Optical Wireless Communications: Attempt to Address RF Spectrum Congestion

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Outline

- *Institut Fresnel*, Brief Introduction
- **Need to New Spectral Resources**
- **Optical Wireless Communications**
- **Outdoor Free-Space Optical Communications**
  - Fundamentals & Adverse Channel Effects
- **Indoor Visible-Light Communications**
  - Potentials & Limitations
- **Underwater Wireless Optical Communications**
  - Advantages & Challenges

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Workforce

- 86 permanent staff
  - Aix-Marseille University
  - CNRS: French Center of Scientific Research
  - Ecole Centrale Marseille
- 89 non-permanent staff including 53 PhD students

Research fields

- Information Processing and Random Waves
  - Telecommunications and Array Processing
  - Teledetection
  - Multidimensional Image and Signal Processing
  - Optical polarization and coherence
- Electromagnetism and Metamaterials
- Advanced Imaging for Living
- Nano-photonics and Optical Components

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➢ High-Data-Rate Information Transmission

– Ever-increasing demand for high data rate transmission
  - HDTV, video calls, cloud-computing…
  - Mobile broadband and mobile Internet

– Proliferation of wireless communication systems
  - Wireless devices and technologies: pervasive
  - Among the most integral elements of modern society
  - > 10 billion IP mobile connected devices by 2020

- Increase the spectral efficiency of RF wireless systems
  - MIMO
  - Cooperative communication
  - UWB
  - Cognitive radio
  - …
- Use the upper parts of the EM spectrum
  - Millimeter waves
  - THz frequencies
  - Optical wireless communication

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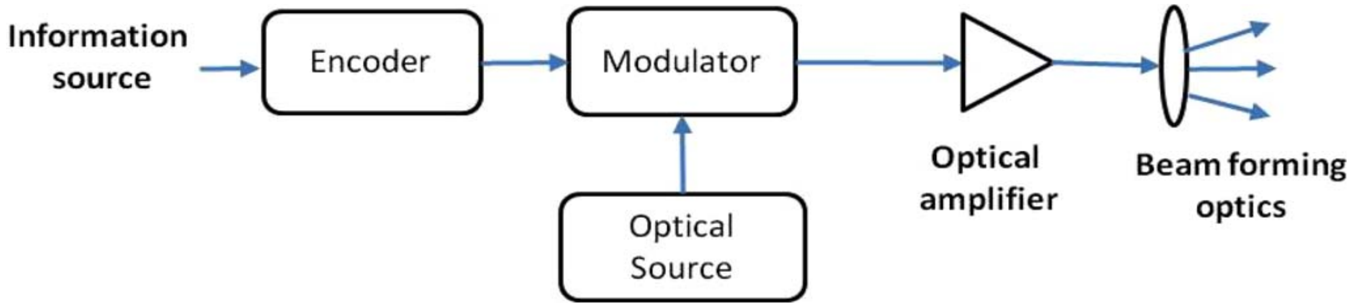
- Main advantage:
  - Very large unlicensed optical bandwidth
    - Data rate can exceed Gbps

OWC, Principles

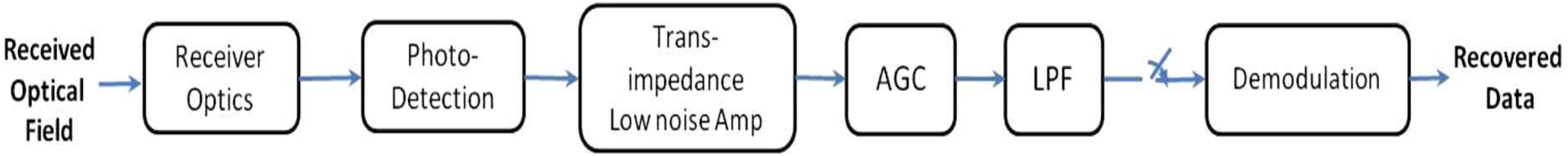
➢ Transmitter



– Optical source: LED or laser diode

– Intensity Modulation & Direct Detection (IM/DD)

