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Using Visible Light for Communications and Positioning

Talk for TelSoc: November 2014

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Talk Outline

- **My Background**
  - OFDM, optical OFDM, visible light communications, visible light positioning
- **Types of optical communications**
- **Why optical wireless is a hot topic!**
- **Advantages and disadvantage of optical wireless**
- **Some optical wireless basics**
  - Intensity modulation and direct detection (IM/DD)
- **Visible light communications (VLC)**
  - Technical challenges and our research
- **Visible light positioning (VLP)**
  - Technical challenges and our research
- **The path to commercialization**
- **(Research groups around the world)**
- **Questions**

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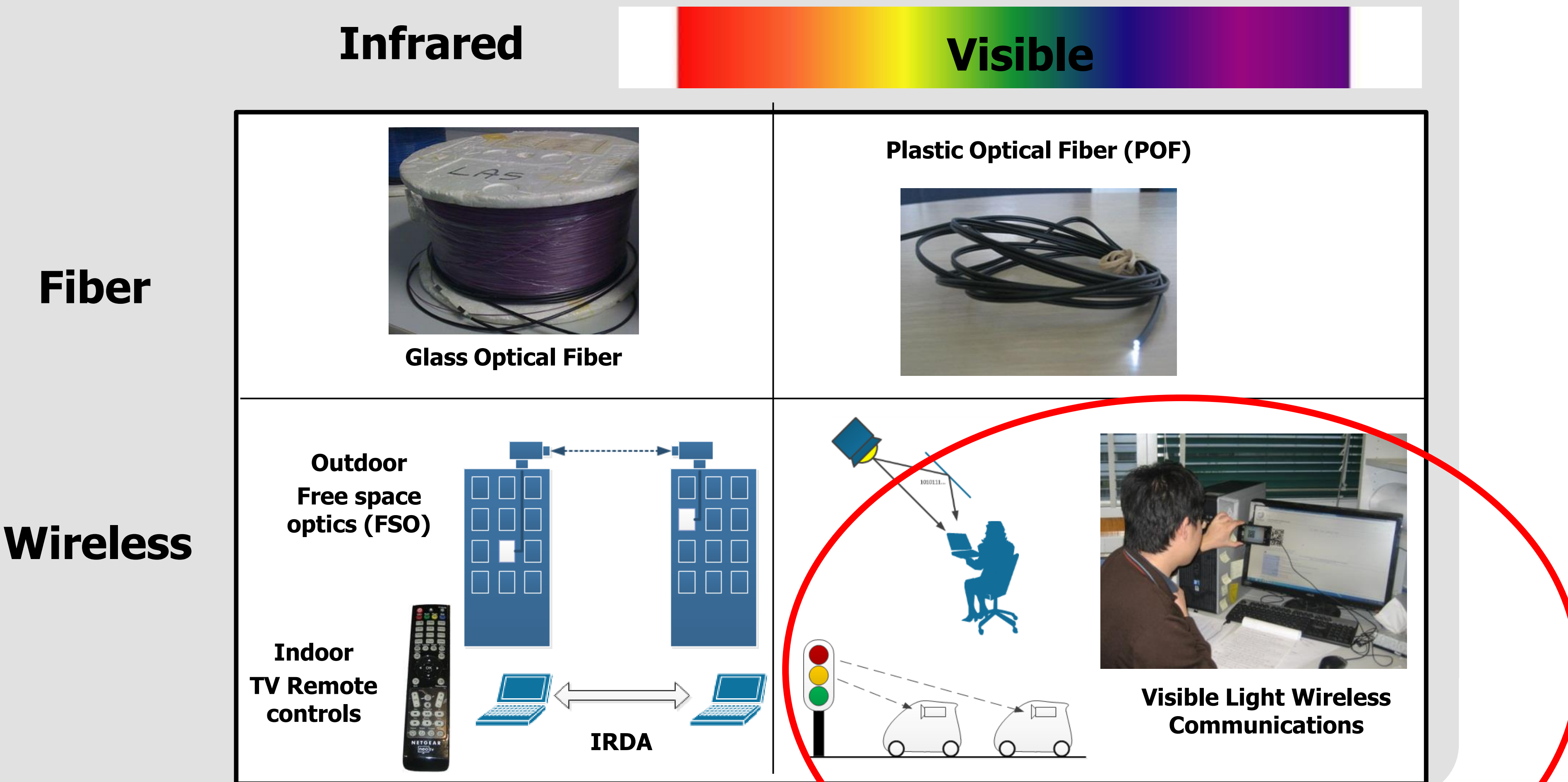
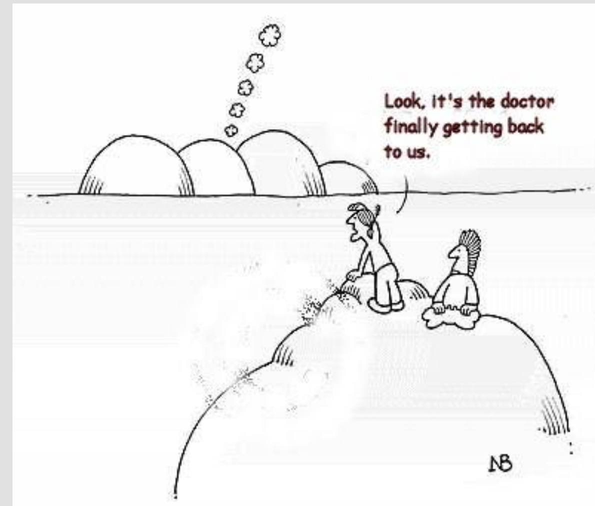
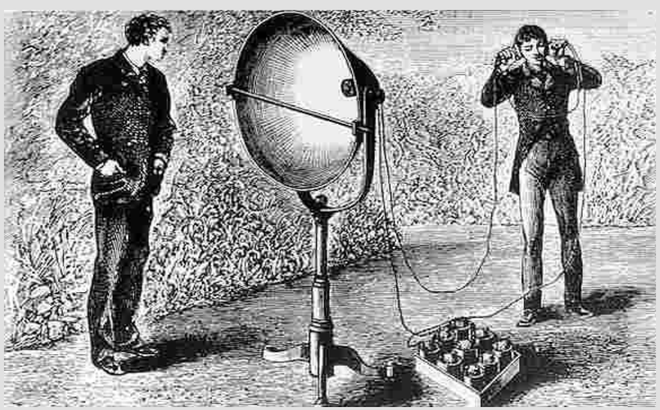
Types of Optical Communication



Optical Wireless is not a new technology!



