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Visible Light Communications:
A Solution to the Spectrum Crunch?

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This work was supported under Australian Research Council's (ARC) Discovery funding schemes (DP 130101265 and DP15010003)

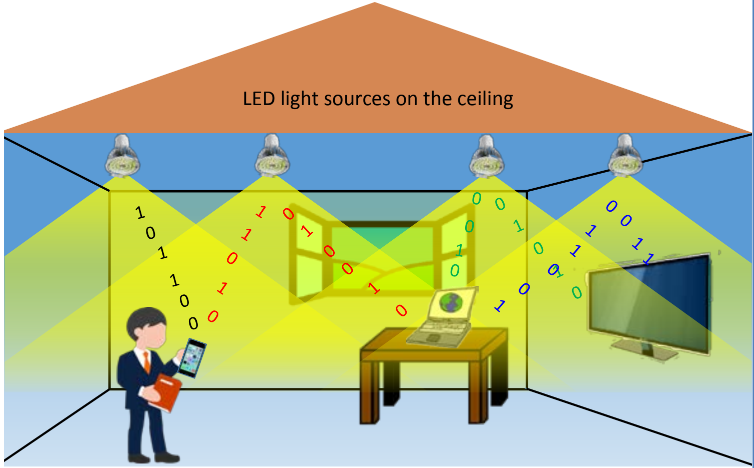
Talk Outline

- What are visible light communications (VLC), visible light positioning (VLP) and LiFi?
- What are the limits to VLC?
  - All you need to know about communications to separate the potential from the hype
- Some examples of practical and experimental VLC systems
- Research by my group
- Recent research from around the world
- Questions

What are visible light communications (VLC), visible light positioning (VLP) and LiFi?

What is Visible Light Communication (VLC)?

- In visible light communications information is transmitted by varying the level of transmitted light much faster than the human eye can detect
- Why is VLC is becoming important?
  - LEDs are replacing conventional lighting
  - LED lights can be varied (modulated) at much higher frequencies than fluorescent or incandescent lights
  - The light from a standard white lighting LED can be varied at between 2 and 20 MHz
- Everybody wants high speed wireless communication and there is no more radio frequency spectrum available



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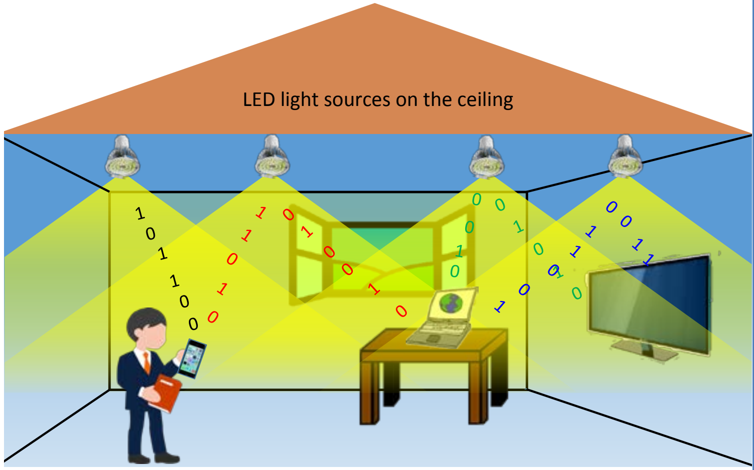
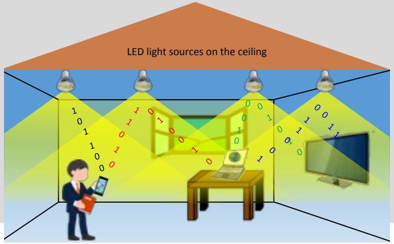


What is the difference between VLC and LiFi?

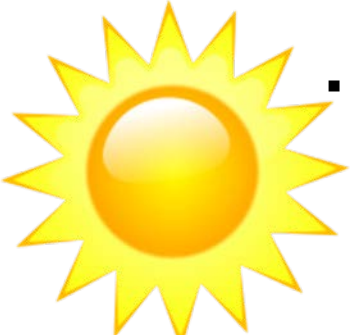
LiFi was a term coined to describe a particular form of VLC but it is now being used more generally.

Advantages and Disadvantages of VLC



ADVANTAGES

- Lights (luminaires) are everywhere and are located with line of sight to most positions
  - No user resistance to ugly infrastructure
  - No safety concerns
  - Have mains power
- No spectrum licensing requirements
- Privacy/security
  - Light doesn’t pass through walls
- Very large bandwidth ????
  - Here is where the hype begins!!!.

