This article has been accepted for publication in IEEE Communications Surveys & Tutorials. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/COMST.2025.3594560

Stochastic Geometry for Modeling and Analysis of Sensing and Communications: A Survey

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***Abstract*—Integrated sensing and communication (ISAC) is a promising technology for next-generation wireless networks, enabling applications that require enhanced communication and precise sensing capabilities. Notable examples include smart environments, augmented and virtual reality, and the internet of things, where the functionalities of intelligent sensing and broadband communications are paramount. Consequently, ISAC has attracted significant research interest from academia and industry, resulting in numerous investigations conducted over the past decade. The literature encompasses a diverse range of articles, including system models, performance evaluations, and optimization studies of various ISAC designs. Stochastic geometry (SG) is the study of random spatial patterns. As such, SG tools have been used to evaluate the performance of wireless networks with different types of nodes. In this paper, we present a comprehensive survey of current research on the performance evaluation of ISAC systems that employ SG tools. The survey covers terrestrial, aerial, and vehicular networks, addressing the random spatial location of network elements, propagation scatterers, and blockages through various point processes. The paper begins with an overview of ISAC technology, SG tools, and performance evaluation metrics for communication and sensing. Next, we elaborate on the technical components of the system models employed in the surveyed literature. Then, we present pertinent literature findings across diverse network types using three levels of integration: sensing-assisted communication, communication-assisted sensing, and collaborative sensing and communication. Lastly, we discuss the challenges and potential directions of forthcoming research.**

***Index Terms*—Integrated sensing and communication, joint sensing and communication, spatial models, sixth generation (6G), stochastic geometry, survey, review.**

I. INTRODUCTION

A. Preliminaries

Sixth-generation (6G) networks are expected to revolutionize communications in order to shape the future of the internet of things (IoT), enabling seamless connectivity among people, computing systems, vehicles, devices, and sensors [1]. To support the various new use cases that are expected to emerge, e.g., augmented/virtual reality, holographic telepresence[1], industry 5.0, autonomous mobility, etc., 6G systems will be designed to meet stringent network requirements. For example, augmented and virtual reality applications require capacity above 1 Tb/s, while autonomous mobility requires reliability above 99.99999% and latency below 1 ms. In IMT-2030[2], it was stated that the enablers of these networks will be artificial intelligence, quantum technology, THz communications, and the integration of sensing and communication functions [3]. To quantify the performance of these technologies, new key performance indicators should be proposed (or existing ones extended), related to positioning accuracy, timeliness and 3D coverage [4]. For example, positioning is a critical function of integrated sensing and communication (ISAC) technology and high-accuracy detection can help in reaching even centimeter (cm) level positioning accuracy. To realize this vision, a new metric namely joint positioning accuracy and coverage can be considered. The metric is defined as the probability that a specified (and stringent) positioning accuracy threshold is met, while the joint communication and sensing coverage probabilities exceed predefined levels.

Stochastic geometry (SG) (also referred to as geometrical probability) is a field of applied probability that aims to provide tractable mathematical models and appropriate statistical methods, to study and analyze random phenomena in $\mathbb{R}^d$. Under the umbrella of wireless communication networks, the location of network nodes is randomly scattered over an enormous number of possibilities, where designing the system for each network realization would be time-consuming and resource-intensive [5, 6]. The task becomes even more challenging when considering the ever-increasing complexity and heterogeneity of 6G wireless networks. Instead, SG tools can model the spatial location of network entities in the wireless environment according to point processes, thus implicitly considering all possible network realizations and generally capturing the main dependencies of the network. As a result, system-level performance analysis in terms of key performance metrics, such as coverage probability and average data rate, is feasible and provides meaningful insight. Although a

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This work was co-funded by the University of Piraeus Research Centre and the EU HORIZON programme under iSEE-6G GA No. 101139291.

[1]Holographic telepresence refers to a real-time communication technology that captures, transmits, and renders a three-dimensional (3D), life-sized representation of a remote participant so that the person appears to occupy physical space at the receiving location [2].

[2]IMT-2030 (International Mobile Telecommunication) is the strategic framework defined by International Telecommunications Union (ITU-R), and specifically the Radiocommunication Sector, to guide the development, standardization, and deployment of 6G technologies.

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cross-fertilization between SG and artificial intelligence can be made to provide more robust and accurate frameworks for performance evaluation [7–10], one can conclude that SG is expected to remain a fundamental area of research for the foreseeable future.

ISAC has gained increasing interest in recent years. In the past, sensing and communication functions were operated separately, requiring the use of dedicated transmitters, receivers, spectrum, and beamformers. However, in recent years, taking advantage of the enormous evolution of technology, it has become apparent that a highly efficient approach is to share these resources [11]. ISAC is expected to revolutionize next-generation wireless networks by seamlessly integrating time, frequency, waveform design and hardware for both functions [12]. This novel approach is expected to enable key applications of 6G networks such as precise localization, tracking, gesture recognition, and augmented reality. In addition, ISAC will increase data rates with improved spectral efficiency and ensure the ultra-low latency required for autonomous vehicle applications. In this context, it is desirable to jointly design the sensing and communication systems so that they can share the same frequency band and hardware to improve spectrum efficiency and reduce hardware costs. This motivates the study of ISAC.

