Optical Wireless for data transmission

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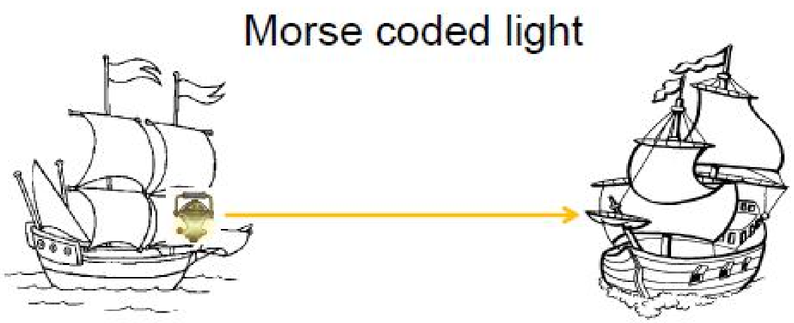
Summary

- Introduction and motivations
- Sources and detectors
- Design issues
- Applications

Transmitting information using free-space light propagation is not exactly new idea

- 800 BC: fire beacons (Romans)
- 150 BC: Smoke signals (Native-Americans)
- 1790: optical telegraph (Claude Chappe)
- 1960: Laser
- >1970 Laser FSO for military secure applications
- 1993: IrDA standard



Some Examples of Applications

- **Satellite communications:**
  - Inter-satellite, satellite-to-earth links, ~10 000 km
  - P-t-P, line-of-sight (LOS), < 1 Gbit/s, Infra Red

- **Terrestrial free-space optics (FSO):**
  - LOS city links (between building rooftops)
  - P-t-P, relaying, ~ km range, ~ Gbit/s range, Infra Red

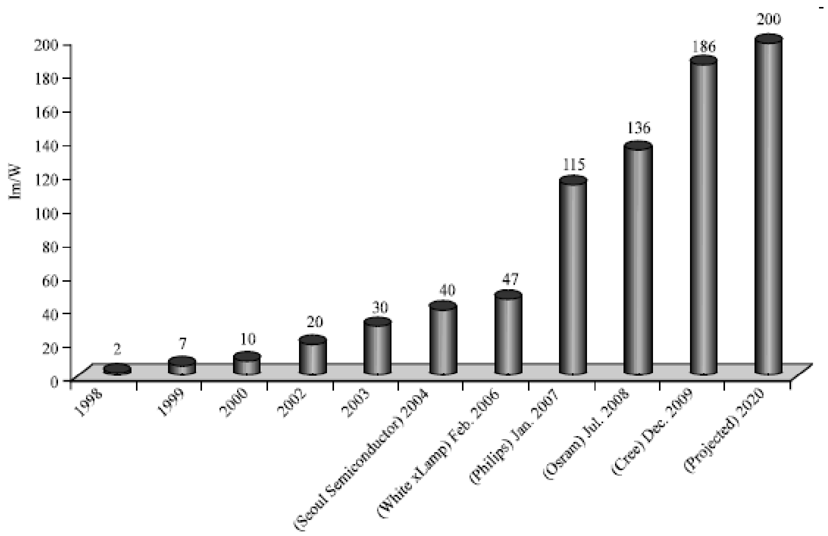
- **Submarine optical wireless**
  - links among unmanned vehicles
  - P2p, tens of meters range, blue/green light

- **Outdoor Optical wireless (OW) communications:**
  - Car to Car, Car to Infrastructures
  - P-t-P, P-t-MP links (LOS)
  - 0.1 … 10 Mbit/s, Infra Red, Visible

- **Indoor Optical wireless (OW) communications:**
  - Indoor applications in ~ m range
  - P-t-P, P-t-MP links (LOS and/ or reflections)
  - 10 … 1000 Mbit/s, Infra Red, Visible

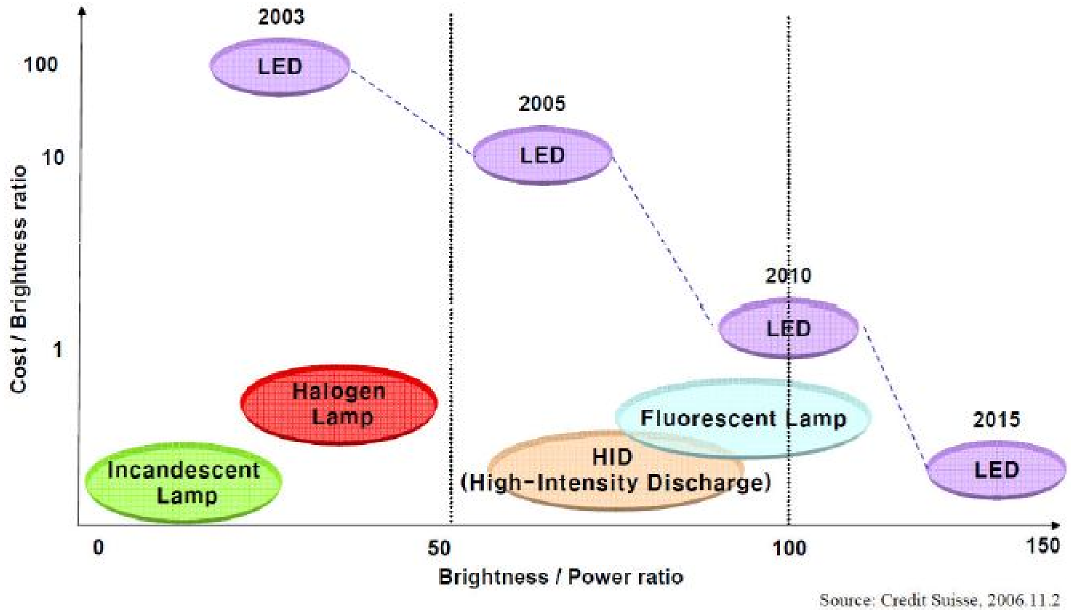
A key technology advancement: LED

- Progress in LED luminous efficiency opens up new possibilities



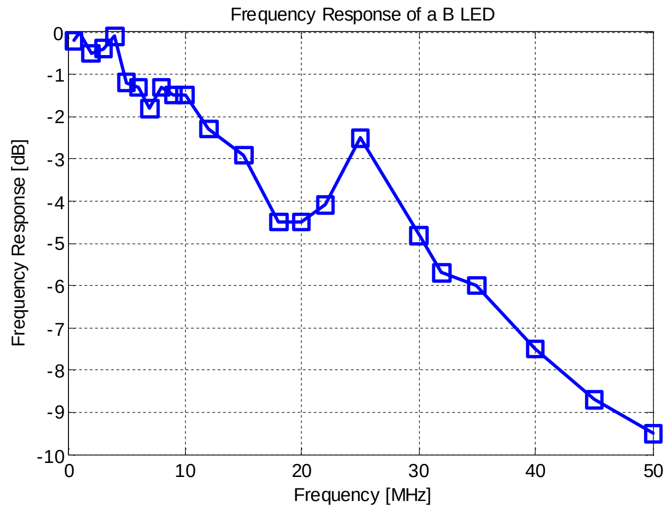
LED impact and evolution

- LED are to be used everywhere (consumer electronics, traffic signalling, illumination etc.) because they are good ... and very cheap



LED bandwidth

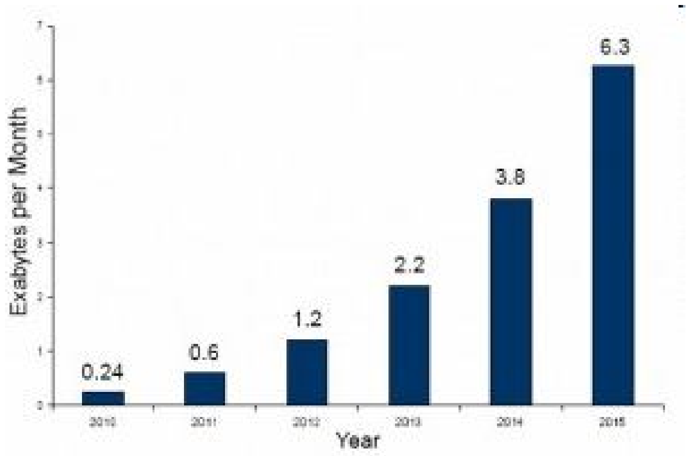
- LEDs can be simply modulated (=turned on/off) at much higher speed than any other previous light source



- All products with visible-LED components can be turned into wireless data transmitters

Motivations VLC: wireless traffic growth

- Traffic/devices (and number of connected devices) increasing steadily
- Potential capacity saturating



Optical Wireless Communications Characteristics

- No EMI with RF-systems, makes it good for:
  - “safe” areas (hospitals)
  - “secure” areas (military, core business etc.)