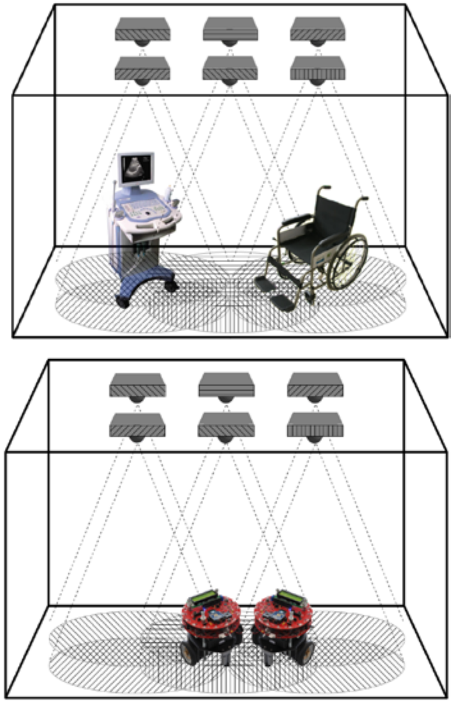


DISADVANTAGES

- What about the uplink?
  - Nobody wants a bright light in their laptop
  - Possible solutions
    - WiFi? Infrared?
- Optical Wireless Communications is very different from RF
  - Difficult to build very sensitive high bandwidth receivers with current technology
- It won’t work when the lights are off, will it???
  - Actually it will work with very low transmit power as long as there is little background light
- Background light causes shot noise
  - Sunlight can be a major problem as it creates very high shot noise levels

What is Visible Light Positioning (VLP)?

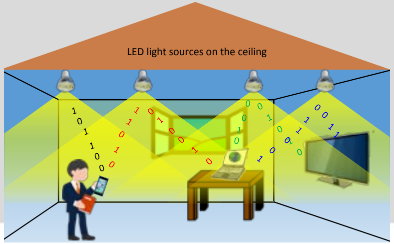
- In visible light positioning LED lights transmit information about the position of the LED
  - Requires much lower data rate than VLC applications
- By combining information from several different LEDs the receiver can calculate its position
  - A bit like GPS but indoors
- Potentially much more accurate than GPS or other radio frequency based systems
- Huge potential market for applications like tracking shoppers in supermarkets



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

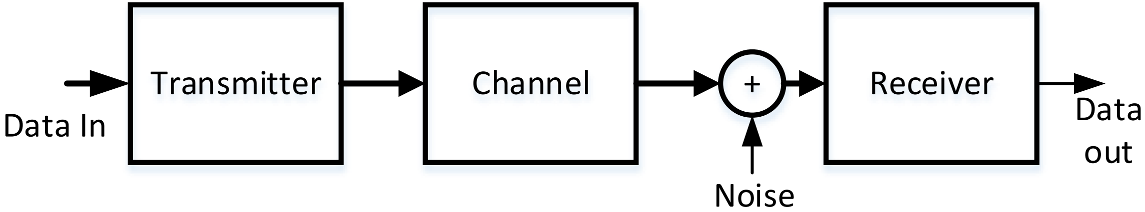
What are the limits for VLC?

Back to basics



We can transmit and receive radio signals over very long distances. Why is it hard to transmit light signals across a room???

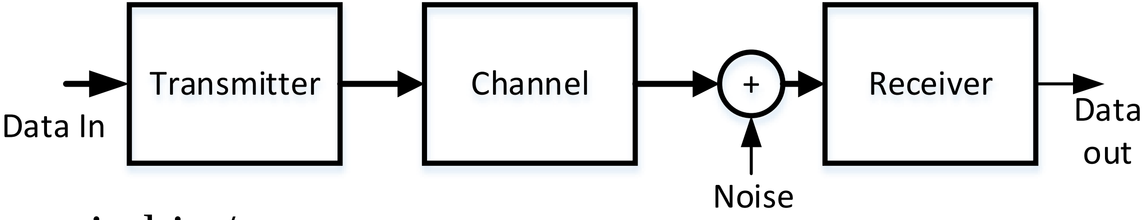
What does Shannon's channel capacity tell us???



$$C = B\log_2\left(1+\frac{S}{N}\right)$$

What limits the data rate?

$$C = B\log_2\left(1+\frac{S}{N}\right)$$



C : Capacity - maximum data rate in bits/sec

B : Bandwidth of received signal

S : Power of the received signal (at the decision point)

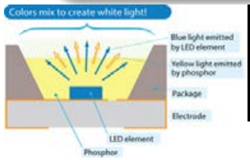
N : Power of the received noise (at the decision point)

