PhD Open Days

The role of photonics in future sustainable smart cities: An Integrated Approach of Visible Light Communications and Luminescent Solar Concentrators

Ph.D. in Electrical and Computer Engineering

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Abstract

With urban populations projected to reach 68% by 2050 (**Fig. 1**), this rapid growth creates two major challenges for smart cities: sustainable **energy supply** and wireless **data traffic congestion**.

Visible Light Communication (VLC) emerges as a high data rate solution to congested radio-frequency networks [1]. However, standard optical receivers are constrained by strict line-of-sight (LOS) requirements and a limited field of view (FOV) [2].

This work proposes a disruptive solution: integrating **large-area Luminescent Solar Concentrators (LSCs)** into smart windows as advanced optical receivers for dual-purpose energy harvesting and VLC reception. By dispersing highly emissive luminescent complexes within a stable thermoplastic elastomer, the fabricated devices successfully mitigate spatial alignment limitations. This architecture establishes a self-powered optical node that seamlessly converges high data rate transmission and sustainable energy generation for **Zero Energy Buildings**.

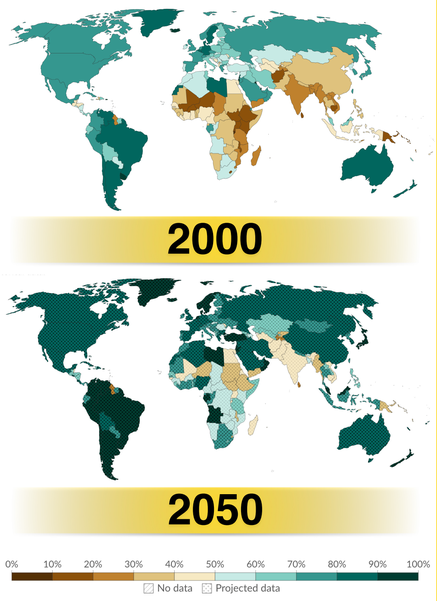


Fig. 1 / Global share of the population living in urban areas in **(a)** 2000 and projections for **(b)** 2050.

1 Visible Light Communication (VLC)

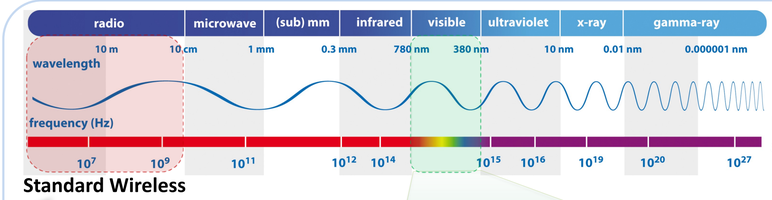


Fig. 2 / The electromagnetic spectrum.

Standard Wireless Networks

Challenges:
- Congested Spectrum
- Limited Bandwidth
- Security and Privacy

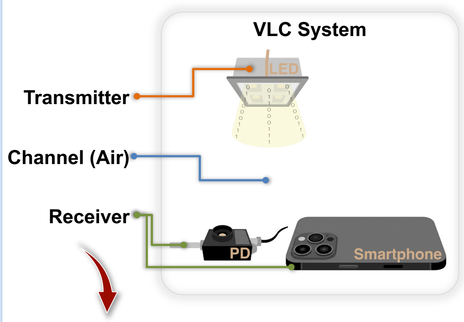
Potential Solution

VLC: A Dual-Purpose Solution

Uses the visible spectrum to provide [1]:

- Environment **Illumination**
- High-Speed **Data Transmission**

VLC System Architecture:



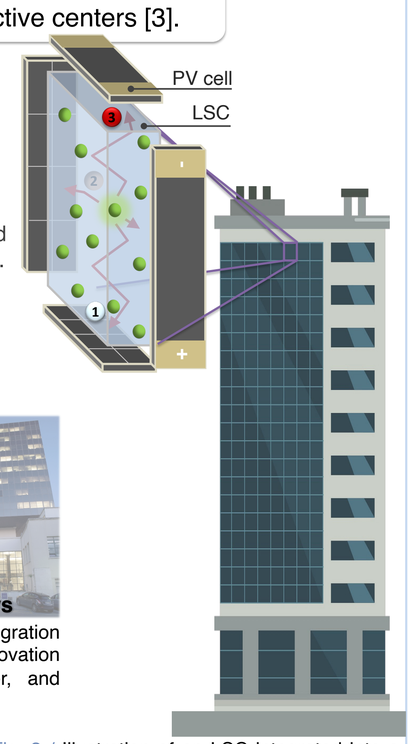
VLC Receiver Challenges:
- Limited FOV and small detection area.
- High sensitivity to ambient light.
- Strong dependence on clear LOS.

