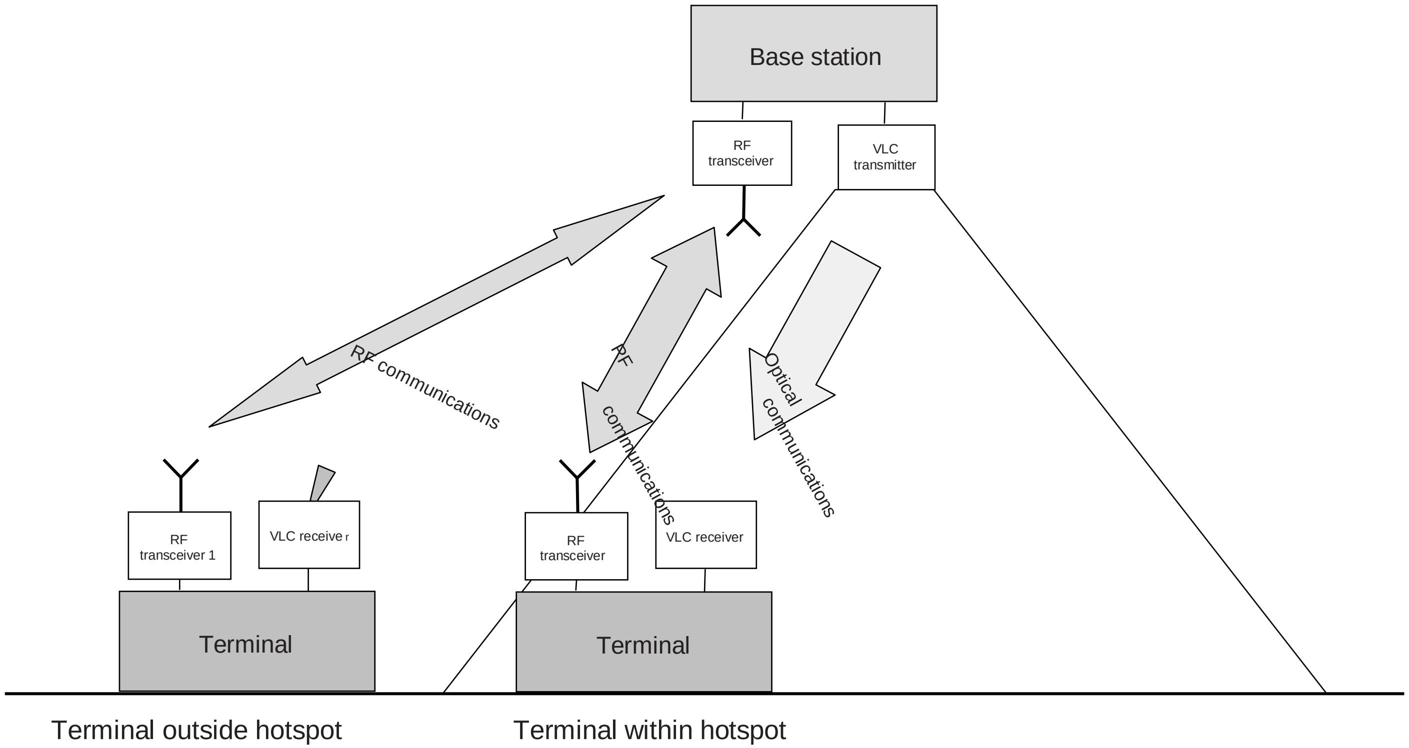
- VLC good at broadcast
- Uplink difficult to achieve
  - Retro-reflectors
    - Low speed
    - Low cost
  - IR uplink
    - Separate system
    - Infrastructure complex and expensive

Retro-Reflecting Link

- Novel optical communications between reader and tag
- Low power (tag has no source)
- Long range (determined by illumination source)
- Visibly secure (user can see beam of light)



Cooperative communications



O'Brien, D.C.: ‘Cooperation and cognition in optical wireless communications’, in Fitzek, M.K.a.F. (Ed.): ‘Cognitive Wireless Networks: Concepts, Methodologies and Visions - Inspiring the Age of Enlightenment of Wireless Communications -’ (Springer, 2007)

Providing an uplink: Cooperative systems

- Combine VLC with RF
- Optical downlink only
- RF uplink/downlink
  - 100Mb/s downlink/10Mb/s RF LAN
  - Fuzzy logic decision making
  - Typical traffic asymmetry
  - Significant performance benefits using combination

Hou-J, and O'Brien-Dc: ‘Vertical handover-decision-making algorithm using fuzzy logic for the integrated Radio-and-OW system’, IEEE Transactions on Wireless Communications, 2006, 5, (1), pp. 176-185

Compatibility with lighting

- Most modern systems use PWM dimming
  - Channel does not exist when light is dimmed
- Solutions
  - Use modulation scheme that ‘incorporates’ PWM dimming (PPM-like)
  - Use sensing to only transmit in active regions
  - But both reduce overall data rate
- Requirement for closer collaboration with lighting industry.

Conclusions

- VLC offers high SNR low bandwidth channel
  - Naturally suited to broadcast
- Challenges
  - Data rate
  - Uplink
  - Compatibility
- If overcome possibility of low cost method to augment wireless capacity