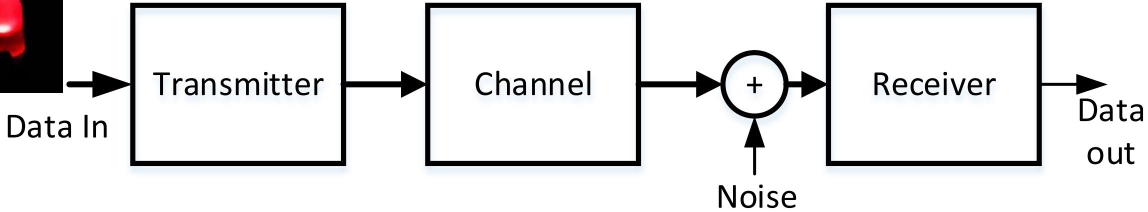
Strictly speaking this form of Shannon's capacity formula **does not** apply in most VLC systems
The actual capacity is much less.

Maximum data rate depends on **bandwidth** and **signal to noise ratio**

What limits the Bandwidth?

The **useful** bandwidth depends on what has the **lowest** bandwidth: the transmitter, the channel or the receiver.





Transmitter Bandwidth
Conventional white LED: 2-20 MHz
RGB LED : 100+MHz
Laser: 10 +GHz

Channel Bandwidth
Line of sight: ~ Terahertz
(reflections reduce the bandwidth)

Receiver Bandwidth
Depends on the area of the photodetector
Small area – high bandwidth but low SNR - 10+ MHz maybe????

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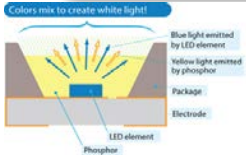

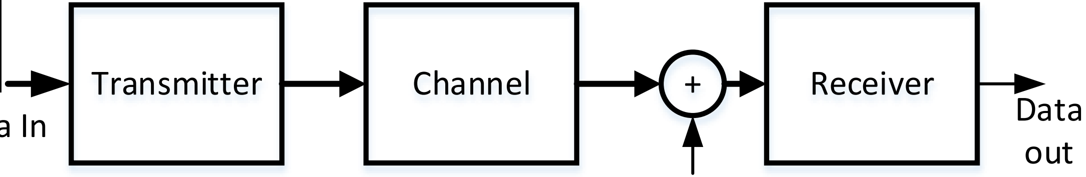

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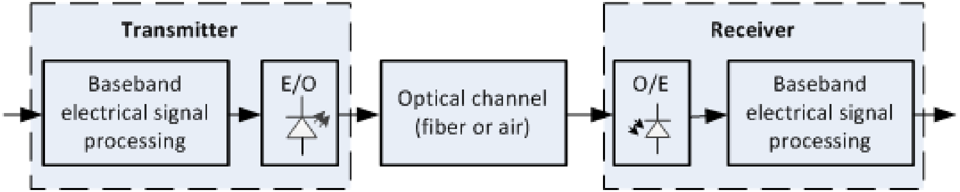
The challenging part of a VLC system is the **receiver**

The hype usually (always?) concentrates on the transmitter or the channel.

but
???

What limits the Signal to Noise Ratio?

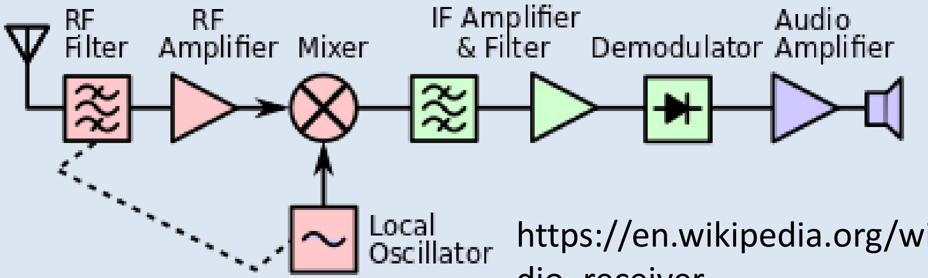
- Systems using LED transmitters always use intensity modulation and direct detection (IM/DD)
  - Information is carried on the intensity (instantaneous optical power) of the transmitted light
  - Receiver detects the intensity of the received light
  - Received signal falls off as d^4 (after optical to electrical conversion)



- Simple transmitter
  - Baseband signal (+DC bias) controls the current to the transmitting LED
- Simple receiver
  - Photodetector converts the intensity of the received light to a current representing the baseband signal
- But
  - Receiver has very low sensitivity

But why can't VLC be more like RF?

