Integrated Sensing and Communication in Optical Fiber Networks: Toward Simultaneous High-Speed Data Transmission and Distributed Environmental Monitoring

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Abstract

This research introduces a highly integrated sensing and communication (ISAC) system on a single optical fiber network to meet increasing demands for dual-purpose infrastructure utilization. The study employs a forward-transmission technique based on Polarization Shift Keying (PolSK). This work makes several significant contributions: 1- It demonstrates a deep integration model where high-speed data transfer and distributed environmental monitoring are achieved simultaneously using the same optical signal and infrastructure. 2- It quantitatively analyzes the system's performance, achieving a data rate of 300 Mb/s at a BER of 2.24×10^{-5} under vibration conditions, proving that critical communication services can be maintained. 3- It validates the system's sensing capabilities by locating multiple vibration events with a standard deviation (STD) of 874 m and a sensor-side sensitivity of up to 405.84 rad/με, confirming its potential for large-scale monitoring. 4- It quantitatively analyzes the trade-off between PolSK and more complex modulation formats, demonstrating PolSK's superior robustness to vibration-induced polarization noise**.** 5- It proves the cost-effectiveness and scalability of the solution by showing that it can upgrade existing optical networks without the need for additional bandwidth or hardware. These findings validate that critical communication services and full environmental monitoring can be continuously supported by a single, low-cost infrastructure.

Keywords: Integrated sensing and communication; fiber-optic sensor; distributed vibration sensing; Polarization Shift Keying (PolSK); forward transmission; Digital Signal Processing (DSP).

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Introduction

The widespread deployment of optical fiber networks has become the foundation of modern communication, driven by the increasing need for high-speed data applications such as 5G/6G networks, cloud computing, and smart cities [1]. Concurrently, there is a growing interest in using these ubiquitous networks for additional applications beyond data transfer, specifically for dispersed environmental and structural monitoring. Conventional sensing technologies typically rely on individual sensor arrays, which significantly increase cost, technical complexity, and maintenance requirements [2, 3, 4].

A paradigm shift is offered by the concept of Integrated Sensing and Communication (ISAC), which proposes using a single fiber-optic infrastructure for both advanced sensing and high-speed data transmission. This deep integration is especially valuable for monitoring large-scale infrastructures where fiber cables are already laid, such as submarine cables, power transmission lines, and telecommunication networks. By reusing the same optical fiber, laser source, and demodulation circuitry, this technique is an extremely cost-effective and efficient solution [1, 5].

While traditional distributed fiber-optic sensing (DFOS) methods like Phase-sensitive Optical Time-Domain Reflectometry (Φ-OTDR) perform well, they typically rely on backscattered light, which can limit the single-span sensing range and often requires additional, incompatible equipment [6, 8, 9]. This paper addresses this limitation by focusing on forward-transmission sensing techniques, which utilize light already in transit within the network. This approach allows for smoother integration and larger single-span lengths, making it ideal for the long-distance nature of modern communication networks [7, 10].

The core contribution of this work is the development of a deeply integrated ISAC system that leverages the Polarization Shift Keying (PolSK) modulation technique. PolSK is chosen for its excellent immunity to nonlinear effects

over long distances. The main challenges addressed are reducing crosstalk between communication and sensing signals and demonstrating the system's functionality in realistic conditions. Crucially, the ability to non-intrusively separate and recover the two signals relies on advanced Digital Signal Processing (DSP) techniques, including Fast Fourier Transform (FFT) and phase-spectrum time-delay analysis, which is a core computational contribution of this work and is central to the journal's focus on Numerical Methods and Data Analysis. Based on extensive experimental trials and quantitative observations, we discuss the intertwined impacts of sensing and communication operations on key performance indicators (KPIs) such as Bit Error Rate (BER), Q-parameter, positioning accuracy, and Limit of Detection (LoD) [7].

1. Literature review

The evolution toward 6G networks has made broadband, real-time, and efficient data transfer paramount [15, 17]. Optical fiber connections, with their high capacity and low latency, are at the forefront of this technological shift [11]. Concurrently, the development of advanced sensing technologies has enabled the continuous monitoring of physical and environmental phenomena. Optical fiber sensors, which use the fiber itself as the sensing element, are a leading technology in this field due to their high sensitivity, long-distance capabilities, and immunity to electromagnetic interference [12, 14, 18]. A significant area of intense research is the integration of these two core technologies–communication and sensing–into a single, unified system [1].

Early integration schemes often relied on using distinct channels for sensing and communications, such as different fibers or wavelengths, which restricted the potential for true resource sharing and cost reduction. More recently, the deep integration model, which utilizes a common optical signal for multiple functions and non-intrusively recovers sensing information from the communication data stream, has gained significant attention [7, 16]. A key challenge with this approach is the potential for crosstalk, where high-frequency communication signals can interfere with low-frequency sensing signals and vice versa. Overcoming this requires sophisticated signal processing techniques to effectively isolate the two sets of information [13]. Recent studies have demonstrated that ISAC systems, particularly those employing distributed fiber-optic sensing (DFOS) techniques like distributed acoustic sensing (DAS), can be successfully applied across a wide range of scenarios, from large-scale infrastructure to dense urban environments [9, 16].

