TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214
DOI: 10.26599/TST.2025.9010099
Volume xx, Number x, xxxxxxx 20xx

Optical Integrated Sensing and Communication: From Theory to Practice

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Abstract: Integrated sensing and communication (ISAC) technology enables simultaneous sensing and communication functions through shared hardware and resources tailored to specific applications. This technology reduces hardware costs and enhances system performance through synergistic interactions. While radio frequency-based ISAC (RF-ISAC) is well-studied, optical-based ISAC (O-ISAC) remains an emerging field. Compared with RF, light offers broader spectra, larger bandwidths, and flexible information transmission methods such as orbital angular momentum (OAM). Thus, O-ISAC research focuses on exploiting these unique optical advantages to significantly improve integrated system performance. This paper provides a comprehensive review of O-ISAC systems from three distinct perspectives: fundamental theory, system optimization design, and potential applications. By revisiting relevant optical theories and introducing novel insights, we propose a comprehensive theoretical framework grounded in light field theory to characterize and analyze the spatial distribution and propagation mechanisms of light. Leveraging this foundation, O-ISAC can be realized by coordinating multidimensional resources and harnessing light's inherent structural properties. We then systematically examine critical performance metrics of integrated systems and propose an optimization framework that highlights essential technologies and corresponding evaluation criteria. Finally, the application of O-ISAC is illustrated with examples drawn from vehicular networks and hybrid optoelectronic base station architectures.

Key words: Optical integrated sensing and communication (O-ISAC), light field theory, performance metrics, system optimization.

1 Introduction

The development of advanced mobile communication technologies, artificial intelligence (AI), and big data technologies is propelling the evolution from fifth-generation to sixth-generation (6G) wireless communication networks[1]. 6G networks aim not only to provide higher transmission rates but also to meet the demands of a wider range of applications, such as intelligent transportation[2], smart cities[3], and secure communications[4]. Integrated sensing and communication (ISAC) is one of the critical supporting technologies enabling 6G to achieve wide-area coverage and comprehensive spatiotemporal sensing, thereby driving technological innovations in next-generation networks[5–7].

ISAC has been extensively explored in the field of radio frequency (RF). A comprehensive review of ISAC signal design[8] has laid the groundwork for subsequent endeavors to refine three key aspects: waveform design[9], peak-to-average power ratio

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Manuscript received: 2024-12-08; revised: 2025-03-28; accepted: 2025-06-06.

(PAPR) control[10], and interference management[11]. In parallel, a scatterer-based ISAC channel model has been introduced, generating environmental scatterers and utilizing simplified ray-tracing to jointly characterize communication and sensing (C&S) channels[12]. At the system level, ISAC employs unified hardware platforms to simultaneously perform C&S, necessitating coordinated resource allocation (spectrum/energy) tailored to application requirements[13]. A representative approach minimizes total energy consumption by jointly optimizing beamforming and radar waveforms under dual-function performance constraints[14]. Another study explores systems with fixed energy budgets to reveal key radar-communication performance trade-offs through joint beamforming design[15]. From a theoretical perspective, an investigation into fundamental performance bounds, including the Cramér–Rao lower bound (CRLB) and mutual information, demonstrates that RF-ISAC can enhance system performance through the mutual cooperation between sensing and communication[16]. At the application level, one approach demonstrates how ISAC can enhance unmanned aerial vehicle (UAV) operations by employing extended Kalman filter-based fusion of C&S, thereby improving target localization accuracy and reducing latency[17]. Another body of research investigates the use of ISAC in the Internet of Vehicles (IoV), highlighting its potential to advance vehicular networks[18].

Nevertheless, existing ISAC research remains predominantly confined to the RF domain. In comparison, optical systems can typically offer spectral bandwidths several orders of magnitude greater, enabling terabit-per-second data transmission and making them particularly suitable for meeting the ultra-high throughput demands of 6G. Furthermore, the shorter wavelength of optical signals enables more precise target localization and distance measurement, which can be further enhanced through the integration of technologies such as light detection and ranging (LiDAR). As a result, optical C&S systems can offer more refined environmental perception capabilities compared with RF radar. The high directionality of light also facilitates precise transmission and sensing through beamforming techniques, effectively reducing interference—an advantage in high-density communication scenarios such as smart cities. In addition, optical communication, particularly visible light communication (VLC), can be seamlessly integrated with existing light emitting diode (LED) lighting infrastructure to support multiple functions, including illumination, coarse-grained sensing (e.g., occupancy detection), and communication. This integration not only reduces deployment costs but also improves resource utilization efficiency[19].

Optical-based ISAC (O-ISAC) has attracted growing research interest in recent years[20–30]. A multi-target O-ISAC system utilizing a 64-channel SiN-Si dual-layer optical phased array (OPA) chip as a high-speed scanning module is proposed in Ref. [24], enabling simultaneous multi-target free-space optical (FSO) communication and range detection. In terms of algorithmic design, an ISAC waveform method for pulse amplitude modulation (PAM)-based visible-light signals optimizes the integrated waveform parameter under peak transmit power constraints, achieving a balanced trade-off between C&S performance[25]. A mobile O-ISAC system that integrates an optical intelligent reflecting surface (OIRS) and a photodiode array has been introduced, offering simultaneous signal relay, position estimation assistance, and beam alignment[26]. Another FSO system combines linear frequency modulation (LFM) and continuous phase modulation (CPM), optimizing parameters under CRLB and bit-error-rate (BER) constraints to maximize data transmission rates[27]. In addition, a direct-current-biased optical orthogonal frequency division multiplexing (DCO-OFDM) scheme for free-space O-ISAC systems is investigated, proposing optimized power allocation strategies suited to both communication-centric and sensing-centric scenarios[28]. A visible light ISAC system leverages distributed optical access points that initially emit non-directional light to enable simultaneous C&S through small aperture imaging, and subsequently employs optical beamforming with collimating lenses to concentrate light, substantially enhancing both capabilities[29]. Another visible light ISAC system adopts movable access points (MAPs), jointly optimizing MAP positions and user associations to maximize communication sum-rate and sensing mutual information, addressing challenges such as line-of-sight (LoS) blockage, user mobility support, random device orientation, and limited transceiver field-of-view (FoV)[30]. Nevertheless, this approach remains restricted to visible-light systems.

Although research on O-ISAC is progressing rapidly, it remains at an early stage. The aforementioned studies primarily focus on specialized optical system configurations, treating optical sensing and communication as separate tasks and offering limited evidence of their collaborative integration. Future O-ISAC systems will go beyond simply co-locating communication and sensing functionalities within a single device, harnessing their synergy to boost efficiency and broaden application potential. However, the lack of a comprehensive theoretical framework continues to hinder further advancements, and critical aspects, such as performance metrics, optimization strategies, and design methodologies, remain underexplored. Furthermore, the absence of O-ISAC specific application cases limits the validation and deployment of corresponding theories and technologies. Consequently, it is essential to investigate the intrinsic interaction between optical communication and sensing, addressing foundational theory, key technologies, and promising applications, in order to establish and advance a robust O-ISAC research framework. This paper aims to provide a comprehensive review of O-ISAC, encompassing fundamental theory, system design, and application scenarios, with the goal of jointly addressing sensing and communication requirements under a unified optimization framework. The main contributions of this paper are summarized as follows.

- We review light field theory as the theoretical foundation and employs a seven-dimensional plenoptic function to characterize the propagation characteristics of light. By fully leveraging light's multidimensional physical resources, we aim to achieve the true integration of optical sensing and communication. Additionally, we investigate the physical properties of free-space optical signal propagation and propose generalized and multi-band channel models to facilitate this integration.

- The key performance metrics for optical sensing and communication are reviewed, with an exploration of unified metrics that characterize both capabilities. Building on these core indicators, the collaborative optimization of optical communication and sensing is examined through case studies on joint transceiver design and physical layer security.

