OAM - Sparse Code Multiple Access for Energy-Efficient   
LiFi-based Proximity Sensor Data Transmission   
for Industry 4.0

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**Abstract.** The massive number of sensors in Internet-of-Things networks instigate interference under limited wavelength resources. In this paper, sparse code multiple access (SCMA) is deployed for energy-efficient LiFi-based data transmission of proximity sensors using orbital angular momentum (OAM) modes in a LiFi system using the Low Projection (LP) codebook and quadrature phase shift keying (QPSK) codebook. A distinct feature of the system is utilizing the Fast Walsh-Hadamard Transform (FWHT) instead of the conventional Fast Fourier transform (FFT), prior to zero forcing and joint iterative detection and decoding (JIDD), to facilitate signal identification through frequency characteristics of the signals. Results demonstrate that the FWHT outperforms FFT in terms of the bit-error rate, packet error rate, modal efficiency and throughput. Under both FWHT and FFT operations, the LP codebook outperforms the QPSK codebook. The findings reveal that integrating SCMA to optical wireless sensing improves real-time monitoring efficiency.

# INTRODUCTION

Industry 4.0 integrates advanced technologies, including sensor technology, cloud computing and artificial intelligence, to enhance production efficiency and decision-making by creating interconnected, intelligent systems. Cyber-physical systems (CPS), where digital technologies are integrated with physical processes, are core to this revolution, facilitated by sensors that collect real-time monitoring data [9]. Interoperability, large-scale data analytics, and smart factories improve automation, quality control, and central system connectivity in electronics manufacturing [4],[10]. However, challenges such as data overload, flexibility, scalability, and sensor accuracy must be addressed for successful Industry 4.0 implementation [11].

Li-Fi is a wireless communication technology utilizing visible light for data transmission, alleviating radio spectrum congestion [1, 2].Li-Fi uses light waves from visible lasers or light-emitting diodes to transmit data at high speeds through the atmosphere, with a bandwidth reaching up to 350 THz. It offers several advantages over traditional wireless communication, including immunity to electromagnetic interference, and enhanced security. These capabilities make it ideal for environments such as smart factories, where vast amounts of data are generated and are in the vicinity of electronics equipment which are susceptible to electromagnetic interference [12-13]. Li-Fi can improve proximity sensor performance in manufacturing by reducing sensor degradation due to electromagnetic fields, enhancing speed, reliability, and accuracy [4],[14].

# Literature Review

Proximity sensors are essential in various industries, offering non-contact object detection through electromagnetic fields. They enhance assembly lines, quality control, and conveyor systems by improving efficiency and accuracy [4]. With Industry 4.0, IoT integration transforms these sensors into intelligent devices capable of real-time data collection and analysis for smart manufacturing [5]. However, traditional proximity sensors face limitations in data transmission quality, in which Li-Fi technology addresses, improving sensor performance in Industry 4.0 applications [6].

Proximity sensors, utilizing infrared, ultrasonic, or magnetic fields, are widely used for position sensing in automated assembly lines and object detection in conveyor systems, enhancing operational efficiency and precision [4],[7]. Hall effect sensors are especially notable for detecting magnetic fields and enabling applications such speed measurement and position feedback in rotary encoders for optimizing industrial operations [8].

The massive number of sensors and devices in Internet-of-Things networks calls for secure, energy-efficient sensing and data transmission within a specific spectrum while minimizing interference between them. Optical multiple-input-multiple-output systems based on space division multiplexing takes advantage of spatial modes as data carriers or resources [15-17].

# Sparse code multiple access (SCMA), under the family of non-orthogonal multiple access schemes (NOMA), addresses this challenge by allowing multiple users to share the same wavelength resources to limit energy consumption, while increasing the capacity and reliability of the system [4]. In [3], discrete Fourier transform (DFT) is performed on the received symbols and used as the input to zero-forcing equalization, before recovering the signals through the message passing algorithm. In [4], SCMA has been deployed for optimizing the power allocation between devices and maximizing the total data rate, leading to better energy efficiency than frequency-based and code-based multiple access schemes.

# In large Internet-of-Things networks, multiple users can be served simultaneously using SCMA by employing different sparse codebooks [3]. For spectrum efficiency, rather than using multiple wavelengths as resources for data transmission on different channels, spatial modes such as orbital angular momentum (OAM) modes and Hermite-Gaussian (HG) modes have recently been exploited as resources in SCMA-based communications systems [18-20].