Typical RF front-end



https://en.wikipedia.org/wiki/Radio_receiver

- Signal transmitted by LED has many optical frequencies
  - It is not coherent
  - No frequency for a local oscillator to tune to
- No optical amplifiers that are suitable for VLC receivers
- No optical components with strong non-linearity required for mixer
- Narrowband optical filtering is difficult
  - Very narrow band filters are also very directional

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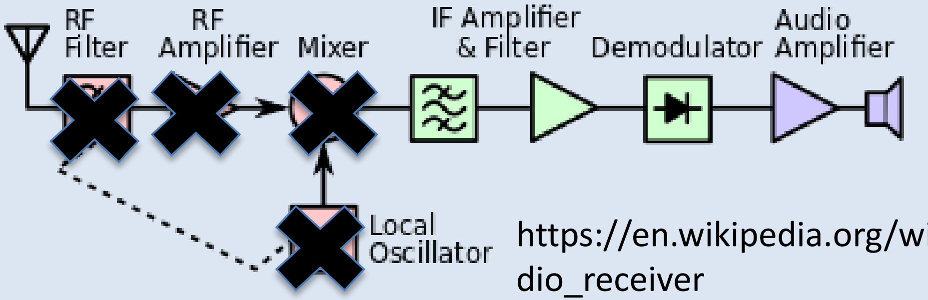

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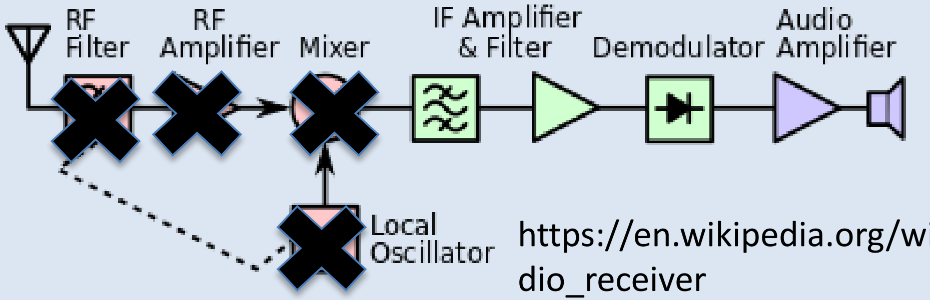

https://en.wikipedia.org/wiki/Radio_receiver

- Signal transmitted by LED has many optical frequencies

1. The transmitted signal in VLC using a LED transmitter has multiple optical frequencies
2. There are no equivalent optical components to those used in RF

  – Very narrow band filters are also very directional

How can we increase the power of the received signal?

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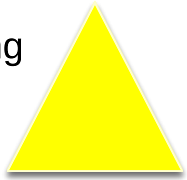
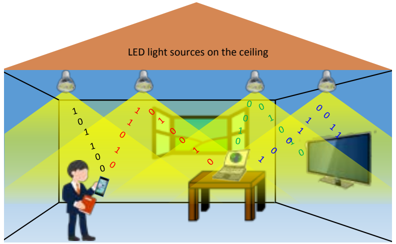
- Transmit more power
  - BUT in VLC maximum power is determined by the lighting requirements
- Receive more power by
  - Having a more directed beam
    - BUT the beamwidth is set by the lighting requirements
- Receive more power by
  - Using larger area photodiodes in the receiver
    - BUT bigger photodiodes have slower response which limits the bandwidth
- Receive more power by
  - using a lens in the receiver
    - BUT this narrows the field of view so that the transmitting light might not be visible



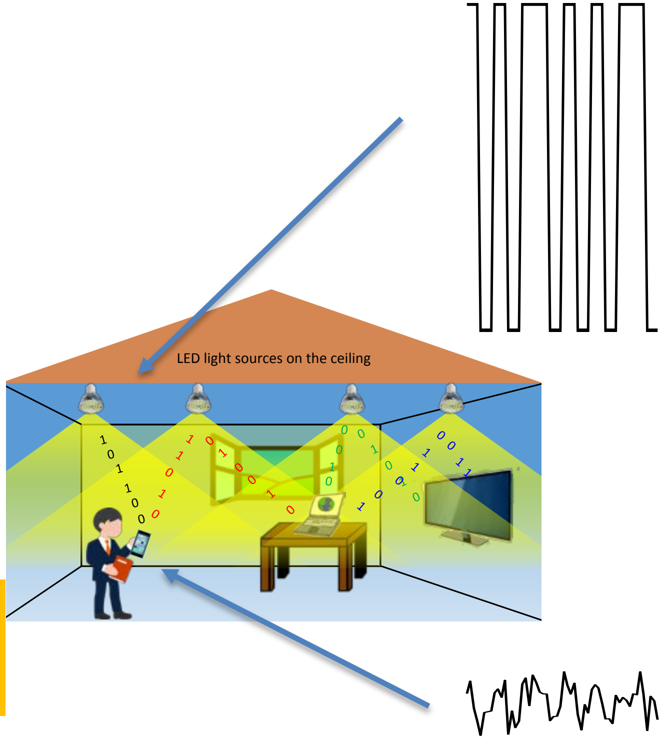


It is difficult to increase the received signal power
All possible techniques have drawbacks