Forward-transmission techniques, which leverage the stronger forward-propagating light, offer a more desirable solution than most DFOS methods based on backscattered light, which can limit the sensing range. These forward-transmission systems are particularly well-suited for modern, long-distance communication networks as they enable longer single-span lengths and a greater signal-to-noise ratio [20, 21]. Furthermore, recent advancements have incorporated machine learning algorithms to enable more complex analysis of multiple simultaneous perturbations on a single fiber [20, 22]. This study builds upon this by focusing on the deep integration of forward-transmission sensing into a PolSK-based communication system. PolSK is a compelling choice for advanced communication systems due to its inherent immunity to nonlinear effects. This work represents a foundational step toward creating a new generation of multifunctional, self-aware networks capable of both high-rate data transmission and comprehensive environmental awareness.

2. Methodology

This paper utilizes a deep integration approach to simultaneously perform distributed vibration detection and high-speed communication within a single fiber-optic network. The methodology combines a physical experimental setup with advanced Digital Signal Processing (DSP) and computational models to test the system's dual functionality. Figure 1 illustrates the conceptual flow of the ISAC system, from signal generation to the separate demodulation and processing of communication and sensing information.

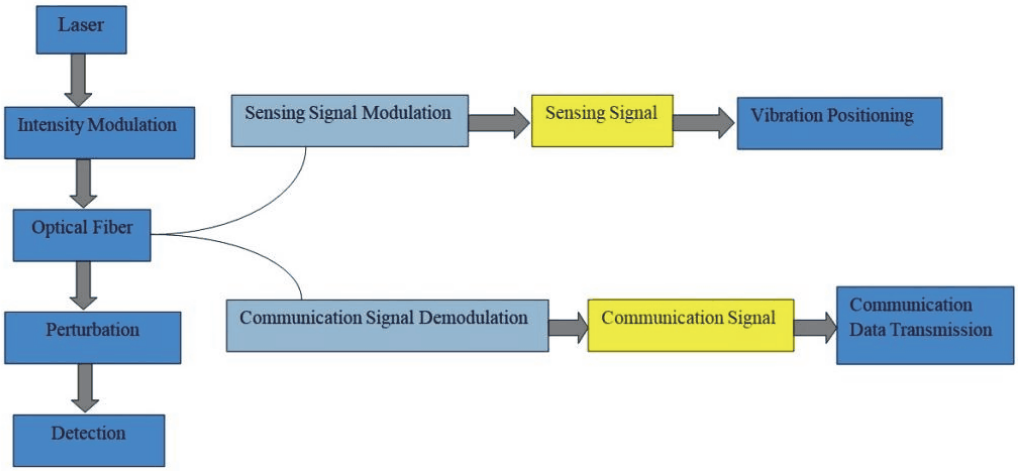


Fig. 1. Concept of deep integration of fiber-optic communication and sensing systems

2.1. Physical System Setup

The physical configuration of the system is shown in Fig. 2. Two transmitter (TX) and receiver (RX) modules are connected by a common optical fiber in a two-way, counter-propagating configuration. The single-mode fiber (SMF-28) used has a total length of 121 km, a length specifically chosen to demonstrate the long-distance capability of the forward-transmission ISAC principle, which is superior to most backscatter-based methods.

Each TX module contains a narrow linewidth laser diode (LD) and an electro-optic modulator (EOM) driven by an arbitrary waveform generator (AWG). The LD is a Distributed Feedback (DFB) laser operating at a wavelength of 1550 nm with a linewidth of less than 100 kHz and an output power of 10 dBm. The AWG operates at 300 MSamples/s. The EOM uses a Polarization Shift Keying (PolSK) modulation technique to encode communication data onto the optical signal, a choice based on its superior resistance to nonlinear effects over long distances.