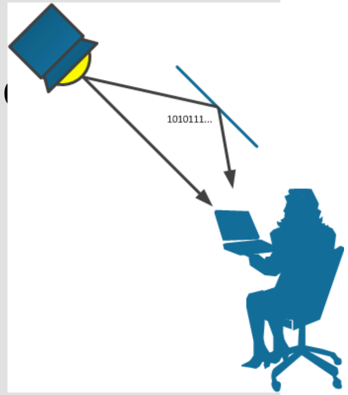


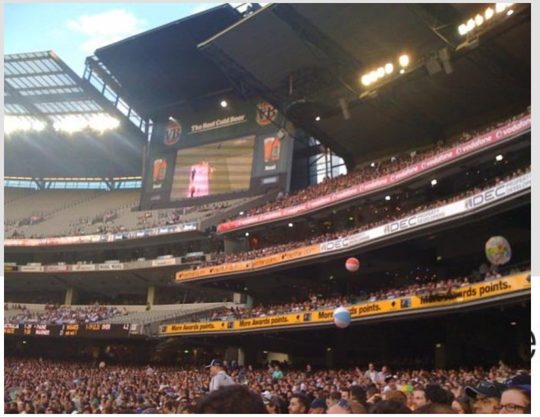
Alexander Graham Bell's Photophone

So why the sudden interest?

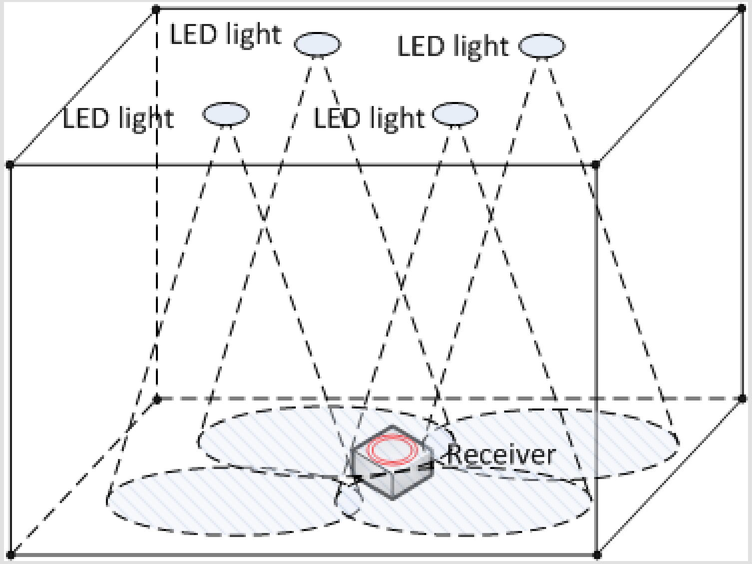
- **Demand for high speed c**
- **Limitations of convention ency) wireless**
- **Opportunity!!!**
  - Visible light optical transmitte s and receivers are everywh
    - > White LEDs for lighting
    - > LED traffic lights
    - > LED headlights and tail-lights
    - > Cameras
    - > I-phones
    - > LED Displays

This talk will concentrate on communications and positioning using lighting LEDs





Typical Scenario for Communication or Positioning using Lighting LEDs



Typical scenario: room with lights in the ceiling and receiver below

- **Signals are transmitted by LED lights located in the ceiling**
  - Signals are at high enough frequency so that they do not cause visible flicker
- **Receiver receives signals from one or more lights**

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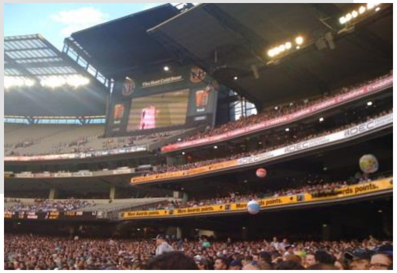
Advantages of Optical Wireless Communications

- **Potentially very high bandwidth**
  - (But not as much as you might think)
- **Unlicensed Spectrum**
- **Cheap and simple transmitters (LEDs) and receivers (photodiodes)**
- **No Radio frequency interference issues**
- **Safe**
- **Secure (shut the curtains and people can't eavesdrop!)**
- **People are used to transmitters being located in prominent positions!**
- **High degree of spatial reuse**
- **Fault finding is easy for visible light**
  - What you see is what you get!



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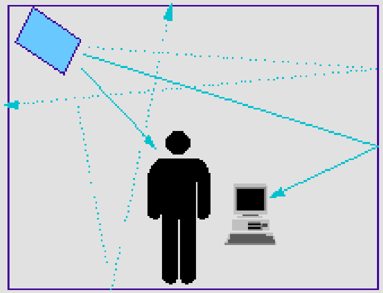
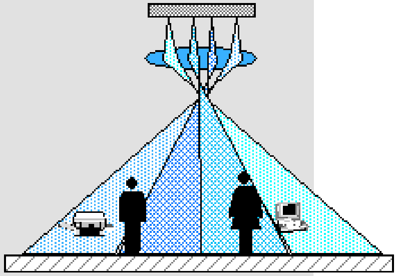
Disadvantages of Optical Wireless

- **Light travels in straight lines (approximately)**
- **Indoor line-of-sight (LOS) transmission typically results in very high signal to noise ratios (SNR) (>60 dB)**
- **But**
  - SNR falls of rapidly with distance (fourth power not square law)
  - SNRs are much lower if only diffuse (no LOS path) is received
    - > Diffuse path typically has a low pass filter effect on the baseband signal in MHz range
      - Bandwidth depends on the size of the room and the reflectivity of the surfaces
- **Interference from ambient light**
- **It doesn't work in total darkness**
  - But with no ambient light
    - > Very low transmit powers are required
      - E.g. level of an indicator LED



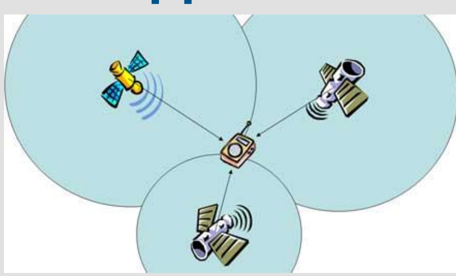
Diffuse Transmission



Line of Sight Transmission

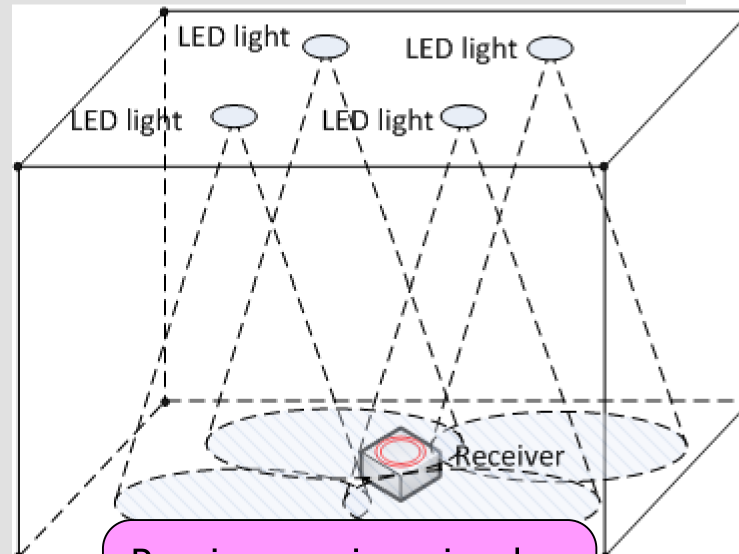
Visible Light Positioning (VLP)