The exponential growth of ISAC-related research is demonstrated by the numerous workshops that have been organized in flagship IEEE conferences, e.g., IEEE International Conference on Communications and IEEE Global Communications Conference, and special issues of journals [13]. In particular, in [14, 15] a double-part special issue on ISAC was presented highlighting various selected papers grouped into: 1) performance bounds and optimization, 2) time-frequency signal processing, 3) spatial signal processing, 4) networking and resource allocation, 5) emerging technologies, and 6) applications. Later, in [16], the special issue entitled "Signal Processing for the Integrated Sensing and Communication Revolution" included 7 high-quality papers. The aim of the call was to pave the way towards the design of solutions robust to hardware impairments, collaborative strategies that enable a multi-perspective view of the sensing targets, or techniques that enable the exploitation of new elements in the wireless infrastructure, such as reconfigurable intelligent surfaces (RISs). Finally, very recently, a special call-for-papers was launched by the IEEE Journal of Selected Topics in Electromagnetics, Antennas and Propagation [17]. The topics of interest include antenna designs, propagation and channel modeling, ISAC-THz based design and prototyping, cellular V2X-based ISAC etc. The call's submission deadline closed at 2 May 2025. Note that recently the IEEE has also introduced an ISAC emerging technology initiative whose purpose is to explore and support a wide variety of research directions and standardization opportunities related to ISAC [18].

B. Brief Historical Background

Throughout the history of communication technology, military and defense research has consistently driven the invention and development of novel ideas and prototypes. This phenomenon is particularly evident in wireless communications

TABLE I: List of Important Abbreviations

Abbreviation	**Description**
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
6G	Sixth-Generation
AI	Artificial Intelligence
AoI	Age of Information
ASE	Area Spectral Efficiency
BPP	Binomial Point Process
BS	Base Station
CAS	Communication Assisted Sensing
CDF	Cumulative Distribution Function
CDM	Code Division Multiplexing
CoMP	Coordinated Multi-point
CP	Coverage Probability
CRLB	Cramer-Rao Lower Bound
DPP	Determinantal Cluster Process
EE	Energy Efficiency
GPP	Ginibre Point Process
HPPP	Homogeneous Poisson Point Process
IMT	International Mobile Telecommunication
IoT	Internet of Things
ISAC	Integrated Sensing and Communication
JCAS	Joint Communication and Sensing
JRDCCP	Joint Radar Detection and Communication Coverage Probability
JRSCCP	Joint Radar Success and Communication Coverage Probability
JSRS	Joint Synchronization Signal Block and Reference Signal-based Sensing
LoS	Line-of-Sight
MCP	Matérn Cluster Process
MHCP	Matérn Hard-Core Point Processes
MIMO/MISO	Multiple-Input Multiple-Output/Single Output
ML	Machine Learning
mmWave	millimeter wave
MU	Mobile User
NLoS	Non-Line-of-Sight
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
PDF	Probability Density Function
PGFL	Probability Generating Functional
PLP	Poisson Line Process
PMF	Probability Mass Function
PPP	Poisson Point Process
PSE	Potential Spectral Efficiency
RCS	Radar Cross Section
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surface
RSU	Road-Side Unit
SAC	Sensing Assisted Communication
SAR	Synthetic Aperture Radar
SCINR	Signal-to-Clutter-plus-Interference-plus-Noise Ratio
SCNR	Signal-to-Clutter-plus-Noise Ratio
SG	Stochastic Geometry
SIMO	Single Input Multiple Output
SINR	Signal-to-Interference-plus-Noise Ratio
SIR	Signal-to-Interference Ratio
SOMA	Spectrum Overlay Multiple Access
SSB	Synchronization Signal Block
TCP	Thomas Cluster Process
TDMA	Time Division Multiple Access
THz	Terahertz
UAV	Uncrewed Aerial Vehicle
UE	User Equipment
UPA	Uniform Planar Array
URLLC	Ultra-Reliable Low Latency Communication
V2X	Vehicle-to-Everything

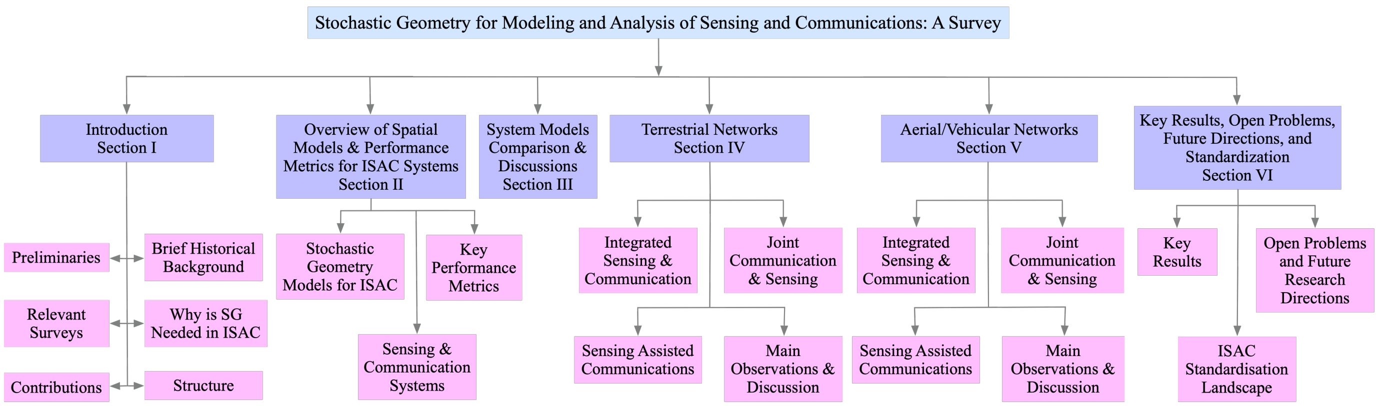

Fig. 1: The structure of the paper.

