

Optical Wireless Communications: Attempt to Address RF Spectrum Congestion

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- *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
 - ...

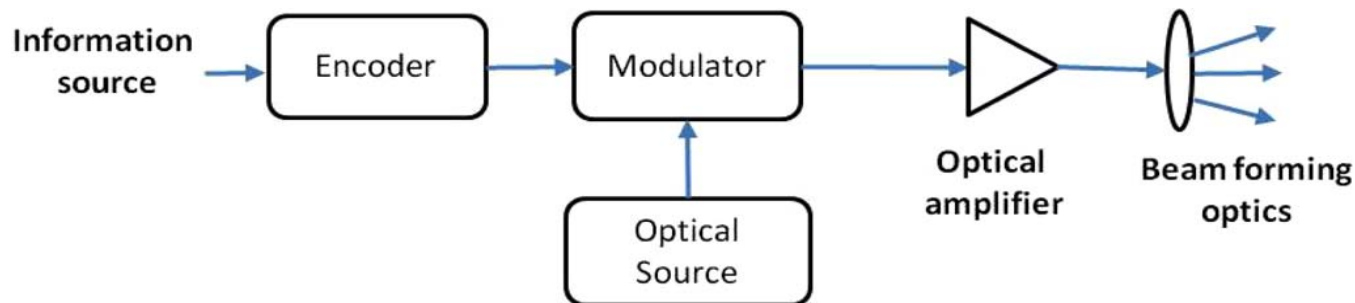
- Use the upper parts of the EM spectrum
 - Millimeter waves
 - THz frequencies
 - Optical wireless communication

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➤ Main advantage:

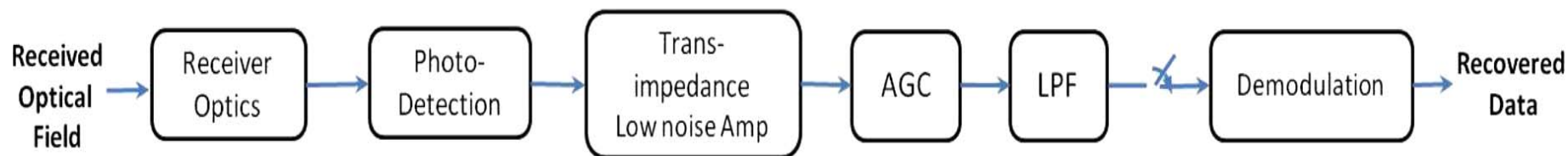
- Very large unlicensed optical bandwidth
 - Data rate can exceed Gbps

➤ Transmitter



- Optical source: LED or laser diode
- Intensity Modulation & Direct Detection (IM/DD)

➤ Receiver



➤ Power distribution grid:

- Security
- Reliability
- Cost efficiency
- Sustainability

➤ Required communications infrastructure:

- Fast (low latency, high throughput)
- Reliable
- Secure

➤ 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

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

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

- Meteorological phenomena
 - **Rain**: low attenuation $< 9\text{dB/Km}$
 - **Snow**: moderate attenuation $< 12\text{dB/Km}$
 - **Thick fog**: high attenuation; up to 200dB/Km