- **Signals transmitted by LEDs can be used to estimate the position of a receiver relative to the LEDs**
- **Receiver receives signals from one or more lights**
  - Receiver could be in a smart phone
- **Required accuracy depends on application**



A bit like GPS only signals are transmitted by lights not satellites

Each light transmits a signal containing information about position of the light



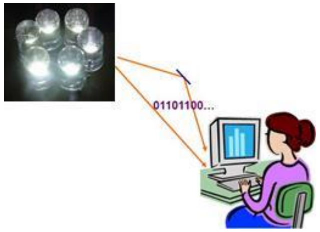
Receiver receives signals from a number of lights and calculates its position

J. Armstrong, Y. Sekercioglu, and A. Neild, "Visible light positioning: a roadmap for international standardization," *IEEE Communications Magazine, ,* vol. 51, pp. 68-73, 2013.

IEEE Communications Magazine December 2013 – special issue on Visible light communications including positioning

Some Optical Wireless Basics:

Intensity Modulated/Direct Detection (IM/DD) Optical Communication System



Transmitter | **Channel** | **Receiver**

Electrical domain | **Optical domain** | **Electrical domain**

Data in → **Electrical Modulator** → $x(t)$ → **optical Intensity modulator** → **Optical Channel** ($h(t)$) → **Optical Direct Detection** → $\oplus$ (+ $n(t)$) → $y(t)$ → **Data Detection** → Data out

Noise is added in the electrical domain

LED or laser

photodiode

Signal is represented by electrical voltage (or current)

⇩

Bipolar Signal

Signal is represented by optical *intensity*

⇩

Unipolar Signal

Signal is represented by electrical voltage (or current)

⇩

Bipolar Signal

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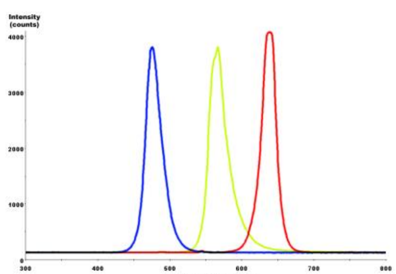
Some background on white LEDs

- **Two ways of making white LEDs**

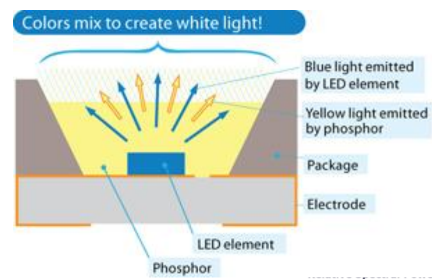
Use three LEDs: red, green and blue

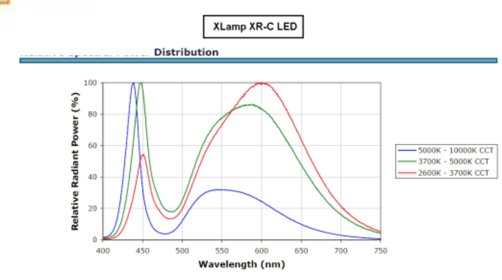
- Adjust colour by adjusting proportions



Use blue LED

- Yellow light is produced by secondary emission
- Colour (cool, neutral, warm light) set at manufacture



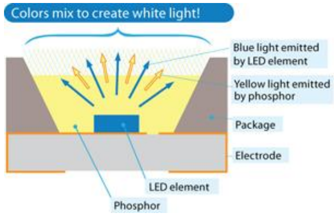


White LEDs as data transmitters

RGB LED

- Three LEDs can be modulated separately
- Modulation bandwidth of each is ~ 15 MHz (Langer 2011)
- Not currently the most popular for lighting
    - May be more popular in future due to more flexible lighting effects

Phosphorescent LED



- Only single LED can be modulated
    - Modulation bandwidth of blue light is ~35 MHz (Langer 2011)
    - But bandwidth of yellow component is only ~ 2 MHz
    - So need optical filter at receiver otherwise intersymbol interference (ISI) occurs
- Currently most common for lighting

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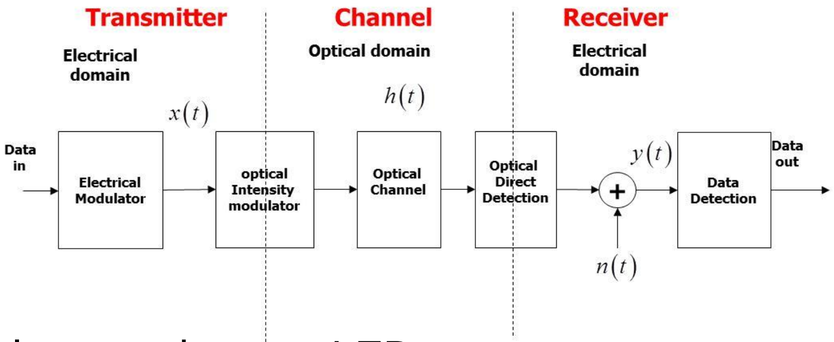
Intensity Modulation/Direct Detection (IM/DD) for optical wireless (continued)



- **System is linear in intensity**
  - Intensity of transmitted light is proportional current input to LED
  - Current out of photoreceiver is proportional to intensity of received light
  - So current out at the receiver is proportional to current in at the transmitter
  - h(t) is real and positive
- **Multipath fading occurs at baseband nor optical frequencies**
  - This is good and bad
    - > **GOOD:** It means that optical wireless systems are less affected by small changes in position than RF systems
      - as long as the change doesn't move the receiver in or out of line-of-sight
      - Doppler is not a problem
    - > **BAD:** It means that diversity is harder to achieve
      - Conventional (RF) spatial multiplexing doesn't work well

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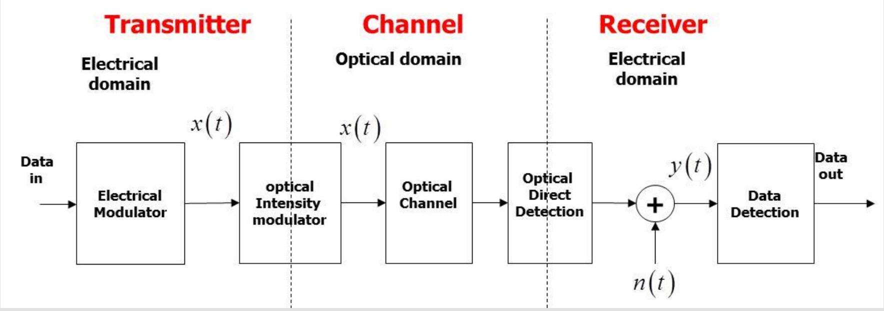
Intensity Modulation/Direct Detection (IM/DD) for optical wireless: why RF engineers need to forget everything you ever learned!



