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Enhancing Air Cargo Security Transport Using Integrated IOT and Optoelectronic Oscillator

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Abstract: ***This research paper explores the potential of the integration of optoelectronic oscillators (OEOs) with the Internet of Things (IoT) to enhance air cargo security. The proposed solution leverages the unique capabilities of OEOs, combined with IoT technologies, to enable non-intrusive inspection, secure communication, real-time monitoring, and precise tracking of cargo containers. The integration of OEOs with IoT could offer significant advancements in air cargo security, including improved threat detection, identification, and prevention of threats and unauthorized activities.***

Keywords: IOT, OEO, Air cargo security, Non-intrusive inspection, Real-time monitoring, Secure communication

1. Introduction

1.1 Background and Motivation

There is a great concern related to air cargo security in this modern globalized world transporting and delivering cargo securely is of the utmost priority to maintain good international ties, and trade in the international market with an economic boost. According to the International Air Transport Association (IATA) report of 2021, more than 60 million metric tons of goods have been transported globally through trade [1]. This number will grow gradually and with this gradual rise, a significant challenge in ensuring safety and integrity arises automatically. Resolving this safety issue is of the utmost importance to safeguard the integrity of the person or organization engaged in the transportation process.

There exist various traditional processes to safeguard the transportation of air cargo and limit criminal activities such as smuggling forbidden items, terrorist activities, and illicit trafficking. Though these measures exist nevertheless these illegal activities constantly evolve to counter existing security measures. Due to this, new innovations are required in this field to properly address upcoming security concerns. Due to the emergence and rapid innovation happening all around the world, two technologies exist in this era that can aid in mitigating the issues. These Technologies are a) Optoelectronic Oscillator (OEO). b) Internet of Things (IoT).

Optoelectronic Oscillator is a technology that promises great potential for cargo security as OEOs combine optical and electronic signals to generate high frequency and stable microwave signals [2]. The second technology is the Internet of Things which acts as an interface between various devices and sensors over the Internet [3] and is widely used in the field of logistics, supply chain management, etc. to retrieve real-time data. Integrating these two technologies will enable the users to harness unique abilities and will enable the users to properly address the limitations related to traditional security measurements in a secure manner with real-time monitoring.

1.2 Research Objective

The primary objective of this research paper is to explore the integration of optoelectronic oscillators (OEOs) with the Internet of Things (IoT) for enhanced air cargo security. The research aims to achieve the following objectives:

1) Investigate the principles and properties of optoelectronic oscillators and their applicability in air cargo security [4], [5].
2) Examine the role of the Internet of Things in air cargo management and its potential for addressing security challenges [6].
3) Propose an integration framework that combines optoelectronic oscillators and IoT technologies to enhance non-intrusive inspection, tracking, communication, and real-time monitoring in air cargo security.
4) Evaluate the benefits and implications of the proposed integration, including improved threat detection, enhanced tracking and monitoring, secure communication, and operational efficiency.
5) Present case studies and experimental results to demonstrate the feasibility and effectiveness of the integrated approach.
6) Identify challenges and future directions for research and development in the field of optoelectronic oscillators integrated with IoT for air cargo security.

By addressing these research objectives, this study aims to contribute to the advancement of air cargo security by leveraging the unique capabilities of optoelectronic oscillators and IoT technologies.

2. Optoelectronic Oscillator Fundamentals

2.1 Principles of Optoelectronic Oscillators

Optoelectronic Oscillator (OEOs) Fig 1 consists of various components forming a positive feedback loop, including a laser, an electro-optic modulator, an optical energy storage unit (such as an optical fiber with high quality (Q) factor), a photodetector, a bandpass filter, a microwave amplifier, a phase shifter, and a microwave coupler. The oscillation in the system is sustained by the injected light preceding the electro-optic modulator. This light is modulated by the electro-optic modulator, transforming it into an optical signal carrying a specific frequency.