- Applications of O-ISAC are investigated through vehicular networks and hybrid optoelectronic base station architectures. Specifically, a hybrid optoelectronic base station is proposed to replace the traditional phase shifter network with an optical network, thereby addressing challenges such as high computational complexity and significant performance degradation in large-scale antenna array systems.

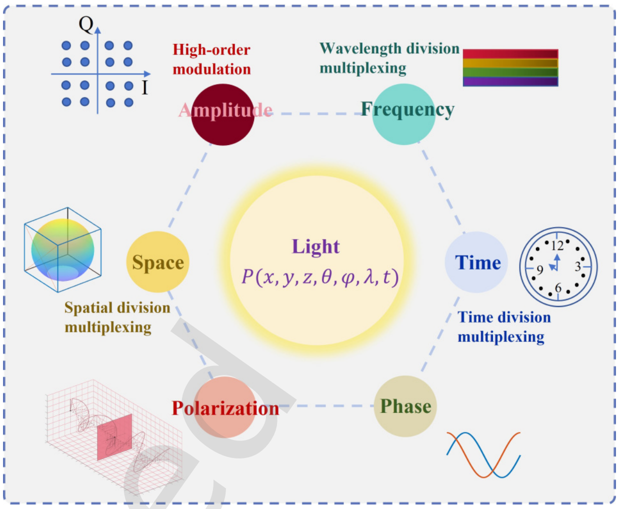

Fig. 1 Multiple-dimensional physical resources of light.

The structure of this paper is outlined as follows. Section 2 explores the fundamental theory of O-ISAC, including light field theory as well as the system and channel models. Section 3 introduces key performance metrics for optical sensing and communication, which underpin the design strategies for optimizing these indicators. Section 4 examines applications of O-ISAC systems, such as vehicular networks and hybrid optoelectronic base station architectures. Finally, the concludes are drawn in Section 5.

2 Fundamental Theory for O-ISAC

This section delves into the physical characteristics of optical signal propagation based on light field theory and the plenoptic function to construct the foundational model of O-ISAC systems.

2.1 Fundamentals of optics

In O-ISAC research, the light field serves as a fundamental theoretical basis[31]. By fully capturing and describing the propagation characteristics of light in space through light field theory, the deep integration of sensing and communication becomes feasible. Moreover, leveraging the multi-dimensional physical and structural properties of light enables the

$$\mathbf{E}\left(x,y,z,t\right)=\mathbf{e}(t)\cdot F\left(x,y,t\right)\cdot A\left(z,t\right)\cdot\Phi\left(z,t\right)\cdot\exp\left[j\left(\frac{2\pi}{\lambda(t)}z-\omega(t)t\right)+\varphi_0\right] \tag{2}$$

seamless unification of efficient optical communication and precise environmental sensing within a single system. This integration is vital for developing next-generation optical communication technologies, enhancing optical sensor performance, and advancing communication-sensing convergence. When applying the physical concept of a light field to signal transmission analysis, a parametric representation of the light field is required, which necessitates the introduction of the plenoptic function. In O-ISAC research, the objectives extend beyond sensing or communication alone, encompassing the simultaneous realization of multiple tasks. Therefore, a plenoptic function incorporating multiple parameter variables and physical resources is required to comprehensively characterize the distribution of light as an information carrier supporting multiple tasks[32]. The concept of a seven-dimensional plenoptic function is

$$P(x,y,z,\theta,\phi,\lambda,t), \tag{1}$$

where (x,y,z) denotes the receiver's coordinates at every possible three-dimensional location, and the intensity of light rays passing through the center of the receiver is recorded for each possible angle (θ,ϕ). Each light ray has distinct color, typically represented by its wavelength λ. Furthermore, the light entering the optical receiver varies over time t.

Subsequently, a detailed parametric description of light has been further developed in the field of optics, as presented in Eq. (2) at the top of this page[33–35]. In Eq. (2), vectors with both magnitude and direction are represented in boldface, physical quantities involving two or more parameters are denoted by uppercase letters, and physical quantities dependent solely on time variables are indicated by lowercase letters. This expression represents an optical-frequency electric field propagating in the z-direction, with a cross-section in the x-y plane. On the right-hand side of the equation, five physical quantities are connected through a dot product: $\mathbf{e}(t)$ represents the polarization, $F(x,y,t)$ denotes the spatial distribution, $A(z,t)$ is the amplitude, $\Phi\left(z,t\right)$ stands for the phase, $\lambda(t)$ and $\omega(t)$ denote wavelength and frequency, respectively. φ_0 denotes the initial phase introduced during the emission of light. The mathematical representation of the plenoptic function illustrates that the light field encompasses multiple dimensions of physical resources, such as polarization, spatial distribution, amplitude, phase, and wavelength, that can be utilized for carrying information.

An illustration of these properties and their applications based on Eq. (2) is provided in Fig. 1. One of the goals of O-ISAC research is to fully exploit the unique advantages of light and optimize its multidimensional physical resources, thereby achieving significant performance improvements in O-ISAC systems. Eq. (2) could serve as a foundation for analyzing and optimizing future O-ISAC system designs.

The plenoptic function serves as a general method for optical analysis and can be simplified to much less complex expression depending on the application needs, while structured light represents an extension and development of plenoptic function theory in practical applications. Structured light integrates the theoretical foundation of Fourier optics with the requirements of application technologies. It can project specific optical patterns to fulfill a range of practical application needs[36]. The structuring of the light field can be achieved through various physical dimensions of the signal design, such as phase and amplitude modulation. In future research, further investigation into the structural properties of light is expected to enhance the performance of O-ISAC systems.

2.2 System and channel model

2.2.1 System model

The authors present a system model for O-ISAC[37], as illustrated in Fig. 2. At the transmitter, random communication signals are first encoded and modulated, then combined with deterministic sensing signals to produce the O-ISAC signal. A direct current (DC) bias is subsequently applied to ensure the aggregated signal remains non-negative before transmission using a laser diode (LD).

As the O-ISAC signal propagates through the atmosphere, it is affected by attenuation, turbulence, ambient light interference, and other environmental factors. Atmospheric attenuation and turbulence are typically mitigated at the receiver, while ambient light interference can be effectively suppressed using

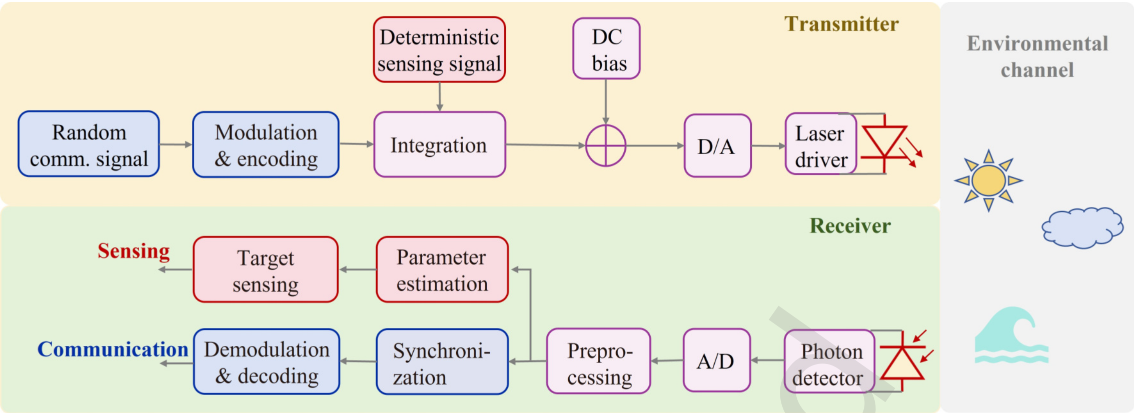

Fig. 2 A Generalized optical wireless transmission system for integrated sensing and communication inspired by Ref. [37]. Blocks illustrated in purple, red, and blue correspond to elements that are shared by sensing and communication, specific to sensing, and specific to communication, respectively.