and applies to ISAC systems. Notably, in the 1960s, the first attempt to incorporate communication signals into military radar pulses was successful [19]. In the following years, many breakthroughs in antenna and digital communications have strengthened the radar and communication application areas. In the 1990s, the US Office for Naval Research launched the advanced multifunction radio frequency (RF) concept program, which investigated the feasibility of building a testbed to integrate multiple RF functionalities into a single system [20].

Subsequently, more military and civilian projects endeavored to incorporate communication signals into radar waveforms, as in [21–23]. With the advent of orthogonal frequency division multiplexing orthogonal frequency division multiplexing (OFDM) and multiple input multiple output (MIMO) technologies, not only sensing-assisted but also communication-assisted functionalities have been explored, as demonstrated in [24–27]. Technological advances in hardware and signal processing techniques have unequivocally demonstrated the feasibility of a more integrated approach to the two functionalities, enabling sensing and communication through a single transmission and facilitating the perception of network surroundings [28–30].

On another front, the concept of geometric probability as a field of study can be traced back at least 300 years. Indeed, the interconnection between probability theory and geometry is historically well-documented, with the earliest recorded challenges related to random scattering and the occurrence of probabilistic events emerging in the 18th century. The term "SG" is relatively recent, having been coined by David Kendall and Klaus Krickeberg [31], in 1969 while preparing for an Oberwolfach workshop. Nevertheless, the term "SG" had already been adopted by Frisch and Hammersley in 1963 [32] as one of two candidate names for the theory of "random irregular structures". Notably, the term "geometric probability" was already well known before 1923. In fact, Maurice George Kendall and Patrick Alfred Pierce Moran had published a book entitled "Geometrical Probability" prior to 1923. Referring to the fundamentals of SG, the most well-known point process in this field is undoubtedly the Poisson point process (PPP). In [33], it is mentioned that a history of the concept of a Poisson process can be found in Guttorp and Thorarinsdottir [34]. They reported that the first recorded use of the Poisson process in spatial statistics appears to be that of Michell [35], who studied distances of stars, followed by other researchers who applied it in the kinetic theory of heat and to the problem of counting blood particles. However, as mentioned in [33], all these scientists were unaware of the modern idea of a Poisson process. In the context of wireless communication networks, the authors in [36] cite [37] as the pioneering work in considering SG tools for evaluating connectivity in a network of stations whose spatial locations were governed by a Poisson point process (PPP). By the late 1990s, performance evaluation of wireless networks at the system level had already been conducted by leveraging fundamental SG tools based on Poisson Voronoi tessellations and Delaunay triangulation.

C. Relevant Surveys

There are several survey papers in the literature on ISAC/joint communication and sensing (JCAS) and SG. In this subsection, we briefly present these papers. In [38], a detailed review of recent developments in ISAC systems is presented, focusing on their fundamental principles, physical layer design, networking considerations, and practical applications. In [39], a detailed literature review of resource management approaches for joint radar and communication systems is presented. In [40], the benefits, functions, and challenges of integrated sensing, communication, and computation are discussed, and the relevant technical literature is cited. In [41], a comprehensive review is provided for three interrelated aspects of connected automated vehicles, namely, sensing and communication technologies, human factors, and information-aware controller design. In [42], a survey of the fundamental limitations of ISAC is conducted to understand the gap between current state-of-the-art technologies and their ultimate performance potential. The presented analysis provides valuable information and guidance for the development of advanced ISAC technologies that can operate closer to these limits. In [43], a detailed review of machine learning (ML)-based ISAC systems is presented, discussing common ML and deep learning models that can be used in ISAC scenarios. In [44], a comprehensive survey charts the convergence of 6G communication, localization, and perception by identifying the primary technology enablers and analyzing their challenges,

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implementation obstacles, and potential solutions. In [45], an in-depth review of systems and technologies related to joint communication and radar sensing in mobile networks is given.In [46], a thorough review of ISAC channel modeling approaches is presented, supplemented by concise syntheses of target and clutter radar cross section (RCS) models and a discussion of future research directions for diverse deployment scenarios. In [47], a comprehensive survey of ISAC systems reviews the sensing-centric, communication-centric and joint co-design paradigms, underscores the advantages of sharing spectrum, hardware and software, and examines the key enabling techniques that make ISAC feasible. In [48], a literature review is performed for ISAC signals in the context of mobile communication systems, covering aspects related to signal design, processing, and optimization. In [49], a detailed survey approaches ISAC from the waveform-design perspective, first laying out the current motivations, applications and challenges of sensing and communication, and then systematically listing state-of-the-art waveform solutions for integrated sensing and communication. In [50], a visionary design for an ISAC-oriented unified IoT architecture is presented that integrates software-defined communication and superintelligent agents. In addition, [51] examines multifunctional and hybrid RISs as enablers of 6G for ISAC, as well as for radar and communication coexistence, describing their architectures, use cases, and deployment challenges. In [52], the evolution of ISAC is described from the early RF dual-function links, to emerging optical and multimodal platforms, relating each stage to the progress in network design, edge intelligence, and ongoing standardization efforts. Furthermore, the review focuses on ISAC technology development over the past decade, highlighting new design principles for artificial intelligence (AI)-powered networks that support intelligent connectivity to strengthen ISAC security.