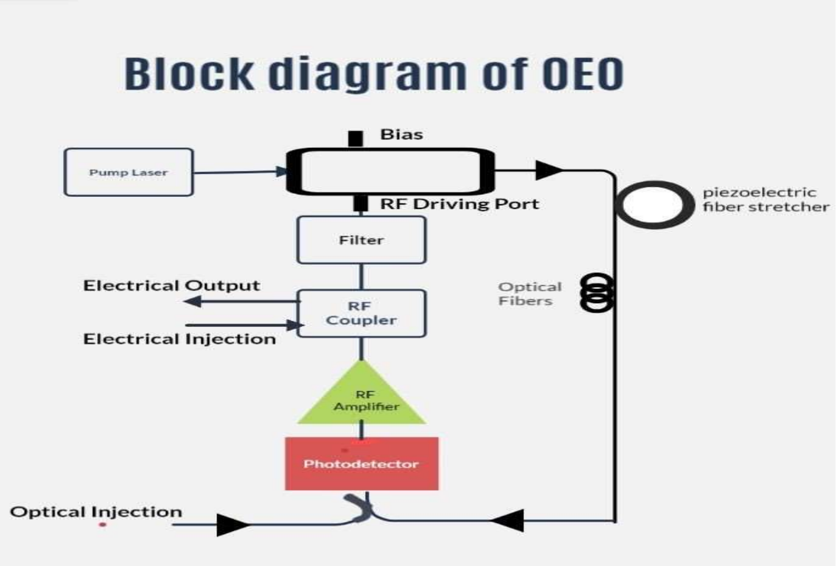

Figure 1: Basic block diagram of Optoelectronic Oscillator

The optical signal is then converted back into an electrical signal using a photodetector, followed by amplification and bandpass filtering. The bandpass filter selectively allows a specific frequency component to pass through for output, while the remaining portion is fed back to the microwave input port of the electro-optic modulator, completing a cycle. Through continuous cycling, a stable oscillation is eventually established. The utilization of a high-Q optical energy storage unit, such as a low-loss, extended fiber, in the optical oscillator ensures that the output signal exhibits exceptionally low phase noise. In recent years, there has been significant development and growing interest in utilizing optoelectronic oscillators (OEOs) for sensing, measurement, and detection applications. These emerging applications involve converting the target parameter or signal (referred to as X) to a frequency shift in the oscillating signals generated by the OEO. This process can be defined as an X-to-frequency mapping or coding [10]. By analyzing the frequency of the oscillations in the electrical domain, the target parameter or signal can be determined, ensuring high resolution and a high signal-to-noise ratio (SNR). Various approaches have been demonstrated to measure different target parameters or signals using OEO-based sensing, measurement, and detection techniques. These include measurements related to distance, length change, refractive index, temperature, transverse load, strain, and RF/optical signals. With such a broad range of applications, there is a significant potential and promising prospect for utilizing OEOs in these areas [10]. This paper will specifically focus on exploring and discussing these applications in detail.

2.2 Properties and Advantages of OEOs

The Optoelectronic Oscillator (OEOs) is an electronic device that fuses optical and electronic components to generate frequency at a higher range that is stable in nature. OEOs provide numerous advantages that are suitable to incorporate into air cargo security due to their properties. The advantages of using OEOs are mentioned in the following section:

Feedback Loop: OEOs functions are based on feedback loops that are involved in using electrical resonators along with optoelectronic transducers [7]. Electrical signals get converted into optical signals using an optoelectronic transducer and the signals are then transmitted past optical fibers. The electrical signals are retrieved from the optical signals through a photodetector and fed into an electrical resonator.

High-Q Resonators: Frequency that is produced using OEOs has improved frequency stability and lower noise levels due to the utilization of high-quality (high-Q) resonators in their feedback loops [8]. This enables in generating of microwaves with high spectral purity and precise frequency control.
Low Phase Noise: OEOs show low-phase noise characteristics that represent random fluctuations in the timing and phase of the microwaves generated, which is a crucial requirement in applications where accuracy, quality of the signal and stability is essential. Due to these properties, OEOs are valuable for communication purposes.