Table 1 System characteristics of RF-ISAC versus O-ISAC

Category	RF-ISAC	O-ISAC
Transceiver	• Employs RF front-end components such as antennas, mixers, and amplifiers • Supports complex modulation schemes • Uses antenna arrays and RF downconverters to obtain baseband signals	• Primarily utilizes lasers or LEDs as optical transmitters • Employs intensity modulation and direct detection (IM/DD), necessitating a DC bias to maintain non-negative optical power • Directly detects incident optical intensity using photodetectors, without requiring downconversion
Channel model	• Supports both line-of-sight (LoS) and non-line-of-sight (NLoS) transmissions, prone to multipath propagation and fading, yet capable of partial obstacle penetration • Provides limited bandwidth but achieves broader coverage	• Primarily LoS propagation with highly directional beams, requiring precise transceiver alignment and exhibiting sensitivity to blockage • Offers enhanced security, minimal interference, high directivity, and broad bandwidth
Signal processing	• Emphasizes multipath equalization and interference cancellation in scattering-rich environments • The signal can be complex-valued	• Focuses on managing clipping noise and filtering out ambient light • The signal must be real-valued and non-negative
System features	• Better suited for wide coverage and stronger penetration, making it ideal for large-scale or mobile scenarios • It can be deployed alongside 5G/6G base stations or Wi-Fi access points to provide both communication and sensing over extensive areas	• Suitable for ultra-precision positioning and high data-rate communications • It can be integrated with lighting infrastructure for indoor visible light communication and positioning (e.g., in smart homes), or combined with LiDAR to enable outdoor optical wireless communication and sensing (e.g., in vehicular networks)

closed-loop circuits or photon coincidence detection techniques. Additionally, a portion of the O-ISAC signal is bounced back from the target, with its spatial information embedded in the reflected signal, which is then extracted by the sensing receiver.

At the receiver, the photodetector (PD) or other optical-to-electrical signal converter, and the analog-to-digital converter (A/D) are commonly shared modules for both the sensing and communication receivers. The subsequent preprocessing unit is responsible for suppressing ambient light noise and amplifying the received signal. With the sensing module, the distance, velocity, and other information of the target can be estimated, while the communication receiver performs synchronization, demodulation, and decoding.

Differences between the RF-ISAC and O-ISAC system models result in distinctions regarding channel modeling and system features. Additionally, compared with RF-ISAC, O-ISAC faces unique challenges arising from differences in the transmission medium, necessitating careful consideration of optical signal characteristics. A detailed comparison of these system characteristics is presented in Table 1.

A detailed discussion on waveform design techniques suitable for O-ISAC, including pulsed waveform, constant-modulus waveform, and multi-carrier waveform, is also provided in Ref. [37], and thus will not be elaborated here.

2.2.2 Channel model

The channel determines the maximum transmission capacity a system can support, thereby directly influencing system design. Most existing channel models focus on individual information carriers, propagation media, or specific environments. However, when a system must support not only communication but also sensing and additional functionalities, the channel environment becomes more complex and diverse, necessitating a broader range of factors and parameters. In the research of O-ISAC, it is therefore essential to establish generalized and multi-band channel models to accommodate complex system demands and various application scenarios.

(1) Generalized channel model: A generalized channel model can encompass multiple channel types, diverse propagation effects, and time- and frequency-varying characteristics. Compared with traditional approaches, a generalized optical channel model accounts for additional parameters, such as wavelength and frequency, while incorporating transceiver characteristics (e.g., beam properties of the light source) and the response characteristics of the detector (e.g., receiving area and the angle of the incident light). Additionally, to accommodate future application requirements, this model integrates environmental factors such as pressure, temperature, and electromagnetic interference, thereby enabling more accurate predictions of the optical channel under extreme conditions, including, but not limited to, high altitudes, anomalous temperatures, and intense electromagnetic interference. This approach facilitates the identification and quantification of adverse environmental impacts on signal transmission and enhances system robustness and interference resilience.

In terms of source beam characteristics, the divergence angle, beam shape, and power distribution of the optical source directly influence channel gain and propagation properties. For LED sources, a Lambertian radiation pattern is typically employed[38], where the intensity distribution is given by

$$L(\theta) = \frac{m+1}{2\pi}\cos^m(\theta), \theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right], \tag{3}$$

where θ represents the angle of irradiance, which is commonly referred to as the angle of departure (AoD). The parameter m denotes the mode number of the radiation lobe, determining the directionality of the optical source. Two representative commercial LEDs with non-Lambertian emission characteristics, the LUXEON Rebel LED and another non-Lambertian optical beam, are introduced alongside a conventional Lambertian source[39]. The LUXEON Rebel LED exhibits a typical rotationally symmetric non-Lambertian beam, whereas another non-Lambertian optical beam features a non-rotationally symmetric intensity distribution. Details of their mathematical models can be found in Ref. [39]. Nevertheless, the generalized channel model discussed in this paper is intended to be broadly applicable to all light sources.

Regarding the detector response characteristics, the optical properties of the receiver determine the received power and the signal-to-noise ratio (SNR). Key parameters include the effective photosensitive area of the photodetector, the FoV, and the spectral responsivity[40]. The optical responsivity of detector can be measured using a spectral power meter to establish a wavelength-dependent photoelectric conversion efficiency model. The detector's FoV affects the effective range of the received optical signal; it can be characterized by measuring variations in received power at different incident angles.

In existing studies on generalized channel modeling[41–47], several channel models have been developed based on a three-dimensional geometric stochastic model, combined with specific ray-tracing tools and channel characteristics[41–43]. A satellite-to-ground channel model is proposed[44], which divides the channel into atmospheric and near-ground components and analyzes the impacts of ionospheric scintillation, rainfall, and multipath propagation. Moreover, a universal channel model capable of covering frequencies from the sub-6 GHz band to the visible light communication (VLC) band has been introduced[45]. Furthermore, a unified scenario classification approach is presented in Ref. [46], which proposes a scenario-adaptive channel modeling theory based on precise classification, complementing the aforementioned universal channel model. OIRS achieve reflection or so-called "channel reconfiguration" of optical signals by intelligently controlling physical parameters such as phase and polarization on the reflecting surface, thereby enhancing or directing signal transmission paths[47]. Therefore, channel models that account for the effects of OIRS on signal paths, reflection angles, multipath propagation, and both natural and artificial interference are also important.

However, most of the aforementioned channel modeling studies remain limited to specific communication scenarios, highlighting the need for future extensions to encompass a broader range of application contexts. A generalized channel model would be employed for three primary reasons. First, O-ISAC technologies are expected to operate in diverse and complex environments, where channel propagation characteristics are influenced by multiple factors, including multipath propagation, shadowing, and path loss. A generalized channel model should comprehensively account for these factors, providing a more accurate channel description for signal design and performance evaluation of O-ISAC systems. Second, O-ISAC technologies are expected to simultaneously support both communication and sensing functions by one set of hardware. A generalized channel model more effectively will capture the diversity and uncertainty of signal propagation, thereby enabling the joint optimization of data transmission and sensing performance under varying channel conditions. Finally, O-ISAC technologies usually operate across various critical application scenarios such as autonomous driving, UAV, and internet of things (IoT), where channel variations are significant. A generalized channel model can offer a universal modeling framework for these scenarios, enhancing the generality and scalability of system design.

In summary, a generalized optical channel model provides a comprehensive and flexible framework for system design and optimization. Leveraging this model enables efficient communication and accurate sensing in complex and dynamic environments, thereby significantly enhancing system performance, reliability, resource efficiency, and adaptability. A generalized channel model is critical for establishing a solid foundation for the future application of O-ISAC technologies.

