Lecture Series

Wireless Communications - Part II - OWC - Visible Light Communication – LED

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Contents

- ICT – Mobil Networks - Energy Efficiency
- 5G Networks
- Optical Wireless Communication
- Visible light communication
    - Light sources
        - LED
        - LD
    - Data throughput
    - Challenges and issues
- OWC and RF

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ICT – Mobil Networks - Energy Efficiency

Global mobile data traffic - Projected to grow at a rate of 19%/year, that is ~473 exabytes/month by 2030 [1].

The carbon footprint - Primarily determined by

- carbon emission intensity of the energy sources
- Overall energy usage from running the network

Intergovernmental Panel on Climate Change's - Repored on the global temperature rise by 1.2°C

→ **The ICT sector - Aiming for a 45% reduction in greenhouse gas emissions by 2030, Via:**

- Technologies driving energy efficiency - *Techniques in time, frequency, spatial, and power domains*
- The role of AL/ML
- System architecture solutions, deployment and architecture strategies for networks
- Applications and services
- Site solutions based on renewable energy

1- Ericsson, "Ericsson mobility report: Mobile traffic forecast," 2024. Accessed: 2024-12-30.

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5G Networks

The growing demand for multi-functional devices in Smart Environments

A notable innovation in RF

The need for meta-surfaces at:

- Dynamically adjusting the phase shifts of reflected EM waves – *No need for decoding, amplifying, or introducing time delays*
  - mmWave
  - THz band
  - Visible band (highly transparent up to 85%)
- In smart glasses

Reconfigurable surfaces

- Polarization-selective devices + Frequency filters – For accurate control
- Dynamically optimizing

Results:

- Signal strength ↑
- Interference ↓
- Energy efficiency ↑
- Improved security
- Beam steering
- Supports NLoS links → Improving performance
- Spectral efficiency ↑

O. ¨ Ozdogan, E. Bj ¨ ornson, and E. G. Larsson, “Intelligent reflecting ¨ surfaces: Physics, propagation, and pathloss modeling,” IEEE Wireless Commun. Lett., vol. 9, no. 5, pp. 581–585, May 2020.

Y. Juan, H. Cen, Y. Chang, and C. Chen, “Dual-band and dual-polarized metasurface antenna for 5G application,” Microw. Opt. Technol. Lett., vol. 66, no. 2, p. e34037, 2024.

C. -Y. Fan, C. -J. Huang and C. -M. Lai, "Polarization-Selective Metasurface for 5G Band Communication with High Visible Light Transmission," in IEEE Photonics Technology Letters, doi: 10.1109/LPT.2025.3626792.

S. Kumar and H. Singh, “A comprehensive review of metamaterials/metasurface-based MIMO antenna array for 5G millimeter-wave applications,” J. Supercond. Nov. Magn., vol. 35, no. 11, pp. 3025–3049, 2022.

W. Yang et al., “Broadband dual-polarized filtering metasurface-based antennas using characteristic mode analysis for 5G millimeter-wave applications,” IEEE Trans. Antennas Propag., early access, 2024.

Y. Liu, X. Liu, X. Mu, T. Hou, J. Xu, M. Di Renzo, and N. Al-Dhahir, “Reconfigurable intelligent surfaces: Principles and opportunities,” IEEE communications surveys & tutorials, vol. 23, no. 3, pp. 1546–1577, 2021.

Data throughput R_{Th} - Defines the speed at which data can be processed and delivered, therefore, affecting applications' responsiveness and functionality

So,

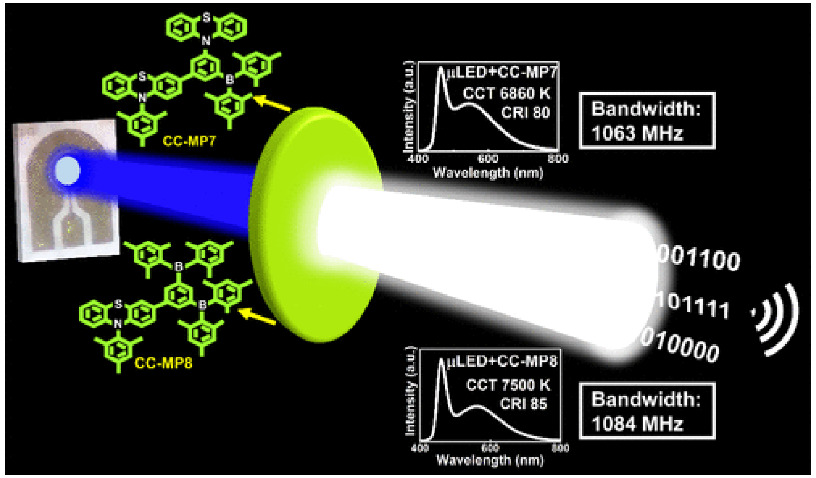
- **Higher R_{Th} →→ improved network's low latency, bandwidth utilization, and performance under heavy traffic loads**
- **Lower R_{Th} →→ bottlenecks →→ delayed responses and increased latency**