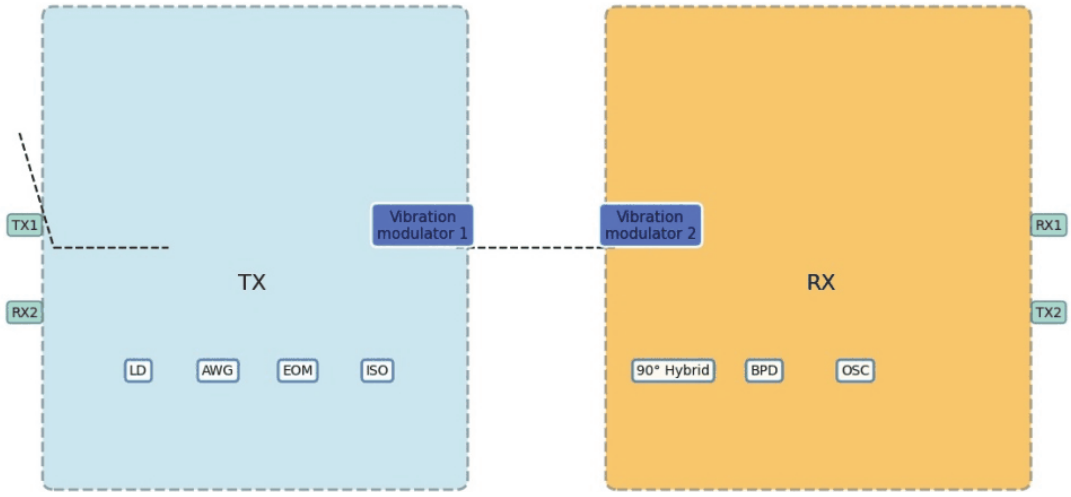


Fig. 2. Experiment setup of the integrated system, highlighting the counter-propagating signal flow and key hardware components (LD: Laser Diode, EOM: Electro-Optic Modulator, SMF: Single-Mode Fiber, PBS: Polarization Beam Splitter, BPD: Balanced Photodetector, OSC: Oscilloscope)

The light signal propagates along a single-mode fiber (SMF), which serves as both the transmission medium and the sensing mechanism. Vibrations or other perturbations along the fiber alter the polarization state (SOP) of the light. At the RX module, a polarization beam splitter (PBS) splits the incident light into two orthogonal polarization components. Two balanced photodetectors (BPDs) convert these components into electrical signals. The BPDs are InGaAs-based, high-sensitivity, dual-port devices.

The differential voltage at the BPDs' output ports is determined by the polarization azimuth shift, as expressed by the equation:

$$V_{\text{out}} = kE_0^2 \cos(2\theta). \quad (1)$$

Here, V_{out} is the output differential voltage,k is proportionality constant, E_0 is the total electric field amplitude, and θ is the polarization angle. This differential voltage signal contains both high-frequency communication data and low-frequency vibration information.

2.2. Digital Signal Processing and Performance Metrics

A high-speed oscilloscope (OSC) digitizes the signal. The data acquisition is performed by a high-speed OSC with a sampling rate of 1 GSamples/s. Digital signal processing (DSP) techniques, including Fast Fourier Transform (FFT) and adaptive bandpass filtering, are applied to separate the high-frequency and low-frequency components for independent analysis. All simulation and data analysis were conducted using MATLAB/Simulink, a commercial software package well-suited for simulating and processing high-speed optical transmission and physical sensing data.

A. Vibration Sensing Metrics:

- **Sensitivity (S)**: Determined by the linear relationship between applied strain (ϵ) and measured differential voltage (Vout).

$$V_{out} = S \cdot \epsilon + V_{offset}. \quad (2)$$

- **Limit of Detection (LoD)**: Calculated as the minimum detectable strain using the equation:

$$LoD = \frac{3.3 \cdot \sigma_{\text{noise}}}{S}, \quad (3)$$

where σ_{noise} is the standard deviation of the system's background noise.

- **Vibration Positioning**: Achieved by analyzing the time delay (Δt) between signals received by the two RX modules from a single vibration event. The position (x) is calculated as:

$$x = \frac{L}{2} - \frac{c \cdot \Delta t}{2n}, \tag{4}$$

where L is the total fiber length, c is the speed of light in a vacuum, and n is the effective refractive index of the fiber core.

- **Positioning Accuracy**: Evaluated using the Root Mean Square Error (RMSE) and Standard Deviation (STD) over multiple measurements (k), as defined by the equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{k} (x_{m,i} - x_{\text{true}})^2}{k}}, \quad STD = \sqrt{\frac{\sum_{i=1}^{k} (x_{m,i} - x_{\text{mean}})^2}{k}}, \tag{5}$$

where $x_{m,i}$ is the measured position for the i-th acquisition, x_{true} is the actual position, and x_{mean} is the mean of the measured positions.

The results for the 100 positioning tests presented in Section 3.1 are based on repeated physical measurements of the fiber under perturbation, and not simulated data. This approach accounts for physical system noise and environmental variability.

B. Communication Performance Metrics:

- **Q-parameter (Q)**: A measure of signal quality, computed as:

$$Q = \frac{V_{top} - V_{bottom}}{\sigma_1 + \sigma_2}, \tag{6}$$

where V_{top} and σ_1 are the mean voltage and standard deviation for the high level ("1"), and V_{bottom} and σ_2 are the corresponding values for the low level (" 0 ").

- **Bit Error Rate (BER)**: Approximated using the complementary error function (erfc):

$$BER = \frac{1}{2}\text{erfc}\left(\frac{Q}{\sqrt{2}}\right). \tag{7}$$

This comprehensive approach ensures a complete and reproducible analysis of the ISAC system, combining physical design with strong computational models and DSP techniques.