(2) Multi-band channel model: Generalized channel modeling is essential yet challenging. A progressive research approach, starting with multi-band channel modeling, benefits O-ISAC systems operating over a wide range of wavelengths by ensuring the selection of appropriate operational bands for various application scenarios. In atmospheric transmission, light of different wavelengths is primarily affected by scattering and absorption. Therefore, it is crucial to characterize the general transmission properties over a wide frequency range and then perform detailed modeling by selecting suitable wavelengths for specific scenarios. For example, in intelligent transportation scenarios, visible light can be used for data transmission through vehicle headlights or traffic lights, enhancing information interaction within the transportation system by vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I)[48, 49]. Ultraviolet (UV) light, due to its strong scattering characteristics in the atmosphere, is well-suited for NLoS when facing with obstacles between transmitter and receiver for the short-range communication, particularly excelling in urban UAV communication networks[50]. In environments with heavy smoke or dust, UV communication, owing to its scattering properties, enables more reliable signal transmission, making it suitable for low-rate, narrow-bandwidth communication scenarios. In contrast, far-infrared radiation light is commonly used for ultra-long-distance communication, such as between satellites and the ground stations.

In O-ISAC application scenarios, cross-domain information transmission is also inevitably involved.

For instance, optical communication from underwater to air must address not only the differences between underwater and atmospheric channels but also the effects of water surface waves and light refraction on transmission. A channel model for blue-green vortex beams has been introduced, accounting for the effects of atmospheric turbulence, the air-sea interface, and oceanic turbulence[51]. Meanwhile, recent investigations into air/water cross-boundary communications categorize existing technologies, analyze key channel challenges, and propose potential research directions for achieving integrated space-air-ground-ocean networks in 6G[52]. In O-ISAC applications, multiple wavelength bands may be used simultaneously for communication and/or sensing; therefore, it is necessary to construct a generalized channel model suitable for multi-band optical transmissions across different wavelengths.

In conclusion, the objective of optical channel modeling for O-ISAC is to comprehensively model the attenuation caused by optical phenomena such as reflection, refraction, and scattering, as well as stochastic channel characteristics resulting from environmental/terrain factors like multipath propagation, turbulence, shadowing, and others. Additionally, it aims to incorporate wavelength and medium-specific factors to establish an optical wireless channel model with broad applicability in general.

3 Performance Metrics and Optimization Design for Optical Sensing and Communication

This section reviews the performance metrics of the O-ISAC system under specific criteria, and then discusses design strategies for optimizing those proposed key performance indicators.

3.1 Performance metrics

In the research of O-ISAC, the establishment of system evaluation metrics is crucial, as this directly affects the subsequent system design and optimization. In this section, fulfilling system major functions and drawing upon relevant research findings in the RF research domain, we integrate the unique characteristics of optical systems to explore and establish the core performance metrics for O-ISAC systems. Notably, RF-ISAC can be achieved using existing communication equipment, where the transmitter sends a single signal to simultaneously perform both communication and sensing functions. In the optical research field, visible light based ISAC systems can simultaneously accomplish communication and sensing tasks using a single light source. However, in laser-based ISAC systems, due to the extremely narrow beam width, it is challenging to achieve both communication and sensing tasks simultaneously with a single light source. Therefore, it is more feasible to be an integrated system that combines laser communication and LiDAR sensing.

The essence of communication is to achieve effective and reliable information transmission under various propagation environment. Communication system performance metrics can be categorized into several key dimensions, including signal quality and reliability, transmission capability, energy efficiency, and latency. Signal-to-interference-plus-noise ratio (SINR) and BER evaluate signal quality and reliability, while data rate and spectral efficiency reflect transmission capability. Energy efficiency measures the power consumption, and latency indicates the timeliness of systems. In contrast, the primary tasks of sensing are detection, estimation, and classification and recognition of targets through sensing surrounding objects, focusing on metrics such as detection probability, false alarm probability, mean squared error (MSE), CRLB, and sensing accuracy, as illustrated in Fig. 3. One objective of this study on O-ISAC performance evaluation is to investigate whether a unified metric can be identified to characterize both communication and sensing capabilities, thereby providing a comprehensive evaluation tool to guide system design and optimization. One study has proposed employing mutual information as a performance metric for RF-ISAC systems[53]. For optical systems, this paper introduces a unified performance metric, named the joint communication-sensing probability (JCSP), to quantify the probability that communication and sensing requirements are simultaneously satisfied in O-ISAC systems.

3.1.1 Performance metrics for sensing

In O-ISAC research, the primary advantage over RF-ISAC is that optical systems can provide more precise sensing capabilities. The primary task of the sensing module involves target detection, estimation, and recognition.

(1) Target detection: Integrating sensing capabilities into communication systems not

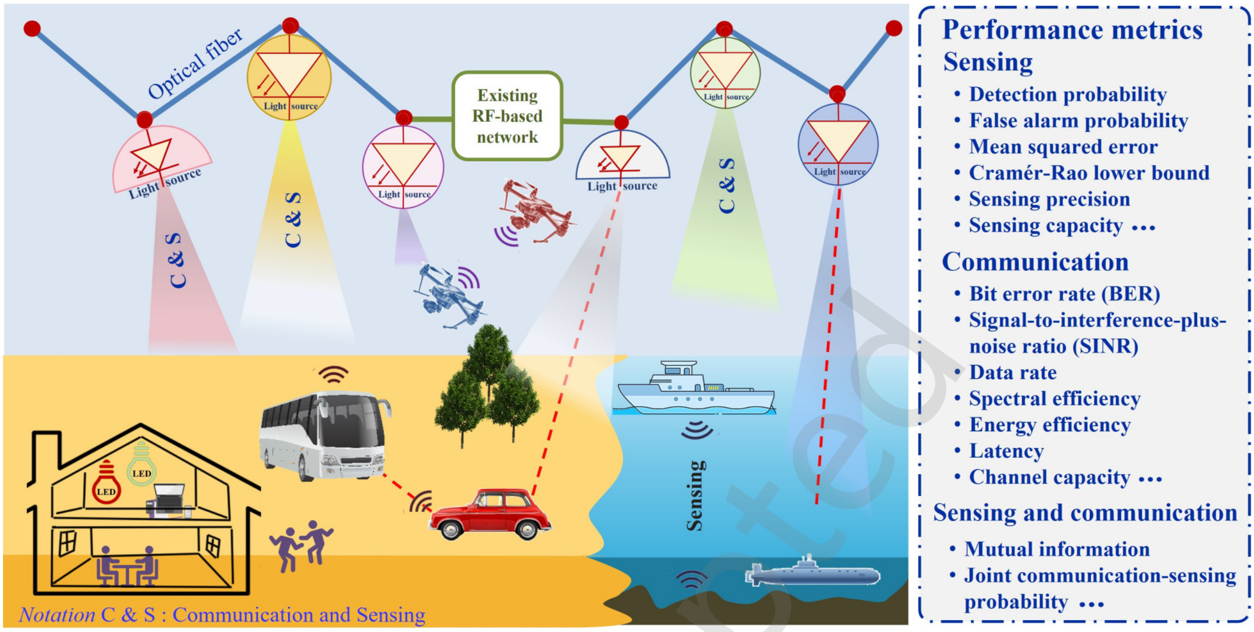

Fig. 3 Illustrative diagram of core performance metrics for O-ISAC system applications.

only enhances transmission efficiency, but also bolsters security through mechanisms such as target detection. For instance, regarding physical layer security issues[54–56], integrating sensing capabilities allows the system to promptly detect eavesdroppers and select optimal transmission intervals for legitimate users, thereby reducing potential information leakage. Subsequently, acquiring detailed information on potential eavesdroppers through sensing further mitigates transmission vulnerabilities and enables robust anti-eavesdropping communication. Moreover, in autonomous driving applications, LiDAR technology enables three-dimensional object detection, significantly enhancing pedestrian detection performance to facilitate the autonomous driving[57]. Additionally, by utilizing the high-precision sensing capabilities of optical systems, minute deformations that cannot be detected through direct visual observation such as structural deformations in roads or bridges, can be detected, thereby enabling the monitoring and ensuring the safety of structures. In detection tasks, the performance evaluation metrics of the sensing module include detection probability and false alarm probability.