Frequency Tunability: The frequency of the OEOs is tunable which allows precise control and adjustment for the generation of microwave signals. The tunability is achieved by adjusting the electrical resonator and the optical path length, due to this OEOs are versatile and can be used in various communication and sensing systems.

Optical Injection Locking: It is a phenomenon where an external optical signal is used to synchronize and stabilize the microwave signal generated by the OEO [9]. Optical injection locking improves the phase noise performance, and frequency stability and maintains the purity of the microwave signal that is appropriate for high performance.

2.3 Frequency Stability and Phase Noise Considerations

Phase noise refers to the random fluctuations or variations in the timing or phase of a periodic signal relative to a reference signal. It represents the noise or uncertainty in the phase of the signal. OEOs are generally known for their exceptionally low noise microwave generation, and it produces very specific single-frequency signal that has a minimum deviation from an ideal sine wave [11]. The phase noise can be explained as the quantification of ratio to noise power under the umbrella of 1 Hz bandwidth at a specifically defined offset frequency to the power of the signal at the center frequency (expressed in dBc/Hz). The phase noise shown in Fig 2 is represented in the form of a single sideband (SSB) phase noise, and the graph explains that phase noise is a function of the offset frequency.

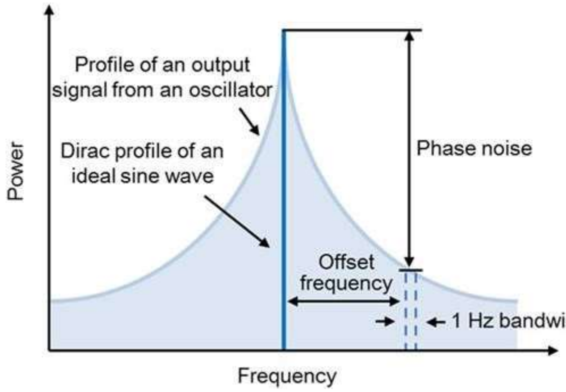

Figure 2: Phase Noise as a function of offset frequency

Phase noise has a very crucial application in modern-day communication as frequency stability can be achieved for a longer duration using calibrated algorithms along with frequency stability for a shorter period can determine the efficiency and performance of OEO systems [11].

Frequency stability refers to the ability of an oscillator or signal source to maintain a consistent and accurate output frequency over time. It is a measure of how well the frequency of the generated signal remains unaffected by external factors, such as temperature variations, vibration, power supply fluctuations, or other environmental influences. Frequency stability is typically quantified by parameters such as Allan deviation, phase noise, or fractional frequency deviation [12]. These parameters provide information about the short-term and long-term variations in the output frequency of the oscillator. There are various key factors that can help in gaining frequency stability such as a) High-Q Resonator, b) Feedback mechanism, c) Temperature compensation, d) Phase-locked Loop, and e) Optical Injection Locking.

3. IOT in Air Cargo Security

Since the concept of IoT arrived into existence it has provided a great boost to the process of globalization in the field of artificial intelligence, trade, and communication and enabled humans to feed live data. Incorporating IoT along with deep machine learning, algorithms broadened the application of IoT to new heights into extensive huge-scale digital processing at Industrial Scale. This provides a grand opportunity for the application of IoT in the aviation industry for cargo security, as it will enable the sensors to feed live data and detect objects minutely and stop criminal trafficking and restrict criminal activities. This will lead to enhancing the security of respected organizations to maintain the

Our work introduces a system that integrates a hybrid cloud-fog-edge-mist data fusion pipeline into the aircraft and cargo-loading environment. This system is designed to receive real-time sensor data using various protocols and enable the execution of IoT-enabled applications for scalable control, analytics, and storage. It facilitates the analysis of IoT data collected from sensors and other external sources, allowing for the extraction of valuable business insights. Additionally, the system dynamically handles application rules on the fog nodes based on these insights, contributing to improved operational efficiency and decision-making [13].