➢ Receiver



Application for Smart Grids

- **Power distribution grid:**
  - Security
  - Reliability
  - Cost efficiency
  - Sustainability

- **Required communications infrastructure:**
  - Fast (low latency, high throughput)
  - Reliable
  - Secure

Smart Grids…

- Communication network solutions
  - Along the entire grid down to consumer access level
  - PON (fiber optic)
  - Power-line
    - NPLC, BPLC
  - Wireless
    - Cellular (2G, 3G, 4G)
    - WiMAX
    - Optical wireless communications (FSO, VLC)

- Use right mix of communications technologies
  - Wide variety of local environment
    - Utilities' needs & availability of necessary infrastructure and resources
    - Availability fiber-optic cables
    - Frequency spectrum for wireless technologies
    - Quality and length of the power cables for BPLC

Smart Grids…

- Wireless solutions
  - Flexibility, independence from the main grid (in the case of network failure)

- RF solutions limitations:
  - Strongly depend on the availability of spectral resources
  - Needs efficient data encryption for cyber-security reasons

- Interest of OWC solutions
  - High data rate
  - Inherent security
  - Energy efficient

  - FSO for connecting power plants, transformer stations, ring main units (RMU)
  - VLC for smart homes (consumers and prosumers)

  - Limitations (FSO): dependence on weather conditions

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FSO, Pros

- Highly directed propagation with narrow beam-widths
  - High transmission security
  - Interference immunity
  - Efficient use of energy

- Unlicensed, easy to install, requires little maintenance,...

FSO, Atmospheric Loss…

- Meteorological phenomena
  - Rain: low attenuation < 9dB/Km
  - Snow: moderate attenuation < 12dB/Km
  - Tick fog: high attenuation; up to 200dB/Km

FSO, Atmospheric Turbulence

- Clear sky conditions & perfect alignment bw Tx and Rx

➢ Temperature variations among air pockets ; wind
  - Variations of the air refraction index

  - Random fluctuations of phase and amplitude of the received signal
    - Intensity fluctuations: Channel Fading

FSO, Atmospheric Turbulence Characterization

- Frequency non-selective (flat) channel
- Quasi-static channel
  - Channel coherence time: ~10ms