In addition, a few survey and tutorial papers have focused on SG analysis of wireless communication networks. In fact, [53] presents an overview of SG and the theory of random geometric graphs as applied to results on connectivity, capacity, outage probability, and other fundamental limits of wireless networks. In [54], a comprehensive tutorial on SG-based analysis for cellular networks is presented. The work presents a unified SG framework for cellular networks that serves as a tutorial. Numerical examples are also presented along with demonstrations and discussions. In [55], a comprehensive survey of SG models for single-tier, multi-tier, and cognitive cellular networks is provided, along with a taxonomy that classifies prior work by network architecture, underlying point processes, and performance-evaluation techniques. In [56], a comprehensive tutorial on SG analysis of large-scale wireless networks that captures the spatio-temporal interference correlation is presented. Methods for characterizing the spatiotemporal signal-to-interference ratio (SIR) correlations for different network configurations are described. In [36], SG models and techniques developed over the last decade for evaluating wireless network performance are presented. In the following, we outline how SG has been used to capture the properties of emerging radio access networks and to quantify the benefits of key enabling technologies.

Table II groups the literature along two binary axes, i.e., SG and ISAC, to immediately identify the areas each survey covers. Although the recent literature contains many ISAC-focused surveys, these surveys do not investigate the use of SG tools. Furthermore, many survey papers address the use of SG tools for one single functionality, such as communication or sensing. However, none of these papers provides an in-depth review of the statistical characterization of communication- and sensing-enabled networks using SG tools. This article is the first to comprehensively address the role of point processes and SG techniques in ISAC networks.

D. *Why Is SG Needed in ISAC Studies?*

For decades, SG has served as a powerful mathematical tool for system-level performance evaluation of complex wireless networks. By modeling the spatial locations of entities in a network through simple point processes, tractable models have been developed to gain a deeper understanding of the performance of these networks. With the advent of 6G ISAC networks, more entities have emerged in the forefront. In fact, due to this increase in types of devices, the ISAC networks may include communication transmitters, radars, users receiving communication services, sensed targets, blockages and clutters [57]. These entities now require a more nuanced spatial modeling with appropriate point processes. Indeed, all these entities can be modeled with up to six point processes some of which may not necessarily be independent. For example, clutters can be assumed to be clustered around the sensed target and therefore will be spatially correlated. This can introduce significant complexity in the performance evaluation of ISAC networks and may result in limited insights. With the ever increasing complexity of 6G ISAC networks, large-scale performance evaluation of these networks to gain meaningful insights at the network level becomes remarkably difficult.

However, with the exploitation of more advanced point processes, i.e., cluster point processes or determinantal point processes (DPPs), SG tools can assist to i) the modeling of spatial correlation between network entities and ii) the derivation of analytical tractable expressions for key performance metrics. In a similar vein, the adoption of time-variant metrics introduced by mobility, as a result of the detection & tracking procedure in ISAC technology, also introduces significant challenges, which are even more intense in UAV networks. Fortunately, the use of inhomogeneous PPP [58] can address the challenges introduced even by complicated mobility models and result to analytically tractable expressions for time-variant performance metrics. In this case, the benefits are, in summary, threefold: i) the effect of real-world spatial randomness of entities on ISAC network performance is considered, ii) analytical frameworks that allow system-level performance evaluation can be explored, and iii) meaningful network-level insights and design guidelines for complicated 6G ISAC networks can be drawn. However, some entities in real-world ISAC networks exhibit some spatial correlation. Fortunately, advanced point processes and SG tools can capture the spatial correlation among different point processes in complex 6G ISAC terrestrial and aerial networks. Therefore,