Factors affecting R_{Th}

- **Network infrastructure**
  - Hardware & software
  - Topology
  - Connection types
- **Data packet management**
  - Packet Size
  - Error handing capability
  - Transmission protocol

- **Bandwidth *B***
- **Signal power *S***
- **Transmission span *d***
- **Interference *I***
- **Latency**
- **Congestion**

Optical Wireless Communication



https://pubs.acs.org/doi/10.1021/acsphotonics.3c01332

- **A disruptive technology offering a free spectrum, security and high data rate!**
- **Integrating space/air/underwater networks with terrestrial networks**
- **Offers higher bandwidth and longer transmission span compared with RF**
- **Lower power usage**

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OWC - Visible Light Communication

Seamless integration with lighting [1]

Sensing + Communication

Sensing + Positioning

Integrated technology

Positioning + Communication

Control + Communication

indoor & outdoor applications:

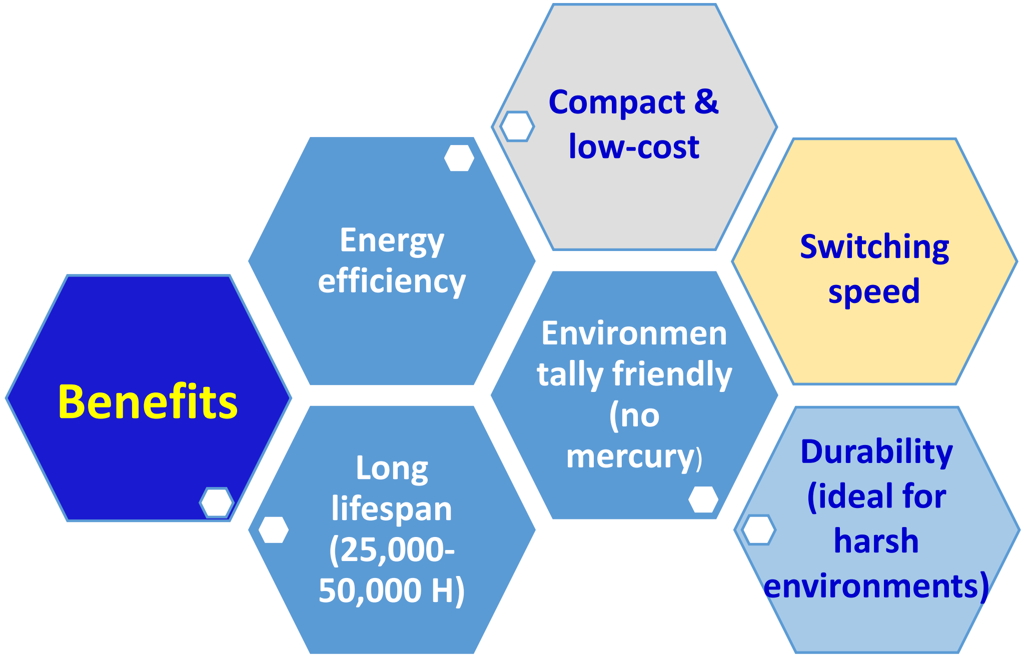
- Last meter access network
- Underground
- In-chip communications
- Farming
- Industry
- Data centres
- AR, VR
- ITS
- IoT
- IoE

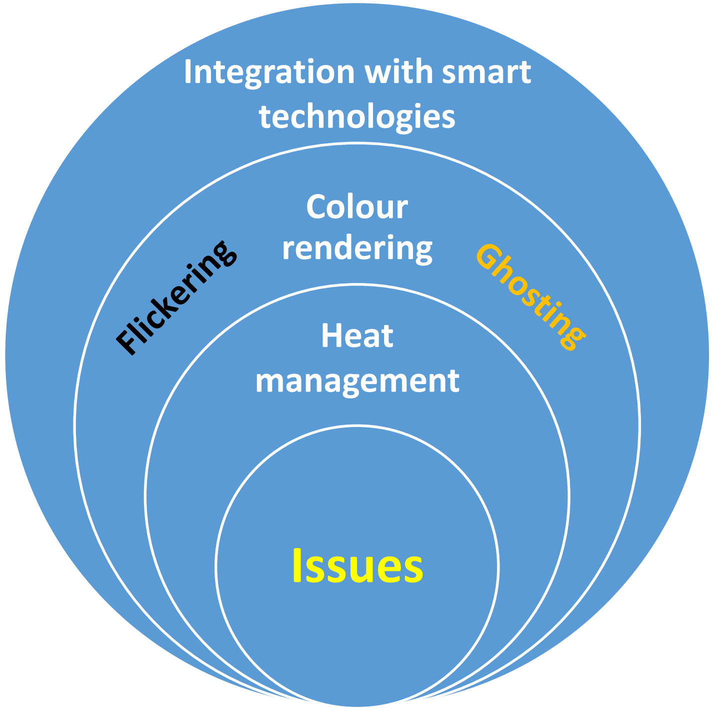
Underwater communications

1- M. H. Memon et al., “Micro-Trench Deep-Ultraviolet LEDs With Boosted Efficiency for High-Speed Solar-Blind Optical Communication,” J. Lightwave Technol., vol. 43, no. 5, pp. 2248– 2254, Mar. 2025, doi: 10.1109/JLT.2024.3486102.