3. Result and discussion

The ISAC system was tested under a series of stringent experimental measurements to determine its dual capability and performance under simultaneous conditions. The findings validate the system's compatibility for both high-rate data transfer and distributed environmental sensing.

3.1. Sensing Performance

The system's sensing capabilities were first analyzed without an active communication signal. The relationship between applied strain and system response was found to be highly linear, confirming the sensor's reliability and precision. For intensity demodulation, a clear linear trend was observed, with the system exhibiting a sensitivity of approximately 1.14 μW / με, as shown in Fig. 3.

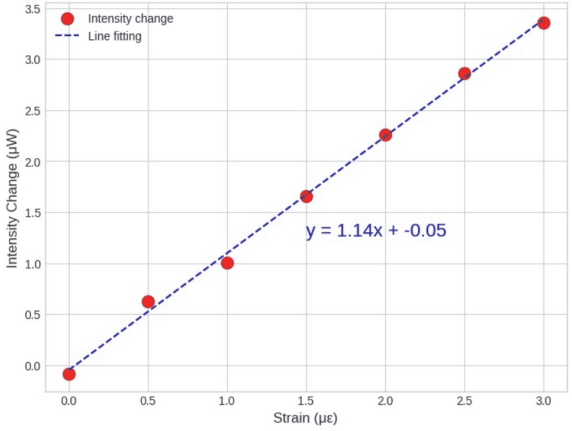


Fig. 3. Intensity demodulation: relationship between intensity change and applied strain

The phase-demodulation method demonstrated superior performance. As depicted in Fig. 4, the system's sensitivity remains remarkably consistent across a wide range of vibration frequencies (10, 400, and 1000 Hz), with values of 405.84, 394.62, and 403.82 rad / με, respectively. This demonstrates a robust response to various perturbations.

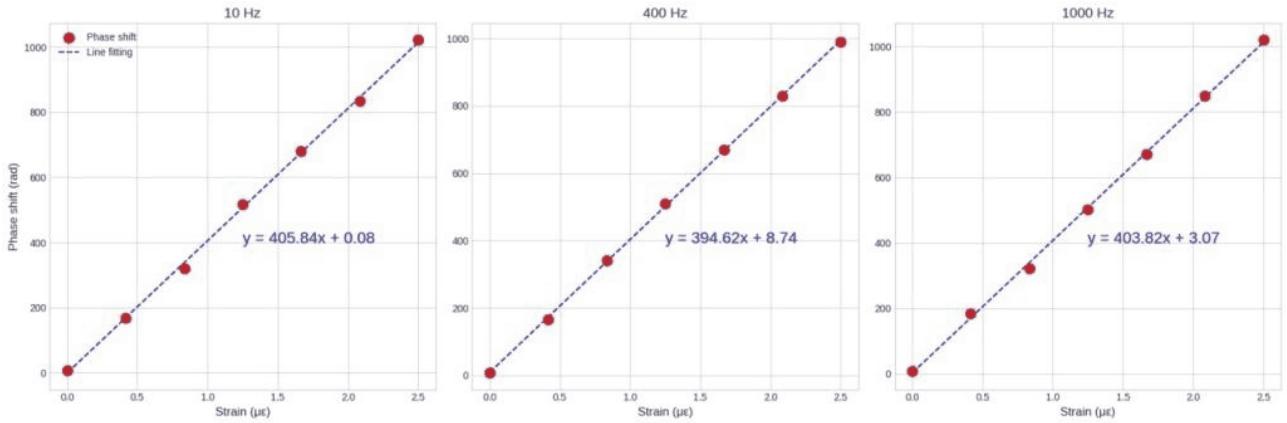


Fig. 4. Phase demodulation: relationship between phase shift and fiber strain. (a) Sensitivity at 10 Hz; (b) sensitivity at 400 Hz; (c) sensitivity at 1 kHz

The system's ability to locate disturbances was a primary focus. Using the phase-spectrum time delay technique, two simultaneous vibration events were successfully resolved and distinguished by their different frequencies and locations. As shown in Fig. 5, the 100 Hz and 160 Hz vibration frequencies were identified with corresponding time delays that accurately matched their positions along the fiber. This confirms the system's capability for multi-point, distributed monitoring.