Why are VLC signals so noisy?

- The main source of noise in VLC systems is shot noise
- The level of shot noise depends on the total light reaching the photodiode
  - This includes any other artificial light and sunlight
  - A sunny window may be a problem for VLC

The sun is a problem for VLC



How can we reduce the noise?

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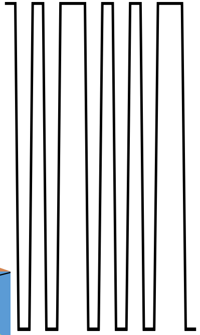
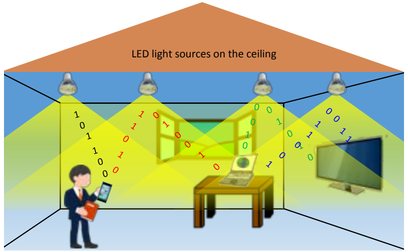
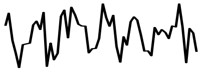
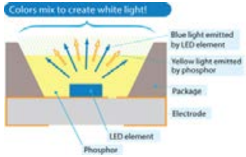
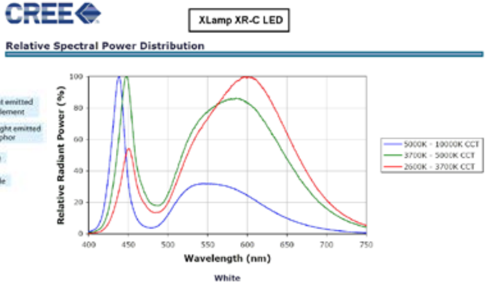
- The level of shot noise depends on the **total light** reaching the photodiode
- Can we use an optical filter to filter out unwanted wavelengths?
  - Yes – but very narrowband optical filters are very directional
  - So limits field of view of receiver
  - So it is very tricky to transmit different signals on multiple laser transmitters

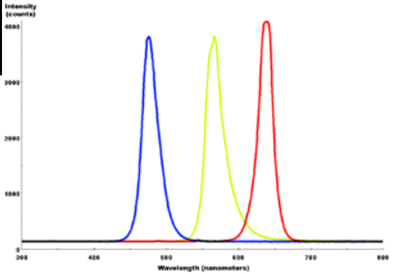


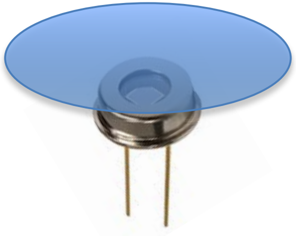












Some examples of practical and experimental VLC systems

Commercially available product from PureLifi

- PureLifi is advertising a product with nominal data rate of 43 Mbit/s
- Uses infrared transmission in the uplink

4.5 Gbit/s system using RGB-LEDs (from leading Chinese University)

- This gives higher data rates than could be achieved in an indoor VLC system because:
  - Short distance
  - Very large lens
  - Directional – Only a narrow beam of light is being received

Y. Wang, X. Huang, L. Tao, J. Shi, and N. Chi, "4.5-Gb/s RGB-LED based WDM visible light communication system employing CAP modulation and RLS based adaptive equalization," *Optics Express,* vol. 23, pp. 13626-13633, 2015

“Streaming HD Video”
An example from a press release

- Typical example of demonstrations on Youtube and the web
- Three reasons that this gives higher data rates than an indoor VLC system
  - Very narrow beamwidth
  - Very large lens
  - Lights are turned off
- Note streaming HD requires only 4 Mbit/s

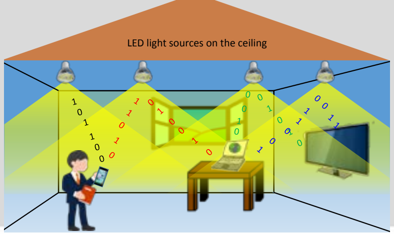
Research results from King Abdullah University (A leading Saudi Arabian University)

- “Scientists in Saudi Arabia claim to have created the fastest li-fi luminaire in the world.
- The experts at the King Abdullah University of Science and Technology (KAUST) have apparently created a device that is able to transmit data 20 times faster than any previously existing li-fi luminaire.