- Available and unregulated spectrum
  - lessens issues of “crowded” RF spectrum

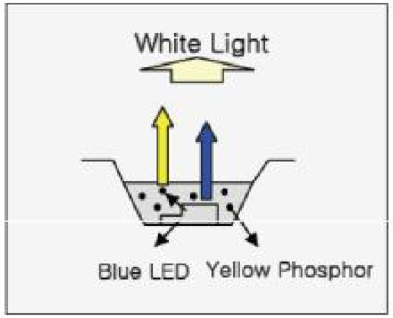
- Simple shielding by opaque surfaces
  - easily obtainable privacy

- Complementary to radio for wireless access

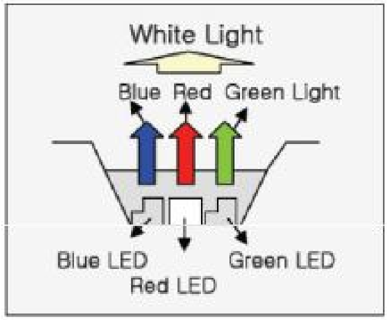
Devices

Two types of (common) white LED

- Either blue+phosphorus (requires blue filtering) or RGB
- Usually LED composed by $GaAs_{1-x}P_x$

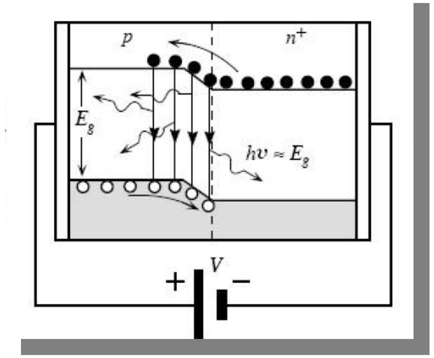


B + Phosphor LED



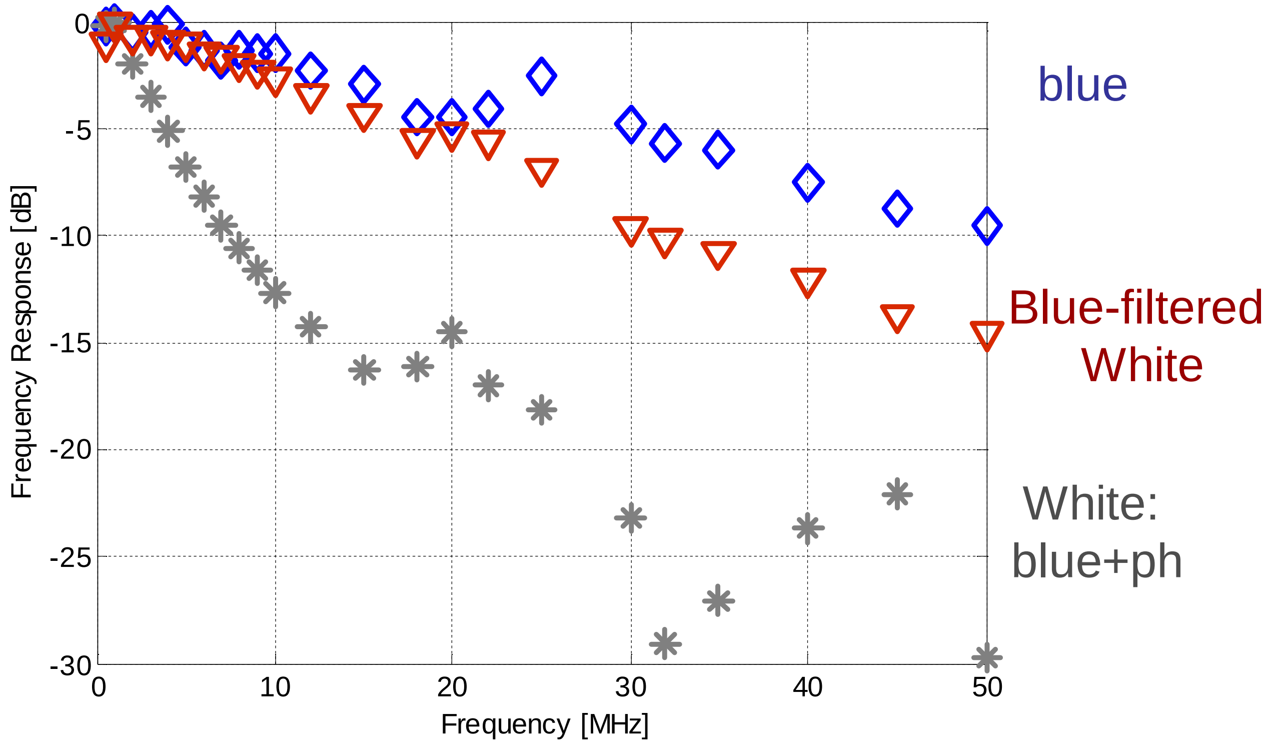
R+G+B LED

Source: IEEE 802.15.7



- Blue+phosphorous: much slower (≈ 1 MHz vs 10 MHz)
- RGB allows for WDM (Wavelength Division Multiplexing)

Bandwidth


0
-5
-10
-15
-20
-25
-30
0
10
20
30
40
50
Frequency Response [dB]
Frequency [MHz]
blue
Blue-filtered White
White: blue+ph

Eye Safety

- Very strict requirements for eye safety if the source emits a collimated beam (laser): class I (IR) or class II (visible)
- Wider margins if source is extended (LED), since eye focuses on different regions of the retina
- Limits maximum transmitter power

Receiver scheme

- Buiding blocks:
  - photodiode (pin or apd)
  - electric amplifiers
  - electrical filtering
  - clock recovery (CR) circuit
  - discriminator

- Also used
  - lenses
  - optical filter

Design issues

Bit Error Rate

- Bit Error Rate (BER) gives the fraction of erroneously detected bits:

$$BER = < \frac{N_{err}}{N_{tot}} >$$

(< > : time average)

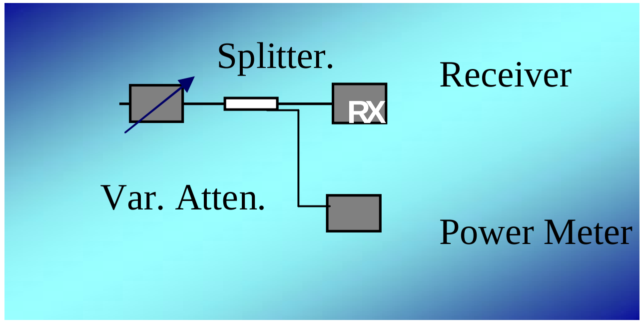
- BER tends to the error probability

- Usually, BER must be lower than a given value (e.g.10^{-9})

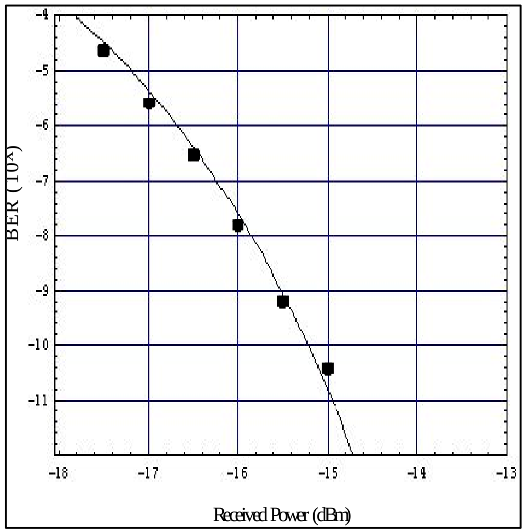
- Forward Error Correction codes: can reduce BER<10^{-3} to BER≈0, with some limited overhead (e.g. +7%)

Measuring Bit Error Rate

BER-measurement setup



Typical BER curve



Sensitivity

- The input power level giving BER=10^{-9} is defined sensitivity
- Sensitivity is specified in the back-to-back configuration, for a RX-TX pair
- Sensitivity depends on:
  - signal bit rate
  - Modulation format
  - photodiode and electronics specs
  - transmitter details
  - optical signal degradation in transmission (e.g. multi-path, noise)

System Sensitivity

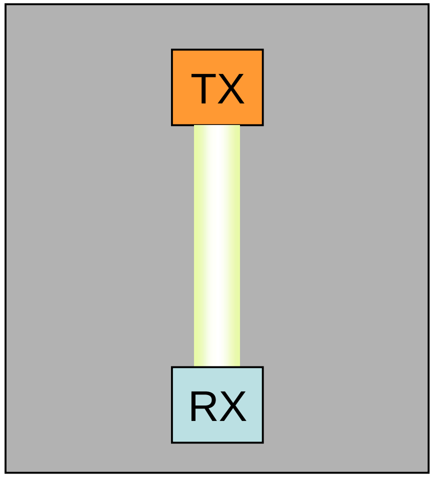
- Noise due to thermal and background
- Mostly, AWG (additive white gaussian)
- White ➔ the higher the filter bandwidth at the receiver, the higher the in-band noise
- Usually, the higher the bit rate, the higher the sensitivity, i.e. need to receive more power

Power Budget

- Attenuation is a key parameter: once known the minimum received power and the transmitter power
- Geometry sets received power, i.e. bit rate
- Optical Wireless can exploit a wide choice …

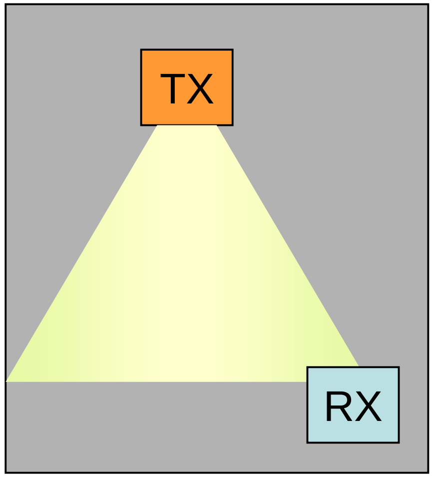
Typical Indoor cases

Directed Line-of-Sight
(LOS)