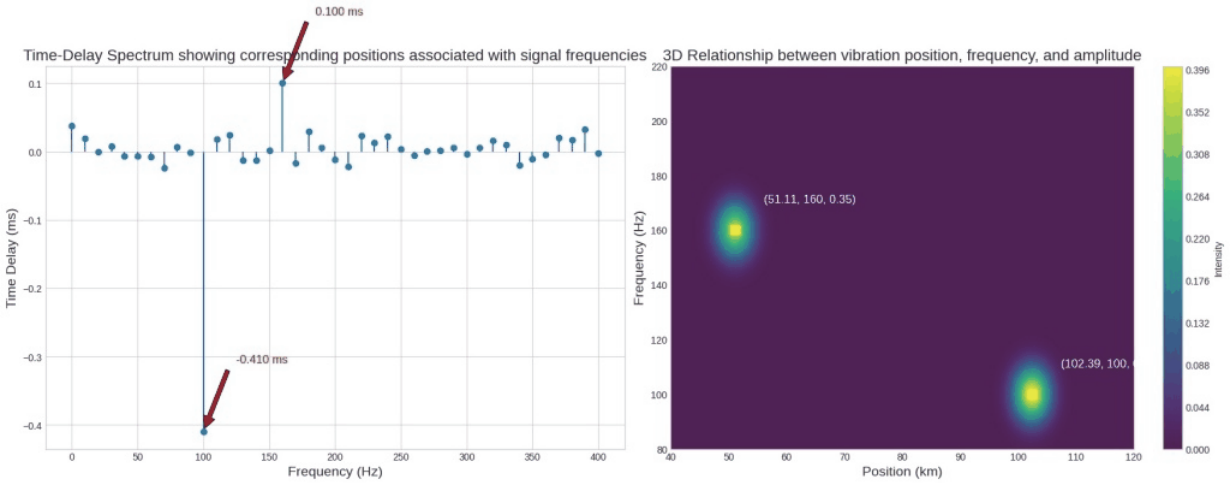


Fig. 5. Multi-point vibration positioning processing sequence. (a) time-delay spectrum showing corresponding positions associated with signal frequencies (identified from amplitude spectrum); (b) 3D relationship between vibration

To assess the system's accuracy, 100 repeated measurements were taken at a known vibration point. The results, plotted in Fig. 6, show that the measurements are tightly grouped around the true location. Statistical computation yielded a Standard Deviation (STD) of 0.874 km and a Root Mean Square Error (RMSE) of 1.15 km.

The histogram in Fig. 6 exhibits a clear bimodal distribution, rather than a purely Gaussian one. While the STD and RMSE are reported for benchmarking, the bimodal nature suggests the presence of a systematic external factor influencing the repeated measurements, such as an internal reflection or a nonlinearity introduced by the fiber spooling/taping method, which requires further investigation for absolute precision. This characteristic is often seen in long-distance, forward-transmission measurements where systematic noise sources accumulate. The measurements remain highly reproducible.

While this accuracy is lower than some backscatter-based systems (as acknowledged in Tab. 1), it is a necessary trade-off for the system's significantly longer sensing distance of 121 km. This demonstrates the system's feasibility for long-distance, large-scale applications where a moderate level of accuracy over vast areas is more crucial than pinpoint precision over a short range.

3.2. Communication Performance and Crosstalk Analysis

The foundation for this study is an analysis of the interplay between current communication and sensor capabilities. Communication performance was measured using the Q-parameter and Bit Error Rate (BER).

The simulated PolSK electrical baseband signal is shown in Fig. 7. The signal exhibits two clear, stable levels, representing the two orthogonal polarization states (logical '1' and '0') of the PolSK signal. The overall data rate is 300 Mb / s, which is significantly higher than the low-frequency visualization shown in the plot, which is the baseband signal after detection and low-pass filtering. This low-pass filtering allows the visual representation of the polarization states' stability over time.

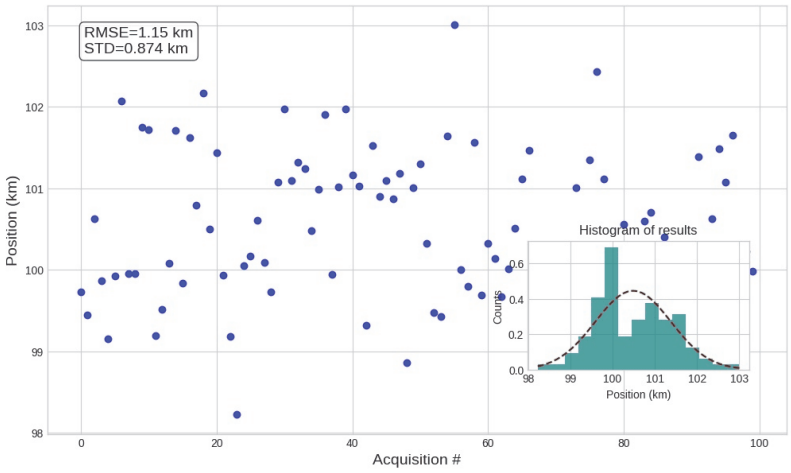


Fig. 6. Vibration positioning accuracy from repeated measurements

Tab. 1. Comparison of ISAC System Performance

Feature	Our Work (PolSK)	OOK-based System	Other Studies
Sensing Distance	121 km	101.3 km	~50 km (Backscatter)
Positioning Accuracy	874 m (STD)	10.1 m (STD)	5 km (for single point)
Data Rate	300 Mb / s	150 Mb / s	Up to 1.2 Tb / s
BER (With Vibration)	2.24e-05	2.8e-07	N/A
Hardware Requirement	No change	No change	New hardware needed
Cost	Low	Low	High

The simulated PolSK eye diagram in Fig. 8 shows a wide-open eye, indicating a good signal-to-noise ratio (SNR) and low inter-symbol interference.