OWC - Visible Light Communication

Mostly, use light-emitting diodes (LEDs) as Txs





VLC - Theory

For intensity modulation with direct detection (IM/DD)

Received power $P_r = P_t . h$

Signal-to-noise ratio $SNR = \frac{[\Re . P_r]^2}{\sigma^2_{total}}$

Channel gain for LOS $h = \frac{A \cdot (m+1)}{2\pi \cdot d^2} \cos^m(\phi) \cos(\psi)$

Where:

$\Re$ is the photodetector responsivity

σ^2_{total} is the total noise variance including ambient induced shot noise

m is the Lambertian order

A is the detector area

d is the distance between the transmitter and the receiver

ϕ is the angle of irradiance

ψ the angle of incidence

VLC - LED

The drive current $I = I_b + I_m e^{j\omega_m t}$

DC bias (I_b); Mod. current (I_m); Mod. frequency (ω_m)

$P_{opt} \propto I$

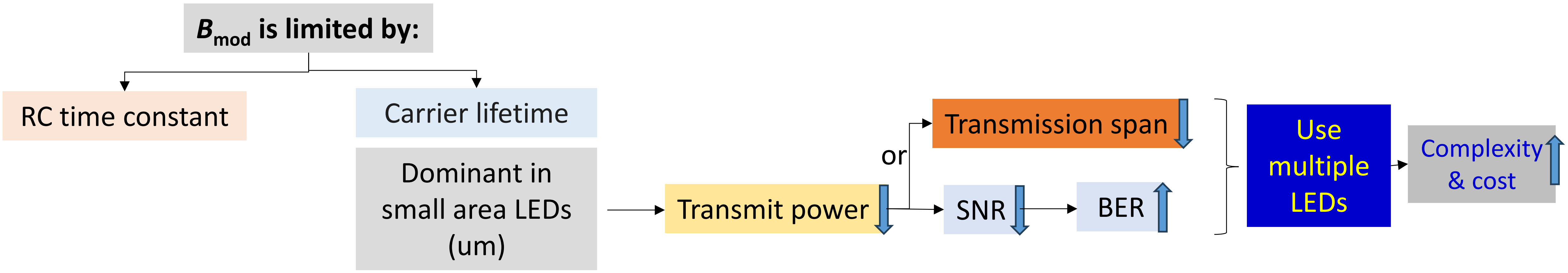
$P_{ele} \propto I^2$

Modulation bandwidth of the LED $B_{\mathrm{mod}} = \frac{\sqrt{3}}{2\pi\tau_c}$

Carrier lifetime (τ_c)

Modulation bandwidth of the electrical driver $B_{\mathrm{mod-elec}} = \frac{1}{2\pi\tau_c}$

$$B_{mod} = \sqrt{3}\, B_{mod-elec}$$



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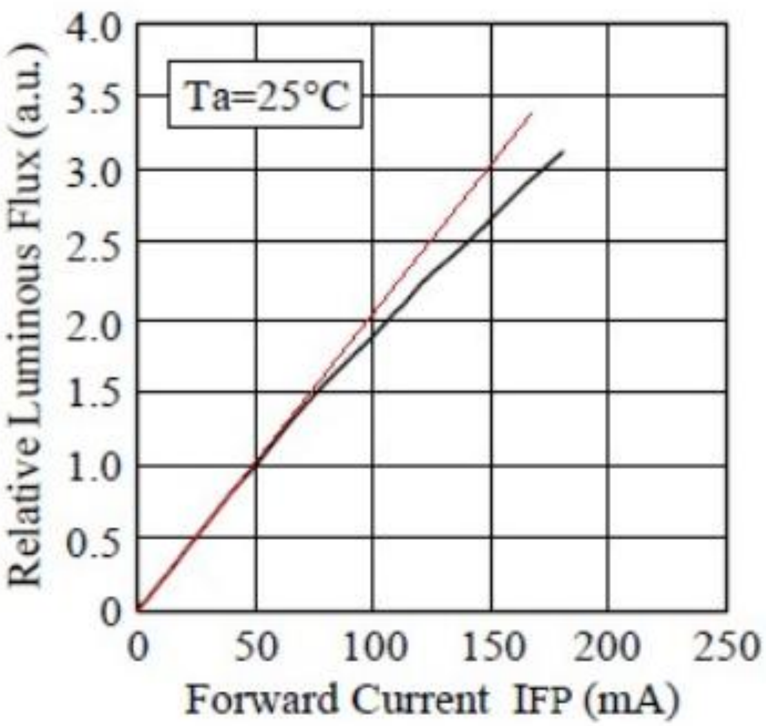
VLC – LED - Nonlinearity



For analogue signals transmission (multi-carrier) - The modulation depth (degree):

$$m_{LED} = \frac{\Delta I}{I_0}$$

AC signal (ΔI), DC bias current (I_0)

B_{mod} is based on power versus current characteristics that show a quasilinear relation