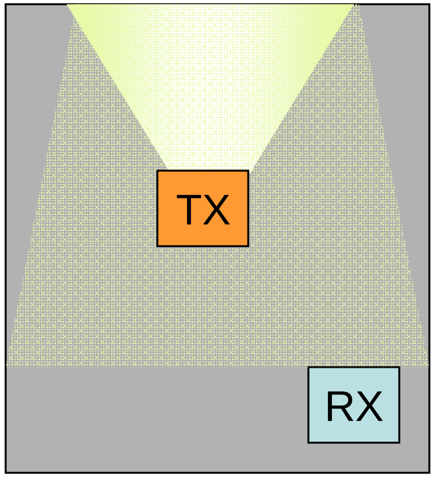
Highest intensity
Highest bitrate (Gbs)
Complex and critical
alignment

Non-Directed Line-of sight
(LOS)



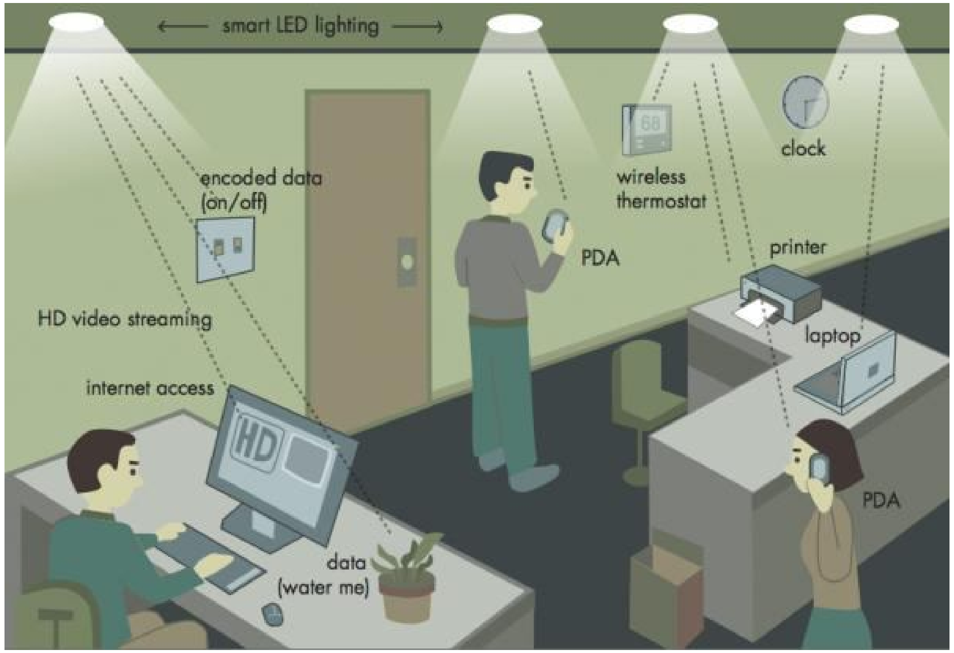
Medium intensity
(high loss)
Limited bitrate (100 Mbs)
Simpler alignment

Diffuse non-LOS



Lowest intensity
Low bitrate (few Mbs)
No alignment

High Speed optical wireless transmission (for today and future indoor communications)



High bit rate transmission

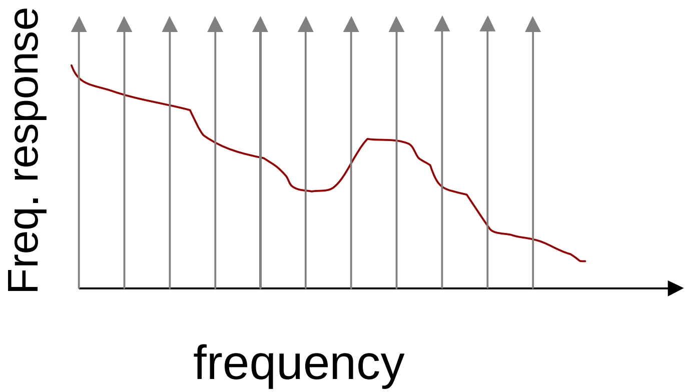
- LED typically have 10 MHz bandwidth: limited bandwidth allows for limited capacity of simplest modulation format (OOK, around 14 Mbit/s)

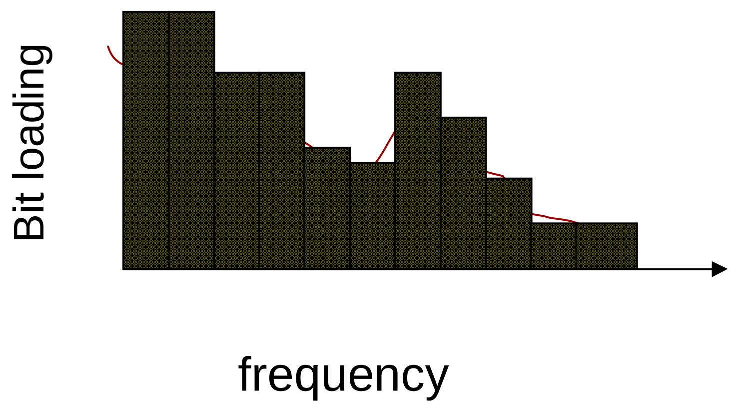
- But we have very good SNR ☺

- Then, you may play with two options
  - Predistort the signal at TX/RX (or both)
    - May require a priori knowledge of the channel
  - Using Discrete Multitone with dynamic capacity allocation

DMT

- Principle used in ADSL
- Allocate orthogonal subcarriers over wide frequency range (>> bandwidth)
- Probe the channel and allocate power and capacity depending on estimated SNR



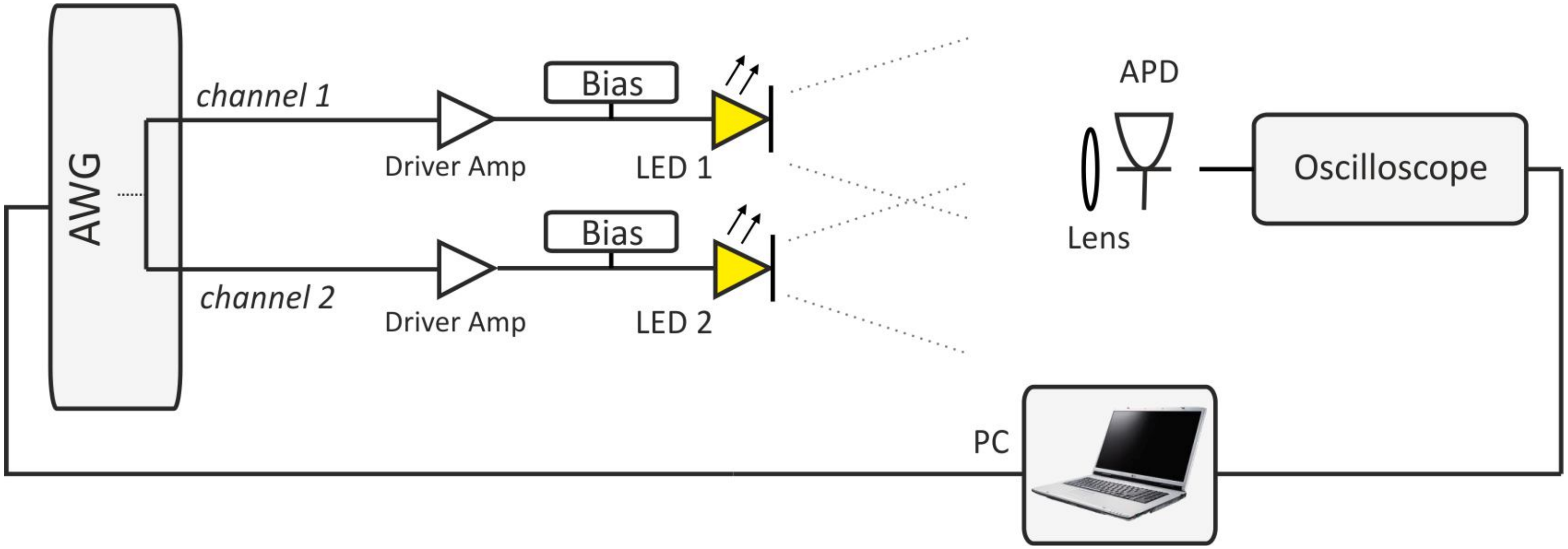


- Power loading similarly performed

Experimental Setup

DMT signal

- Home-made software (Matlab)
- **512 subcarriers** within a bandwidth of **180 MHz**
- Optimal **Bit/Power loading** (Hughes-Hartogs) apply after Channel Estimation
- Linear **pre-emphasis** (0->12 dB) (around 14% capacity gain)
- 10 Acquisition x 600 DMT symbols
- Training Sequence (1,6 %); Cyclic Prefix (4 %)
- Off-line processing