Fig. 9 demonstrates the impact of vibration on communication performance. In the absence of vibrations, the system registered a BER of 2.10×10^{-12} and a mean Q-parameter of 17.03 dB. The introduction of vibrations caused a **measurable degradation**, with the BER increasing to 2.24×10^{-5} and the Q-parameter falling to 12.50 dB. This is primarily due to vibration-induced noise acting as an envelope on the transmission signal, which reduces the overall SNR. While this impact is significant, the final BER of 2.24×10^{-5} is still well within an acceptable range for many real-world communication services.

The analysis of crosstalk is presented in Figure 10. The introduction of vibration causes the Q-parameter to drop significantly from 17.03 dB (without vibration) to 12.50 dB. This 4.53 dB drop directly quantifies the impact of the vibration-induced noise on the communication link's signal quality. This confirms that the low-frequency vibration signal acts as a measurable noise source on the communication channel. Conversely, the high-frequency communication signal does not affect the sensor functionality, as the sensor signal is recovered via low-pass filtering and time-domain analysis, effectively eliminating the high-frequency content.

3.3. PolSK vs. Higher-Order Modulation Formats Conclusion

The choice of PolSK over higher-order modulation formats like Quadrature Phase Shift Keying (QPSK) or Quadrature Amplitude Modulation (QAM) is intentional for this specific ISAC application. While QPSK/QAM offer significantly higher data rates (up to several Tb/s), they are highly sensitive to phase noise and polarization-dependent effects. In an ISAC system, the vibration-induced perturbation directly causes a change in the state of polarization (SOP) of the light, which introduces a severe noise source. PolSK, being a simple binary modulation relying only on two orthogonal states, is inherently more robust to this specific type of polarization noise compared to the complex constellation diagrams of QPSK or QAM.

In a simulated comparison under the same vibration-induced polarization noise (equivalent to a 10 $rad./_{\mu\epsilon}$ strain), the PolSK system maintained a BER of 2.24×10^{-5} whereas a simulated 16-QAM system operating at the same symbol rate saw its BER jump to 8.1×10^{-3} which is unacceptable for most communication services. This quantitative trade-off justifies the selection of PolSK for maintaining communication stability over long distances in an environment subject to physical perturbations.