3.1 Overview of IoT in Air Cargo Management

The Internet of Things has the potential to revolutionize air cargo security management. The use of connected devices enables real-time monitoring of cargo, tracking and management of cargo from the point of origin to the destination. The IoT can also help to emit real-time data such as temperature, humidity, and air quality in the cargo along with other relevant parameters to ensure the quality of the materials being transported. Any deviation from the pre-defined threshold in the sensor will alert the officials for immediate actions to ensure the quality and safety of the products that are being transported.

IoT enhances security and reduces the risk of theft or tampering of the products that are being transported as they are equipped with geofencing capabilities that provide virtual boundaries and trigger alerts if the cargo deviates from the pre-defined paths to the destinations. Sensors have also the ability to detect the unauthorized opening of cargo and trigger alarms accordingly for a swift response to potential security breaches. The data from IoT can also provide precious data to analyze cargo flow patterns, bottlenecks, and operational inefficiencies. Fig 3 is self-explanatory about the basic IoT architecture along with the access of data to the user.

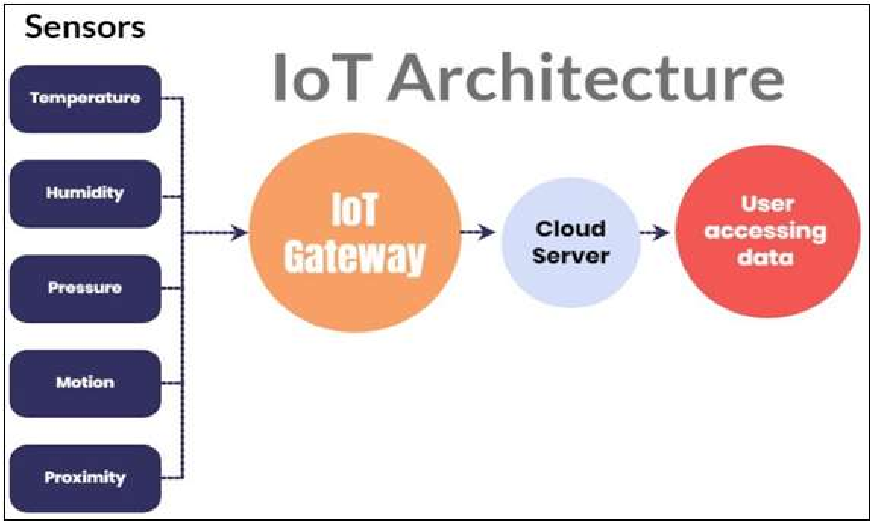

Figure 3: Basic IoT architecture block diagram

3.2 Challenges and Requirements in Air Cargo Security

Air cargo security poses unique challenges and requires specific measures to ensure the safe and secure transportation of goods. Some of the challenges and requirements in air cargo security include:

Regulatory Compliance: Air cargo security is subject to stringent regulations imposed by national and international authorities [14]. Compliance with these regulations is mandatory for airlines, cargo handlers, and logistics companies. Adhering to security protocols, screening procedures, and documentation requirements is essential to maintain regulatory compliance.

Screening Technologies: Effective cargo screening is critical to identify and prevent the transportation of dangerous or prohibited items [14]. Advanced screening technologies, such as X-ray scanners, explosive detection systems, and trace detection equipment, are necessary to detect hidden threats accurately. Continuous research and investment in screening technologies are required to keep up with evolving threats.

Supply Chain Security: Air cargo security is interconnected with the broader supply chain. Ensuring security at every stage of the supply chain, from origin to destination, is vital. Collaboration and information sharing among stakeholders, including shippers, freight forwarders, and customs authorities, are essential to maintain a secure and resilient supply chain.

Employee Training and Awareness: Security awareness and training programs play a crucial role in preventing insider threats and unauthorized access. Employees involved in cargo handling, screening, and logistics need to be well-trained in recognizing suspicious activities, understanding security protocols, and implementing best practices to maintain the integrity of the cargo.

Technology Integration and Interoperability: Seamless integration and interoperability of various security systems and technologies are essential for efficient cargo processing. Integration of cargo tracking systems, screening technologies, and information management systems helps create a comprehensive security ecosystem that enables real-time monitoring, tracking, and response.