# CONTRIBUTIONs

# Proximity sensors in conventional radio networks encounter electromagnetic interference (EMI) from nearby electronics equipment, leading to latent data transmission, impeding the potential of Industry 4.0 [14]. Motivated by previous work on SCMA, an energy-efficient LiFi-based data transmission system for optical proximity sensors is demonstrated through SCMA. Instead of utilizing distinct wavelengths as resource elements, in this work, spatial modes are utilized as resource elements for SCMA deployment. Compared to previous papers which utilize the Fast Fourier transform (FFT) to facilitate signal identification through frequency characteristics of the signals, for the first time, we have deployed the Fast Walsh-Hadamard Transform (FWHT) prior to zero forcing equalization and joint iterative detection and decoding (JIDD) for signal recovery.

# METHODOLOGY

A sensor (Figure 1(a)) comprising a Helium Neon laser and a photodiode is configured for proximity detection based on the photoelectric effect, operating between 0˚–40˚ temperature and 20%–85% humidity, powered by a 5V/1A supply. The SONOFF ZigBee 3.0 USB Dongle (Model ZBDongle-P) (Figure 1(b)) serves as the ZigBee coordinator within the Home Assistant API, functioning within -10˚ to 40˚, powered by DC 5V (max 100mA), and enclosed in an aluminum alloy shell. For environments lacking Ethernet, a USB 3.0 Wi-Fi adapter (Figure 1(c)) ensures network connectivity, supporting up to 1000 Mbps with a frequency range of 2.4 GHz to 5.4 GHz.

The Home Assistant API, an open-source platform, is used to control devices such as door sensors and retrieves data through its RESTful API (port 8123), as shown in Figure 2(a). It is installed using a VirtualBox hypervisor configured with a Bridged Adapter for network access over Ethernet (Figure 2(b)). MATLAB is utilized to fetch and process sensor data by setting endpoint URLs, including authentication headers, and parsing the JSON response for analysis.

|  |  |
| --- | --- |
| A device with a magnetic object  Description automatically generated  (a) | A usb adapter on a white surface  Description automatically generated  (b) |
| A black usb device with a black handle  Description automatically generated  (c) |

**FIGURE 1.** (a) Proximity Sensor, (b) SONOFF ZigBee 3.0 USB Dongle MODEL ZBDongle-P, (c) Realtek 8811CU Wireless LAN 802. 11ac USB NIC

|  |  |
| --- | --- |
| A screenshot of a computer  Description automatically generated  (a) | A screenshot of a computer  AI-generated content may be incorrect.  (b) |

**FIGURE 2.** (a) Home assistant API interface, (b) VM virtual box

MATLAB is used to access the proximity magnetic door sensor data through the Home Assistant API. To enable this, the Home Assistant hypervisor is installed via VirtualBox on a Windows OS to access the local host at Home Assistant.local:8123. The ZigBee USB dongle acts as the coordinator and gateway within Home Assistant, controlling the door sensor. As the testing environment lacks an Ethernet connection, a Wi-Fi adapter is employed. Figure 3 illustrates the system's initial design. MATLAB is used to read real-time data from physical proximity door sensors. The sensor outputs a binary state: 1 when detecting a light beam and 0 otherwise. This data helps determine the optimal detection distance.

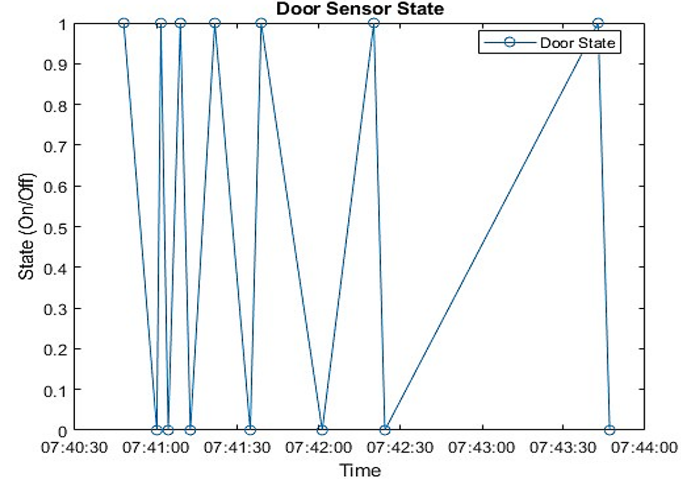
The MATLAB script interacts with the Home Assistant REST API, using a bearer token for authentication. It runs in a loop for a set duration (e.g., 190 seconds), making periodic HTTP GET requests via the webread function to fetch the sensor’s state. JSON responses are parsed to extract sensor readings—1 for "on" (magnet detected) and 0 for "off" (no detection)—which are timestamped and stored in arrays.

A plot of sensor activity over time is generated as shown in Figure 4, with labelled axes and a legend for clarity. The collected data is saved as a “. mat” file for further analysis. A 1-second pause between iterations ensures consistent data collection, enabling continuous monitoring and improved object detection accuracy.

For the initial calibration, a ruler is used to determine the distance required for the sensor to detect the approaching object to determine the distance of detection for best reading accuracy as shown in Figure 5. Figure 6 shows the flow chart of how the process is carried out. Table 1 shows the test results.