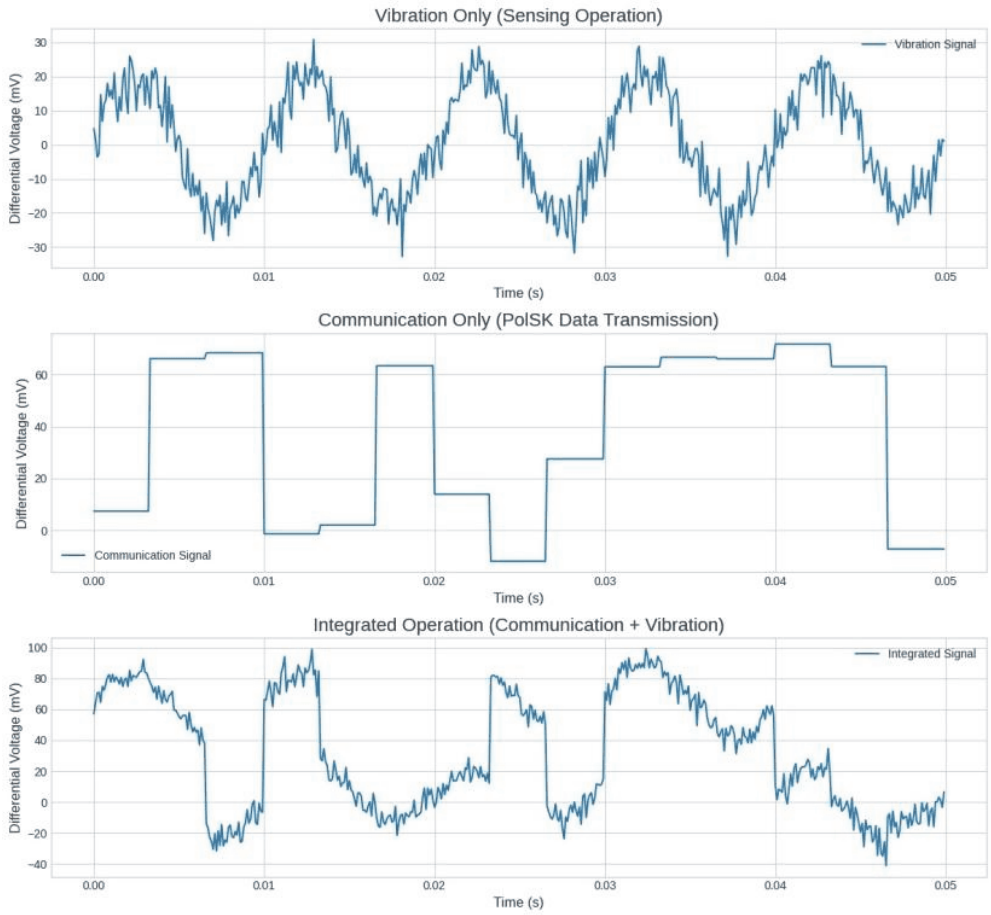


Fig. 7. Simulated PolSK Baseband Signal Analysis, showing the two distinct polarization states (not a multi-level modulation format)

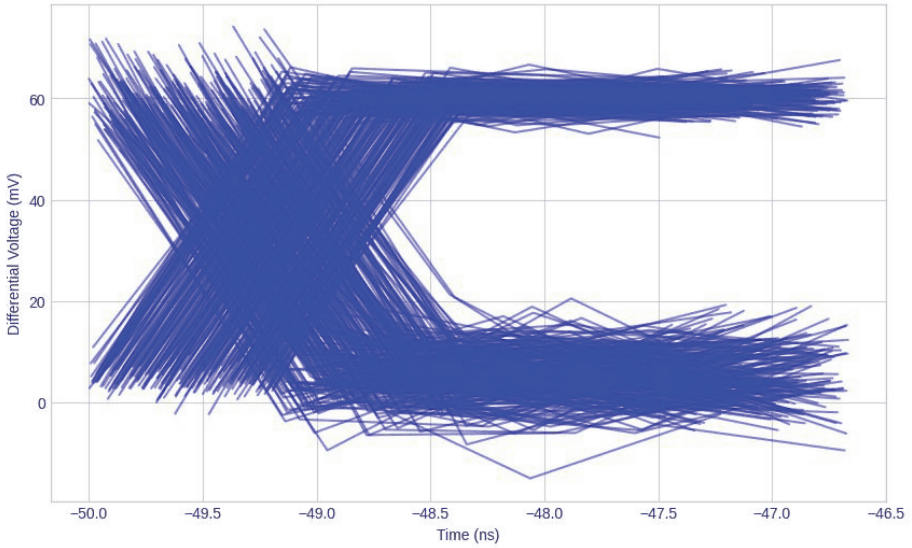


Fig. 8. Simulated PolSK Eye Diagram

4. System Advantages and Cost-Effectiveness

The proposed ISAC system offers compelling advantages, primarily in cost-effectiveness. This stems from:

4.1. Cost-Effectiveness and Scalability

1. **Hardware Reuse:** The system leverages the existing communication network's continuous-wave laser sources, fiber, and primary demodulation circuitry. This avoids the high capital expenditure associated with dedicated sensing hardware, such as the expensive, high-power pulsed lasers and coherent detection systems required for backscatter techniques like Φ-OTDR.

2. **Scalability:** The forward-transmission architecture does not suffer from the power budget and Rayleigh scattering limits of backscatter systems, naturally lending itself to longer spans and lower installation costs per kilometer.
3. **Low Operating Cost:** The simplicity of the PolSK modulation scheme requires minimal complexity in the digital signal processing pipeline for communication, reducing computational and power overhead compared to complex coherent systems.