- 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**

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

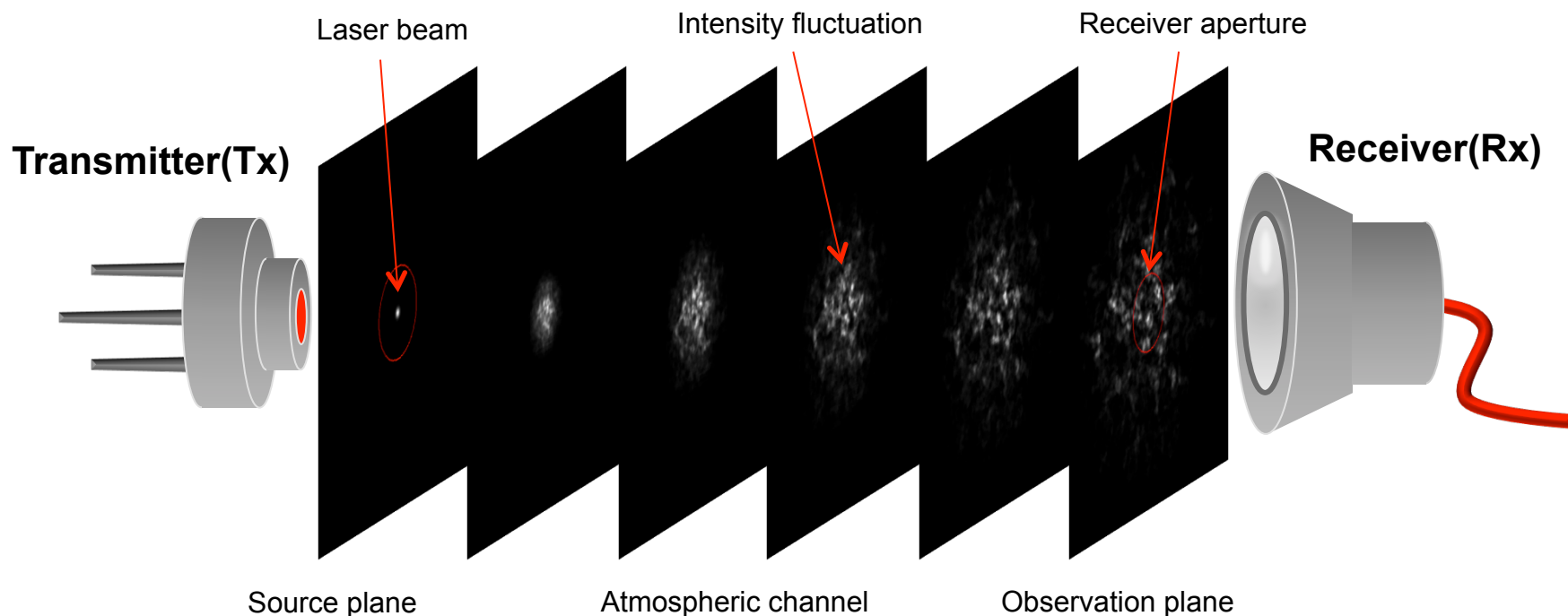
➤ Rytov variance: $\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6}$

- Weak turbulence regime: $\sigma_R^2 \ll 1$; $\sigma_I^2 \approx \sigma_R^2$
- Moderate turbulence regime: $\sigma_R^2 \sim 1$
- Strong turbulence regime: $\sigma_R^2 \gg 1$