➢ Rytov variance: $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$

– Weak turbulence regime: $\sigma_R^2 << 1$; $\sigma_I^2 \approx \sigma_R^2$

– Moderate turbulence regime: $\sigma_R^2 \sim 1$

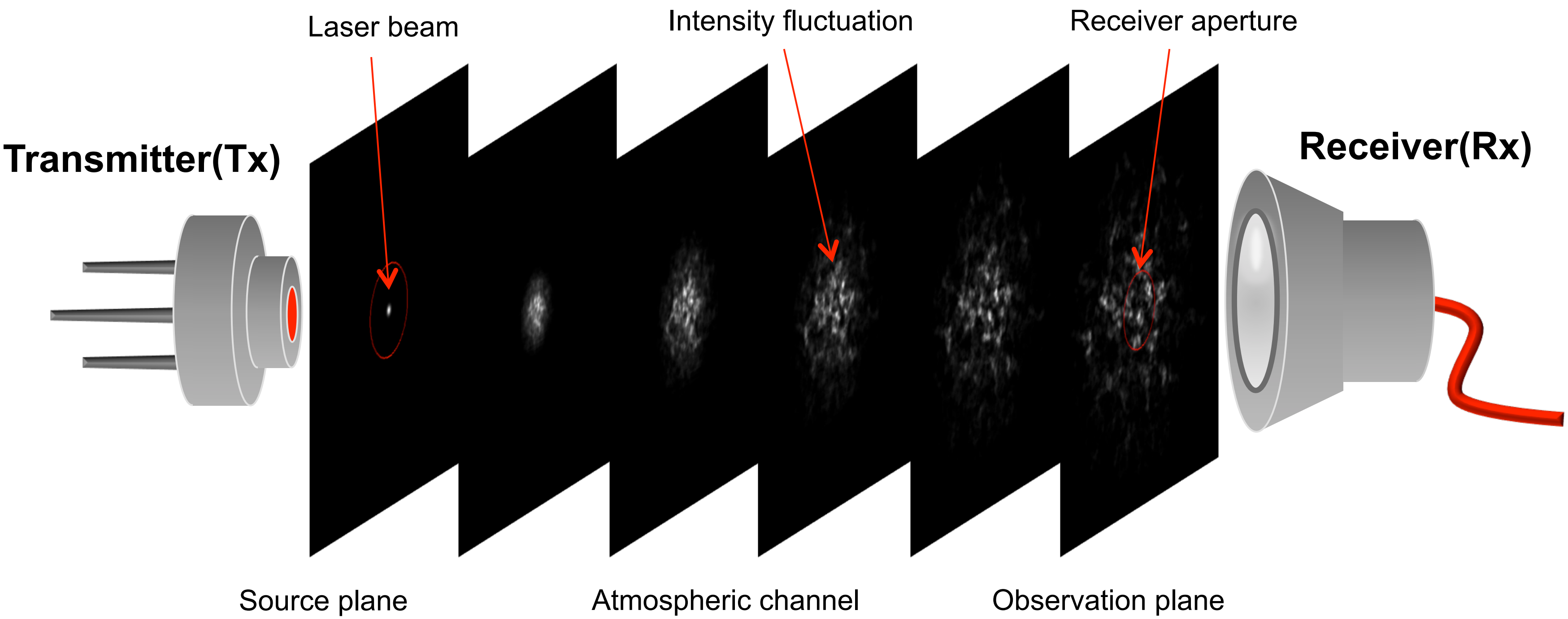
– Strong turbulence regime: $\sigma_R^2 >> 1$

L.C. Andrews and R.L. Phillips, *Laser beam propagation through random media*, SPIE Press,, 2nd ed., 2005