(2) Estimation: Sensing enables the estimation of a target's distance, azimuth, and velocity, thereby facilitating precise positioning and tracking of moving objects[58–62]. For instance, sensing information can be used to acquire the position information of transceivers, thereby optimizing beamforming in communication. The main performance metric used to evaluate such estimations are MSE and CRLB.

(3) Recognition: Sensing also enables the recognition and classification of different objects in the surrounding environment. For example, cameras and radar in vehicular networks sense information about roads and obstacles (sensing), while the system uses image processing algorithms to identify whether the object ahead is a vehicle, pedestrian, or traffic light (recognition)[63]. Moreover, sensing-based recognition technology can be also leveraged in military contexts for a friend-or-foe identification. The classification performance metrics corresponding to recognition include sensing precision, reflecting the accuracy of object recognition.

In addition, researchers have proposed the concept of sensing capacity for RF-ISAC systems, defined as the maximum number of targets that can be detected per unit volume while satisfying sensing quality of service requirements, such as detection probability and sensing accuracy[64].

3.1.2 Performance metrics for communication

The primary objective of the communication module is to achieve effective and reliable information transmission. Communication system performance metrics can be categorized into several key dimensions, including signal quality and reliability, transmission capability, energy efficiency, and latency[65].

(1) Signal quality and reliability: SINR and BER are primary metrics used to assess signal quality and reliability in communication systems. SINR quantifies the quality of a transmitted signal by comparing the power of the desired signal with the total power of interference and noise present in the communication channel; a higher SINR indicates that the received signal is stronger relative to interference and noise, resulting in better signal quality and more reliable transmission. BER represents the proportion of bits received incorrectly compared with the total transmitted bits, serving as a key indicator of transmission reliability; a lower BER signifies fewer errors in the transmitted data, reflecting higher reliability and better signal integrity in the communication system.

(2) Transmission capability: Given the extremely high data rates supported by optical systems, data rate and spectral efficiency are crucial indicators that reflect the transmission capability of systems and the effective utilization of available resources. Data rate refers to the amount of data successfully transmitted per unit time over a communication channel, typically measured in bits per second (bps). Spectral efficiency quantifies how effectively the available bandwidth is utilized for data transmission, usually expressed in bits per second per hertz (bps/Hz).

(3) Energy efficiency: Energy efficiency evaluates how efficiently a communication system utilizes energy to transmitting data. It is a key metric for assessing the sustainability of wireless networks, especially in contexts where energy consumption is a concern.

(4) Latency: Latency measures the response time of the communication system, reflecting its ability to process and deliver data in real-time. Low latency is particularly crucial for time-sensitive applications such as real-time communication and interactive services.

(5) Channel capacity: Channel capacity is a theoretical upper bound that quantifies the maximum possible information transmission capability of a communication channel, serving as a benchmark for system design and optimization[66].

3.1.3 Common performance metrics for sensing and communication

Based on the previous discussion of key performance metrics for communication and sensing, there is a pressing need for in-depth theoretical research to identify a unified metric capable of simultaneously evaluating the core performance of both functions. Such a metric would facilitate system design and optimization. Preliminary findings from the field of radio frequency research suggest that mutual information could serve as a promising unified metric[67–72]. It not only quantifies the efficiency of information transmission in communication systems but also characterizes the estimation accuracy of target parameters in sensing systems, effectively capturing the system properties under the integration and cooperation of sensing and communication functionalities.

In communications systems, mutual information has been applied to quantify the amount of information contained in the received signal given the transmitted signal, reflecting the correlation between the transmitter and the receiver. To establish an analogous concept in the sensing domain, recent studies have introduced sensing mutual information (SMI) as a metric to evaluate sensing system performance[67,68]. This metric has the potential to enable a unified performance evaluation for both communication and sensing systems.

Further study demonstrates that radar waveform can be optimized by maximizing the mutual information between a Gaussian-distributed target response and the received signal, while simultaneously minimizing the minimum mean square error (MMSE) of target response estimation[69]. Another line of research detailed derives the SMI between stochastic target responses and the received signal[70,71], as shown

$$I_S \triangleq \log \left| \mathbf{I} + \frac{\mathbf{R}_R \otimes \mathbf{R}_T^{\frac{1}{2}} \mathbf{X}\mathbf{X}^H \mathbf{R}_T^{\frac{1}{2}}}{\sigma_N^2} \right|, \quad (4)$$

where $\mathbf{R}_T$ denotes the spatial correlation matrix at the transmitter, characterizing the spatial correlations among the transmitter antennas and reflecting the degree of correlation between the signals transmitted by different antennas. Similarly, $\mathbf{R}_R$ denotes the spatial correlation matrix at the receiver, characterizing the spatial correlations among receiver antennas and the degree of signal correlation between them. $\mathbf{X}$ denotes the transmitted signal; and σ_N^2 stands for the power of the additive white Gaussian noise.

In a subsequent study, mutual information was introduced as a unified performance metric for both communication and sensing in RF-ISAC systems[72]. The authors of Ref. [72] make two key observations regarding the role of mutual information in ISAC.

First, this metric sets a lower bound on the MSE, so that higher values yield lower estimation errors. Second, under a constant false alarm rate, target detection probability is determined by the sensing mutual information; as this metric increases, detection probability correspondingly improves.

3.1.4 Limitation of existing performance metrics

Current research on mutual information primarily focuses on RF-ISAC, with theoretical derivations based on RF signals. Given the significant differences between optical and RF signals, determining whether the mutual information metric can be extended to O-ISAC, and how to accurately define and characterize it, remains an important theoretical challenge in this field. Moreover, a single metric is insufficient to comprehensively assess system performance or guide resource allocation and optimization. Therefore, it is crucial to establish complementary unified performance metrics.

3.1.5 Proposed performance metric for O-ISAC

We introduce a unified performance metric, named the *joint communication-sensing probability (JCSP)*, to evaluate O-ISAC systems. The JCSP characterizes the likelihood that both communication and sensing requirements are satisfied simultaneously. Specifically, let C_{comm} denote the actual communication capacity (e.g., data rate) and E_{sens} denote the sensing error (e.g., positioning error). We denote the minimum acceptable communication capacity by $C_{\min}$ and the maximum tolerable sensing error by $E_{\max}$. Accordingly, the JCSP is defined as the probability that

$$P_{\mathrm{joint}} = \Pr(C_{\mathrm{comm}} \geq C_{\min} \cap E_{\mathrm{comm}} \leq E_{\max}). \quad (5)$$

In an optical system, the communication capacity C_{comm} can be derived from the received SINR, to which it is proportional[73]. The sensing error, quantified by the MSE, also depends on the SINR (see Ref. [74] for details), as higher SINR values yield lower sensing errors, such that yield lower MSE. Consequently, when both communication and sensing performance rely on the same received SINR, the corresponding probability simplifies to

$$P\big(\mathrm{SINR} \geq \max\{\Gamma_c, \Gamma_e\}\big), \quad (6)$$

where Γ_c and Γ_e are the SINR thresholds required to meet the communication capacity constraint $C_{\min}$ and the sensing error constraint $E_{\max}$, respectively.

This metric can serve as a unified reliability measure, taking the value 1 if and only if both communication and sensing requirements are simultaneously met, and 0 otherwise. Consequently, it provides a performance indicator for mission-critical O-ISAC systems, such as autonomous driving that demand both reliable data connectivity and high-precision sensing to ensure operational safety.