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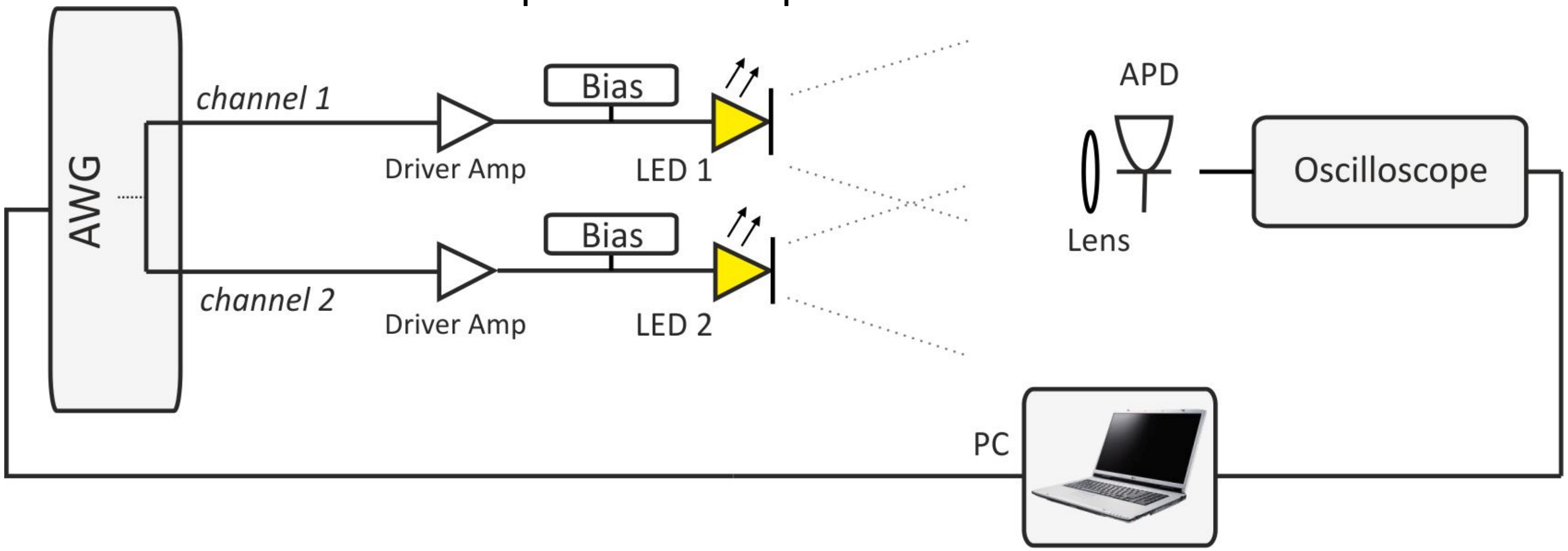
Experimental Setup

Tx source: 2 commercially available RGB leds, distance 1.5 cm
Peak wavelength: 620 nm (red), 520 nm (green) and 470 nm (blue)
Luminous Flux: 105 lm @ 350 mA
Angle of emission: 120° lambertian emission
Driver amplifier (25 dB gain, 29 dBm minimum output, 120 MHz BW)
Bias current: 250 mA
Power to LEDs: 12 dBm
No optical filter required



Experimental Setup

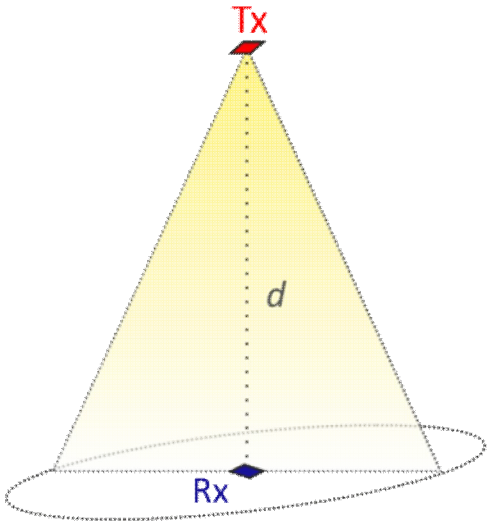
Rx

APD module: Avalanche photodiode (3.14 mm^2 active area, 280 MHz 3-dB BW) + TIA

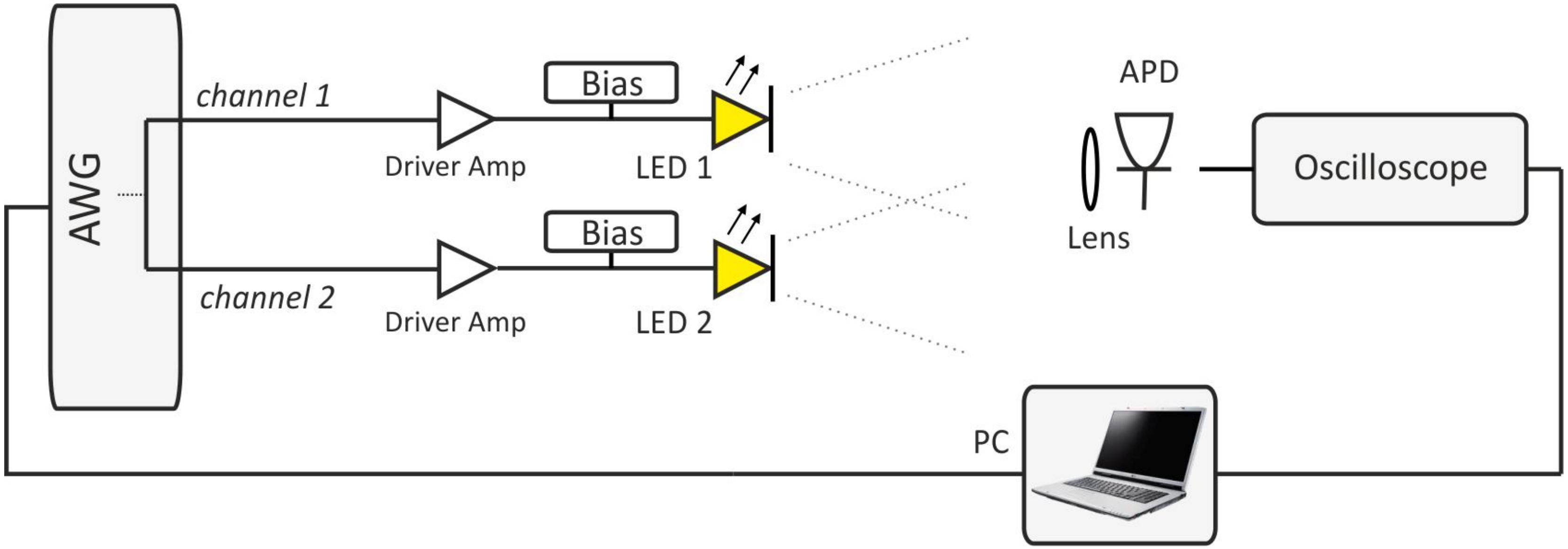
Bi-convex lens (50 mm diameter, 60 mm focal length)

Real-time oscilloscope (LeCroy, 2 GSa/s)

Acceptance angle < 2°

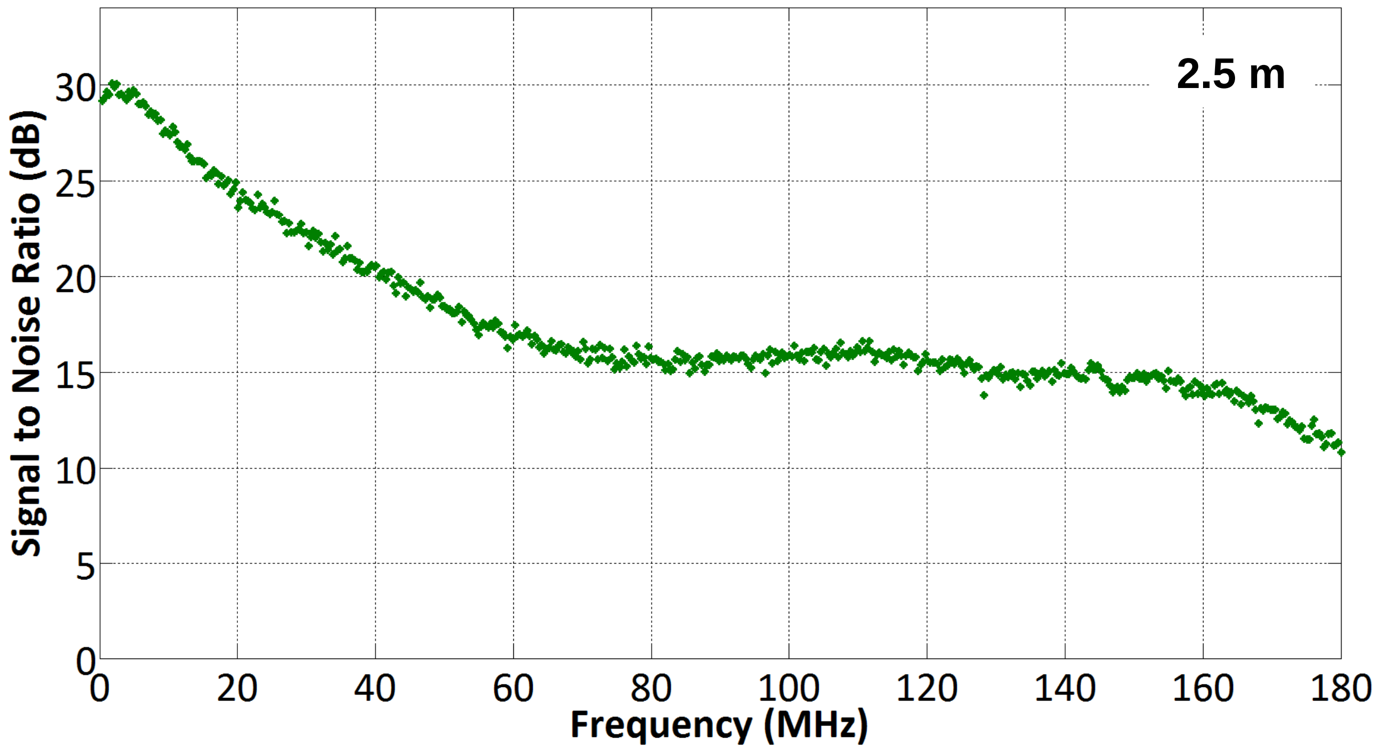


Experimental Conditions: from 1.5 to 4 m (from 30 to 5 lux)