FSO, Turbulence Mitigation by Aperture Averaging

- Weak to moderate turbulence regimes

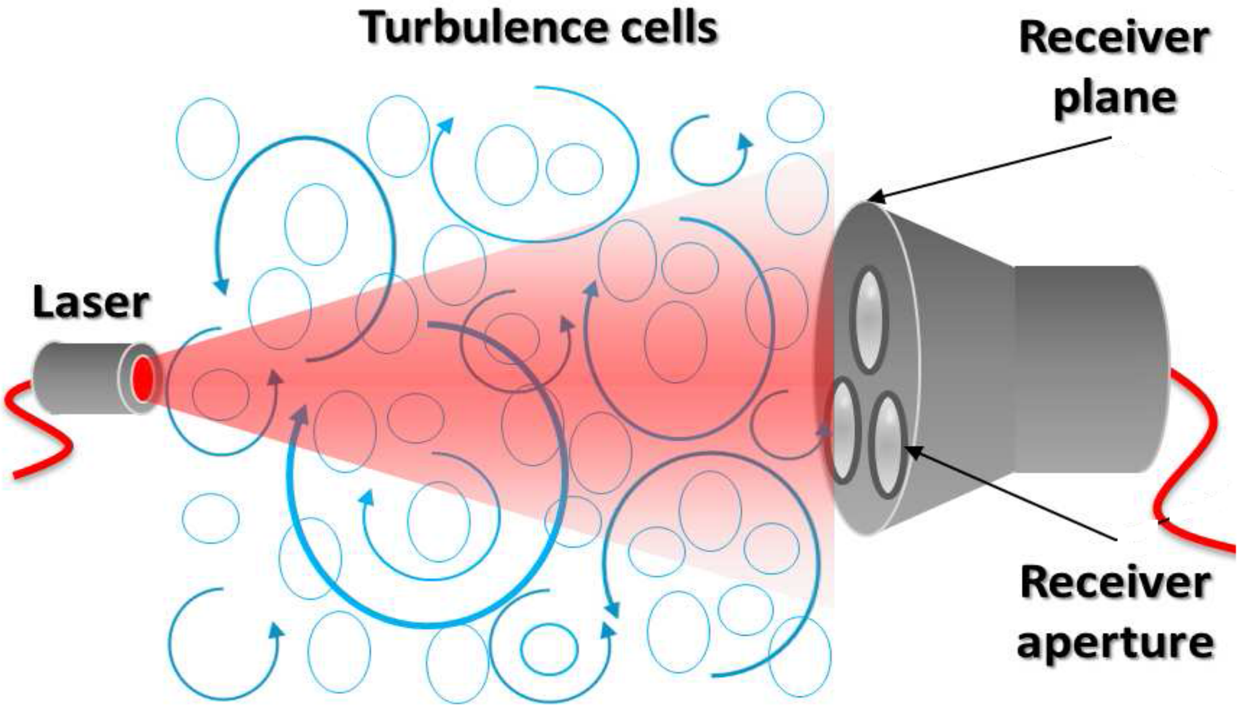
- Wave-optics simulations



FSO, Turbulence Mitigation by Space Diversity

- Space diversity:
  - Moderate to strong turbulence regimes (large link distances)
  - Multiple beam (MISO)
  - Multiple aperture (SIMO)
  - Multiple beam, multiple aperture (MIMO)