Harmonic distortion (HD)

$$x(t) = A\cos\omega t$$

Non-linear LED

$$y(t) = A_0 + A_1\cos\omega t + A_2\cos 2\omega t + \ \ldots$$

2^{nd} HD

Intermodulation distortion (ID)

$$x(t) = A_1\cos\omega_1 t + A_2\cos\omega_2 t$$

Non-linear LED

$$y(t) = \sum_{j,i} B_{ji} \cos\left(j\omega_1 + i\omega_2\right)t$$

Harmonics

ID: $\omega_1 \pm \omega_2, 2\omega_1 \pm \omega_2, \omega_1 \pm 2\omega_2, \ldots.$

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OWC – VLC – LED - Types

Flexible

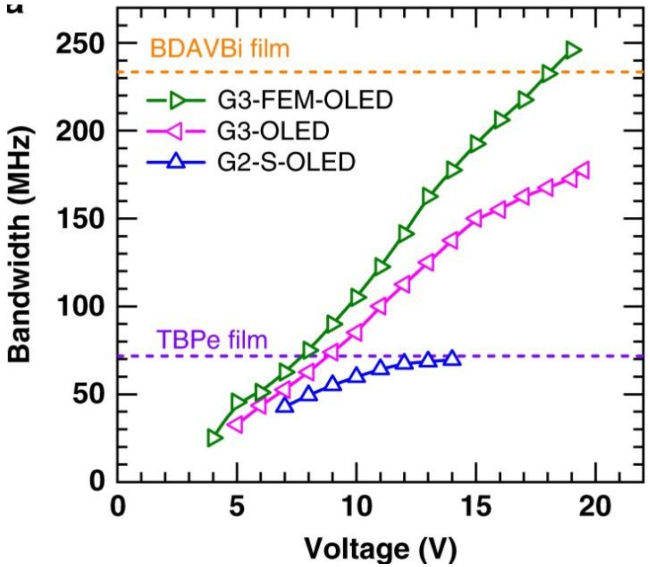
B_{mod}: 1 -250 MHz

B_{mod} < 4-5 MHz

B_{mod}: Up to 20 MHz

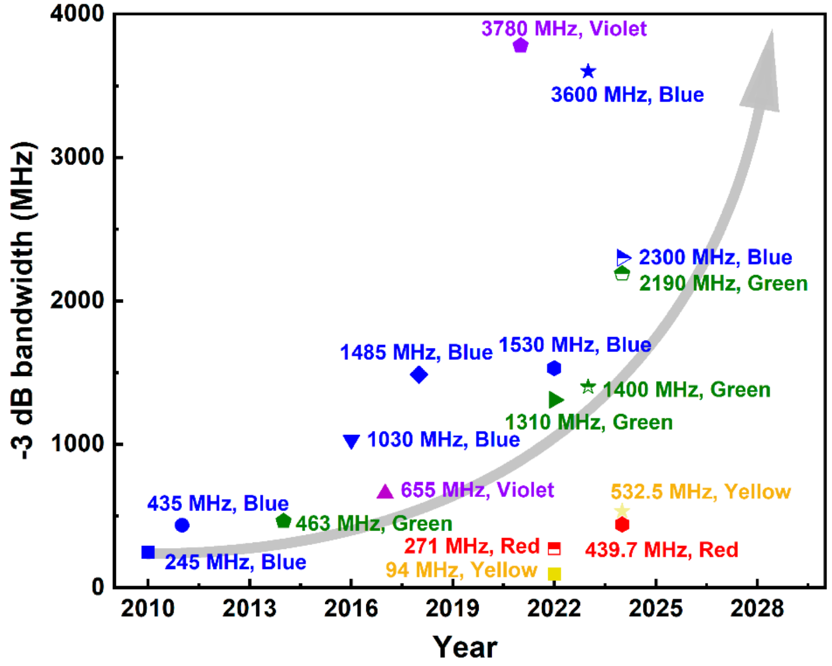
Balancing is an issue

Semi-polar [1]	InGaN	GaN [2]	InGaN/GaN [3]
50 µm	< 100 um	B_{mod}: ~ 650 MHz	B_{mod}: 1485 MHz
B_{mod}: 1030 MHz	Low power usage	High efficiency	
	Rapid response times	Long lifespan	
	B_{mod}: ~ 70-90 MHz	Colour tunability	
	Exceptional colour modulation	Fast response	
		Robust stability	



[5]

Facilitating higher transmission data rates



[4]

1- Dinh, et al., GHz bandwidth semipolar (1122) InGaN/GaN light-emitting diodes. Opt. Lett. 2016, 41, 5752–5755.
2- L. Lei, et al, "Design of AlInGaN electron blocking layer of micro-LED arrays grown on Si substrates for high-speed visible light communication," in IEEE Electron Device Letters, doi: 10.1109/LED.2025.3623365.
3- Rashidi, A.; et al., Nonpolar m-plane InGaN/GaN micro-scale light-emitting diode with 1.5 GHz modulation bandwidth. *IEEE Electron Device Lett.* 2018, *39*, 520–523.
4- Xu, et al., Recent Progress in GaN-Based High-Bandwidth Micro-LEDs and Photodetectors for High-Speed Visible Light Communication. Photonics 2025, 12, 730.
5- K. Yoshida, et al., 2020 Mar 3;11:1171. doi: 10.1038/s41467-020-14880-2