TABLE II: Positioning of prior surveys and tutorials with respect to SG and ISAC

Ref.	Year	Primary focus	Scope	SG	ISAC
[53]	2009	SG for wireless networks	Generic communication	✓	✗
[55]	2013	SG for multi-tier and cognitive cellular networks	Cellular	✓	✗
[54]	2017	SG tutorial for cellular networks	Cellular	✓	✗
[41]	2020	Sensing, communication & control for connected vehicles	Vehicular	✗	✓
[56]	2021	Spatio-temporal SG tutorial	Generic communication	✓	✗
[36]	2021	New trends in SG for wireless networks	Generic communication	✓	✗
[39]	2021	Radio-resource management for joint radar/communication	Cellular	✗	✓
[44]	2021	Convergent communication, sensing and localization	6G vision	✗	✓
[45]	2022	Joint communication & radar sensing in mobile networks	Cellular	✗	✓
[49]	2022	ISAC waveform design	Waveform	✗	✓
[42]	2022	Fundamental limits of ISAC	Generic ISAC	✗	✓
[47]	2022	Techniques, tools, datasets and standardization for ISAC	Generic ISAC	✗	✓
[48]	2023	ISAC signal design toward 6G	Waveform	✗	✓
[43]	2024	Machine-learning-enhanced ISAC	Generic ISAC	✗	✓
[46]	2024	ISAC channel modeling	Propagation	✗	✓
[40]	2024	Joint sensing, communication & computation	Multi-layer 6G vision	✗	✓
[38]	2024	Advances and open challenges of ISAC	Generic ISAC	✗	✓
[50]	2024	Secure ISAC in 6G networks	Security	✗	✓
[51]	2025	Multi-functional and hybrid RIS as enablers for ISAC	RISs for ISAC	✗	✓
[52]	2025	Evolution of ISAC across RF, optical and multimodal platforms	ISAC evolution	✗	✓
ours	2025	SG modeling and analysis of ISAC	SG for ISAC	✓	✓

SG is expected to enable realistic modeling and analysis of 6G networks by realistic capturing spatial randomness, interference, and user mobility. As a result, it will support the design of ultra-reliable, low-latency systems required for various 6G use cases, e.g., holographic telepresence, by optimizing node placement, coverage, and resource allocation, while also accommodating 3D environments and advanced technologies like RIS and THz communication. Nevertheless, the integration of SG tools into the ISAC paradigm has become more important than ever.

E. Contributions

Motivated by the above observations, this review paper aims to shed light on a wide range of recent state-of-the-art works on communication and sensing enabled networks, and more specifically on: i) the exploitation of point processes in the spatial modeling of their entities and ii) the role of SG tools in their performance. While a plethora of survey works focus on JCAS and ISAC networks, no review papers focus in the SG context. In this direction, the main contributions of this paper can be summarized as follows.

- First, we present the fundamental knowledge of SG processes used in ISAC networks, as well as the basic concepts of sensing and communication systems. We also present the main metrics used to analytically evaluate the performance of these systems;
- We present and compare the system models that have been studied in the literature, with the goal of highlighting the commonalities among the studies and identifying any gaps in the existing research;
- We review and discuss the relevant technical literature in terrestrial, vehicular, and aerial communication networks for the three main types of sensing and communication networks, namely JCAS, sensing assisted communication (SAC), and communication assisted sensing (CAS);
- We discuss the key results associated with the reviewed papers and present potential research directions related to SG modeling in sensing and communications.

F. Structure

The structure of this article is illustrated in Fig. 1 and is also summarized as follows. In Section II a brief tutorial is presented, which overviews the fundamentals of SG tools, the basic principles of ISAC systems, and the key performance metrics of ISAC technology used in the survey. Then, Section III provides an analysis of the technical components of the system models developed in the corresponding literature. This section provides a first overview of the challenges that the spatial models of ISAC networks raise along with some possible solutions. In Sections IV and V, we comprehensively review the articles dealing with terrestrial and aerial/vehicular networks, respectively. To obtain meaningful insights, comparisons with respect to technological aspects of ISAC are also conducted. The survey follows a categorization of systems into ISACs, JCAS, and SAC. Each of these categories is split into subcategories. In Section VI, we summarize the key results of the presented papers, discuss the open technical challenges and future research directions, and present the standardization landscape for ISAC. Finally, in Section VII, we conclude the paper.

II. Overview of Spatial Models & Performance Metrics for ISAC Systems

The aim and structure of this tutorial are now described. The tutorial concisely presents i) fundamental concepts of communication and sensing-enabled networks and ii) theoretical preliminaries on the SG modeling in the context of communication- and sensing-enabled networks to help understand the discussions presented later in this paper. First, the tutorial defines the key spatial point processes and answers in *how* and *why* that have been employed in communication

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and sensing networks. It also introduces the key concept for statistically characterizing aggregate interference when two-dimensional (2D) point processes are used. Next, the tutorial delves into the fundamental principles of ISAC networks to provide a deeper understanding of these networks. Finally, the tutorial presents communication- and sensing-based key performance metrics in the context of SG. Since, it is essential to answer the question *how each subsection is linked to the survey*, a connecting paragraph is introduced at all subsections.

A. SG Models for ISAC

In this subsection, on overview of SG modeling is provided to help understand the discussions presented in this paper.

1) Point Processes: In communication- and sensing-enabled wireless networks, the spatial modeling of network entities is abstracted to convenient point processes that capture the peculiarities of the network, i.e., based on the type of network as well as the application scenario. A point process can be characterized by the number of points falling in sets. The number of points falling in these sets is called a counting measure, and it may be random. In the context of ISAC networks, when a number of (random) entities is randomly deployed in a region or space, the spatial arrangement of networks' entities can well be described by point processes. Following the point processes' properties, one can, for example, statistically characterize random distance distributions between different entities and accordingly conduct performance evaluation of the network at system level. The most common point processes used in communication- and sensing-enabled wireless networks are defined below, along with their key properties.

Homogeneous PPP (HPPP): The HPPP is considered to be the most popular point process due to its tractability and analytical flexibility, and thus is widely adopted for the analysis of wireless networks performance.