- **In the optical domain signal is represented by the intensity (instantaneous power) of the signal x(t)**
  - **x(t) must be non-negative – power cannot be negative!**
  - Average power = E{x(t)}
    - This is called ***optical*** power
- **Noise depends on the total light reaching the photodiode**
  - **Sunshine may be a problem**
- **Noise (shot noise) is added and data is detected in the electrical domain**
  - Bit error rate (BER) depends on E{x^2(t)}
    - This is called the ***electrical*** power
- **Usually there is a limit on the mean value of the transmitted signal (the optical power), but the BER performance depends on the mean square value of the transmitted signal**

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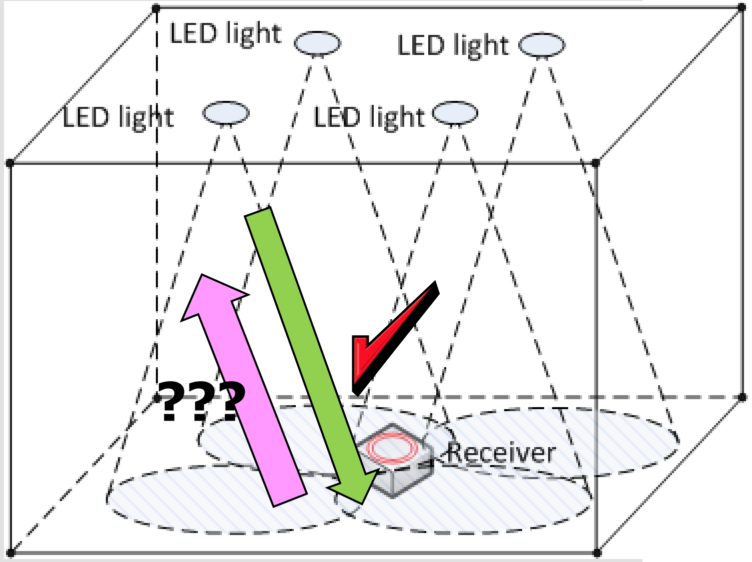
What are the main challenges for communication using lighting LEDs

- **What about the uplink?**
  - VLC can be used from LEDs to user but what about the other way?
    - Complementary technology to RF WiFi?
- **What modulation technique should you use?**
- **How do you ensure energy efficiency?**
- **How do you make VLC compatible with lighting functions like dimming?**
- **How do you ensure reliable communication for different receiver positions and orientation?**
- **How do you separate signals from different LED transmitters?**
- **How do you integrate VLC in an overall system?**
  - Backhaul - How do you get the data to the light?
    - Powerline communications? (not fast enough?)
    - Power over ethernet?
    - Or something entirely different?
  - How do you integrate a WiFi uplink with a VLC downlinK?



Recent Article by researchers at Qualcomm

A. Jovicic, L. Junyi, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," *IEEE Communications Magazine*, vol. 51, pp. 26-32, 2013.

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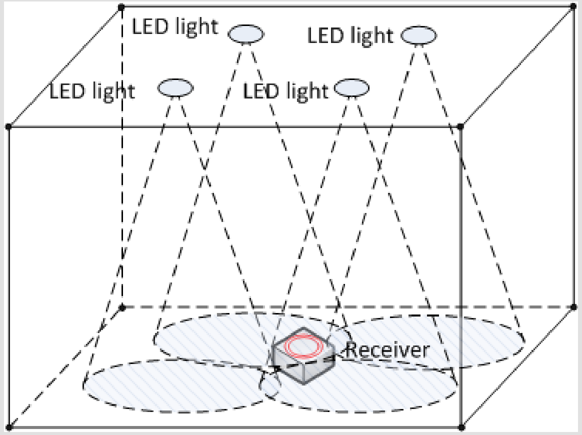
Recent Research by My Group at Monash

- **Modulation techniques for optical IM/DD systems**
- **How to ensure reliable transmission at all positions?**
- **How to separate the signals received from different LED transmitters?**
- **How to ensure energy efficient systems can be designed?**



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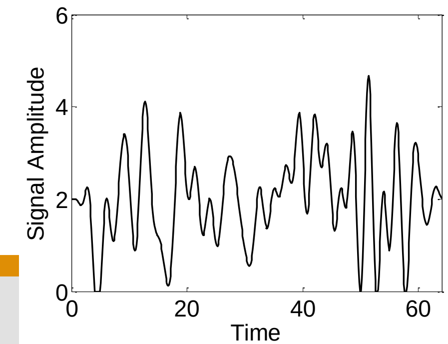
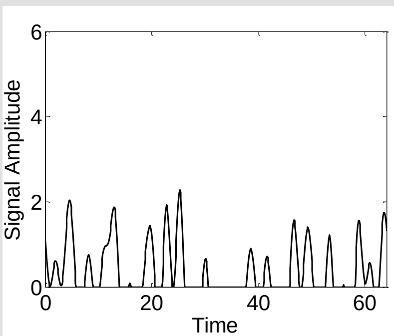
Recent Research by Group: Modulation Techniques



× Add a DC bias?

Very inefficient in optical power

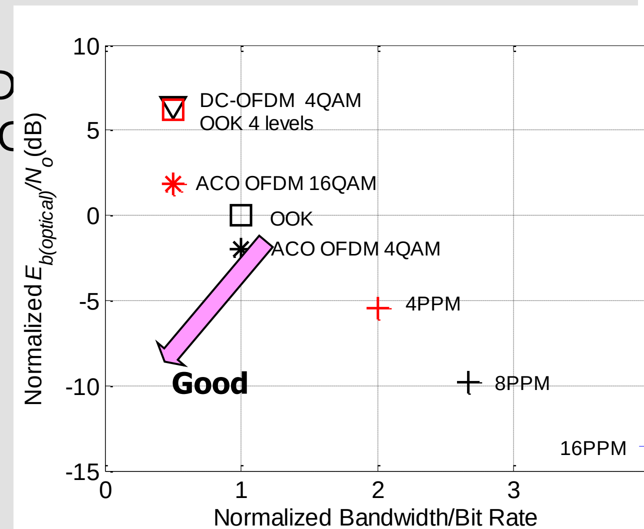
- **Modulation techniques**
  - Developed new forms of orthogonal frequency division multiplexing (OFDM) for IM/DD optical communications
  - Signal must be real and non-negative
    - > Invented asymmetrically clipped optical OFD (ACO-OFDM) and improved versions of ACC OFDM



✓ Clip the negative signals

May cause intercarrier interference (ICI)

BUT – if only odd frequencies are used, all ICI falls on even frequencies



ACO-OFDM gives much better performance than conventional modulation schemes for optical wireless and solves the multipath problem!!!