OWC – VLC – Laser Diode

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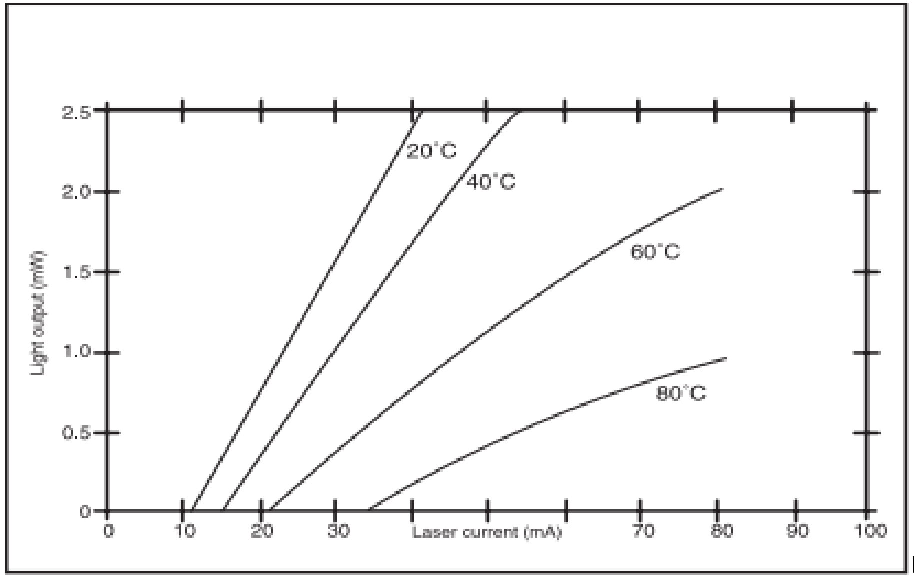
Not widely used in VLC!

https://beamq.com/all-brands-diodes-c-297_202.html

Modulation bandwidth

Determined by the photon lifetime (i.e., at the picosecond range) → A higher modulation bandwidth [1]

Improved optical directionality + Optical spectrum purity → Extending the transmission range in VLC



Newport.com

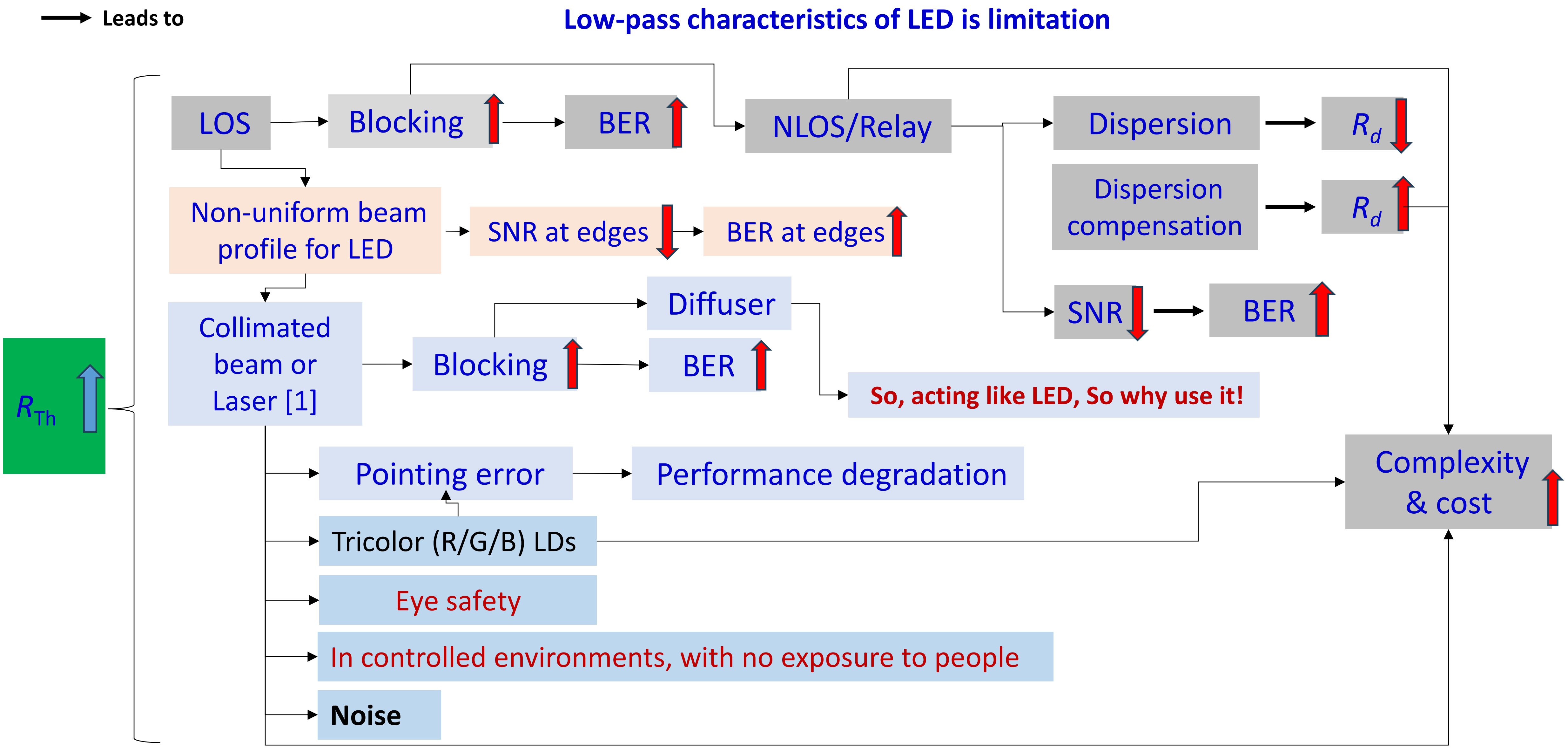
Noise sources:

- **Intensity noise** - Normally smaller than other noise sources
- **Phase noise** - In coherent systems, not important in IM/DD
- **Timing jitter**
- **Mode partition noise**
- **Reflection noise**

1- C. Shen, O. Alkhazragi, X. Sun, et al., “Laser-based visible light communications and underwater wireless optical communications: a device perspective,” Proc. SPIE 10939, 109390E (2019).

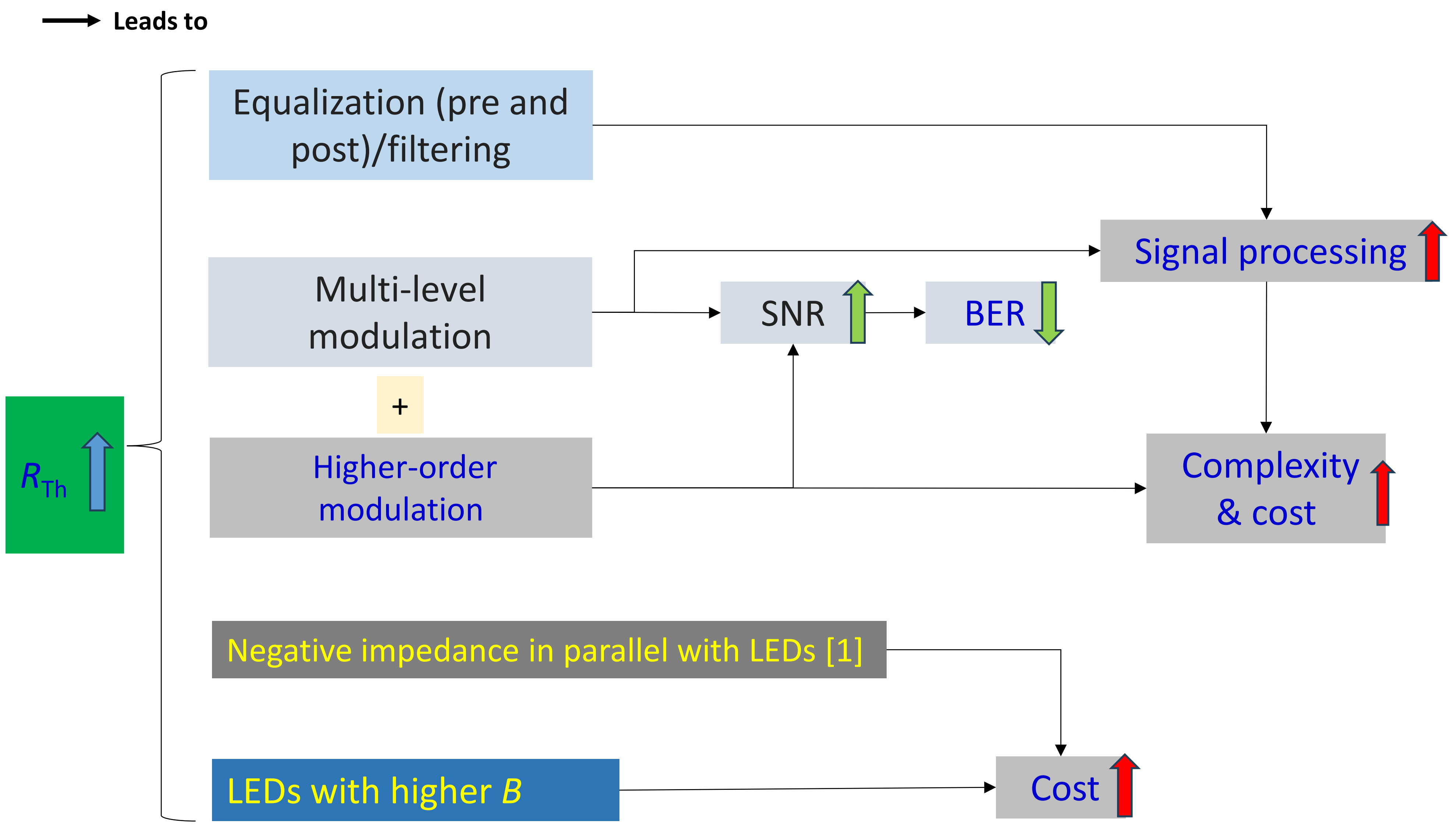
OWC – VLC - Throughput