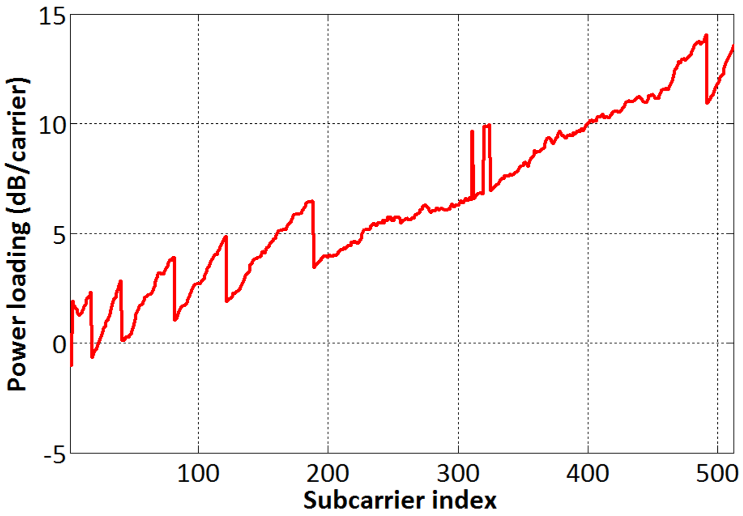


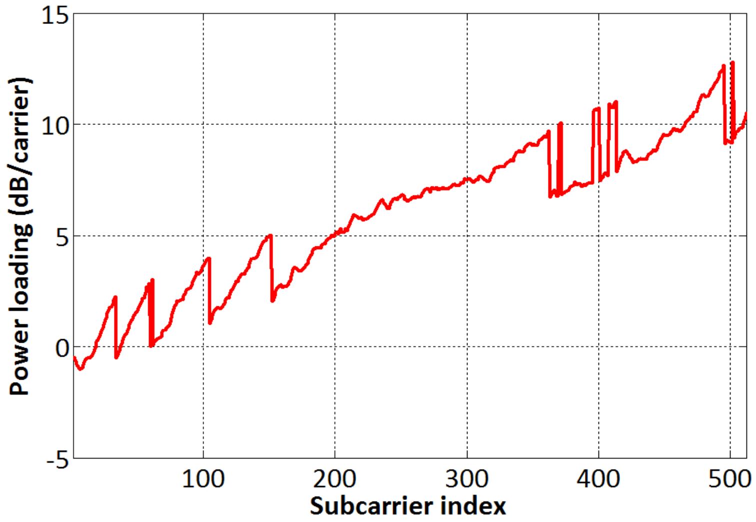
SNR ESTIMATION

- SNR values quite similar because of wide area PD (3.14 mm^2) and focusing effects due to lens and 2 LED-TX