- **What is the capacity of IM/DD systems?**
  - How close to capacity is ACO-OFDM?

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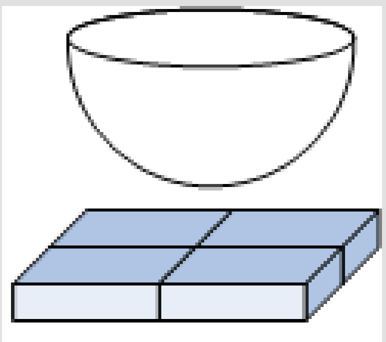
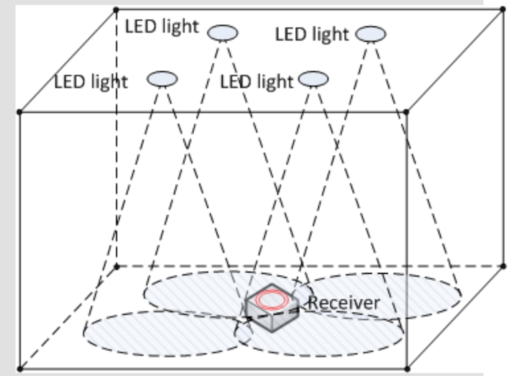
Recent Research by Group:

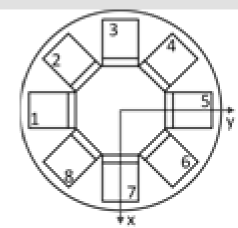
How to ensure reliable reception at all positions?

- **How to ensure reliable transmission at all positions?**
- **Need receiver with a wide field of view**
  - Hemispherical lens
  - Prism array

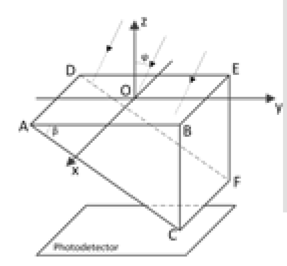


Hemispherical lens above array of photodetectors





Top view of an array of eight prisms



Prism above photodetector

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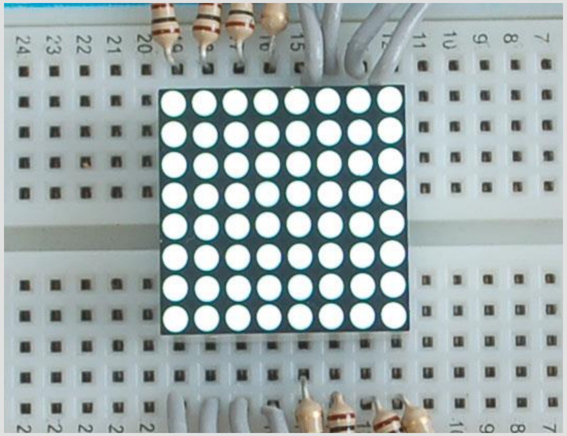
Recent Research by Group:

How to design energy efficient systems?

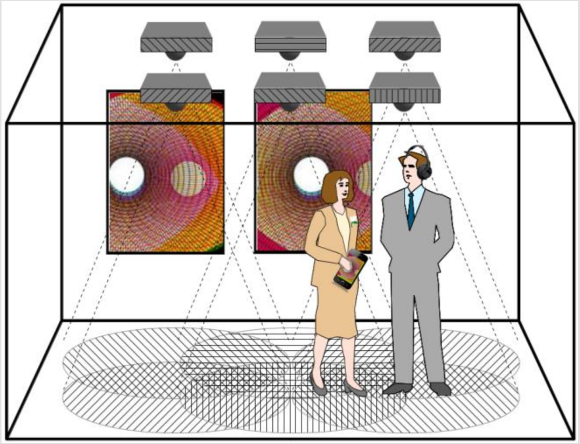
- **How to design energy efficient systems?**
  - For energy efficiency want LEDs to be fully ON or fully OFF
  - Generate 'analog' light signal by using an array of LEDs

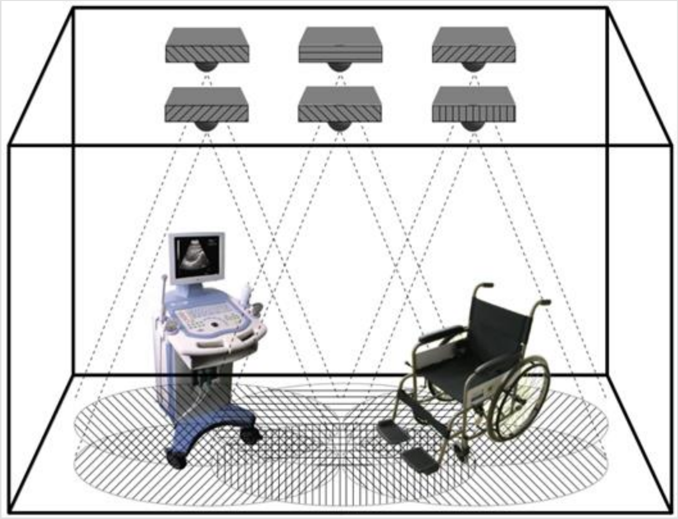
LED arrays

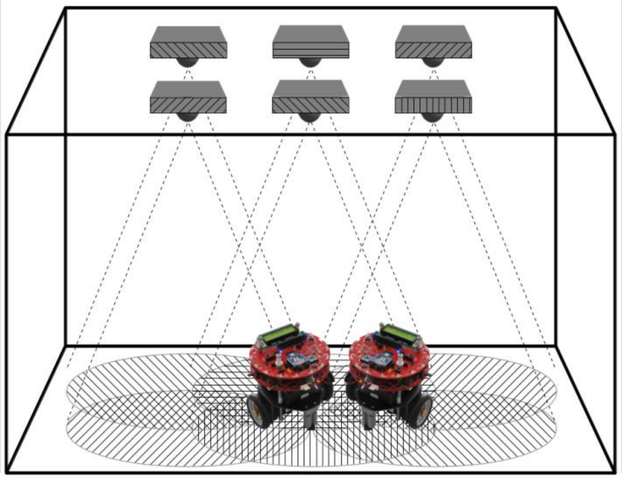


  - More LEDs on = more light = bigger signal
  - 'Analog' signal generated efficiently

Applications of Visible Light Positioning (VLP)







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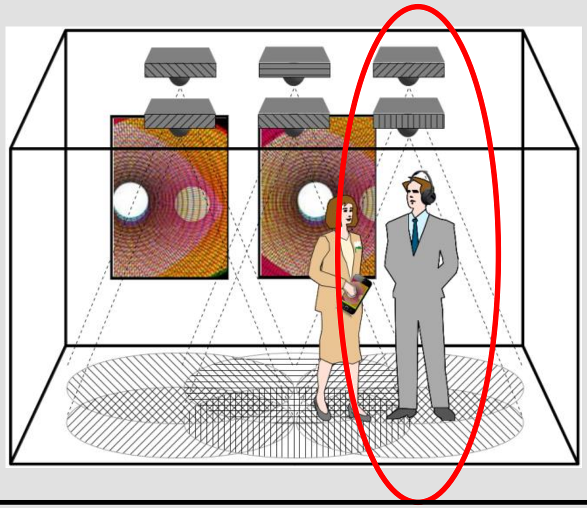
Some Potential Applications of VLP and the accuracy required:
Example 1: An art gallery or museum