FSO, Turbulence Mitigation by Aperture Averaging

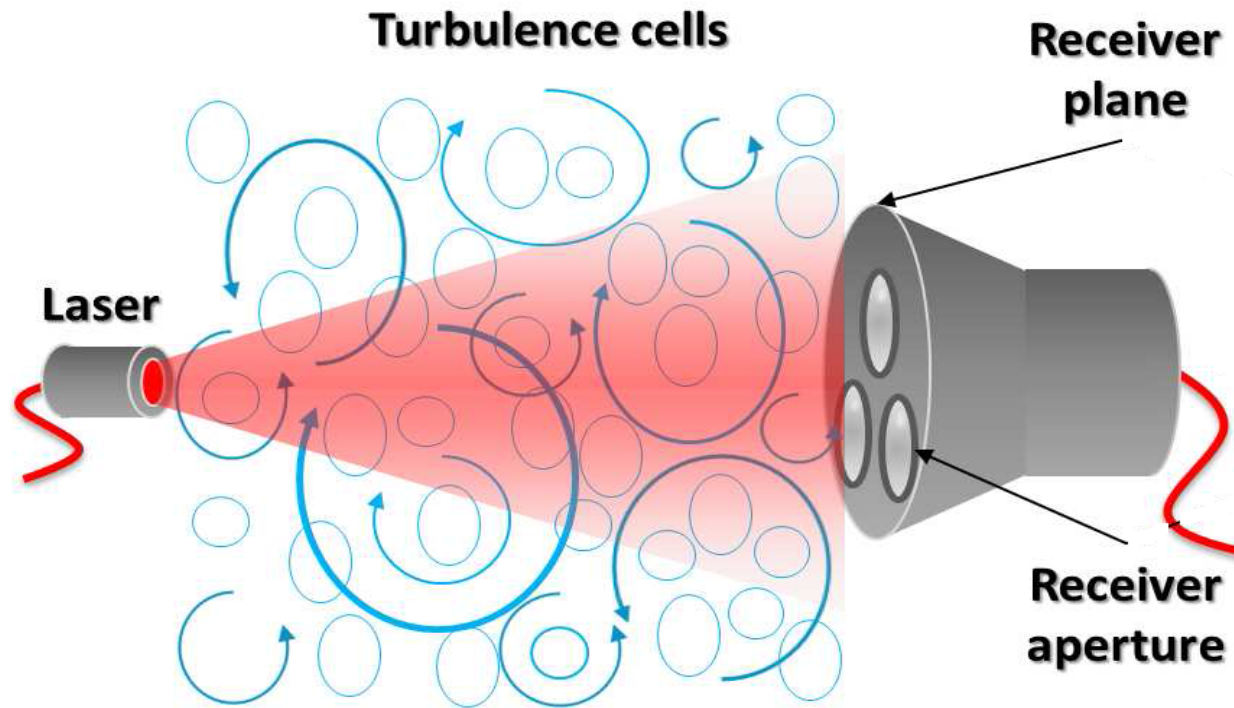
- Weak to moderate turbulence regimes

■ Wave-optics simulations



➤ Space diversity:

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



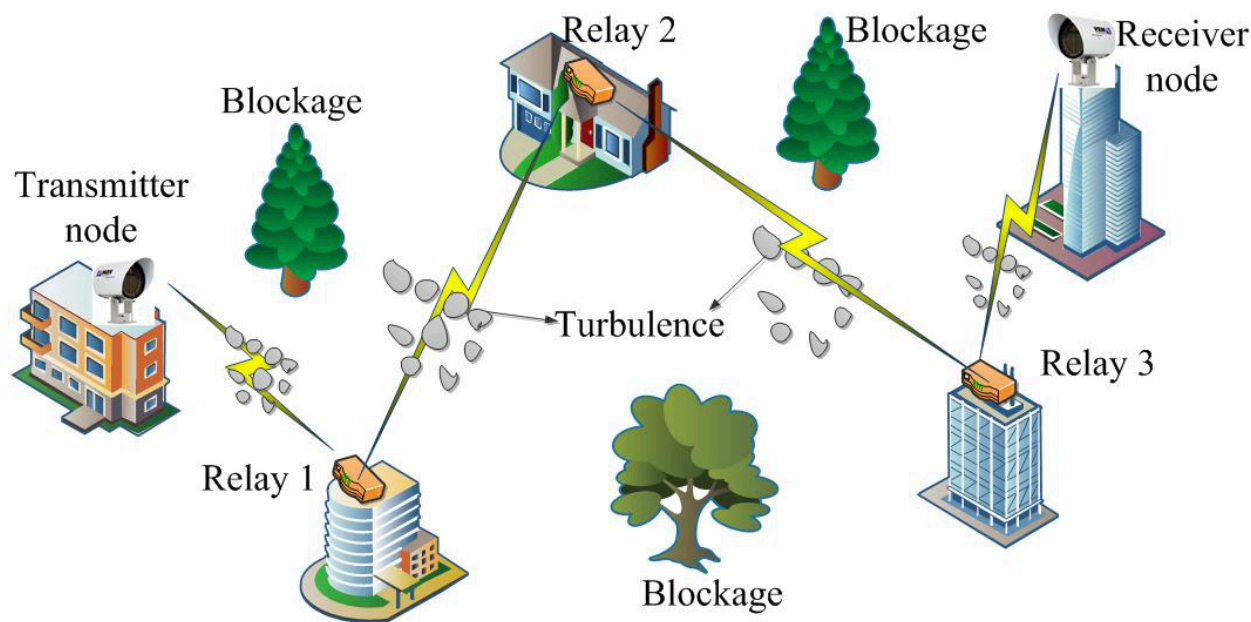
- Significant fading reduction
- Signal transmission schemes
 - Space-time (ST) coding
 - Trade-off between multiplexing and diversity gains
 - < Gbps: Repetition coding seems to be optimal !