In general, an HPPP Ψ of density λ is a point process in $\mathbb{R}^d$ such that [59]:

- For every compact set $W \subset \mathbb{R}^d$, $N(W)$ has a Poisson distribution with mean $\lambda|W|$ and is characterized by a probability mass function (PMF) as
$$\mathbb{P}[N(W) = m] = \frac{(\lambda|W|)^m}{m!} e^{-\lambda|W|}, \tag{1}$$
where $|\cdot|$ denotes the Lebesgue measure or the d-dimensional volume of the subset W and $N(\cdot)$ is the counting measure, i.e., the number of points falling in W.
- If $W_1, ..., W_n$ are disjointly bounded sets, then $N(W_1), ..., N(W_n)$ are independent random variables.

Motivation: The 2D HPPP has widely been adopted in communication- and sensing-enabled wireless networks to model the spatial locations of base stations (BSs), user equipments (UEs), and sensing targets [60–62] or to model the spatial locations of BSs, MTs, and blockers [63, 64]. In general, the PPP is used to model a network composed of a possibly infinite number of entities randomly and independently coexisting in a finite or infinite area (e.g., in a large-scale wireless network or in a cellular network). If we are interested in modeling the spatial locations of an infinite or unknown number of nodes in a finite or infinite area, the PPP is a suitable choice. Infinite networks are usually considered for simplicity and because of the common assumption that the contribution of far nodes to the aggregate interference is negligible. However, HPPP is not always the best approach for realistic spatial deployment of nodes in real-world ISAC networks, and one should carefully consider the trade-off between analytical tractability and accuracy when designing spatial models based on SG.

Matern Cluster Process (MCP): The 2D MCP is a doubly Poisson cluster process constructed from a parent PPP $\Phi_p = \{\mathbf{x_i}\}_{i\in\mathbb{N}}$ with intensity λ_p, with each point of Φ_p substituted by a daughter cluster consisting of a PPP with an average number of points N within a disk of radius R centered at that point. Formally, the first-moment density for an MCP is given by $\lambda_{MCP} = N\lambda_p$. Each daughter point $\{\mathbf{y_i}\}$ is located uniformly and independently within a disk of radius R around the origin. The probability density function (PDF) of the spatial location of each element $\{\mathbf{y_i}\}$ is given by

$$f(\mathbf{y_i}) = \begin{cases} \frac{1}{\pi R^2}, & \|\mathbf{y_i}\| \le R \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Motivation: When we are interested in modeling the spatial locations of nodes according to a clustering behavior around another network entity, then the MCP is the most suitable choice. To meet the requirements of URLLC and accurate detection and tracking in communication- and sensing enabled wireless networks, users and targets tend to be distributed around the transmitting nodes, making them suitable for modeling by cluster processes [65].

Thomas Cluster Process (TCP): The 2D TCP is a doubly Poisson cluster process where each cluster is a finite PPP with a Gaussian intensity function. Formally, the intensity function of a cluster is given by

$$\lambda_0(x) = \frac{\bar{c}}{2\pi\sigma^2} e^{-\frac{\|x\|^2}{2\sigma^2}}, \tag{3}$$

thus the daughter points are normally distributed with variance σ^2 around each parent point, and the mean number of daughter points is $\bar{c}$. The intensity of the process is given by $\lambda_{TCP} = \bar{c}\lambda_p$.

Motivation: The only difference between MCP and TCP is the deployment area where the nodes are randomly located. In each TCP cluster, each individual point is located according to two independent zero-mean Gaussian distributed variables with variance σ^2 describing x and y coordinates from the center of the cluster. In contrast, each point of an MCP is uniformly distributed on a disk. In [66], ISAC devices are modeled by a PPP, while the relative 2D spatial location of a sensing target clustering around each ISAC device follows an independent 2D normal distribution, thus forming a TCP.

DPP: Let $\mathbb{C}$ denote the complex plane. Then, for any function $K : \Lambda \times \Lambda \to \mathbb{C}$, we use $K(x_i, x_j)$ to denote the square matrix with $K(x_i, x_j)$ as its (i, j)-th entry. Formally, the point process Φ defined on a locally compact space Λ is called a DPP with