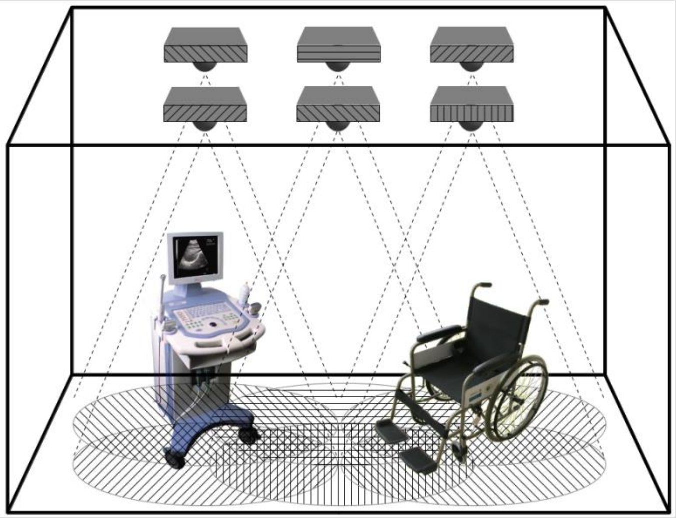


Man is wearing a headset containing an optical receiver.

The headset detects which work of art he is near and plays commentary about the artwork.

- **Receiver needs only to identify which is the closest light**
- **Simple receiver and system**

Some Potential Applications of VLP and the accuracy required: Example 2: Tracking equipment in a hospital



Wheelchair has an optical receiver which detects which light it is close to.

Radio such as Wifi or Zigbee radios back to centre saying where the wheelchair is.

- **Receiver needs to identify the closest light**
- **A separate radio transmitters is required to transmit information to a central point**
- **Central database must know which light is in which room**

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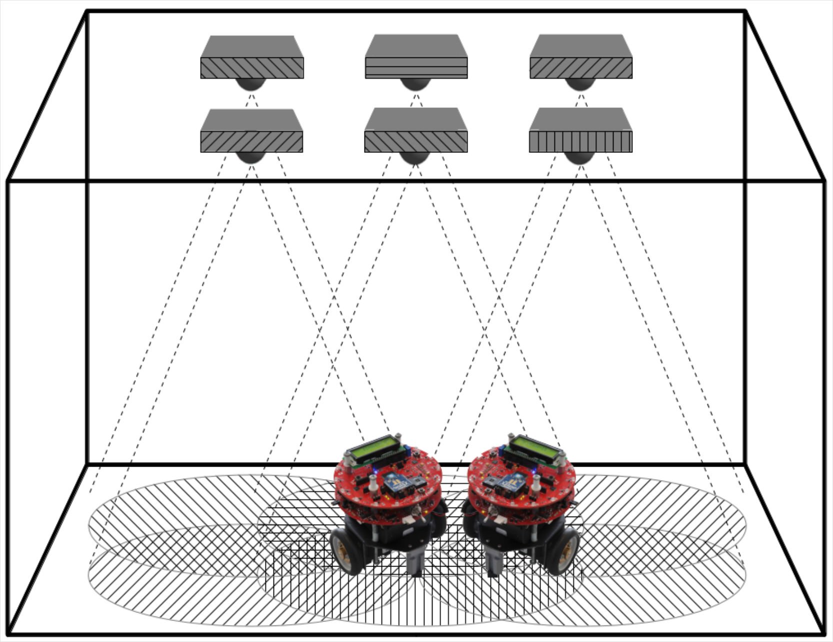
Some Potential Applications of VLP and the accuracy required:

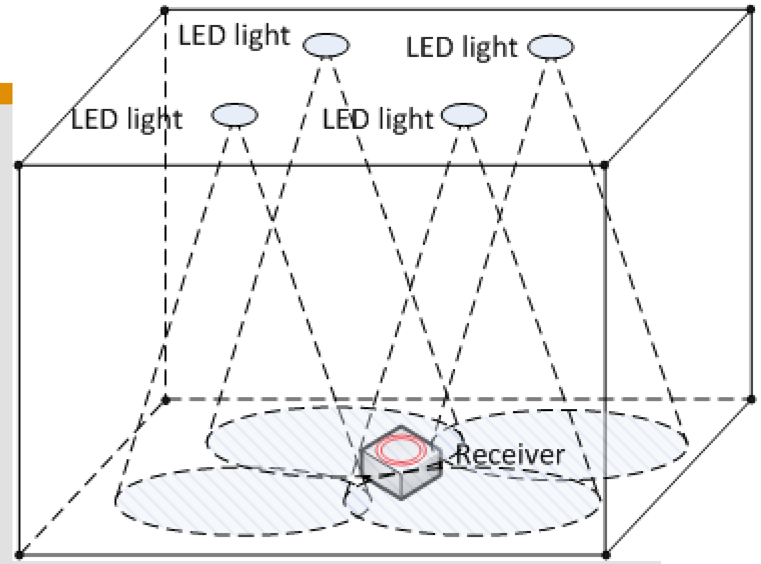
Example 3: Providing accurate location information for mobile robot

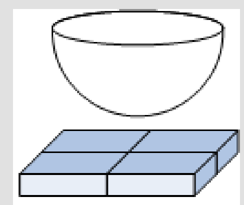


- **Mobile robots calculate position accurately and use this information to control their motion**
- **Need to be able to receive signals from several lights**
- **Various techniques for calculating position**
  - Triangulation/trilateration
  - Received signal strength/ time of arrival/angle of arrival

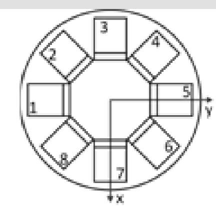
Our Research on VLP

- **What method of localization to use?**
  - Received signal strength (RSS)
    - > Doesn't work if lights get dim or dirty or someone partially obscures light
  - Time or arrival (TOA)
    - > Requires very accurate timing/synchronization
      - Light travels at the speed of light!
    - > But theoretically very accurate positioning can be achieved
      - Much more accurate than GPS ~ cm
  - Angle of arrival (AOA)
    - > Potentially very accurate
      - Doesn't depend on the brightness of the light
        - » Needs receivers with angular diversity!

