SPAD-Based Optical Camera Communications in a Warehouse Application

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Abstract

Modern logistics depends on accurate inventory visibility and automation, yet existing methods such as RFID, barcodes, and GPS remain limited in range, data rate, or power requirements. Optical Camera Communications (OCC), leveraging the spatial resolution of imaging sensors and the single-photon sensitivity of SPAD arrays, offers a promising alternative by combining reliable data exchange with precise localization.

We present a scalable OCC receiver architecture with SPAD-based edge processing, prototype passive tags, and a live warehouse deployment. Trials in collaboration with industry demonstrated the feasibility of OCC for inventory tracking, while highlighting challenges such as line-of-sight constraints and lighting interference. These results underscore OCC's potential as a complementary technology for logistics automation.

CCS Concepts

• **Hardware** → **Wireless devices**; **Sensor applications and deployments**.

Keywords

Single-Photon Avalanche Diode, SPAD, Optical Camera Communication, OCC, Warehouse Automation, Inventory Tracking, Worker Monitoring, Optical Wireless Communication

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Table 1: Comparison of available inventory tracking methods for logistics applications.

Technology	GPS-based	RFID-based	1D/2D Barcode	Our Work
Range	*Radio range*	2m-200m	1m	**10m-1km**
Line-of-Sight Required	N	N	Y	**Y**
Data Rate	Radio speed	27Mbps	~1200fps	**10-100Mbps**
Accuracy (Outdoors)	3m to 10m	~10m	N/A	**<5cm to 10m**
Accuracy (Indoors)	N/A	~2m	N/A	**<5cm to 10m**
Cost Per Tag	~US$100	~US$0.005	~US$0.001	**<US$5**
Tag Power	Wired	Passive/Batt	Passive	**Passive/Batt**

1 Introduction

Modern logistics relies on inventory visibility and automation to achieve efficiency. Existing technologies such as RFID, barcodes, and GPS (Table 1) provide partial solutions but suffer from limited range, data rate, and battery [2].

Optical Camera Communications (OCC) offers an attractive complement. By exploiting the fine spatial resolution of cameras and SPAD sensors for photon-level detection, OCC enables both reliable data exchange and precise localization.

In this work, we contribute: (i) a scalable OCC receiver architecture with SPAD sensors and edge processing for high performance, (ii) prototypes of passive optical tags, active optical anchors and OCC receivers, and (iii) the first deployment of OCC in a live warehouse setting.

2 Optical Camera Communications

Optical camera communications (OCC) [1] has attracted the interest of communication engineers since the early 2010s, coinciding with the advent of modern mobile phones equipped with video-capable camera sensors and powerful portable computing capabilities. OCC leverages pixel information captured by a camera sensor over time to recover data transmitted by optical wireless communication (OWC) transmitters. Multiple transmitters can be resolved simultaneously if sufficient spatial separation exists between them.

OCC (Figure 1) functions as an optical analogue to receiver-side beamforming. A lens maps incoming light from different angles to distinct sensor regions, creating thousands of quasi-orthogonal channels. Unlike conventional image sensors limited by frame rate, SPAD-based OCC detects photons at nanosecond resolution in an event-driven manner.

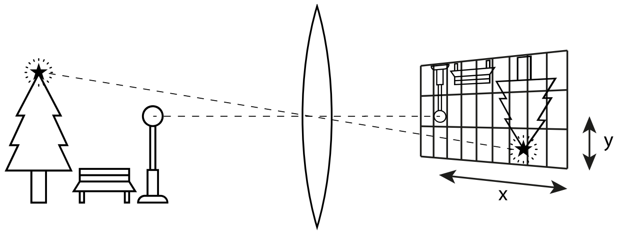

Figure 1: Simplified diagram of how a camera sensor can isolate signals from multiple transmitters simultaneously – when the lens forms an image of the scene on the sensor, each pixel can be thought of as a receiving beam in a spatial beamforming receiver. Due to how lenses work, these beams operate simultaneously.

Figure 2: The SPAD array used for the OCC receiver (left) and photo showing the shelves along the warehouse lane where our system was deployed (right).

This enables both communication and sensing: transmitter positions can be localized by angle-of-arrival and ranging while supporting data rates on the order of tens of megabits per second.

3 System Design

The OCC receiver employs a 512x512 pixel SPAD array (Figure 2) with edge processing units dynamically assigned to pixels or pixel groups. Each edge processing unit independently tracks and decodes one optical stream, enabling scalability depending on the number of optical streams that are to be simultaneously decoded. The receiver is connected to a computer for the user interface and consumption of the data streams.

Two transmitter types (Figure 3) were prototyped for the system: (i) passive tags using a solar panel, retroreflector and LC shutter to modulate incoming light, and (ii) active anchors mounted to and powered by infrastructure that provides high-speed data and fixed anchor points for command, control and localization.

4 Deployment

Through our collaboration with a logistics company, we were granted access to an operational warehouse, providing a valuable opportunity to evaluate OCC under realistic industrial conditions. This environment was critical for testing and gathering feedback for both the technical performance and practical usability of OCC-based systems, ensuring that research outcomes aligned with real operational needs. The warehouse manages a wide range of inventory, broadly classified into three categories: (i) just-in-time (JIT) high-value products requiring rapid delivery, (ii) fast-moving consumer goods (FMCG) under integrated logistics, and (iii) high-mix palletised returns.