2 Luminescent Solar Concentrator (LSC)

LSC for Energy Harvesting

Transparent substrate doped with optically active centers [3].

1. The transparent device captures direct or diffuse light.
2. Luminescent species absorb and re-emit light at specific wavelengths.
3. The re-emitted radiation is guided towards the PV cells at the edges.



Potential integration sites:

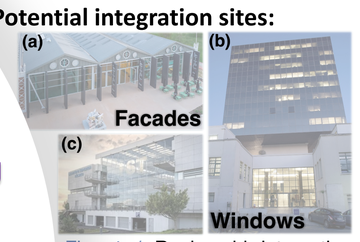


Fig. 4 / Real-world integration examples: **(a)** Técnico Innovation Center, **(b)** North Tower, and **(c)** Taguspark Campus.

Fig. 3 / Illustration of an LSC integrated into a window / façade of a building in smart cities.

3 Proposed Concept

Smart City Integration:
LSCs as large-scale **VLC receivers.**

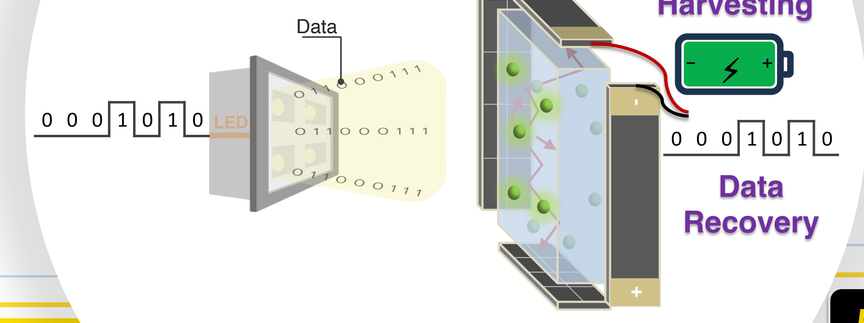


Fig. 5 / Schematic of LSC-VLC technology. Data-modulated light from LEDs is collected by the LSC and directed to PV cells, establishing a dual system for simultaneous **data recovery** and **energy generation** [4].

4 Experimental Setup

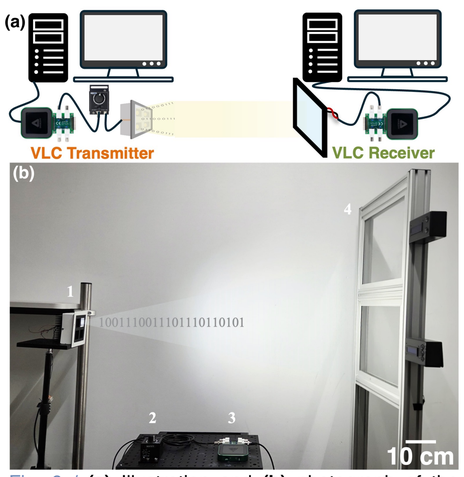


Fig. 6 / **(a)** Illustration and **(b)** photograph of the proposed system: **1** Codex-E Lamp (Lightenjin), **2** LED Driver (Thorlabs), **3** Analog Discovery 3 (Digilent), and **4** prototype based on distinct LSCs.

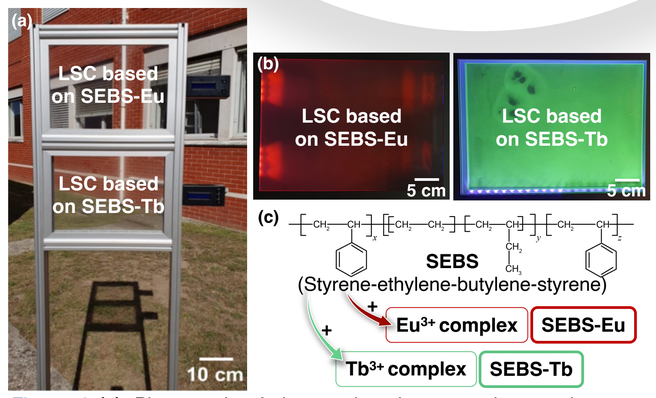
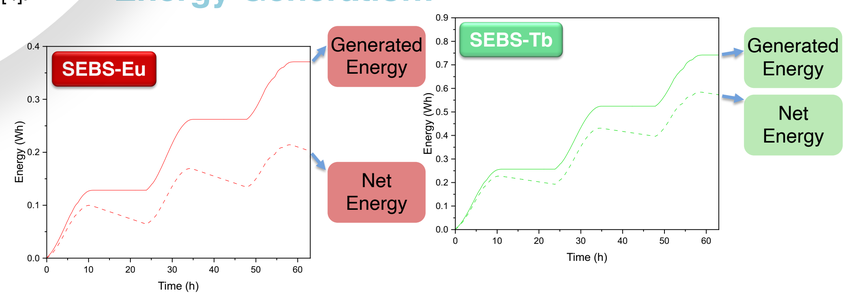