FSO, Space Diversity…



MIMO FSO

- Significant fading reduction

- Signal transmission schemes
  - Space-time (ST) coding
  - Trade-off between multiplexing and diversity gains
  - < Gbps: Repetition coding seems to be optimal !

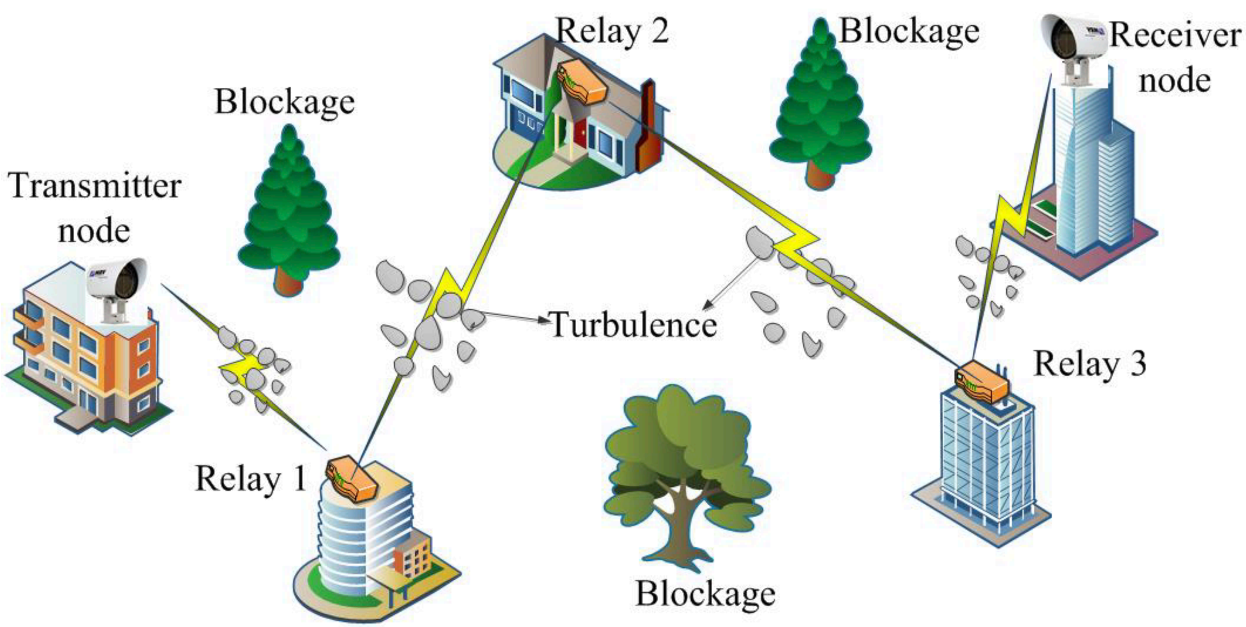
- Cooperative networks
  - Long-haul links
    - Strong turbulence regime
    - Significant path loss
    - Obstructions