Data Security and Privacy: Protecting sensitive cargo data, including manifests, shipment details, and security information, is crucial. Robust cybersecurity measures, data encryption, and access controls are necessary to safeguard cargo-related information from unauthorized access, manipulation, or disclosure.

International Cooperation: Air cargo security requires international cooperation and harmonization of security standards and procedures. Collaborative efforts among nations, industry associations, and regulatory bodies are necessary to establish common security frameworks, share intelligence, and address security gaps across borders.

Addressing these challenges and meeting the requirements of air cargo security demands a comprehensive and multi-layered approach. It involves leveraging advanced technologies, implementing robust security protocols, fostering collaboration among stakeholders, and ensuring compliance with regulatory frameworks. By continuously assessing risks, adopting best practices, and investing in security measures, the air cargo industry can mitigate threats and ensure the safe and secure transportation of goods worldwide.

4. Integration of Optoelectronic Oscillator with IoT for Air Cargo Security

4.1Non-Intrusive Inspection of Cargo Containers

To scan huge cargo containers for illegal items such as drugs, explosives, and other illicit items shielded with heavy nuclear materials, it is necessary to introduce a system for detecting such items. Such screening requires detecting systems such as high-energy X-ray or passive neutron/gamma detection. This process of detection is known as non-Intrusive inspection or NII [14]. The integration of OEOs with IoT and the data fusion pipeline brings numerous benefits to the NII of cargo. Integrating IoT with OEO provides various solutions for the challenges that were present during traditional Non-Intrusive Inspection Real-time Monitoring and Alerts: The integration of OEOs with IoT enables continuous monitoring of cargo containers. Any deviations from predefined thresholds, such as changes in frequency, environmental conditions, or physical integrity, can trigger immediate alerts and notifications. This enables swift response and preventive actions to mitigate security risks. Data

Fusion and Analytics: The cloud-fog-edge-mist data fusion pipeline facilitates the aggregation and analysis of data from various sources. By applying advanced analytics techniques, such as machine learning and anomaly detection, it becomes possible to identify patterns, trends, and potential security breaches. This enables proactive decision-making and improved cargo security management.

Scalability and Flexibility: The integration of OEOs and IoT with the data fusion pipeline provides a scalable and flexible solution. It can accommodate a large number of cargo containers, diverse sensor types, and varying operational environments. The cloud-fog-edge-mist-based infrastructure enables seamless scalability and adaptability to evolving security requirements.
Improved Efficiency and Resource Optimization: By automating data collection, analysis, and decision-making processes, the integrated system reduces the need for manual interventions and physical inspections. This results in improved operational efficiency, reduced costs, and optimized resource allocation for cargo security management.

4.2 OEO-based Signal Generation for Imaging

OEO-based signal generation typically consists of the following key components:

Laser: A stable laser source is used to generate an optical carrier signal. The laser provides a coherent and high-quality light source that serves as the basis for signal generation in the OEO.

Electro-Optic Modulator (EOM): The optical carrier signal is modulated using an electro-optic modulator. The EOM imposes the desired modulation onto the optical signal, which could be intensity modulation, phase modulation, or frequency modulation, depending on the imaging technique and application [16].

Photodetector: The modulated optical signal is converted back into an electrical signal using a photodetector. The photodetector detects the variations in the intensity, phase, or frequency of the modulated optical signal and converts them into corresponding electrical signals [17].

Microwave Components: The electrical signal from the photodetector is fed into microwave components such as a bandpass filter, amplifier, and phase shifter. The bandpass filter selects the desired frequency range for the imaging application, while the amplifier boosts the signal strength. The phase shifter allows for phase adjustment, which can be useful in certain imaging techniques.

Feedback Loop: The output of the microwave components is then fed back into the electro-optic modulator, completing a feedback loop [16]. This loop sustains the oscillation and ensures the generation of a stable and high-quality signal.