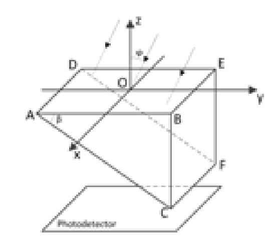




Hemispherical lens above array of photodetectors



Top view of an array of eight prisms



Prism above photodetector

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The future of VLC/VLP

- **VLC/VLP are challenging technologies to commercialize**
  - Involves several traditionally different industries (LED manufacturers, light fitting manufacturers)
    - +possibly mobile phone manufacturers etc
- **Predict VLP for niche applications will be commercialised first**
  - Can be as simple as changing a light bulb
  - No standardisation required
  - Already some start ups
- **Then VLC for niche applications**
  - Hotels? Supply dongles as receivers?
- **Published research work by a number of well known companies: Qualcomm, Intel, Phillips, Disney, Toyota …**

Recent Research from around the world?

Vucic (Grubor), Langer, Lee et al (Germany, part of European Omega project)

- **World speed record for transmission from one white LED**
- **Uses a form of orthogonal frequency division multiplexing (OFDM) – more later!**
- **513 Mbit/s using phosphorescent LED and off line processing**
  - Bit loading on subcarriers
  - Blue optical filter
- **803 Mbit/s using RGB LED**
  - Different bit loading on each colour
  - Optical filters at receiver to separate different colours

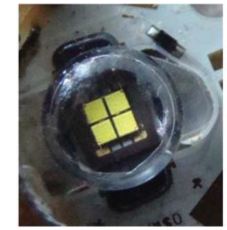


Fig. 2. Photograph of the commercial LED luminary (with spherical lens), as used in the measurements.

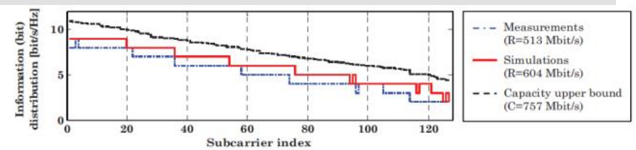


Figure 4. Performance comparison of the experimental system (measurements) and its linear system model (simulations), on condition that BER ≤ $2\cdot10^{-3}$. Optimal loading masks applied in measurements and simulations.

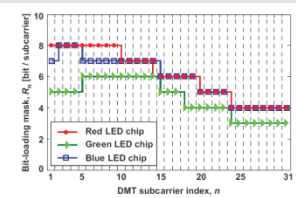


Figure 5. Bit-loading mask for each WDM channel.

K. D. Langer*, et al.*, "Exploring the potentials of optical-wireless communication using white LEDs," in *2011 13th International Conference on Transparent Optical Networks, 26-30 June 2011*,

J. Vucic, C. Kottke, S. Nerreter, K. Langer, and J. W. Walewski, "513 Mbit/s Visible Light Communications Link Based on DMT-Modulation of a White LED," *Journal of Lightwave Technology,* vol. 28, pp. 3512-18, 2010.

Recent Research from around the world?

O'Brien (Oxford, England, part of European Omega project)

- **Lots of interesting experimental work on diversity receivers**
- **Angle diversity**
  - Receiver with multiple elements pointing in different directions
- **Diversity using an imaging receiver**
  - Lens and array or receive elements
  - Uses OFDM!

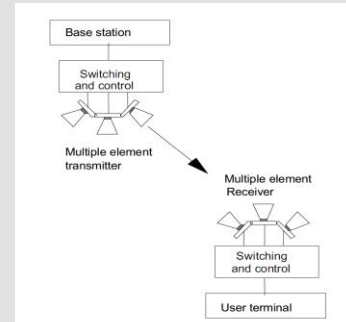
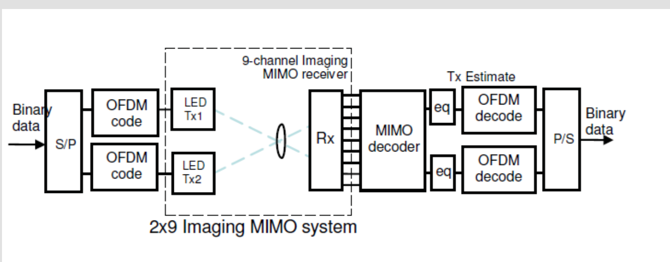
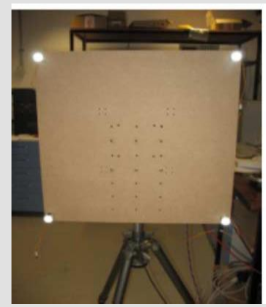
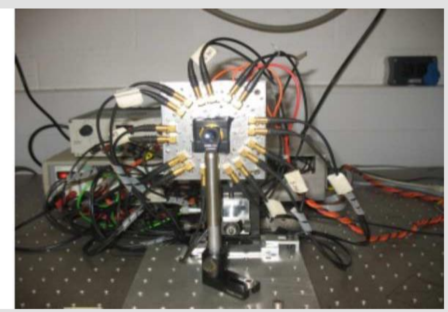


Figure 1. Schematic of system configuration







D. C. O'Brien, *et al.*, "Gigabit class high-speed indoor optical wireless: system design, challenges and results," in *Free-Space Laser Communications X, 2-3 Aug. 2010*, USA, 2010

K. D. Dambul, D. C. O'Brien, and G. Faulkner, "Indoor Optical Wireless MIMO System With an Imaging Receiver," *IEEE Photonics Technology Letters,* vol. 23, pp. 97-9, 2011.

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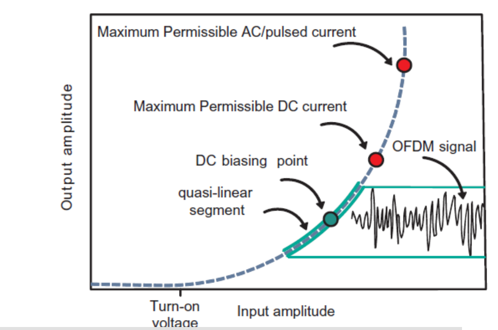
Recent Research from around the world?

Haas (Edinburgh, Scotland, part of European Omega project)



- **Lots of work on practical aspects of OFDM implementation**
- **Non-linearities in DC biased OFDM**
- **Non-linearities in ACO-OFDM**
- **Transmitting different data from different lights**

I. **Stefan, H. Elgala, R. Mesleh, D. O'Brien, and H. Haas, "Optical Wireless OFDM System on FPGA: Study of LED Nonlinearity Effects," in *2011 IEEE Vehicular Technology Conference (VTC 2011-Spring), 15-18 May 2011*, Piscataway, NJ, USA, 2011**

II. **S. Dimitrov, S. Sinanovic, and H. Haas, "Double-Sided Signal Clipping in ACO-OFDM Wireless Communication Systems," in *Communications (ICC), 2011 IEEE International Conference on*, 2011**

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Recent Research from around the world?