3.2 System optimization design

Based on the core performance metrics discussed, this section explores the joint optimization design of transceivers and physical layer security issues. The goal is to enhance the transmission rate and secrecy of the communication system with the aid of sensing. Improvements in communication performance could handily enhance the system's sensing capabilities, such as providing more precise location information and reducing the complexity and time required for large-scale sensing. This creates a positive relationship of mutually reinforcement, ultimately enhancing the overall performance of the system.

3.2.1 Joint optimization design of transceivers

In traditional wireless communication systems, determining the transmitter parameters for optimal performance relies on acquiring channel state information (CSI). Using the uplink communication from user terminal to base station as an example, CSI is typically obtained by transmitting frequency-domain pilot sequences or time-domain training signals, allowing the base station to perform channel estimation based on the received known information. This estimation is then used to optimize the beamforming and power allocation design from the transmitter to the receiver. However, in optical systems, due to the relatively weak received signal on the uplink, relying solely on this available information for channel estimation may result in significant errors. Under these circumstances, conventional channel estimation methods struggle to provide accurate channel information, thereby compromising subsequent optimization designs.

To address this issue, optical systems incorporate sensing modules that perform environmental mapping, acquiring and constructing models of the surrounding environment through methods such as beam scanning, to obtain more accurate CSI and interference which may jeopardize the communication performance. Based on the sensing-obtained CSI and surrounding environment information obtained via sensing the system seeks a near-optimal beamforming and power allocation scheme under specific constraints, while meeting the core requirements of the communication system. Specifically, the goal is to maximize the achievable sum-rate by optimizing the multi-user precoding scheme for the downlink broadcast channel, subject to a total transmit power constraint. Precoding design relies on accurate CSI, and sensing assistance can improve the accuracy of channel estimation, enabling the implementation of optimal precoding schemes and thereby enhancing communication quality. Moreover, with more precise beamforming, LiDAR can direct beams more accurately toward the target receiver while minimizing unwanted environmental reflections and interference. This enhanced signal focusing capability allows sensors to acquire target information more reliably, thus significantly improving sensing precision. As a result, mutual enhancement between communication and sensing can be achieved, advancing the vision of an O-ISAC system. The process can be mathematically modeled as the following maximization problem:

$$\begin{aligned} \max_{\{\mathbf{b_k}\}_{\mathbf{k=1}}^{\mathbf{K}}} & \sum_{k=1}^{K} \log_2 \left(1 + \frac{\mathbf{h}_k \mathbf{b}_k \mathbf{b}_k^H \mathbf{h}_k^H}{\sigma_n^2 + \sum_{i=1, i\neq k}^{K} \mathbf{h}_k \mathbf{b}_i \mathbf{b}_i^H \mathbf{h}_k^H}\right) \\ \text{s. t. } & \mathrm{CRLB}(\theta) \leq \mathrm{CRLB}_0, \\ & \sum_{k=1}^{K} \mathrm{Tr}(\mathbf{b}_k \mathbf{b}_k^H) \leq P_t, \end{aligned} \tag{7}$$

where $\{\mathbf{h_k}\}_{\mathbf{k=1}}^{\mathbf{K}}$ denote the channels of the K users, which are dependent on the parameter θ and can be estimated through the sensing process. $\{\mathbf{b_k}\}_{\mathbf{k=1}}^{\mathbf{K}}$ represent the precoding matrices to be optimally designed. σ_n^2 refers the noise power at the receiver. CRLB_0 represents the bound that the sensing estimation must satisfy. The second constraint is about the total transmit power P_t. $\mathrm{Tr}(\cdot)$ denotes the trace of a matrix. The core idea emphasizes a unified evaluation approach, where the overall system performance is limited by the weaker of the communication and sensing capabilities.

When solving optimization problems, one can apply the nonlinear conjugate gradient method from convex optimization theory[75], or employ second-order derivative optimization algorithms such as Newton's descent method combined with backtracking line search[76]. Additionally, machine learning-based methods may also be considered for effectively solution.

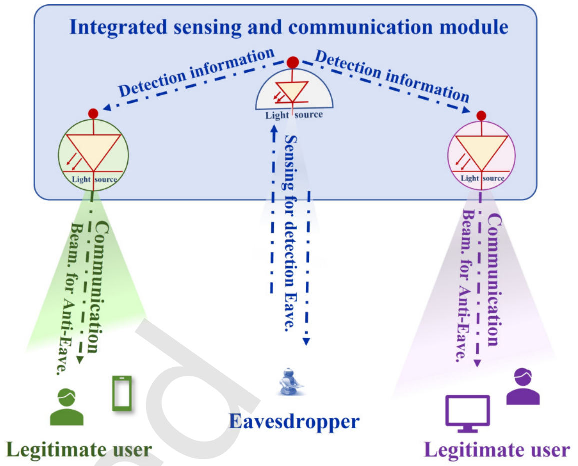

Fig. 4 Illustrative diagram of physical layer security issues in O-ISAC.

3.2.2 Physical layer security

Physical layer security provides an effective confidentiality mechanism for wireless transmission, simplifying subsequent security protocols and improving overall efficiency. Although optical fiber are generally regarded as a highly secure transmission medium, optical wireless signals propagate through the air and are susceptible to interception by third parties. Eavesdroppers (Eves) can employ highly sensitive optical receivers to capture these signals without detection by legitimate users (Alice), thereby posing serious security risks.

In an O-ISAC system, sensing can play a pivotal role in enhancing security by detecting the presence of active Eve and ensuring secure communications, as illustrated in Fig. 4. The core idea of our preliminary sensing-based detection scheme is to use the uplink received signal to determine the presence of Eve by employing an adaptive threshold decision mechanism in O-ISAC systems. Theoretically, by analyzing the received signals obey different statistical distributions in the presence or absence of Eve, one can derive the detection probability and the false alarm probability. Finally, the effectiveness of the detection method can be demonstrated via the receiver operating characteristic (ROC) curve.

The detection strategy is distilled into the following fundamental principles and critical implementation steps.

1) Channel model: For $i \in \{\mathrm{A}, \mathrm{E}\}$, Lambertian model is used for example with its LoS gain given by

$$H_i = \frac{(m+1)A_{\rm PD}}{2\pi d_i^2}\cos^m(\phi_i)\cos(\psi_i)\cdot \mathbf{1}_{\{\psi_i \le \Psi_{\rm FoV}\}}, \tag{8}$$

where $A_{\rm PD}$ is the effective receiving area of the photodetector, d_i is the distance between transmitter i and the legitimate receiver (Bob), ϕ_i is the angle of irradiance, ψ_i is the angle of incidence, $\Psi_{\rm FoV}$ is the receiver's FoV, $\mathbf{1}_{\{\cdot\}}$ is the indicator function.

The Lambertian order m is defined as

$$m = -\frac{\ln 2}{\ln(\cos\Phi_{1/2})}, \tag{9}$$

where $\Phi_{1/2}$ is the transmitter's half-power angle.

The received optical powers at Bob from Alice and Eve are given by

$$P_r^{\rm A} = P_{\rm A}H_{\rm A}, \quad P_r^{\rm E} = P_{\rm E}H_{\rm E}, \tag{10}$$

where $P_{\rm A}$ and $P_{\rm E}$ denote the optical transmit powers of Alice and Eve, respectively.

2) Signal model: At symbol interval k, the received signal at Bob is modeled under two hypotheses

$$\mathcal{H}_0: \quad y[k] = P_r^{\rm A}\, m_{\rm A}[k] + n[k], \tag{11}$$

$$\mathcal{H}_1: \quad y[k] = P_r^{\rm A}\, m_{\rm A}[k] + P_r^{\rm E}\, m_{\rm E}[k] + n[k], \tag{12}$$

where $m_{\rm A}[k], m_{\rm E}[k] \in \{0,1\}$ are independently generated on-off keying (OOK) symbols, and $n[k] \sim \mathcal{N}(0,\sigma_n^2)$ is additive white Gaussian noise. Let $k = 1,\dots,N$, where N denotes the total number of transmitted symbols considered in the detection process.