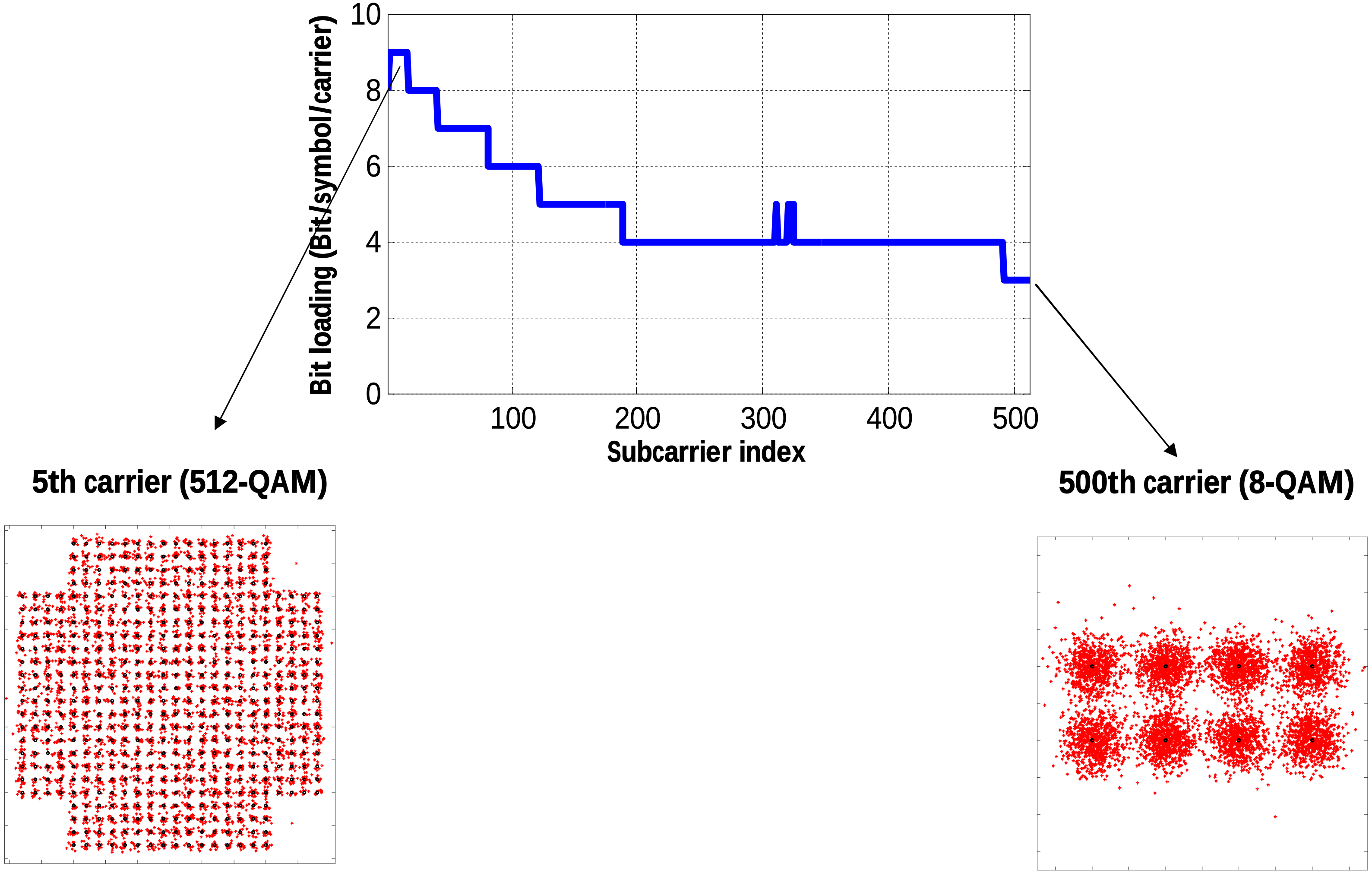


Power loading

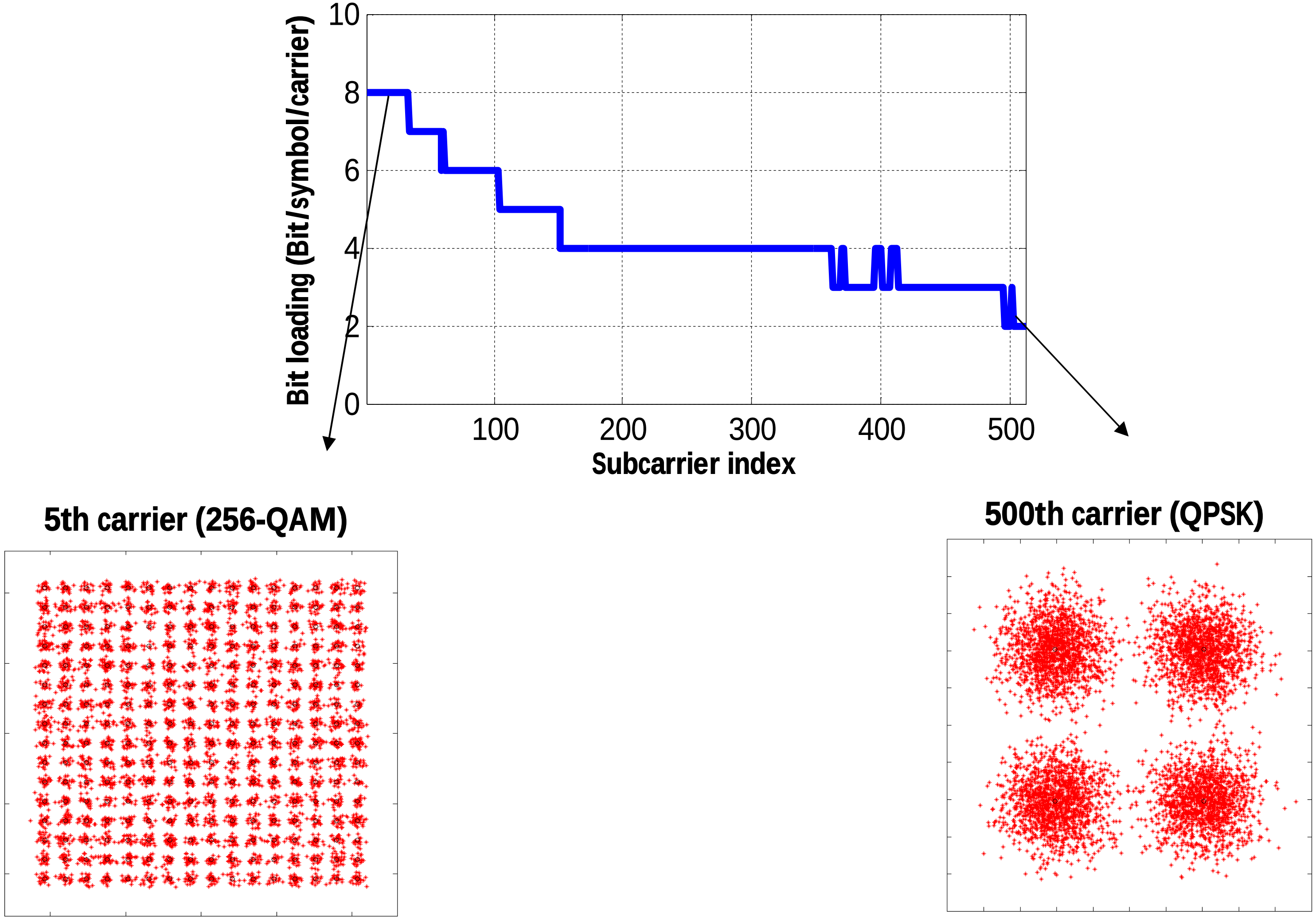




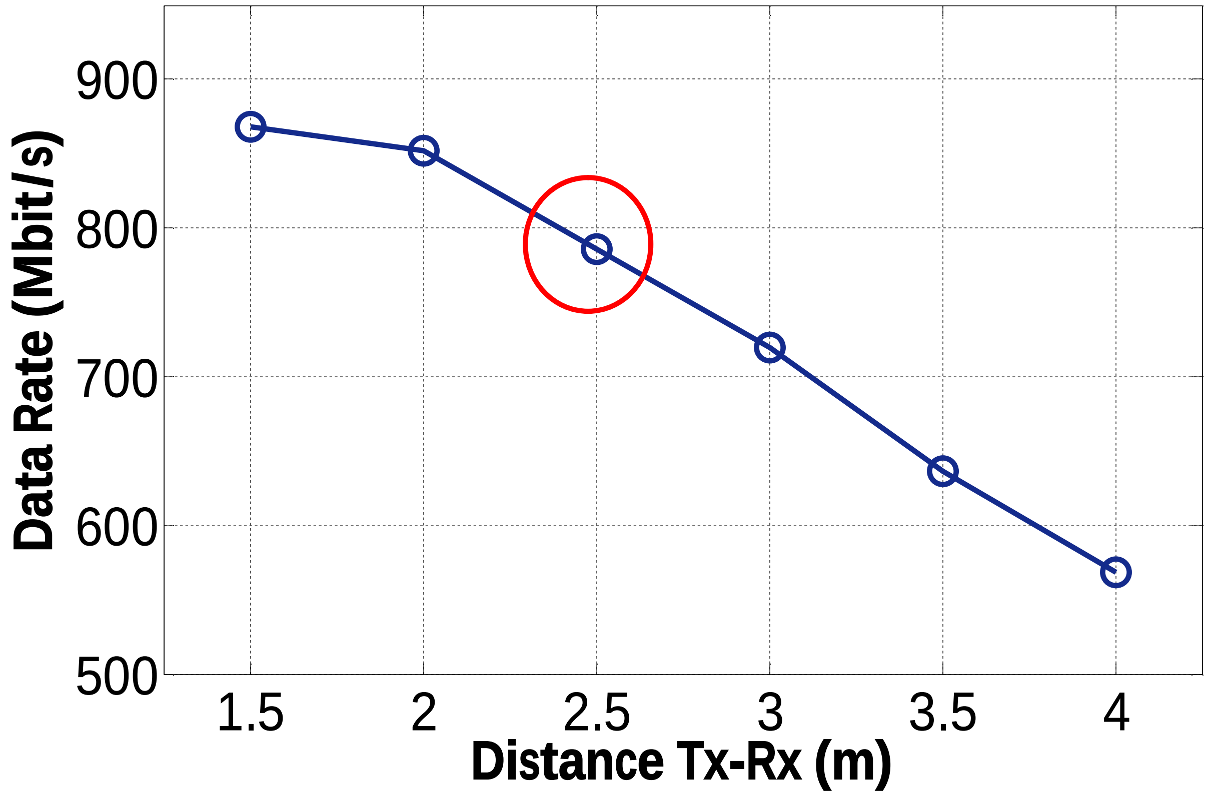
Transmitted signal at 1.5 m (30 lux)



Transmitted signal at 2.5 m (around 15 lux)



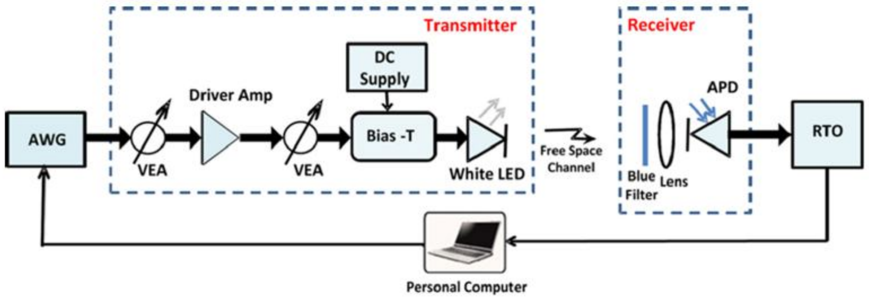
Results

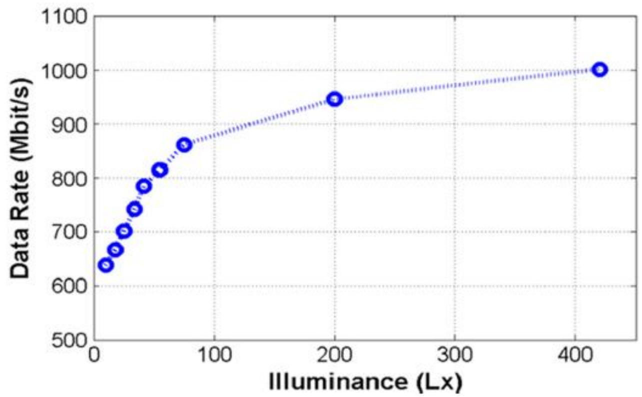


870 Mbit/s @ 1.5 m (30 lux)
780 Mbit/s @ 2.5 m (15 lux)

1 Gbs using phosphorous-based LED

- Similar DMT modulation on short distance (15 cm), with low illuminance level
- Blue filter used to improve frequency response

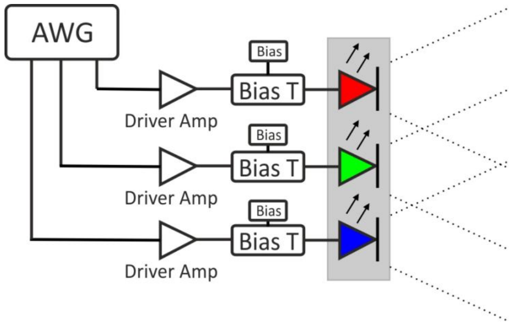


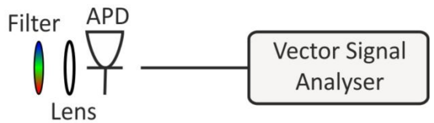


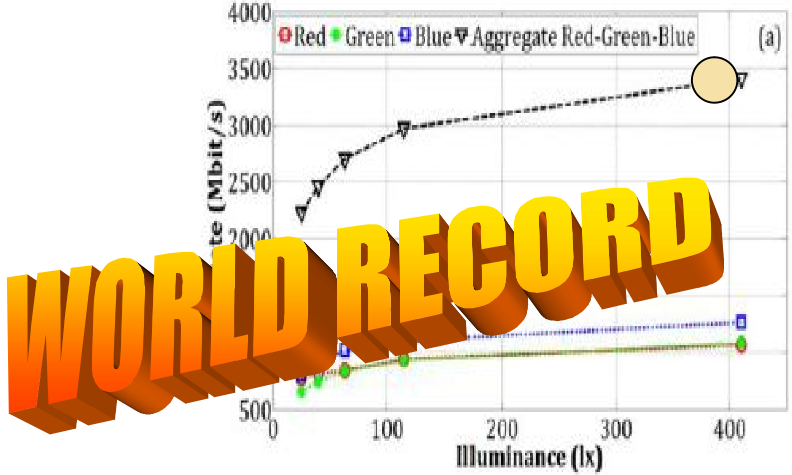
"1-Gb/s Transmission Over a Phosphorescent White LED by Using Rate-Adaptive Discrete Multitone Modulation" Photonics Journal, IEEE, Volume: 4 , Issue: 5Page(s): 1465 - , 1473Oct. 2012