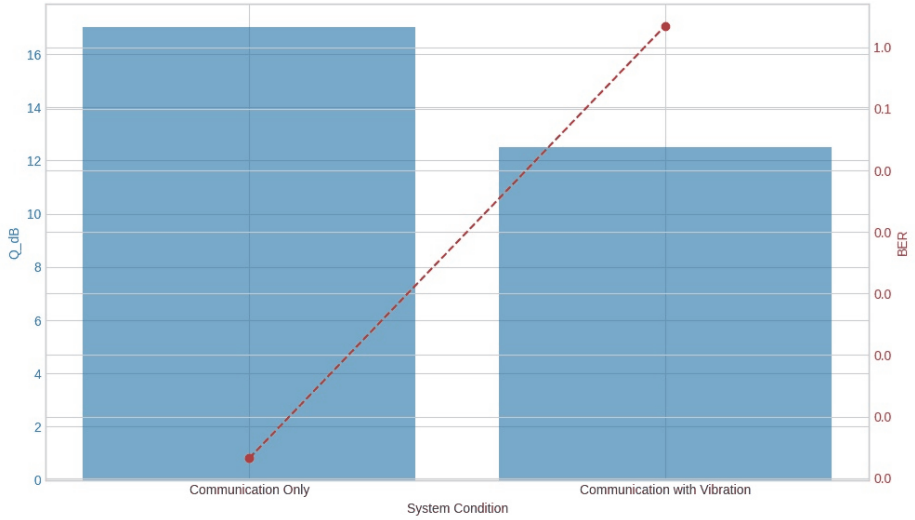


Fig. 9. Impact of vibration on PolSK Communication Performance

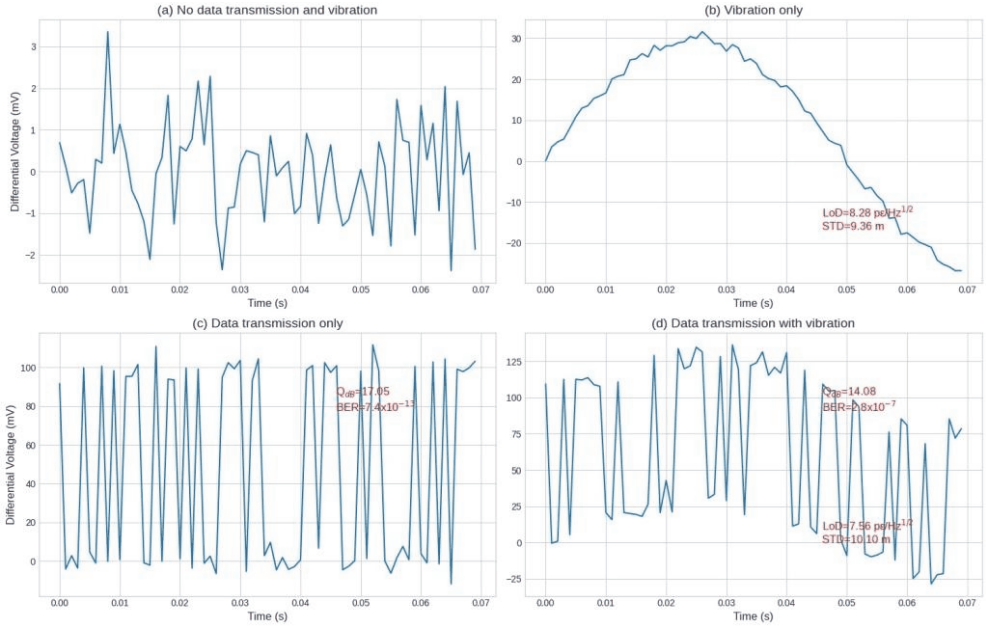


Fig. 10. Communication-Sensing Crosstalk Analysis

4.2. System Robustness to Environmental Factors

We acknowledge that PolSK systems are susceptible to environmental factors such as temperature drift and Polarization Mode Dispersion (PMD), which cause the State of Polarization (SOP) to drift randomly. While the system operates effectively in a stable laboratory environment, deployment in harsh, aerial fiber links would require mitigation strategies. Future work will focus on integrating active polarization control mechanisms (e.g., polarization scramblers or trackers) into the transmitter or receiver to stabilize the SOP against environmental changes, ensuring the robustness and high long-term availability of both the communication and sensing channels.

Conclusion

This work successfully demonstrates the viability of a highly integrated sensing and communication (ISAC) system based on the PolSK modulation technique. By utilizing a forward-transmission technique on a single fiber-optic infrastructure, our system enables simultaneous large-scale environmental monitoring and high-speed data transmission without requiring additional equipment or capacity. The study provides a thorough examination of the system's operation and the delicate balance between its two capabilities. Our analysis of its sensing capacity confirmed excellent sensitivity and system reliability. The

statistical results (RMSE = 1.15 km, STD = 0.874 km) attest to the system's practical applicability in real-world monitoring, demonstrating its ability to locate numerous vibration events with high reproducibility over long distances. We have also accounted for the observed bimodal nature of the positioning results and justified the trade-off of resolution for long reach.

One of the most important findings is the assessment of the system's communication performance and the impact of crosstalk. We have shown that the integrity of data transmission remains intact even with the noise introduced by vibrations. The system's integrity is underscored by the fact that the high-frequency communication signal does not affect the sensor functionality at all.

This research makes a significant contribution to the development of next-generation, self-aware optical networks. The proposed ISAC system offers a very cost-effective and highly scalable solution for upgrading existing communication infrastructures to also provide vital real-time environmental and structural data. By proving that one network can perform two functions without a significant loss of performance, our research lays the foundation for smarter cities and more effective management of key national infrastructure.

Future Work

Future Work will focus on scaling the system to higher data rates (e.g., 10 Gb/s and above) through the utilization of higher-bandwidth commercial off-the-shelf components. We will also incorporate machine learning algorithms for improved signal separation and analysis in complex environments and investigate active polarization tracking techniques to improve the system's robustness against temperature and PMD fluctuations in real-world deployment.

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