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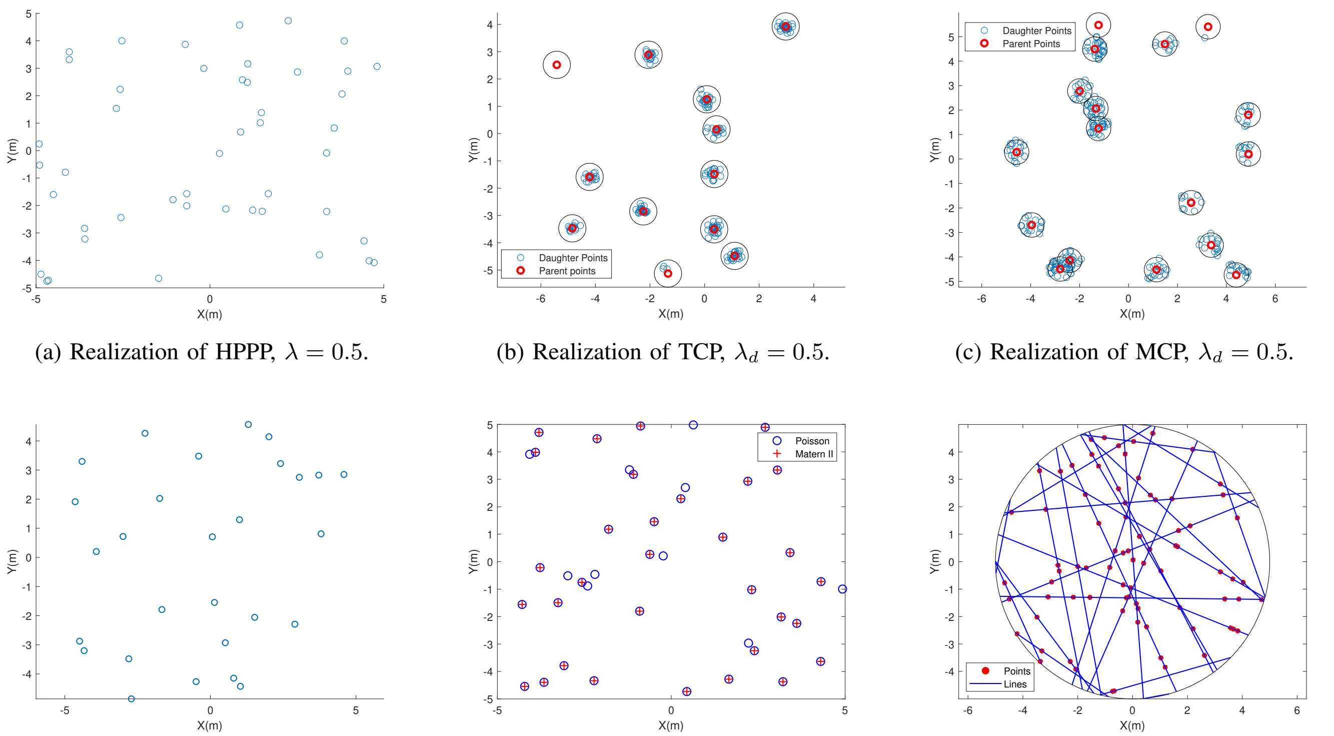

(a) Realization of HPPP, $\lambda = 0.5$. (b) Realization of TCP, $\lambda_d = 0.5$. (c) Realization of MCP, $\lambda_d = 0.5$.

(d) Realization of β-GPP, $\beta = 0.5$. (e) Realization of MHCP, $\lambda = 0.5$. (f) Realization of Cox process, λ_l=λ_p=0.5.

Fig. 2: Realizations of point processes for communication and sensing networks.

kernel $K : \Lambda \times \Lambda \rightarrow \mathbb{C}$, if its n-th order product density is given by

$$\rho^{(n)}(x_1, ..., x_n) = \det(\mathrm{K}(\mathrm{x_i}, \mathrm{x_j})), \quad (x_1, ..., x_n) \in \Lambda^n. \quad (4)$$

In this case, we denote the DPP Φ with kernel K by $\Phi \sim \mathrm{DPP(K)}$. Detailed information and more general and formal definitions of DPP are presented in [67]. In general, three DPP models have been proposed [68], namely the Gauss DPP model, the Cauchy DPP model, and the Generalized Gamma DPP model.

Motivation: DPPs capture the repulsive behavior of nodes, i.e, their tendency to repel each other and produce accurate spatial models for the location of nodes in communication and sensing enabled networks, when a certain spatial correlation is required. In [67], DPPs were shown to outperform PPPs in predicting key performance metrics, such as coverage probability in cellular networks. In the context of communication and sensing-enabled networks, in [69], the Gauss DPP model was used to model the spatial locations of users in a JCAS enabled multi-user MIMO network. By employing the Gauss DPP, the mitigation of communication system and radar interference was achieved while analytical tractability was maintained. In general, DPPs are an excellent choice for spatial modeling in simplistic sensing and communication system models where certain spatial correlation modeling is required. However, in practical scenarios, in which various network entities must be taken into account, e.g. terrestrial or aerial BSs, UEs, targets, and blockages, employing DPP would result in an extremely challenging analytical framework.

β-Ginibre Point Process (β-GPP): Let $\Phi = \{\mathbf{x_i}\}_{i\in\mathbb{N}}$, be a β-GPP with density λ and repulsion parameter β, i.e., $\Phi \sim \mathrm{GPP}(\lambda, \beta)$. Then, Φ is a DPP with the kernel given by

$$\mathcal{K}_{\beta,\lambda}(x, y) = \lambda e^{-\frac{\pi\lambda|x-y|^2}{2\beta}}, \quad (5)$$

where $x, y \in \mathbb{C}$. Note that $\mathcal{K}_{\beta,\lambda}(x, y)$ represents the interaction force among the points of the process.

The β-GPP represents a repulsive point process in which the parameter $\beta \in (0, 1]$ can be used to smoothly approach the PPP from the GPP. More specifically, when $\beta \rightarrow 1$, the points in the β-GPP experience strong repulsive behavior. On the other hand, when $\beta \rightarrow 0$ or $\lambda \rightarrow \infty$, the correlation among the points disappears, which corresponds to the case where the locations of the points are independent, i.e., the PPP case.