3 Gbs LED indoor transmission

- Using RGB, WDM can also be used





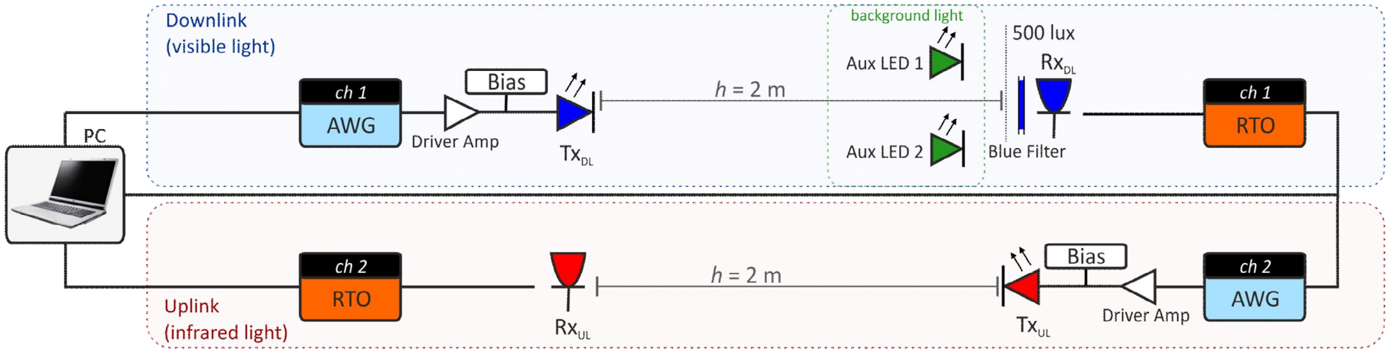


•RGB LED (3 chips: Red, Green, Blue

* "3.4 Gb/s visible optical wireless transmission…", Opt. Express, 20, 26, 2012

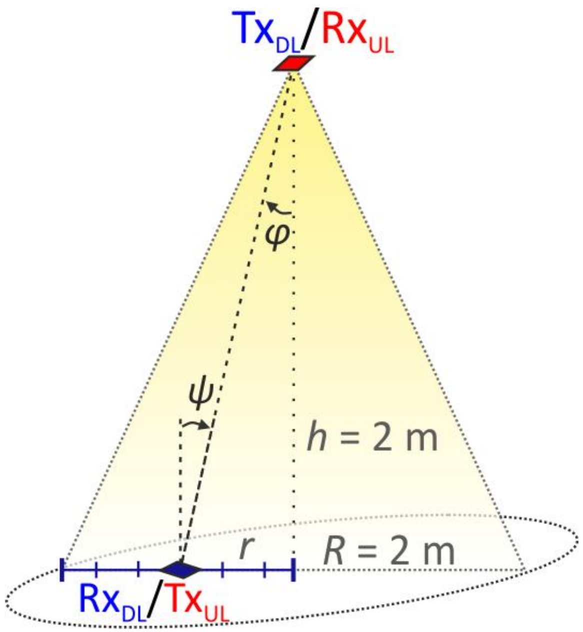
Transmission without lenses

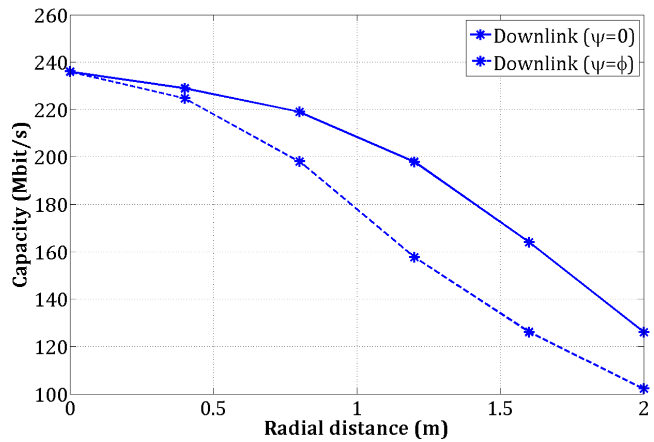
- Bidirectional (US, using IR)

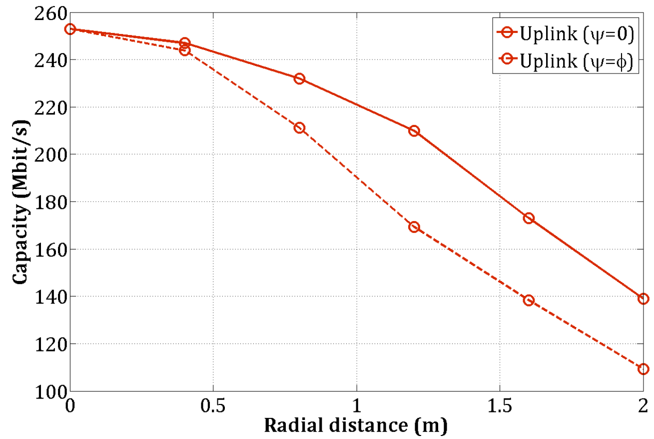


US and DS performance

- Speed>100 Mbs,garanteed







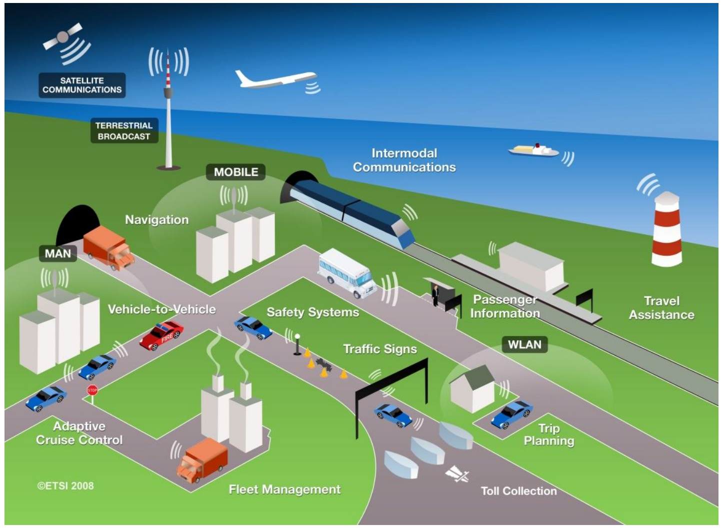
Summary of Indoor Results

- High speed visible OW transmission is achieved based on commercial LEDs and DMT modulation
- Illuminance << standard illuminance level for working environments
- Key achievements (latest figures):
  - **High speed: 3.4 Gbs (RGB-LED, WDM) or 1 Gbs (phosph. B-LED)**
  - **Long distance: 600 Mb/s @7 m**
  - **Un-lensed: >100 Mbs (2 m)**
- These results show that proper balance between system performance and reach can be met

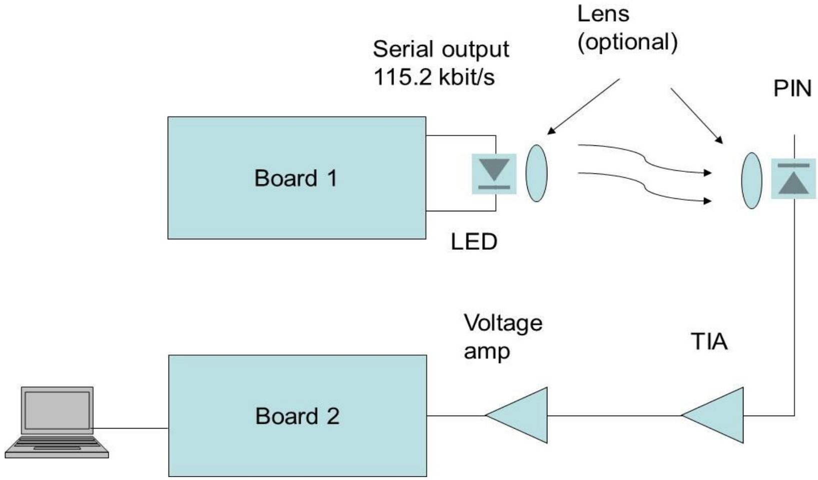
Alternative applications

Intelligent Transport System (ITS)

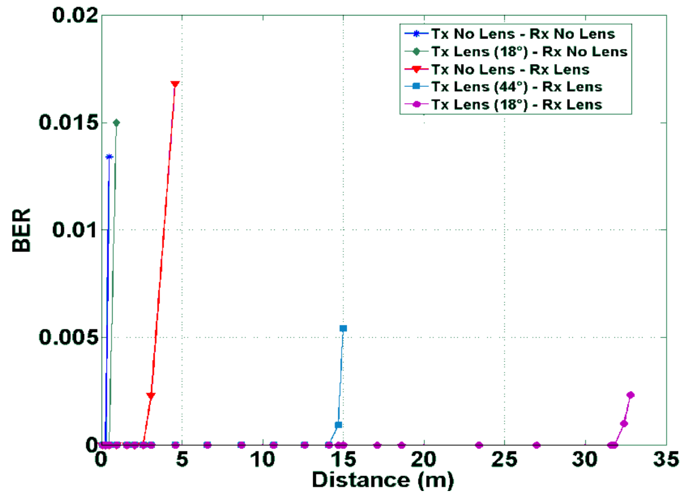
- Increase safety, reduce congestion, enhancing mobility, boosting productivity
- Vehicle-to-Infrastructure (V2I): roadside sensor, traffic lights
- Vehicle-to-Vehicle (V2V): safety-critical communication



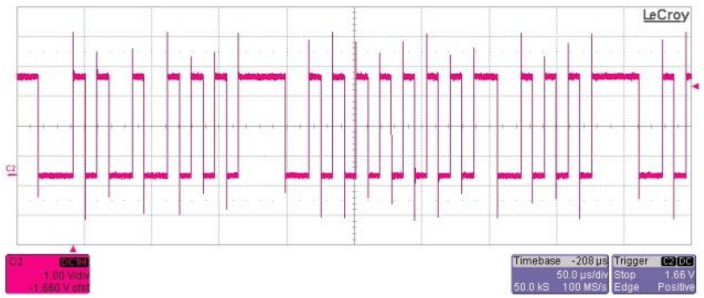
Car to Car Transmission: Experimental data