➤ Cooperative networks

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

➤ Multi-hop (serial) relays

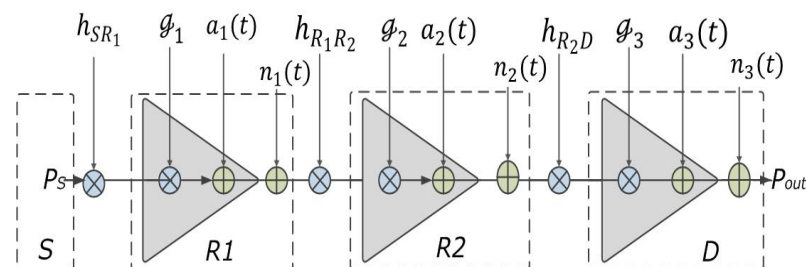
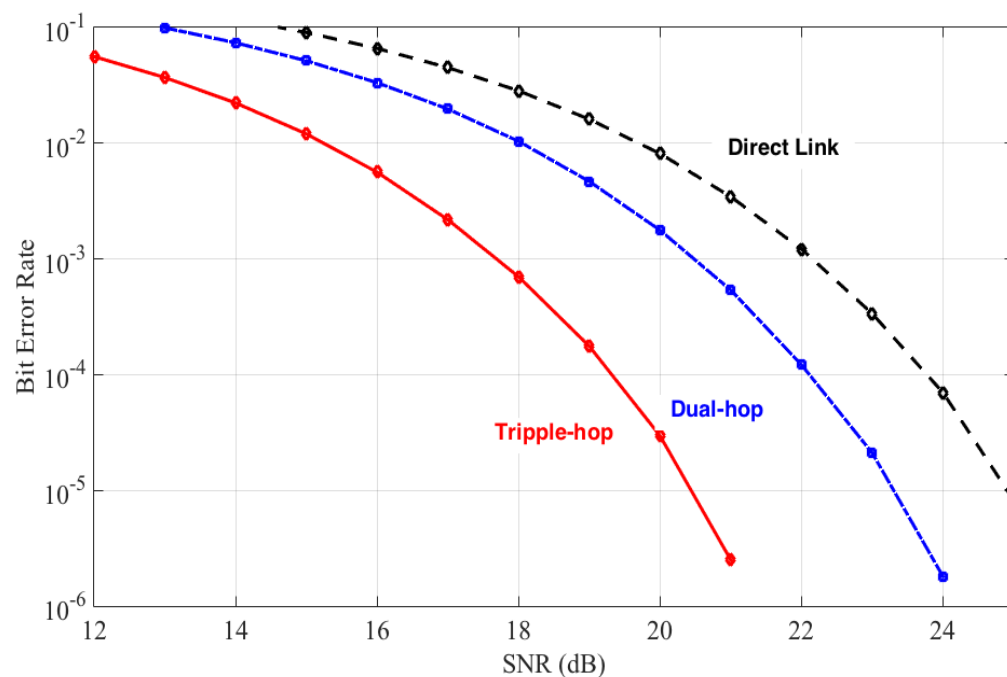
- Fading variance depends on the link distance
- Relaying protocols:
 - Amplify-and-Forward, Decode-and-Forward, Detect-and-Forward