- Does this mean the data rates can be increased 20 times?
  - No
  - Data rates depends on the receiver as well and also on the transmit power

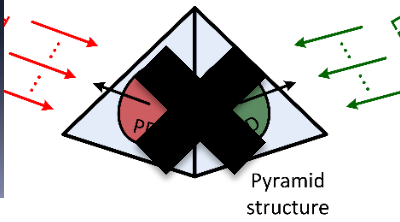
Research by my group at Monash?

Our Current Main Research Topics



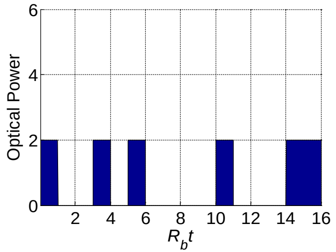
1. Compact Directional Receivers

- VLC and VLP must be useable with a compact device
  - Must be small, must be flat
- Must be able to separate signals from different LEDs
  - So must be directional
- Must have wide field of view



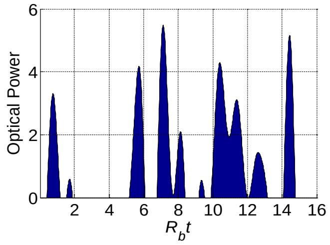
2. Modulation Schemes for intensity modulated optical systems

- Information is carried on the intensity (instantaneous optical power) of the transmitted light
  - Signal must be non-negative

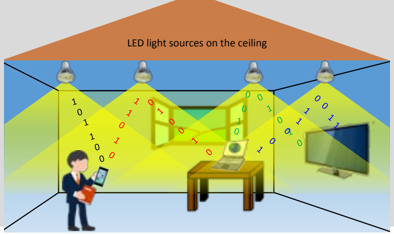


3. Visible Light positioning (VLP)

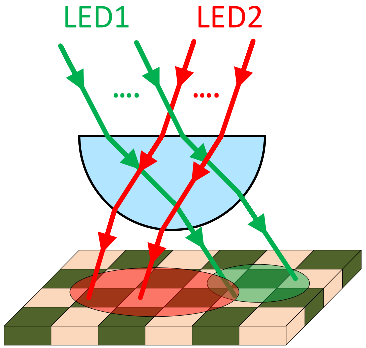
- Positioning systems using angle of arrival to calculate position

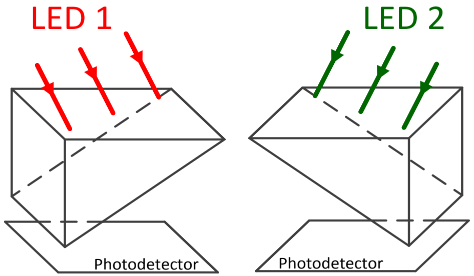


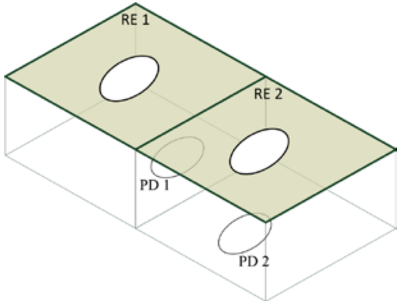
1. Compact Directional Receivers



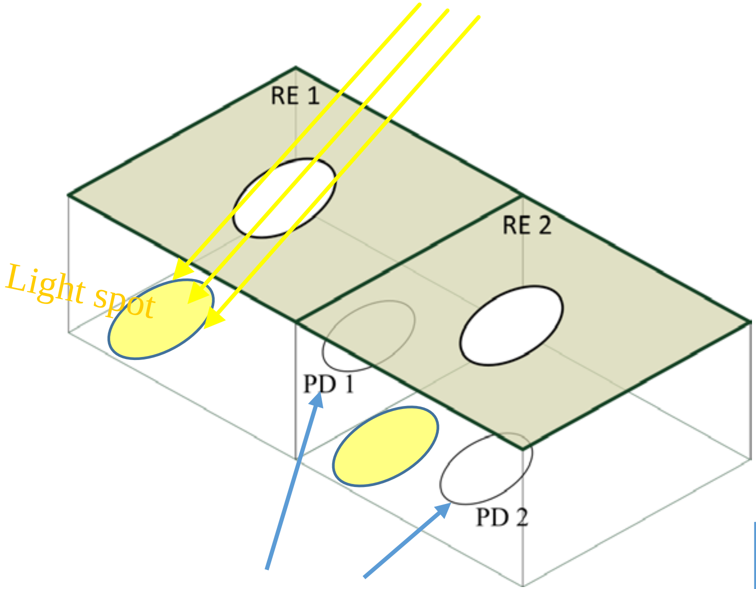
- We have developed a number of new designs over the last few years
  - Hemispherical Lens Receiver
    - Has wide field of view and separates signals
  - Prism Array Receiver
    - Has wide field of view and is less bulky
  - Aperture Receiver – the Angular Diversity Aperture (ADA)
    - Has wide field of view and is well suited to integration