Low-pass characteristics of LED is limitation



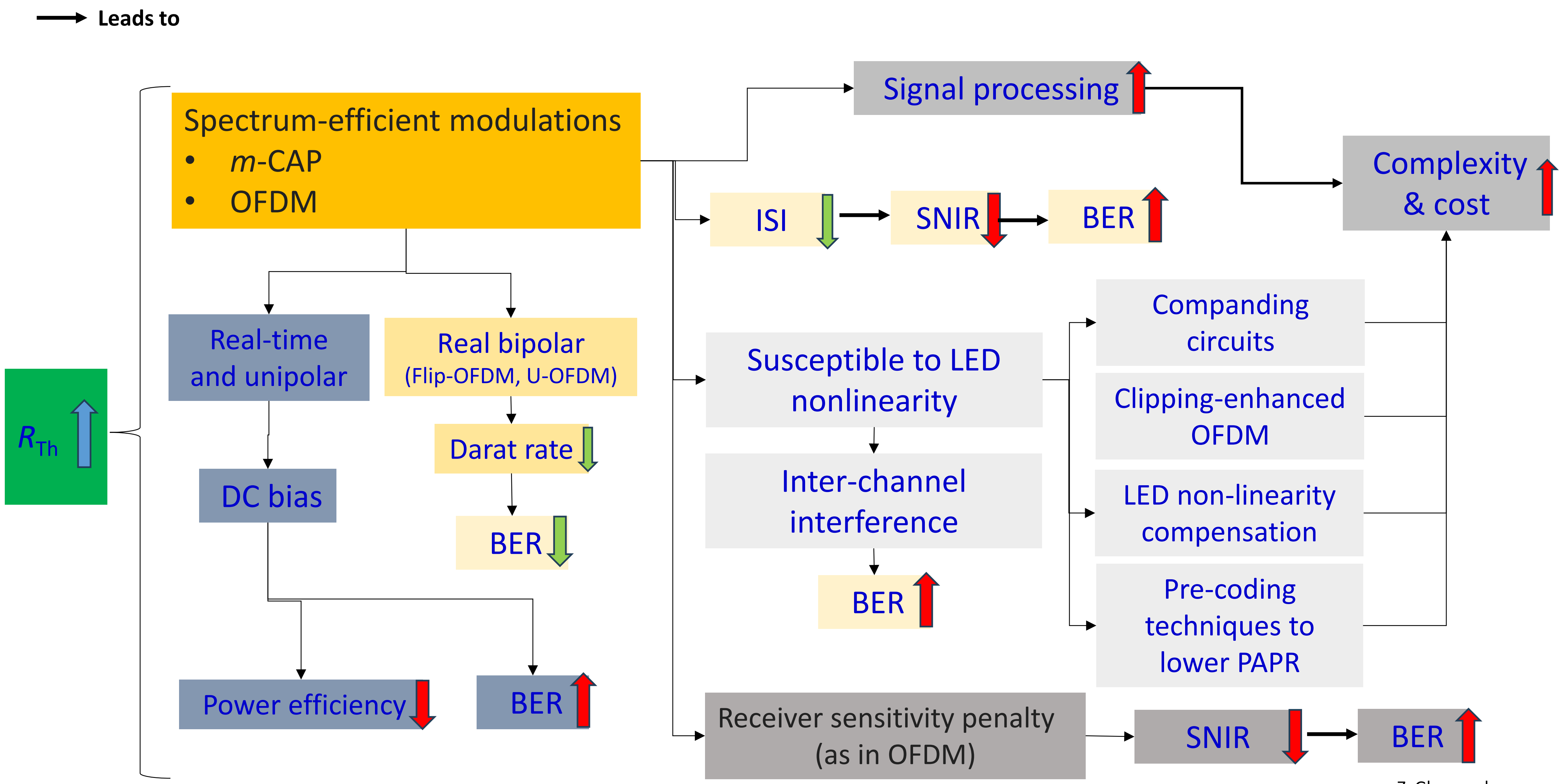
Junhui Hu, et al, 46.4 Gbps visible light communication system utilizing a compact tricolor laser transmitter, Opt. Express, 30 (2022), pp. 4365-4373

OWC – VLC - Throughput



1- A. Kassem and I. Darwazeh, "Use of Negative Impedance Converters for Bandwidth Extension of Optical Transmitters," in *IEEE Open Journal of Circuits and Systems*, vol. 2, pp. 101-112, 2021, doi: 10.1109/OJCAS.2020.3048304