➢ Multi-hop (serial) relays

- Fading variance depends on the link distance

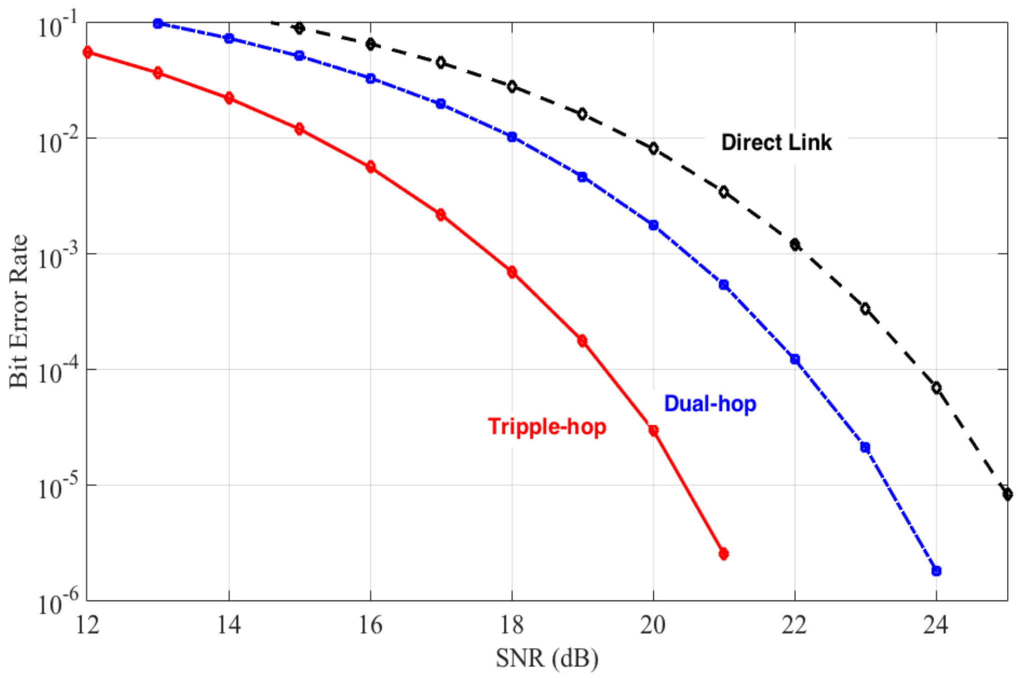
▪ Relaying protocols:

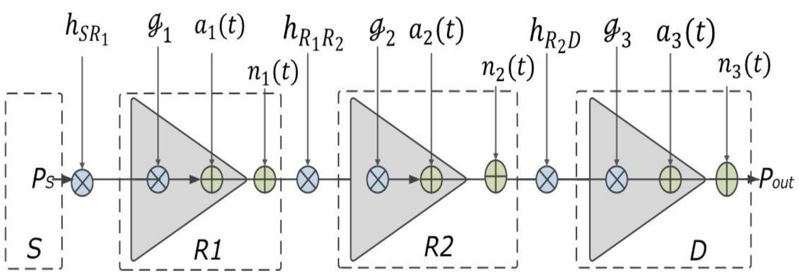
- Amplify-and-Forward, Decode-and-Forward, Detect-and-Forward



Relay-Assisted FSO Networks…

- **All-optical relaying:**
  - Using erbium-doped fiber amplifier (EDFA)
  - Faster, less expensive
  - Amplified spontaneous emission (ASE) noise