More recent UK funded research
http://up-vlc.photonics.ac.uk

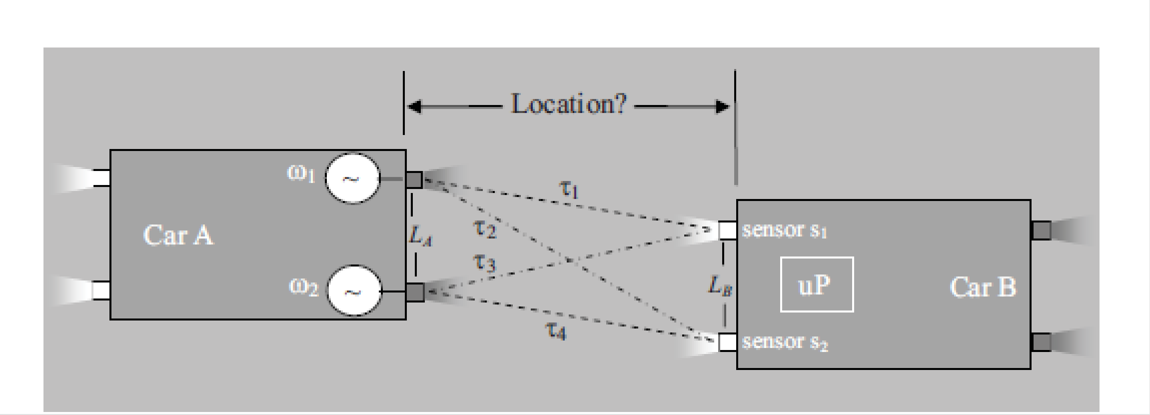
Welcome to the web pages of EPSRC's Ultra-parallel visible light communications (UP-VLC) project.

Running from October 2012 to September 2016, **UP-VLC** is an ambitious EPSRC-funded £4.6 million Programme Grant which will explore the transformative technology of communications in an imaginative and foresighted way. The vision is built on the unique capabilities of gallium nitride (GaN) optoelectronics to combine optical communications with lighting functions, and especially on the capability to implement new forms of spatial multiplexing, where individual elements in high-density arrays of GaN based light emitting diodes (LEDs) provide independent communications channels, but can combine as displays. We envisage ultra-high data density - potentially Tb/s/mm^2 - arrays of LEDs driven via CMOS control electronics in novel addressing and encoding schemes and in compact and versatile forms.

Recent Research from around the world?

Roberts (Intel, USA)

- **Lots of interesting experimental work on optical wireless systems**
  - Chairs IEEE standardization body
- **Novel technique of measuring distance between cars based on LED tail-lights.**



R. Roberts, P. Gopalakrishnan, and S. Rathi, "Visible light positioning: Automotive use case," in *2010 IEEE Vehicular Networking Conference (VNC 2010), 13-15 Dec. 2010*, Los Alamitos, CA, USA, 2010, pp. 309-14.

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Recent Research from around the world?

Japan: Komine Yamazato, Haruyama,

- **Komine – first papers on communication using white LEDs**
- **Okada et al (Yamazato)**
  - Transmission of data from LED traffic lights to cars
    - > Have demonstrated experimentally

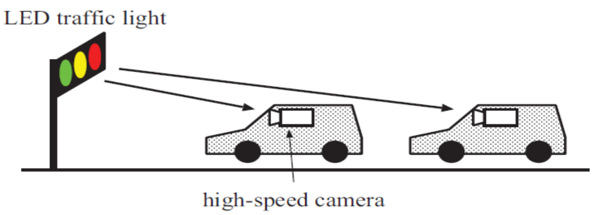


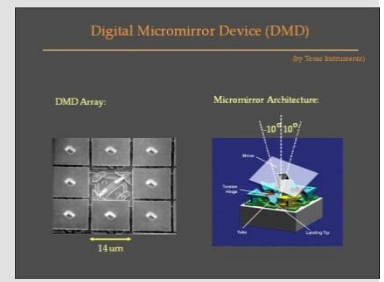
Fig. 1. Road-to-vehicle visible communication system using an LED traffic light.

H. Okada, T. Ishizaki, T. Yamazato, T. Yendo, and T. Fujii, "Erasure coding for road-to-vehicle visible light communication systems," in *2011 IEEE Consumer Communications and Networking Conference (CCNC 2011), 8-11 Jan. 2011*, Piscataway, NJ, USA, 2011, pp. 75-9

Recent Research from around the world?

Canada: Hranilovic, Mc Master University

- **Hranilovic**
  - Research from information theory to practical implementation
  - Lots of very innovative approaches
  - Use of digital micromirrors to overcome scintillation in outdoor free space optical links
  - Spatial modulation techniques



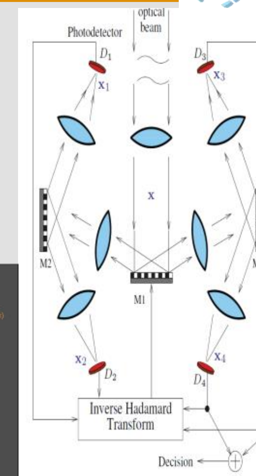


Fig. 6. DMD optical receiver [16]–[18].

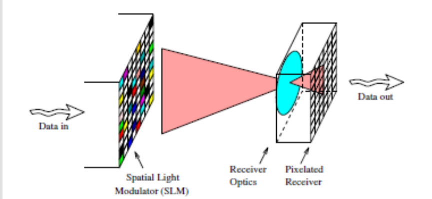


Figure 1. A wireless optical MIMO link

S. Hranilovic and F. R. Kschischang, "Capacity bounds for power- and band-limited optical intensity channels corrupted by Gaussian noise," ***IEEE Transactions on Information Theory,*** **vol. 50, pp. 784-95, 2004.**

A. Dabbo and S. Hranilovic, "Receiver design for wireless optical MIMO channels with magnification,"

Recent Research from around the world?

USA: Tom Little: Boston University

- **Boston University Smart lighting center** **http://www.bu.edu/smartlighting/**
  - Multidisciplinary centre looking at many aspects of lighting
  - Tom Little’s group works on a range of visible lighting communications and visible light positioning topics

Recent Research from around the world?

China: Zhengyuan (Daniel) Xu, University of Science and Technology of China

- **Zhengyuan (Daniel) Xu**
  - Returned to China from USA under thousand professor scheme
  - Multiple projects
    - > Atmospheric UV communications
    - > Visible light communications and navigation
    - > Vehicle based systems
    - > Underwater optical wireless communications

Recent Research from around the world?

Many other countries

- **Research on optical wireless is increasing around the world**
- **Research teams in many countries**
  - Korea, Singapore, Israel, Turkey +…
- **Public industry involvement**
  - Intel and Samsung
  - Many others watching on the sidelines

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Conclusions

- **Demand for high speed data transmission and emergence of LED lighting has created a new opportunity**
- **Research in visible light wireless communications and visible light positioning is rapidly increasing around the world**
- **Lots of potential**
- **Lots of unsolved practical and theoretical problems**

???

Any questions?