OWC – VLC - Throughput



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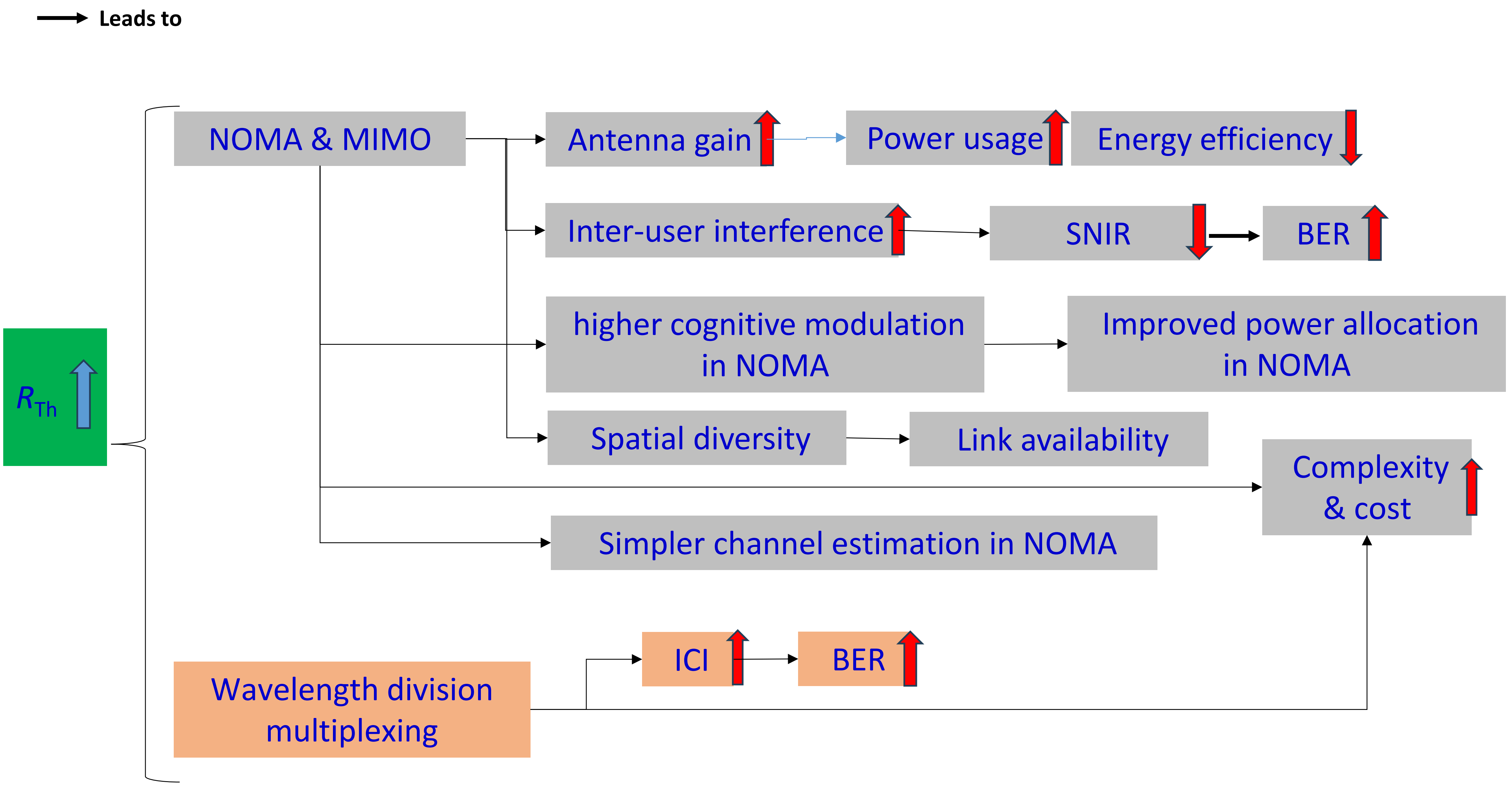
OWC – VLC - Throughput



OWC/VLC – Challenges and Issues

Light Sources

- The need for energy efficient and wide bandwidth light sources as well as arrays with new materials and mechanisms
- Linearity dynamic range –
  - Clipping and saturation → nonlinear distortion → higher order inter-modulation distortions
- Light sources with build in drivers and reconfigurable lenses
- LED – A limited bandwidth
- LD – Suffer from speckle noise, and chirping
- Use of super-luminescent diodes

Beamforming + Beam Shaping

- Optical phased arrays –
  - interfere constructively in the desired direction - → not unique across all angles when the emitters are spaced with a pitch greater than half the wavelength → formation of side-lobs
  - and ideally, destructively everywhere else.
- Narrow dynamically steered beams using meta surfaces to devices with tunability and higher functional capability
- AI/ML-based optimization
- Parctical use-cases

OWC + RF

5&6G - With Multi-access Edge Computing, Fibre and OWC

Offer huge bandwidth

Allowing more devices (e.g., IoT) to be connected

Connected devices & equipment can be monitored and data being analysed

Reduced equipment outages

Smarter, faster, more informed decision-making

Reduced waste

Decreased latency

Better energy usage

Reduced delays in data processing and increased data security

Reduced trips to work sites, saving on fuel and employee time

Next series on Optical Detectors.

Thank you!

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