Triple-hop FSO:
10 Gbps data rate with simple OOK

Hybrid RF/FSO Links

- Limitations of FSO links:
  - Strong attenuation in dense fog and heavy snowfalls
  - Misalignment and pointing errors
  - Severe turbulence over long distances
- RF link in parallel with FSO
  - Serve as back-up in the case of FSO link outage
  - Millimeter waves (MMW) around 60 GHz
    - Less subject to atmospheric turbulence and pointing errors
  - Current systems: Hard-switching
  - Fog and rain rarely occur simultaneously

- More efficient use of RF and FSO links
  - Monitoring constantly the two channels
  - Switched transmission progressively from one link to another
  - Soft switching

- Joint data encoding and decoding over RF and FSO links
  - Exploiting fully the available link diversity
  - Rate-compatible coding

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- Arguments
  - Unregulated frequency band
  - EMI / health concerns
  - Green

- Indoor VLC
  - High-rate data transmission
    - Internet access, information broadcast, etc.
    - Li-Fi
  - Low data rate
    - Indoor localization

Indoor VLC Channel

- If no BW limitation by LED:
  - Practically flat channel if LOS exist
  - Blocked LOS: diffuse channel: highly frequency selective

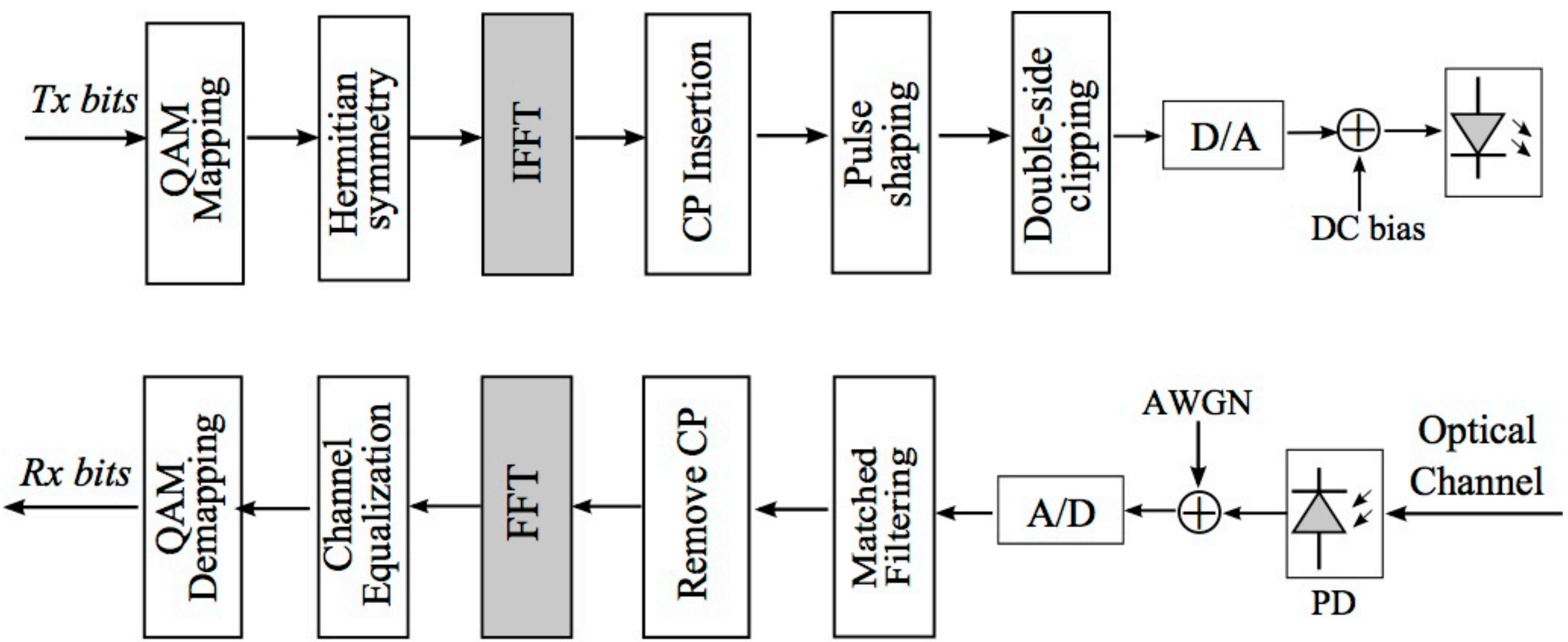
VLC, LED Technologies

- Blue chip + yellowish Phosphor

  - Popular for today general lighting industry
  - Standardised for illumination and communications
  - Limited modulation bandwidth

- More spectrally efficient signaling schemes
  - DMT (optical OFDM)
    - Efficient solution for BW-limited LEDs
    - Robust against channel dispersion
    - Non-optimal in terms of energy and spectral efficiency
    - High peak-to-average power ratio (PAPR)

- DC-biased Optical (DCO) – OFDM



Optical OFDM…

- Highly non-coherent LED source
  - IM is used
  - signal has to be real and positive before modulating the LED intensity

- Condition of real time-domain OFDM signal:
  - Imposing Hermitian symmetry on the modulated subcarriers

$$X(N-k) = X^*(k), \quad k = 1, 2, ..., \tfrac{N}{2} - 1 \qquad X(0) = X\left(\frac{N}{2}\right) = 0$$

After IFFT:

$$x(n) = \frac{1}{N}\sum_{k=0}^{N-1} X(k) exp\left(j2\pi\frac{kn}{N}\right)$$

$$= \frac{1}{N}\sum_{k=1}^{\frac{N}{2}-1}\left\{2X_R(k) cos\left(j2\pi\frac{kn}{N}\right) - 2X_I(k) sin\left(j2\pi\frac{kn}{N}\right)\right\}$$

Optical OFDM…

- Condition of positive time-domain OFDM signal:
  - Simplest solution: add a DC (DCO-OFDM)

