High-Performance Optical Camera Communications for ISAC Localization & Sensing

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Abstract

High-Performance Optical Camera Communications (HP-OCC) extends OCC by combining SPAD sensors with on-sensor edge processing to deliver high-speed optical links and cm-level localization in one platform. This optical ISAC alternative is well-suited for RF-restricted or congested environments.

In a live warehouse with Kuehne+Nagel, HP-OCC supported passive tag inventory search and Automated Guided Vehicle (AGV) automation with 5Mbps video and ~10cm localization at up to 25m away, simultaneously.

Motivation

Integrated Sensing and Communication (ISAC)[1] aims to unify data transmission and perception. RF-centric ISAC faces spectrum congestion and regulatory/performance limits, motivating optical alternatives.

What is HP-OCC? [2]

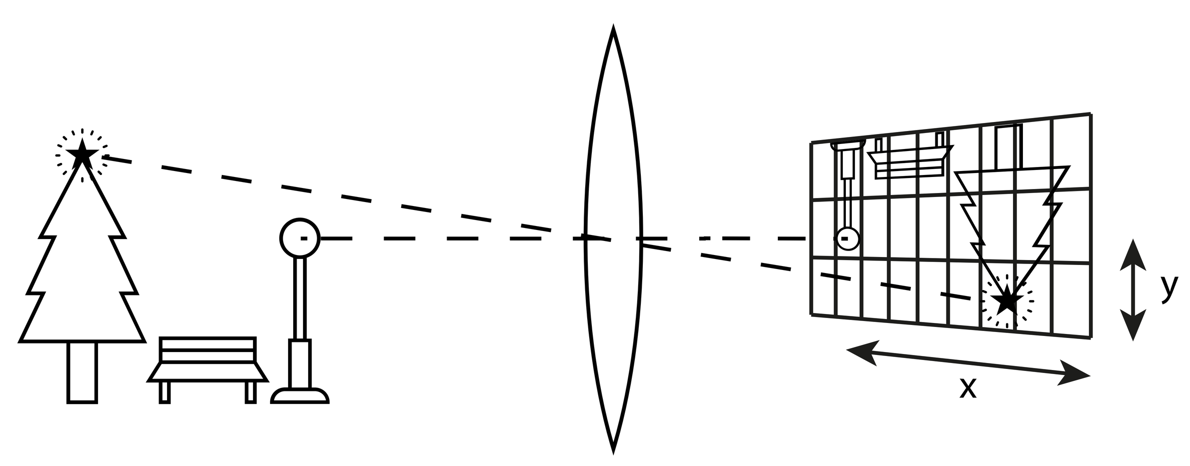

Figure 1: A camera sensor can isolate signals from multiple transmitters simultaneously.

High-Performance Optical Camera Communications (HP-OCC) augments conventional OCC by pairing single-photon avalanche diode (SPAD) sensors with on-sensor edge processing to decode high-speed optical signals while preserving spatial information for localization/sensing.

It acts like an optical analogue to receiver-side beamforming: the lens maps different directions to different sensor regions, enabling simultaneous multi-transmitter reception with fine spatial resolution. (*Figure 1*)

Spatial Multiple-Access

Fine spatial mapping, like optical angle diversity[3] yields quasi-orthogonal point-to-point channels ("pixels" on the HP-OCC sensor), reducing interference and simplifying front-end/protocol design. Similar communications-only applications using "communication sensors" exist as surveyed by Hasan et al[4].

Angle-of-arrival with ranging enable precise transmitter localization; with onboard synchronised emitters, self-reflection sensing can reconstruct 3D structure of the environment. Similar localization-only applications using SPAD sensors exist such as that by Chen et al[5].

Why Optical for ISAC?

Precision: High temporal & spatial resolution for cm-level localization & detailed mapping.

Efficiency: SPAD sensitivity enables low-power links; supports passive retro-reflective tags (no tag-side light source).

Compatibility: Resistant to RF congestion/EMI; suited for RF-restricted or congested environments (industrial, medical, military).