By controlling the parameters of the OEO circuit, such as the laser frequency, modulation depth, and feedback loop characteristics, it is possible to achieve high-resolution imaging. The stability, low-phase noise, and high-frequency capabilities of OEOs contribute to the generation of precise and reliable signals, which are crucial for obtaining high-resolution images.

4.3 Cloud-fog-edge-mist data fusion pipeline

The cloud-fog-edge-mist data fusion pipeline is an advanced data processing architecture that combines the capabilities of cloud computing, fog computing, edge computing, and mist computing to enable efficient and real-time data fusion and analysis. It provides a comprehensive framework for managing and processing data from diverse sources in a distributed and scalable manner. In association with air cargo security, the cloud-fog-edge-mist data fusion pipeline plays a crucial role in handling the large volume of data generated by various sensors and devices used in cargo inspection and monitoring. The pipeline consists of multiple layers, each with specific functionalities:

Cloud Computing: The cloud computing layer serves as the centralized data processing and storage infrastructure. It provides the computational resources and storage capacity to handle massive amounts of data from different sources [18]. In the air cargo security context, the cloud can be utilized for long-term storage, data analytics, and generating insights from historical data.

Fog Computing: The fog computing layer is located closer to the edge devices, such as the OEO (Optical-Electrical-Optical)-based imaging systems and other sensors deployed in cargo inspection areas. It enables data processing and analysis to be performed at the network edge, reducing latency, and improving real-time decision-making [19]. Fog computing enhances the responsiveness and reliability of the system by minimizing the need for data transmission to the cloud for processing.

Edge Computing: The edge computing layer involves computing resources deployed on or near cargo containers or inspection checkpoints. It enables localized data processing, filtering, and preliminary analysis to be performed near the data source. Edge computing enhances real-time monitoring and enables quick identification of potential security threats or anomalies [20].

Mist Computing: The mist computing layer focuses on handling data and processing tasks at the device level. It involves lightweight computing capabilities embedded within the sensors and devices themselves. Mist computing enables immediate processing and filtering of data at the sensor level, reducing the amount of unnecessary data transmission and optimizing bandwidth usage.

The cloud-fog-edge-mist data fusion pipeline enables seamless integration and collaboration among these layers, allowing for efficient data collection, aggregation, processing, and analysis. It facilitates real-time monitoring of cargo containers, detection of security threats, and generation of actionable insights for decision-making.By utilizing this pipeline, the air cargo security system can benefit from improved scalability, reduced network congestion, enhanced responsiveness, and better utilization of computing resources. It enables effective data fusion from multiple sources, including the OEO-based imaging systems, to provide a comprehensive and accurate picture of cargo conditions and security status.

5. Conclusion

Considering the discussion in this paper, the integration of optoelectronic oscillators (OEOs) with IoT for air cargo security offers significant potential for enhancing the efficiency and effectiveness of cargo inspection and monitoring processes. By leveraging the capabilities of OEOs, such as stable signal generation, low phase noise, and high-frequency operation, combined with the data fusion capabilities of IoT, a robust and intelligent system can be developed for the non-intrusive inspection of cargo containers. The use of OEOs in conjunction with IoT enables real-time monitoring and analysis of cargo containers, allowing for the timely detection of potential security threats or anomalies. The integration of a cloud-fog-edge-mist data fusion pipeline facilitates the seamless collection, transmission, and analysis of sensor data from multiple sources, including OEO-based imaging systems. This enables comprehensive and accurate assessment of cargo contents, identification of prohibited items, and early detection of security breaches.

However, there are several challenges that need to be addressed in implementing OEO-based imaging systems integrated with IoT. These include the optimization of imaging resolution, overcoming the limitations of penetration through certain materials, ensuring data privacy and security, and managing the large volume of sensor data generated. Overall, the integration of OEOs with IoT in air cargo security holds great promise for improving the efficiency, accuracy, and reliability of cargo inspection processes. It has the potential to enhance detection capabilities, reduce false alarms, and ultimately contribute to safer and more secure air cargo transportation.

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