Structure and Operation of the ADA receiver



Different positions of the photodiode (PD)

- Features of the aperture receiver

1. An aperture is created in the opaque screen.
2. A bare Photodiode (PD) is located under the screen.

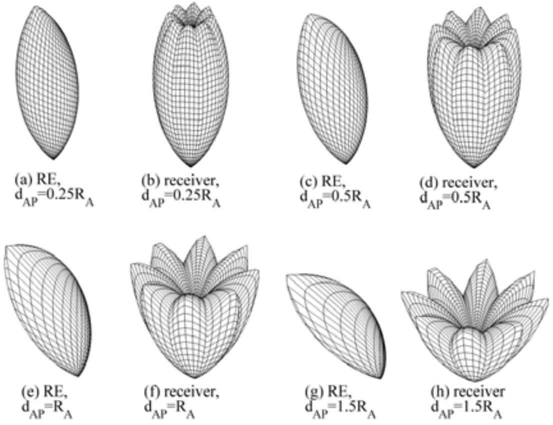
The relative positions between the aperture and the PD are different.

Channel gain: $h = \frac{(m+1)A_o}{2\pi l^2}\cos^{m+1}\varphi$

For the light from a certain direction, the channel gain depends on the ***overlap area***, and the overlap area depends on the PD's location.

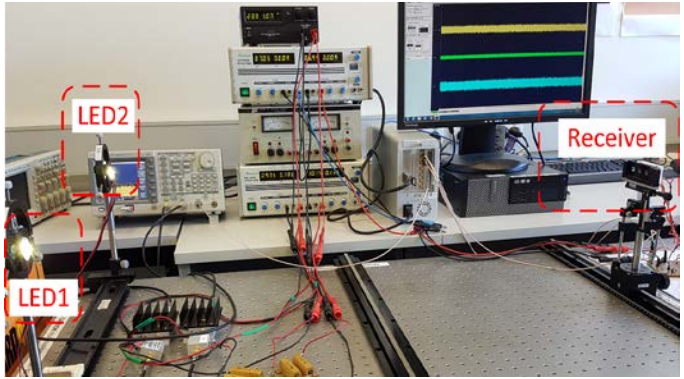
More about ADA Receiver

- Directionality of receiver can be easily designed by choosing the offset of photodiode



Receiving patterns of 8 element receivers

- Have demonstrated performance theoretically and experimentally
- Patented
- Attracting increasing interest



2. Our Work on Modulation Schemes for IM/DD

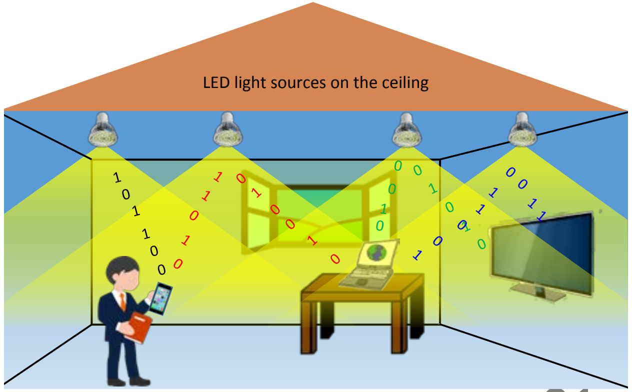
- New forms of orthogonal frequency division multiplexing (OFDM) for intensity modulation
  - Invented asymmetrically clipped optical OFDM (ACO-OFDM)
    - Now an important research topic >200 papers
  - Other forms of OFDM : asymmetrically clipped DC biased optical OFDM (ADO-OFDM)
- Research on capacity of IM/DD systems
  - No closed form solution

$$C = B\,\mathrm{l}\ldots\left(1+\frac{S}{N}\right)$$

Wrong!!!