The system uses a photoelectric-based proximity sensor for object sensing, which is then converted to optical form for transmission over 600 meters to a remote site. As shown in Figure 7, optical data from six channels are transmitted on four selected OAM modes for each channel, OAM +1, OAM +2, OAM +3 and OAM +4, using either the Low Projection (LP)- or quadrature phase shift keying (QPSK) - Sparse Code Multiple Access (SCMA) codebook, in conjunction with orthogonal frequency division multiplexing (OFDM). At the receiver, the performance of the conventional Fast Fourier transform (FFT) and Fast Walsh-Hadamard Transform (FWHT) for signal recovery, applied prior to zero forcing equalization, are compared. The  joint iterative detection and decoding (JIDD) algorithm [21] is emplyed after zero forcing to recover the transmitted data.

A diagram of a computer system

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**FIGURE 3.** System Design **FIGURE 4.** Sensor state with time

|  |  |
| --- | --- |
| **TABLE 1.** Detection Range | |
| Distance (cm) | Detection |
| 3 | No detection |
| 2.7 | detected |
| < 2.7 | detected |

# RESULTS and discussion

The goal of the measurements is to assess the system performance under varying signal-to-noise ratios (Eb/N0) and analyze key performance metrics such as Bit Error Rate (BER), Packet Error Rate (PER), throughput, and spectral efficiency. The BER is calculated based on the ratio of bits received in error to the total bits transmitted. The packet error rate (PER) is then calculated based on the BER as:

(1)

The throughput T (bps) is computed as: (2)

The data rate (bps) is computed as: (3)

whereB = 1GHz is the channel bandwidth.

The modal efficiency SE (b/s/Hz) can be calculated by dividing the throughput by the bandwidth using:

(5)

Finally, the signal-to-noise ratio, is computed as:

(6)

The experiment involved testing two different codebooks to determine the most suitable for low-cost sensors. The first was a traditional 4x6 SCMA codebook with quadrature phase shift keying (QPSK), while the second was a Low Projection (LP) SCMA codebook, designed for ultra-low decoding complexity in IoT networks using low-cost devices. The experiments were performed in the foyer of Sunway University, and included a comparison of performance between using FFT and FWHT.

A computer and a usb adapter

Description automatically generated with medium confidence A diagram of a program

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**FIGURE 5.** Distance testing **FIGURE 6.** Flow chart for the detection process

## A diagram of a computer program Description automatically generated

**FIGURE 7.** SCMA LiFi-based proximity sensor data transmisison system

Figure 8(a) shows the BER versus SNR using the LP-SCMA codebook and the QPSK-SCMA codebook, using FFT and FWHT. The BER curves demonstrate that the QPSK-SCMA codebook outperforms the LP-SCMA codebook. The BER curves also indicate that employing FWHT achieves better results than with FFT. Similarly, in Figure 8(b) illustrates that the PER attained by the LP-SCMA codebook outperforms the PER attained by the LP-SCMA. The PER curves also indicate that employing FWHT achieves better results than with FFT. In Figure 8(c), it is observed that the spectral efficiency of LP-SCMA is the highest using FWHT, followed by LP-SCMA with FFT, QPSK-SCMA using FWHT, and lastly QPSK-SCMA using FFT. Figure 8(d) illustrates that the highest throughput is attained using LP-SCMA with FWHT, followed by LP-SCMA with FFT, QPSK-SCMA with FWHT, and finally QPSK-SCMA using FFT.

# Conclusion

Industry 4.0 is the driving force for innovations to current proximity sensors for enhanced sensing and remote monitoring capabilities using optical signals. SCMA enables efficient wirelesss optical communictaions from six channels on four OAM modes. Results indicate that FWHT enhances the BER, PER, throughput and modal efficiency of the SCMA system when used in conjunction zero forcing and JIDD compared to the conventional FFT. Under both FWHT and FFT operations, the LP codebook outperforms the QPSK codebook. The new SCMA approach enables grant-free data transmission without prior scheduling in smart factories for industrial automation, allowing a large number of sensors to transmit data efficiently utilizing only a single wavelength, due to the leverage of OAM spatial modes as resources, instead of multiple wavelengths. The abundance of OAM modes offers system scalability, particularly in high-density, spectrum-limited environments.

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| **A graph with different colored lines  Description automatically generated**  (a) | **A graph with different colored lines  Description automatically generated**  (b) |
| **A graph with different colored lines  Description automatically generated**  (c) | **A graph with different colored lines  Description automatically generated**  (d) |

**FIGURE 8.** (a) BER vs EbN0, (b) PER vs EbN0, (c) Modal efficiency vs EbN0, (d) Throughput vs EbN0

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