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

➤ 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

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

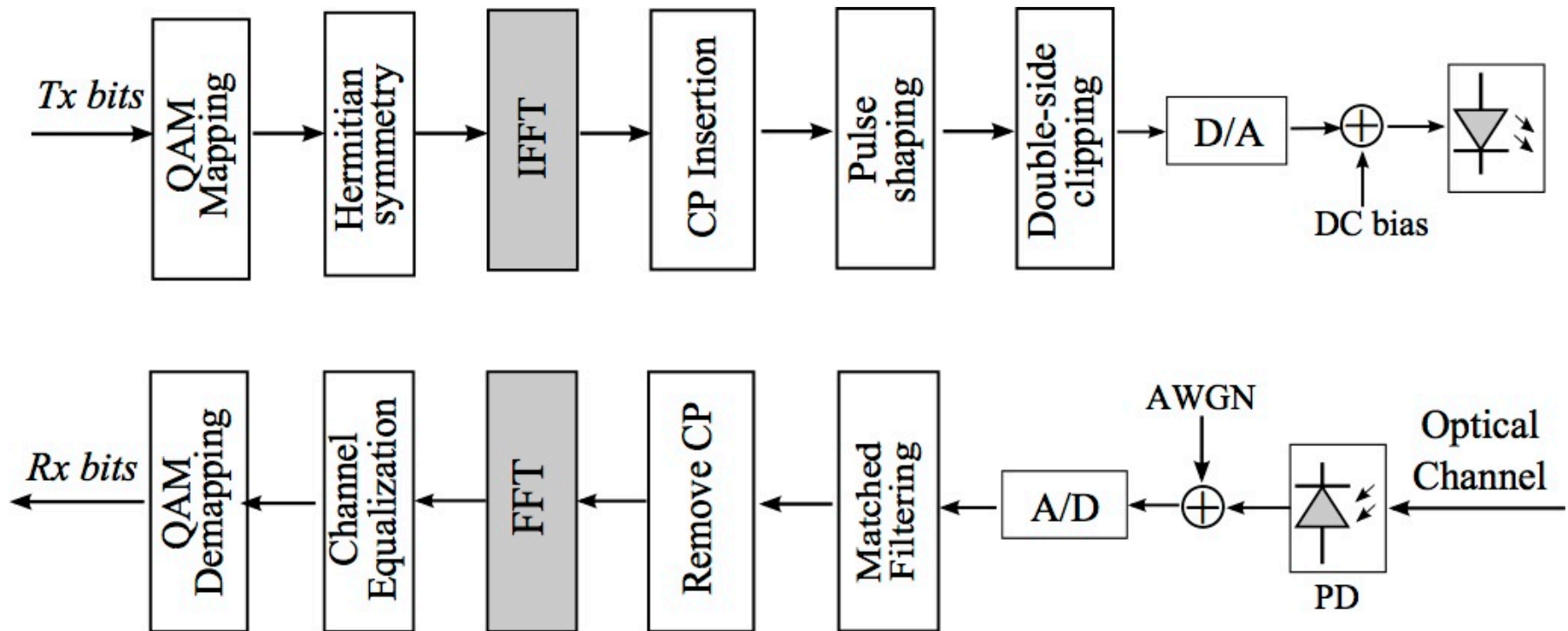
- Blue chip + yellowish Phosphor
 - Popular for today general lighting industry
 - Standardised for illumination and communications
 - Limited modulation bandwidth

➤ 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



- 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

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

$$\begin{aligned} \text{After IFFT: } x(n) &= \frac{1}{N} \sum_{k=0}^{N-1} X(k) \exp\left(j2\pi \frac{kn}{N}\right) \\ &= \frac{1}{N} \sum_{k=1}^{\frac{N}{2}-1} \left\{ 2X_R(k) \cos\left(j2\pi \frac{kn}{N}\right) - 2X_I(k) \sin\left(j2\pi \frac{kn}{N}\right) \right\} \end{aligned}$$