3) Detection method: The proposed detection scheme is summarized in Algorithm 1.

4) Theoretical analysis: The designed received signal follows a Gaussian distribution. Based on detection theory, the analytical expression for the detection probability of the proposed scheme is derived as

$$\begin{aligned}\mathrm{P_D} &= \mathrm{P}(y[k] > \tau \mid \mathcal{H}_1)\\ &= \int_\tau^{+\infty}\frac{1}{\sqrt{2\pi\sigma_n^2}}\exp\left\{-\frac{(x-P_r^{\rm A}-P_r^{\rm E})^2}{2\sigma_n^2}\right\}dx\\ &= Q\left(\frac{\tau - P_r^{\rm A} - P_r^{\rm E}}{\sigma_n}\right),\end{aligned} \tag{13}$$

where the Q-function is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty}\exp\left(-\frac{t^2}{2}\right)dt. \tag{14}$$

And the false alarm probability of the proposed scheme is derived as

$$\begin{aligned}\mathrm{P_{FA}} &= \mathrm{P}(y[k] > \tau \mid \mathcal{H}_0)\\ &= \int_\tau^{+\infty}\frac{1}{\sqrt{2\pi\sigma_n^2}}\exp\left\{-\frac{(x-P_r^{\rm A})^2}{2\sigma_n^2}\right\}dx\\ &= Q\left(\frac{\mu - P_r^{\rm A}}{\sigma_n}\right),\end{aligned} \tag{15}$$

where τ denotes the value of the decision threshold.

5) Simulation validation: Under the assumption that each of Alice, Bob, and Eve is equipped with a single LED or photodetector, the performance of the proposed scheme was initially evaluated through simulations with the following parameter settings: transmitter power $P_{\rm A} = P_{\rm E} = 250$ mW, Lambertian order $m = 2$, photodetector effective area $A_{\rm DP} = 10^{-4}$ m^2, and $N = 10^5$ transmitted symbols. The corresponding results are illustrated in Fig. 5. Specifically, the simulated values (obtained by Algorithm 1) were compared with the theoretical results (derived from Eq. (13) and Eq. (15)). The comparison demonstrates close agreement between simulated and theoretical results, thereby confirming the reliability of the proposed scheme. Moreover, as the

Algorithm 1 Detecting eavesdropper for O-ISAC.

Input: Received samples $\{y[k]\}_{k=1}^N$, sliding-window length L, ground-truth labels $\{\text{label}[k]\}_{k=1}^N$;
Output: Detection probability $\mathrm{P_D}$, false alarm probability $\mathrm{P_{FA}}$;
Initialization: Set $N_0 = 0$ indicating the total number of symbols without Eve; $N_1 = 0$ indicating the total number of symbols with Eve; $N_{\rm D} = 0$ denoting the number of correctly detected Eve; and $N_{\rm FA} = 0$ representing the number of false alarms when Eve is absent.

for $k = L$ to N **do**
  $\tau = \frac{1}{L}\sum_{i=k-L+1}^{k} y[i]$;
  if $\text{label}[k] = \mathcal{H}_1$ **then**
    $N_1 = N_1 + 1$;
    if $y[k] > \tau$ **then**
      $N_{\rm D} = N_{\rm D} + 1$;
    end if
  else
    $N_0 = N_0 + 1$;
    if $y[k] > \tau$ **then**
      $N_{\rm FA} = N_{\rm FA} + 1$;
    end if
  end if
end for
Calculate $\mathrm{P_D} = \frac{N_{\rm D}}{N_1}$;
Calculate $\mathrm{P_{FA}} = \frac{N_{\rm FA}}{N_0}$;
return $\mathrm{P_D}$, $\mathrm{P_{FA}}$.

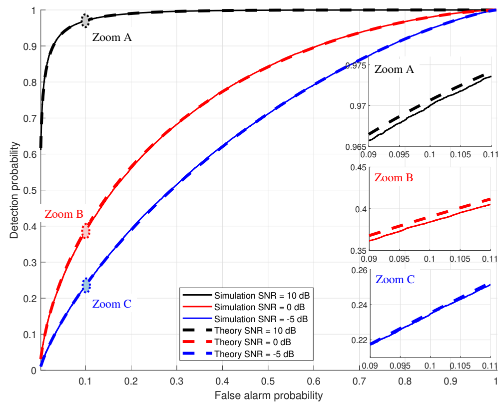

Fig. 5 Performance evaluation of the eavesdropping detection scheme.

SNR increases, the ROC curves shift distinctly toward the upper-left corner, indicating enhanced detection probability at lower false alarm probability. This clearly underscores the beneficial impact of higher SNR on improving detection sensitivity while effectively suppressing false alarms.

Once real-time active eavesdropping detection has been performed through sensing, secure communication can be established. Under a total transmit power constraint, the system's secrecy capacity defined as

$$C_s = \frac{1}{2}\log_2\left(1+\frac{P||\mathbf{h}_B||^2}{\sigma_B^2}\right)-\frac{1}{2}\log\left(1+\frac{P||\mathbf{h}_E||^2}{\sigma_E^2}\right) \quad (16)$$

can be maximized by optimizing beam direction and resource allocation, thereby enhancing overall security performance[77]. In Eq. (16), $\mathbf{h}_B$ denotes the legitimate user's channel, $\mathbf{h}_E$ denotes the eavesdropping channel; σ_B represents the noise power at the legitimate user, σ_E represents the noise power at the eavesdropper; and P is an average transmit power constraint. The O-ISAC system employs a sensing module to detect the presence of eavesdroppers and selects appropriate time slots for transmitting information to legitimate users. By utilizing sensing technology to determine the positions of both legitimate users and eavesdroppers, the system adjusts the phases of optical components to form optimal optical beam pattern. This approach enhances signal reception quality for legitimate users while preventing information leakage to eavesdroppers. Meanwhile, based on the CSI obtained through sensing, the system can effectively allocate resources

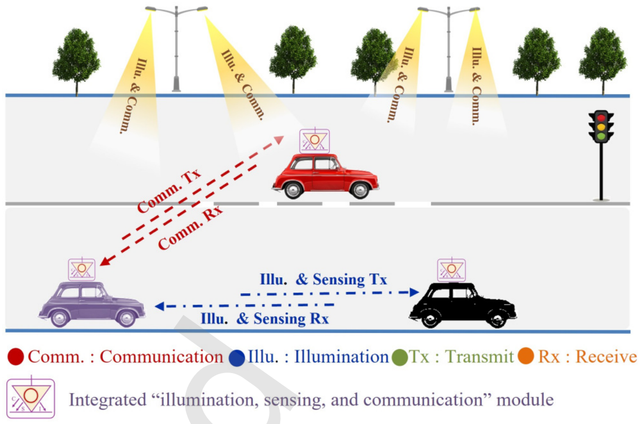

Fig. 6 O-ISAC application scenario: A vehicular network.

to maximize the secrecy capacity. As the beam directionality becomes more precise, the energy or time required for secure communication is reduced, allowing more resources to be allocated to the sensing module, thereby facilitating additional target detection or estimation tasks.

4 Applications for O-ISAC

This section focuses on the practical implementation of O-ISAC technology, using vehicular networks and hybrid optoelectronic base station architectures as case studies. These case studies aim to evaluate the feasibility and effectiveness of O-ISAC technology in real-world applications and to highlight the potential advantages of optical technologies in improving communication efficiency and sensing capabilities.