HP-OCC Receiver Architecture

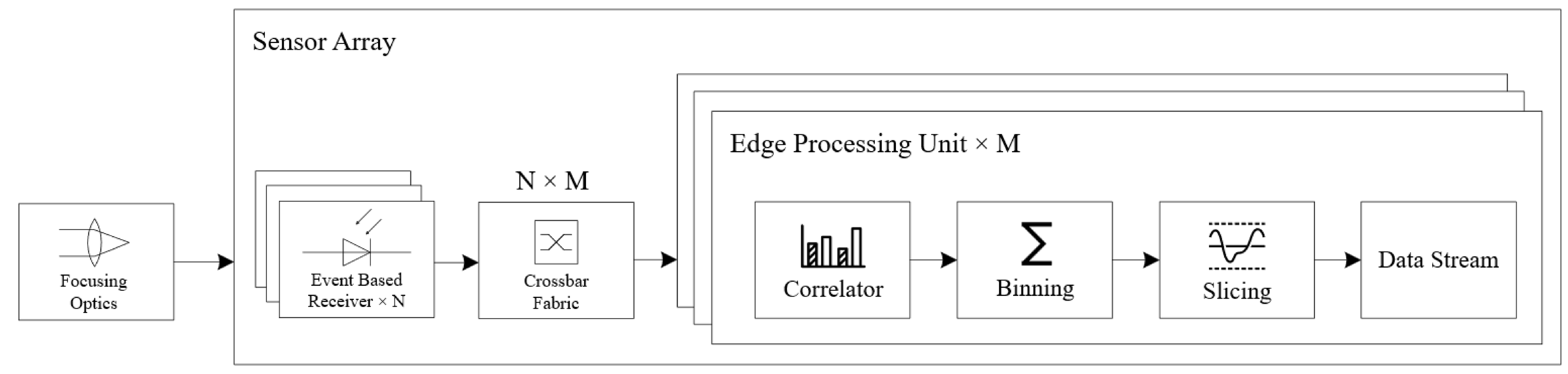

Figure 2: Architecture of HP-OCC receiver designed for OOK and ASK transmissions. The crossbar and multiple edge processing units within the sensor array allows each processing unit to be dynamically assigned to a pixel or group of pixels.

Event-based, frameless processing: Process photon-arrival events directly (no framerate bottleneck).

On-sensor edge processing pool: Dynamically assigned to pixels/groups via a crossbar, each unit demodulates a single optical stream as the transmitter moves across the SPAD array.

Dynamic symbol correlation & binning: Automatically adjusts binning window to maximize photon count for OOK/ASK demodulation pipelines; enables ranging via time-difference measurement of bin edges.

Real-World Deployment with Kuehne+Nagel

We present two logistics scenarios:
(i) Inventory tracking with passive optical tags.
(ii) Warehouse automation with HP-OCC-equipped AGV for simultaneous video streaming + localization.

Inventory Tracking with Passive Tags

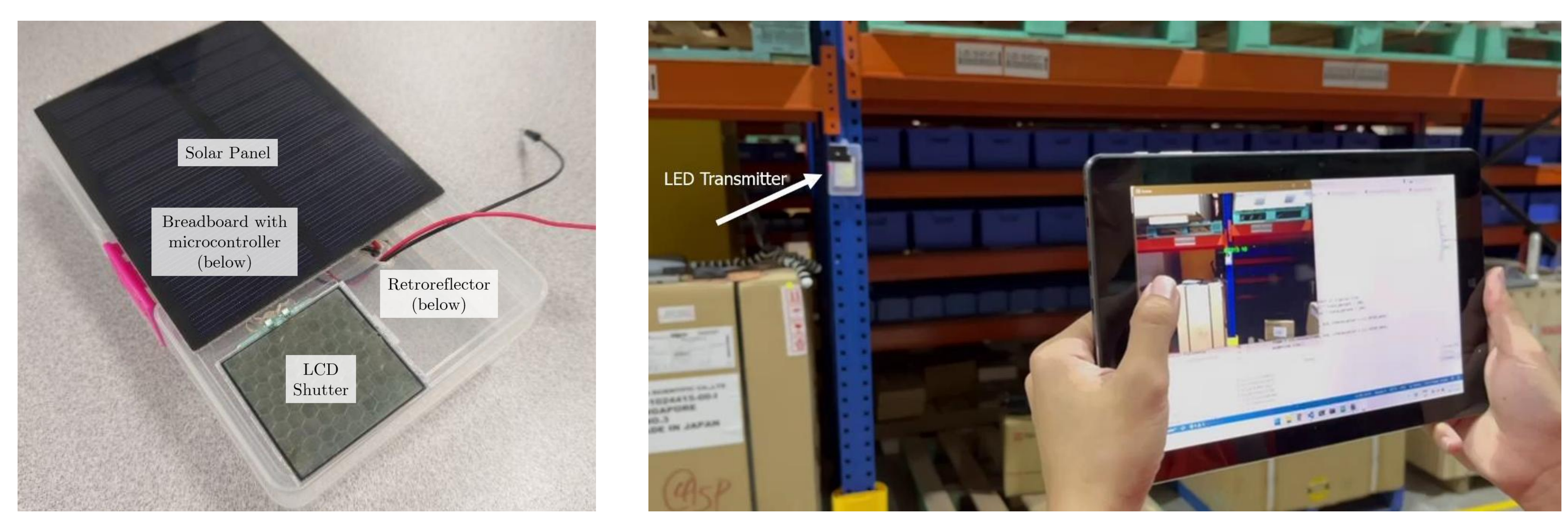

Figure 3: (Left) Annotated image of passive tag prototype, (Right) Portable HP-OCC receiver being used for inventory search.

Tags: Solar panel + retroreflector + LC shutter modulating tag ID.

Challenge: 100 Hz flicker from mains LED lighting degraded tag performance.

Mitigation: Shift to higher optical data rates (above flicker), noting reduced range due to LC shutter speed limit (lower contrast at high rate).