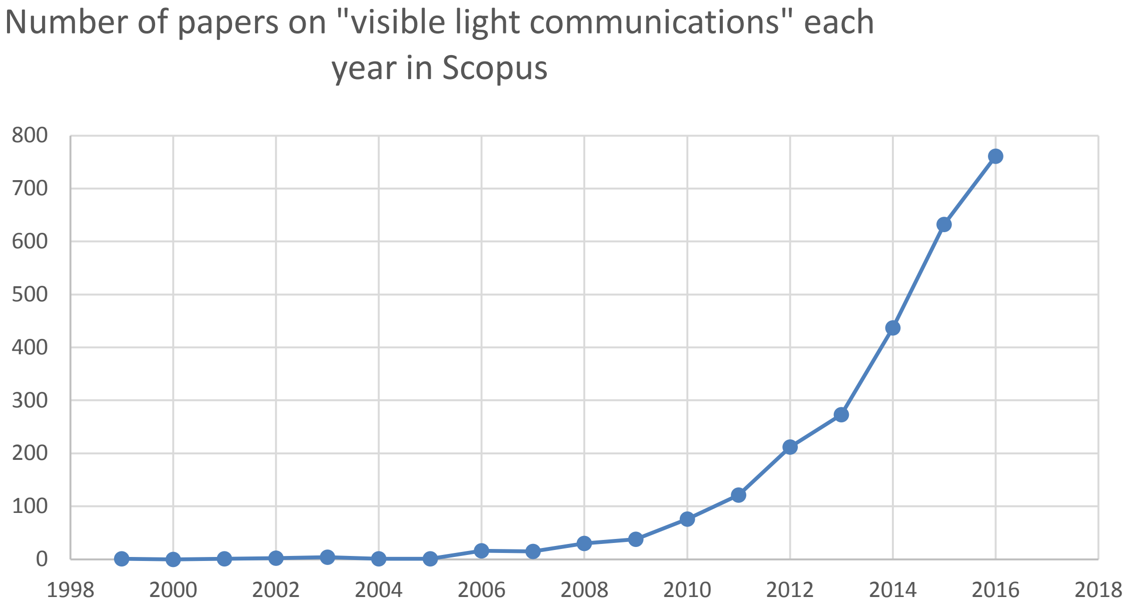
3. Our Work on Visible Light Positioning

- We have concentrated on angle of arrival (AOA) based positioning
  - Use aperture receiver (ADA) to determine AOA
- Have shown theoretically and experimentally that some configurations of ADA receiver can give very accurate positioning



Recent research from around the world

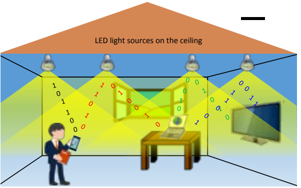
Research on Visible Light Communications has increased dramatically since 2005

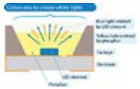


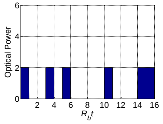
- Increase from 0 to >700 per year
- Note : also many other papers using different keywords
  - e.g. optical wireless communications

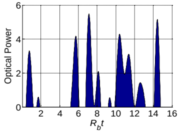
Huge and diverse range of research on visible light communications

Similar areas to our research

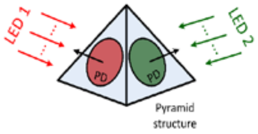








- Systems using indoor lighting
  - Cellular, MIMO
  - Different types of LED
  - Different modulation schemes
  - Different multiple access schemes
- Positioning systems
  - Techniques based on received signal strength
  - Angle of arrival using 3 D receivers



Completely different topics

- Cameras as receivers
  - Limited by frame rate of camera
    - Work arounds using ‘rolling shutter’ property of digital cameras, or specially designed modulation schemes
  - Runs down battery in phone

- Systems using car lights as transmitters
  - “see through’ car in front

- Systems using traffic lights to transmit data to cars
- Details of transmitters and receivers like effect of nonlinearities

Conclusions: The future for VLC and VLP

- The introduction of LEDs for lighting creates a new communications opportunity: visible light communications (VLC)
- Downlink speeds ~40 Mbit/s are possible using current technology
- There is a lot of hype which exaggerates the potential
- In my opinion
  - Downlink speed may increase to 1Gbit/s with innovative receiver design
  - The most likely application is in combination with WiFi for the uplink and VLC in the downlink
- Visible Light Positioning has the potential to provide a much more accurate positioning system that RF based systems
  - There already are some simple systems available
  - Market predictions for VLP are huge.

Acknowledgments

Thanks to the many postgraduates, postdocs and collaborators who have contributed to this research and whose diagrams I have 'borrowed' for this presentation.

Questions