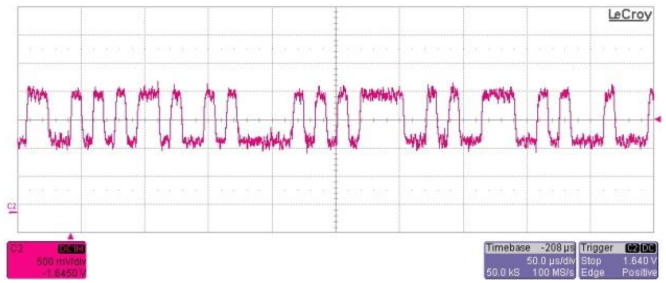
Set Up



System Performance



Board Signal

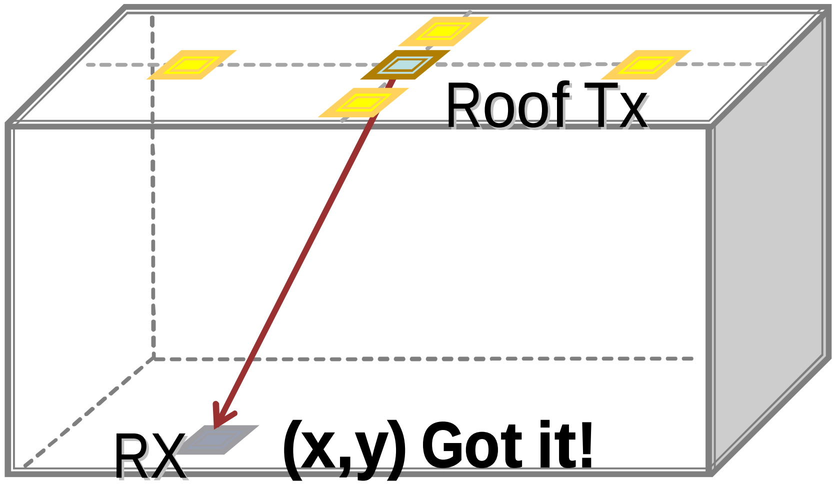


Voltage amplifier Signal

"Free space optical communication in the visible bandwidth for V2V safety critical protocols" Proceedings of *Wireless Communications and Mobile Computing Conference* (IWCMC), 2012, 27-31 Aug. 2012, Page(s): 1097 - 1102

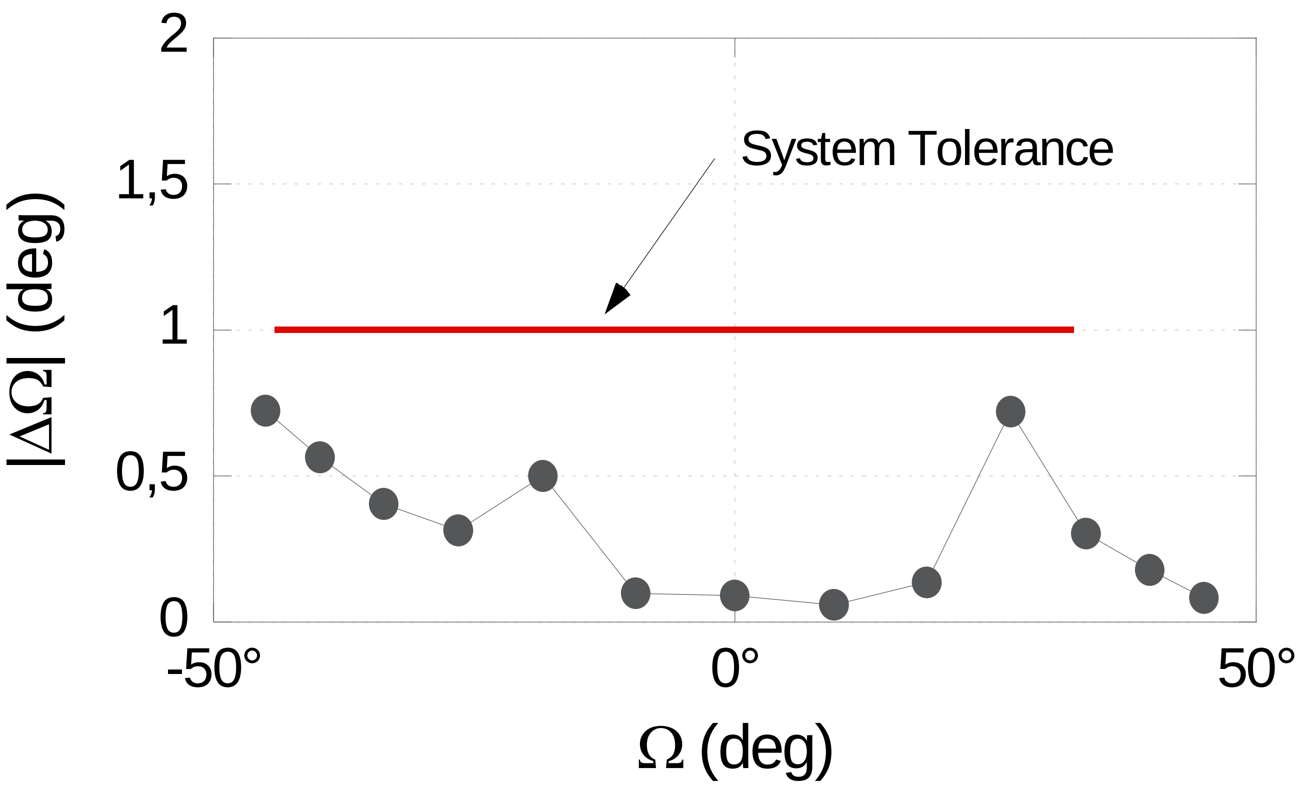
Indoor localization

- Key issue for unmanned vehicles/handicapped people etc.
- RF techniques not combining precision and simplicity
- Based on the information sent by the auxiliary transmitters, the receivers can determines its position



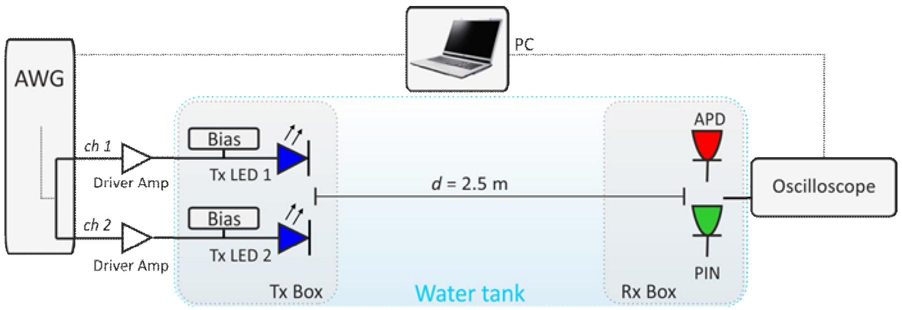
Experimental results

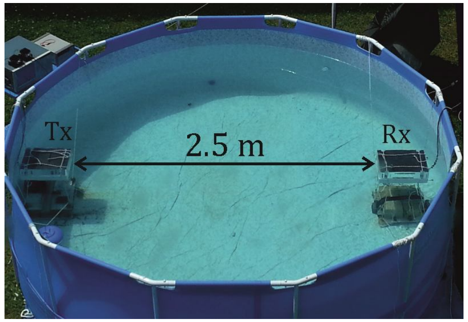
- Angle estimation with accuracy <1° in a 90° range.



Underwater

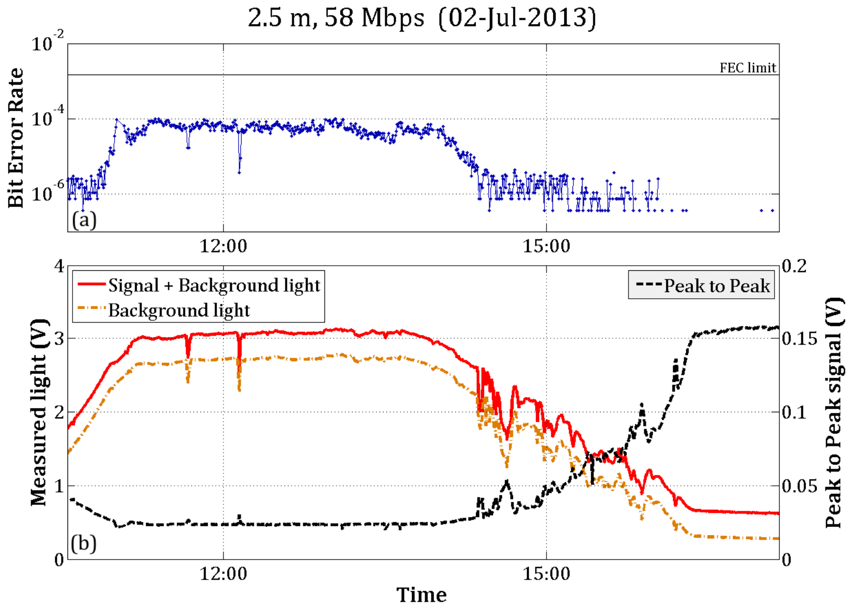
- Arsh environment
  – Background noise, MPI, attenuation, scattering, etc.
- No simple wireless solution (RF does not work, acoustic waves give low bit rate)





Preliminary results

- Underwater transmission at Mbit/s rates feasible



Conclusions

- Optical wireless can become a powerful alternative to RF-wireless
- It can now exploit very cheap devices, increasingly popular
- Design is very critical, strictly depending on the application
- Various potential areas:
  - Indoor high speed
  - Hybrid solutions
  - Vehicular networks
  - Underwater transmission

Thanks for your kind attention

email: e.ciaramella@sssup.it