Fig. 7 / **(a)** Photograph of the receiver in an outdoor environment, featuring two windows (each 280 × 380 × 8 mm³). **(b)** Photographs of the prototype indoors under 385 nm and 365 nm monochromatic radiation. **(c)** Chemical structure of the transparent matrix. The SEBS thermoplastic elastomer and complexes were incorporated as in [5].

5 Experimental Results

Energy Generation:

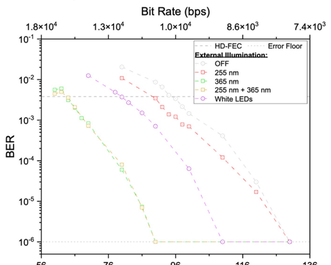


- **Self-Sustaining Operation:** An outdoor 63-hour test demonstrated that both LSC prototypes successfully harvested solar energy to power integrated IoT sensors.
- **Positive Balance:** Results show a positive Net Energy balance during daytime, confirming the viability of supply-less smart windows.

Data Communication:

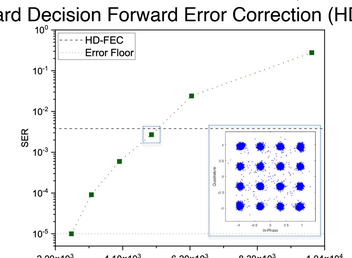
The LSC functions as a large-area optical VLC receiver.

On-Off Keying (OOK) Modulation



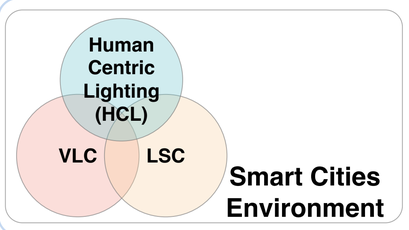
- Optical gain provided by external UV excitation significantly enhances the Signal-to-Noise Ratio (SNR) at the receiver end.
- The improvement expands the maximum achievable data rate, reaching a Bit Error Rate (BER) floor below the Hard Decision Forward Error Correction (HD-FEC) limit.

Quadrature Amplitude Modulation (QAM)



- To maximize data throughput within the device's limited modulation bandwidth, the 16-QAM format was investigated for the transparent SEBS-Tb receiver.
- Signal processing and coherent demodulation yielded well-separated constellation clusters, maintaining a Symbol Error Rate (SER) strictly below standard HD-FEC thresholds, even at high symbol rates.

6 Future Work



Advanced VLC Transmitters:
- **Dynamic White Light for HCL:** Synthesize high-fidelity, tunable white light for various indoor scenarios using advanced luminescent polymeric coatings on LEDs.
- **Ultra-Broadband VLC:** Exploit multi-chip RGB LEDs combined with advanced DSP and FEC algorithms to maximize data rates over extended distances.
- **Smart City Convergence:** Seamlessly integrate adaptive well-being illumination (HCL) with secure, high-speed optical networks.

Conclusion

Luminescent Solar Concentrators offer a novel approach to building-integrated photonics, operating as large-area receivers that overcome the LOS limitations of Visible Light Communication (VLC) systems.

- **Autonomous Energy Harvesting**: A 63-hour test validated their operation, demonstrating the capacity to power IoT sensors without external sources.
- **High Data Rate Transmission**: The system proved highly efficient, achieving an error floor for OOK modulation and successfully decoding 16-QAM signals below standard HD-FEC thresholds.

References

[1] G. Figueiredo et al., J. Opt. Commun. Netw. **16**, D1-D9 (2024).

[2] G. Figueiredo et al., CLEO: Appl. Technol., JTu2A-88 (2024).

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[4] G. Figueiredo et al., Handb. Phys. Chem. Rare Earths **66**, 51-123 (2024).

[5] G. Figueiredo et al., Adv. Sci. **11**, 2400540 (2024).

Acknowledgements

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