Warehouse Automation with AGV

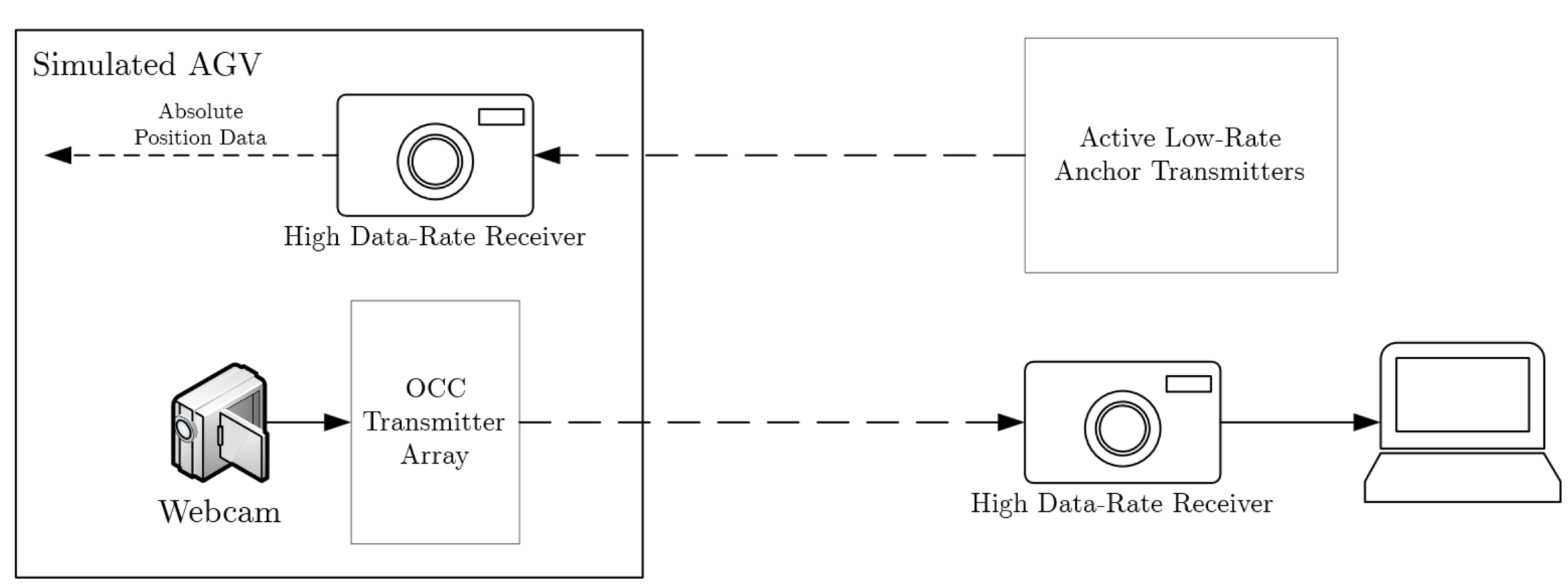

Figure 4: Illustration of the warehouse automation setup.

Localization & Command: Active anchors on shelves + single HP-OCC receiver on the vehicle.

Video & Telemetry: OCC transmitter array on vehicle + single HP-OCC receiver for video reception.

Result: Stable 5 Mbps video with low packet loss & ~10cm localization accuracy at up to 25m away.

Takeaways

- ✓ HP-OCC is a practical optical-domain ISAC solution for logistics: high-speed comms + cm-level localization in one receiver, with positive feedback from K+N on retrieval speed and automation opportunities.
- ✓ Limitation: requires line-of-sight; coverage can be impacted by clutter/occlusions. Consider densified placements and hybrid optical-RF designs (RF for coarse/NLoS, optical for fine once LoS is available).

Further Reading & References

[1] X. Luo, Q. Lin, R. Zhang, H. -H. Chen, X. Wang and M. Huang, "ISAC – A Survey on Its Layered Architecture, Technologies, Standardizations, Prototypes and Testbeds," in IEEE Communications Surveys & Tutorials, doi: 10.1109/COMST.2025.3565534.
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[3] Z. Chen, N. Serafimovski and H. Haas, "Angle Diversity for an Indoor Cellular Visible Light Communication System," 2014 IEEE 79th Vehicular Technology Conference (VTC Spring), Seoul, Korea (South), 2014, pp. 1-5, doi: 10.1109/VTCSpring.2014.7022832.
[4] M. K. Hasan et al., "Optical Camera Communication in Vehicular Applications: A Review," in IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 7, pp. 6260-6281, July 2022, doi: 10.1109/TITS.2021.3086409.
[5] G. Chen et al., "A Novel Visible Light Positioning System With Event-Based Neuromorphic Vision Sensor," in IEEE Sensors Journal, vol. 20, no. 17, pp. 10211-10219, 1 Sept.1, 2020, doi: 10.1109/JSEN.2020.2990752.

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