4.1 Application scenario: Vehicular networks

As illustrated in Fig. 6, the integrated "illumination, sensing, and communication" module in vehicle-mounted light sources aims to consolidate lighting, sensing, and communication functions into single multifunctional unit, enabling coordinated functionality and resource sharing. By integrating LiDAR sensing technology with the adaptive headlight systems of the vehicle, precise target localization and efficient data transmission can be achieved. Within this framework, the O-ISAC can be subdivided into following two typical interaction modes for the better overall performance: (1) LiDAR-assisted communication: In this mode, LiDAR is used to obtain the directional information of communication targets and provide it to the vehicle's headlights for precise communication, significantly enhancing data transmission rates. (2) Communication-assisted

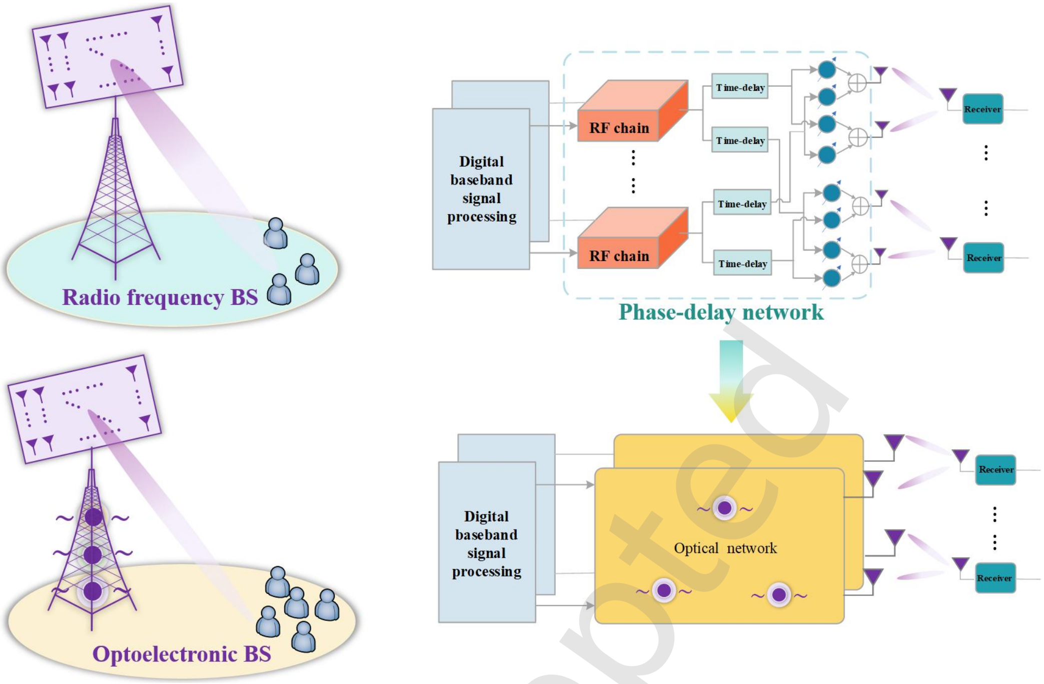

Fig. 7 System block diagram of the hybrid optoelectronic base station architecture.

LiDAR sensing: Communication is used to acquire target location information, assisting LiDAR in optimizing its detection range, thus avoiding energy consumption, delay, and interference with inter-vehicle communication caused by wide-range blind scanning.

Future research directions include robust beamforming techniques and sensing-communication technologies characterized by low latency and high reliability. Additionally, optimizing system performance through multi-sensor fusion and multi-frame joint processing methods aims to enhance vehicle-to-vehicle connectivity and service quality in intelligent transportation systems, thereby ensuring safety and system efficiency in complex traffic scenarios.

4.2 Hybrid optoelectronic base station architecture

In O-ISAC research, it is essential not only to focus on the integration of communication and sensing tasks but also to explore the collaborative optimization of optical and electrical transmission media to achieve more comprehensive system integration[78]. Advancements and breakthroughs in optical technology and devices are expected to drive significant progress in the development of information technology. We propose a novel hybrid optoelectronic architecture designed for large-scale (or ultra-large-scale) antenna array systems. This study aims to address the bottleneck issues faced in traditional RF wireless communication systems, such as high hardware costs, computational complexity, and significant performance degradation due to frequency non-selectivity in the analog domain. The key idea is that replacing the traditional phase shifter network (PSN) with optical links enables joint amplitude and phase control in the analog domain, thus overcoming the conventional constant modulus constraint. This approach is expected to facilitate the performance improvements achievable with large-scale antenna arrays.

Large-scale antenna arrays, also known as massive multiple-input multiple-output (MIMO)[79], represent a key technology for significantly improving channel capacity and system throughput. Massive MIMO typically involves base stations equipped with hundreds or even thousands of antennas, enabling substantial enhancements in data transmission rates. A major practical challenge, however, is the high hardware cost associated with implementation. Specifically, assigning a dedicated RF chain to each antenna would require hundreds or even thousands of RF chains, dramatically increasing both hardware expenses and power consumption.

To enable large-scale or extremely large-scale antenna arrays to be driven by a limited number of RF chains, prior studies have proposed incorporating a PSN between the RF chains and the antenna elements. However, the frequency-independent nature of the PSN leads to suboptimal beamforming for analog domain signals and significant degradation in system performance[80]. To address this issue, further research has focused on integrating a time-delay network between the RF chains and the PSN to enable frequency-dependent phase shifts. By employing a joint phase-delay control network, this approach enhances frequency-dependent phase shifting in the analog domain, thereby improving the performance of wideband systems[81].

Unfortunately, since hardware phase shifters and time-delay networks can only be optimized in terms of phase, each element of the optimization matrix in the transceiver design is constrained to a constant modulus. This constraint renders the precoding design a highly non-convex optimization problem. Existing solutions to this issue still involve high computational complexity, and the suboptimal algorithms often experience considerable performance degradation.

To address this issue, we propose replacing the PSN, time-delay networks, and even other components with an optical network to achieve their corresponding functions, as illustrated in Fig. 7. This optical network can enable simultaneous control of amplitude and phase, facilitating optimal precoding schemes and substantially reducing the computational complexity with transceiver design. Furthermore, photonic devices are anticipated to provide benefits such as lower power consumption and higher transmission bandwidth, thereby further reducing hardware expenses and overall energy consumption and enhancing the energy efficiency of systems.

To realize the above concept, future research on hybrid optoelectronic base station design could begin by exploring the theoretical foundations and integration techniques of optical link components within the context of microwave photonics[82, 83]. Second, the dimensions of the optical network can be determined by leveraging the inherent channel sparsity in massive MIMO systems, such as through the selection of fully or partially connected architectures, with the aim of maximizing energy efficiency with minimal link complexity. Finally, for such a hybrid base station architecture, corresponding linear or nonlinear precoding design can be developed, along with related studies such as channel estimation and beam training.

5 Conclusions

ISAC is an emerging trend in future communication systems that seamlessly integrates communication and sensing functions while significantly enhancing overall system performance through mutual empowerment. Leveraging light as an information carrier offers additional advantages that facilitate the realization of this integrated vision. This paper offers a comprehensive review of O-ISAC by addressing three pivotal aspects: fundamental theory, system design, and applications. Our discussion of the fundamental theory clarifies the transmission characteristics of optical signals, thereby establishing a robust foundation for channel modeling in O-ISAC systems. We further investigate performance metrics for system design optimization, focusing on core performance indicators and exploring frameworks for transceiver optimization and physical layer security. Finally, by examining practical scenarios, such as vehicular networks and hybrid optoelectronic base station architectures, we illustrate the critical role and feasible implementation pathways of O-ISAC in real-world applications.

Acknowledgment

This work was supported by Guangdong Innovative and Entrepreneurial Research Team (No. 2023ZT10X137).

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