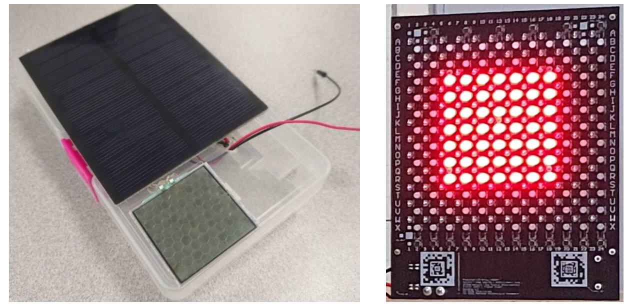

Figure 3: A passive tag (left) and active anchor (right).

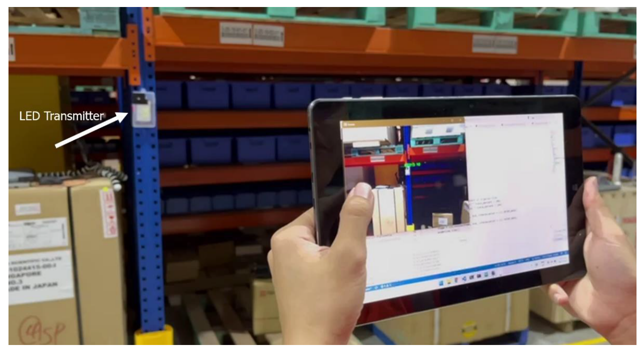

Figure 4: Image of the portable OCC receiver being used for inventory search.

The deployment was scoped to a single 25 m × 3 m lane (Figure 2) containing a representative mix of JIT goods and consumer returns. Trials were conducted over three full-day sessions, combining controlled measurements with hands-on use by warehouse staff, who provided feedback on usability and workflow integration.

A OCC receiver paired with a tablet interface was developed to simulate the task of locating specific items within shelves. Workers could query an item ID through the application, which provided coarse location details (lane and shelf). As the worker approached the shelf, the portable receiver displayed annotated overlays of detected tags, allowing the item's exact position to be pinpointed (Figure 4).

In controlled laboratory tests, the tags had performed reliably (>80% success) within 4 metres. However, warehouse trials revealed markedly reduced reliability (<50% success) even up close. This was later traced to flicker from ceiling-mounted LED lighting, powered directly from mains without voltage smoothing. The 100 Hz flicker overlapped with the low-rate optical signals, overwhelming the weak modulation of the passive LC tags. Although the issue could be mitigated by operating at higher optical data rates well above flicker frequency, this came at the cost of reduced range, particularly for passive tags constrained by LC shutter speed and modulation depth.

Despite these challenges, the inventory search demonstrator successfully illustrated the workflow to warehouse staff, who responded positively to its potential for reducing search time in high-mix inventory scenarios. Feedback highlighted that while prototype stability and range required improvement, the ability to visually pinpoint items on shelves through OCC provided an intuitive and valuable enhancement to existing processes.

5 Challenges & Future Work

The warehouse trials revealed both the potential and limitations of OCC in practical warehouse deployments. Environmental lighting proved to be a significant challenge with flicker from mains-powered LEDs and other dynamic light sources introducing interference. Operating at higher data rates can mitigate these effects, but low-power or bandwidth-limited transmitters remain vulnerable to such impairments.

Another key limitation is OCC's reliance on line-of-sight. In cluttered environments or when items are stored within containers, transmitters cannot be observed, limiting system coverage. Worker feedback emphasized that while simple occlusions can be overcome by moving the receiver, truly obstructed items remain inaccessible. Similarly, current passive tag designs showed poor angular performance and limited range due to inefficiencies in LC shutters and retroreflectors, restricting usability in warehouse layouts where tags are not easily viewed head-on. Localization accuracy was also tied to angular resolution and receiver orientation, with wide fields-of-view reducing precision and handheld use introducing variability.

Future work will focus on addressing these shortcomings. On the transmitter side, miniaturised and customized retroreflective tags, possibly based on other modulation methods, could improve performance and reliability. Receiver-side integration with SPAD arrays on portable devices, including AR glasses, could provide hands-free inventory search and stock-taking. Finally, hybrid OCC+RF approaches, repeaters, and system refinements such as time-of-flight ranging are promising paths to overcome line-of-sight constraints and improve localization precision.

6 Conclusion

This paper has briefly demonstrated a successful deployment of SPAD-based OCC in a warehouse application. The system was designed with custom-built transmitters and receivers, specifically tailored to address key operational objectives in inventory tracking.

The system effectively facilitated inventory tracking by enabling pinpoint and visual localization of items. However, the deployment also revealed several challenges such as occlusion, interference from ambient lighting, and localisation precision limitations – areas for future improvement.

Future research directions include the development of custom miniaturised transmitters, integrated OCC receivers, and system refinements such as repeaters, aggregators and the use of hybrid OCC-RF networks to mitigate occlusion and improve localisation performance. With continued advancements, we believe that SPAD-based OCC holds potential as a transformative technology for real-time tracking and automation in logistics and broader industrial applications.

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Additionally, this work uses the XillyUSB IP by Xillybus Ltd. [3] under the Education License, in various FPGA designs, for interfacing with host computers.

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