➤ Condition of positive time-domain OFDM signal:

- Simplest solution: add a DC (DCO-OFDM)

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

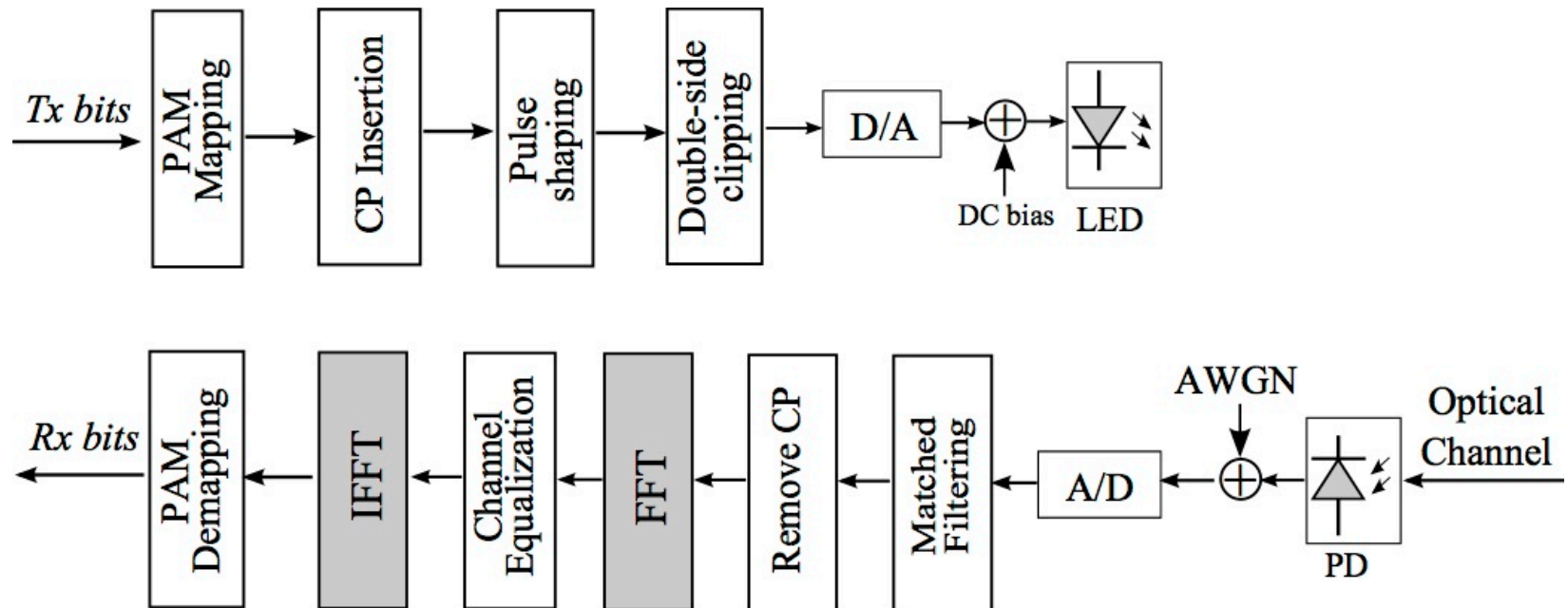
- Remaining negative parts: set to zero: Clipping

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

- Clipping noise

- **Main concern: high PAPR**
 - Clipping noise, non-linear LED characteristics
- **Possible alternatives: PAM or CAP**
 - Frequency-domain equalization (FDE)

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



- 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 $\mathbf{H}$ results in a significant noise amplification = high BER.

- Mobility
- Light Dimming
- Uplink

Organic VLC Applications

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

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

VLC for Indoor Positioning

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

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➤ 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: $\sim 10^6 - 10^7$

➤ SiPM (Si photo-multiplier)

- Dense array of small, electrically- and optically-isolated SPADs: 100-1000/mm²
- Output: proportional to photon count value

- 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?