$$x_{DC}(t) = x(t) + K_b$$

    - Remaining negative parts: set to zero: Clipping

$$x_{u,DCO}(t) = x(t) + K_b + n_c(K_b)$$

    - Clipping noise

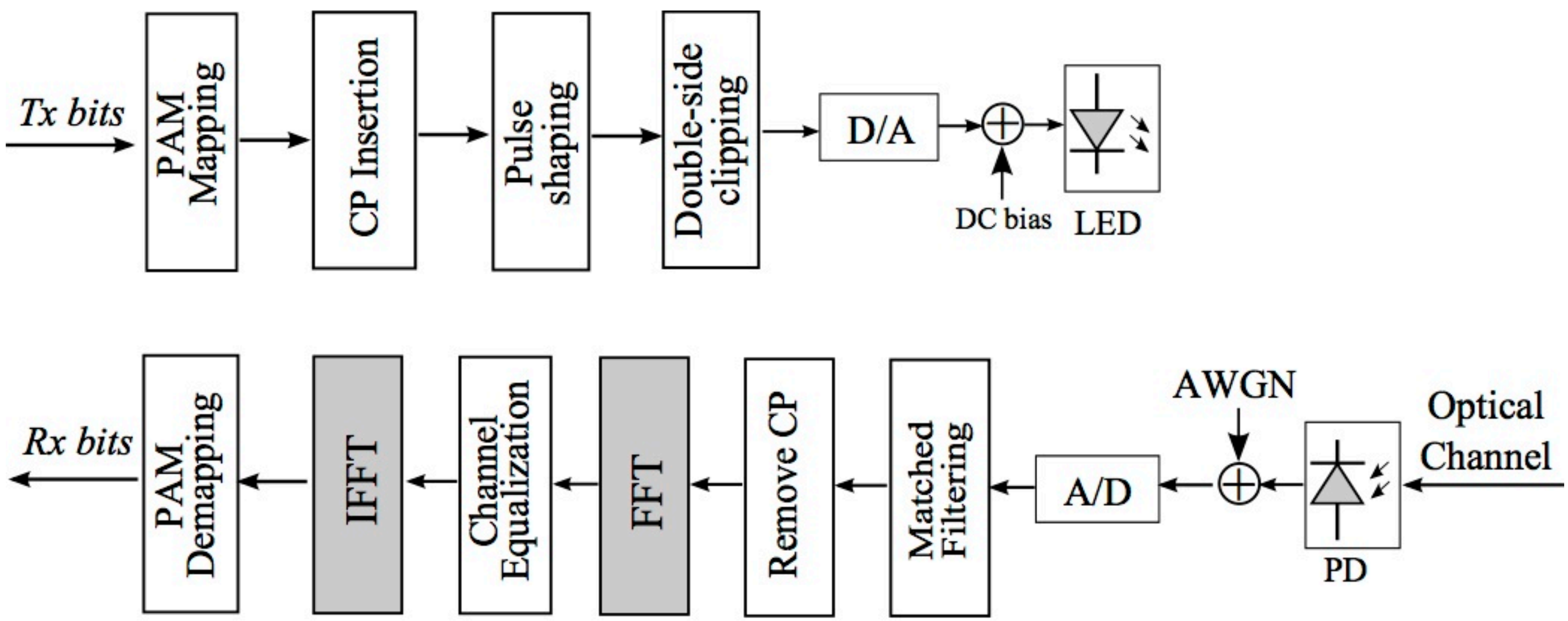
VLC, Alternative to OFDM

- Main concern: high PAPR
  - Clipping noise, non-linear LED characteristics

- Possible alternatives: PAM or CAP
  - Frequency-domain equalization (FDE)

PAM-FDE

- Advantages: High spectral efficiency, low PAPR
  - Need to equalization: FDE: low-complexity



MIMO VLC

- Channel bandwidth is position dependent
  - Depends on LED configuration geometry and Rx position
  - Channel matrix can be ill-conditioned, and in the worst case, rank-deficient.
  - Ill-conditioned ***H*** results in a significant noise amplification = high BER.

VLC, Key Challenges

- Mobility
- Light Dimming
- Uplink

Organic VLC Applications

- Organic devices (OLED, OPD)
  - Mostly for D2D applications
  - Challenge: Low modulation BW of organic devices: ~ KHz

VLC in 5G

- Key points: Mobility/Ubiquity, Ultra-high spectral efficiency, Low energy consumption, Security.
  - Internet of Things (IoT)
- **VLC integrating 5G networks!**

Source: H2020 European Commission

VLC for Indoor Positioning

- Transmitter: LED Ceiling Lights
- Receiver: Camera, Photo-detector
- Map: Preloaded or downloaded over a wireless network

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UWOC, applications

- Data-rate greedy underwater applications
  - Sea exploration and monitoring (oil, gas, mining…), port security
  - Real-time control of underwater robotics (AUVs)
  - Communication between submarines / submarine-AUV
  - Data harvesting from underwater wireless networks

- Acoustic waves
  - ☺Low attenuation → large link distances: several Km
  - ☹ Low propagation speed & large latencies → low data rate
  - ☹ Subject to multipath dispersion and signal fading

➢ Optical waves

- ☺ High propagation speed → high data-rate
- ☺ Low energy consumption

- ☹ Strong intensity attenuation due to absorption and scattering
  - Relatively short link distances
  - 450-550 nm: minimum absorption
- ☹ Requirement of LOS

- PIN: no gain
- APD: ~100
- PMT: ~10^6 - 10^7

➢ SiPM (Si photo-multiplier)

- Dense array of small, electrically- and optically-isolated SPADs: 100-1000/mm^2
- Output: proportional to photon count value

UWOC, Open Research Directions

- Channel characterization
  - Turbulence modeling
- Efficient transmission schemes
  - Powerful channel codes
- Smart Tx and Rx
  - Self-adapting to operational situations

Thank you for your attention!

Any question?