Motivation: When we are interested in modeling the spatial locations of entities with a certain repulsive behavior, then β-GPP is the most accurate choice. In fact, in real-world network deployment scenarios, BS locations are typically spatially correlated and exhibit repulsive behavior [70]. In this case, β-GPP is a fairly tractable model for random points with spatial repulsion.

Cox Point Process: Let $Z = \{Z(x) : x \in \mathbb{S}\}$ be a non-negative random field such that with probability one $x \rightarrow Z(x)$ is a locally integrable function. Then we say that a point process Φ defined on some underlying space $\mathbb{S}$ is a Cox point process driven by Z if the conditional distribution of Φ is a PPP with intensity function Z.

It is important to acknowledge that vehicular networks exhibit dynamic spatial inhomogeneity and road constraints,

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rendering traditional Poisson models inadequate for their application in such networks. In contrast, the Cox process, characterized by its random intensity function, effectively captures clustering, temporal variation, and hierarchical randomness, making it an ideal model for realistically simulating vehicle distributions. In this context, a Cox point process is constructed to model the spatial locations of entities in a vehicular network as follows. We first model the spatial distribution of road systems using a motion-invariant Poisson line process (PLP) Φ_L with line intensity μ_L. We then model the spatial locations of wireless nodes, including vehicular nodes and road-site units (RSUs), on each line (road) using a one-dimensional (1D) HPPP with density λ_n. Now, we can say that the set of spatial locations of vehicular nodes and RSUs is modeled by the Cox processes Φ_r and Φ_t, respectively, and driven by the same PLP Φ_L.

Motivation: The Cox point process is a particularly well-known point process for modeling the spatial locations of vehicles and/or RSUs in vehicular networks. In the context of vehicular networks enabled by communication and sensing, the Cox point process has already been used in [71]. Although the Cox point process is the most realistic model for spatially modeling entities in a vehicular network because it builds on the PLP for modeling the roads and highways of vehicular networks, it usually results in intractable expressions for key performance metrics. Therefore, the feasibility of a large-scale performance evaluation of ISAC vehicular networks at system-level is questionable.

Matérn Hard-Core Point Processes (MHCP) of type II: Starting with a basic uniform PPP Φ_b with intensity λ_b, add to each point x an independent random variable $m(x)$, called a mark, uniformly distributed in $[0,1]$. Flag to remove of all points that have a neighbor within distance r that has a smaller mark. Then remove all flagged points. Formally,

$$\Phi_h \triangleq \{x \in \Phi_b : m(x) < m(y) \,\text{for all}\, y \in (\Phi_b \cap b(x,r)) \backslash \{x\}\}, \tag{6}$$

where $b(x,r)$ denotes a 2D sphere of radius r centered at x. Assume that Φ_h is a 2D MHCP. To determine the intensity λ_h of Φ_h, we first condition on a point with a mark t. This point is retained with probability $e^{-t\lambda_b|b(0,r)|}$, since $t\lambda_b$ is the density of points with marks smaller than t. Deconditioning over t yields

$$\lambda_h = \lambda_b \int_0^1 e^{-t\lambda_b|b(0,r)|}\mathrm{d}t = \frac{1-e^{-t\lambda_b|b(0,r)|}}{|b(0,r)|}, \tag{7}$$

where $|.|$ denotes the Lebesgue measure.

Motivation: Hard-core processes are point processes for modeling the spatial locations of nodes, where the nodes are forbidden to be closer than a certain minimum distance. The key idea for building hard-core point processes and achieving the minimum distance constraint is to start with a conventional PPP with no restriction and then remove the points that violate the minimum distance condition. In the context of communication- and sensing-enabled networks, the type II 1D MHCP has been used in [72] to model the spatial locations of each vehicle, where a minimum safety distance between vehicles is ensured. The 1D MHCP serves as an alternative and mathematical convenient choice to model vehicles in ISAC-enabled vehicular networks compared to the Cox point process. In fact, in [72], the signal-to-interference-plus-noise ratio (SINR)-based coverage probability is derived in terms of a single first-order Marcum-Q function.

2) Statistical Characterization of Aggregate Interference for General 2D Point Processes: With the ever-increasing complexity of communication- and sensing-enabled wireless networks and the vast number of novel smart applications that these networks now support, the statistical characterization of the aggregate interference power distribution becomes extremely difficult. This is because aggregate interference now includes many random factors such as RCS, antenna gains, etc. Due to the many random terms, it is not feasible to statistically characterize the aggregate interference by directly building on the distribution for the sum and product of random variables. In this case, the derivation of the PDF for the sum or the product of random variables may not be feasible, even if the random variables are independent, due to the fact that the computation of integrals may not result in closed or even in exact form. The latter is usually a result of very complicated integration limits. Instead, the most widely adopted techniques for characterizing the aggregate interference power distribution are Campbell's theorem and the probability generating functional (PGFL), which are defined for the practical case of 2D point processes.

- **Campbell Theorem:** Let Φ denote a general point process in $\mathbb{R}^2$ and $f:\mathbb{R}^2 \to \mathbb{R}$ be a measurable function. Then,
$$\mathbb{E}\left\{\sum_{x_i\in\Phi} f(x_i)\right\} = \int_{\mathbb{R}^2} f(x)\lambda(x)\mathrm{d}x, \tag{8}$$
where $\lambda(x)$ denotes the intensity function of the 2D point process Φ.
- **PGFL:** For $u(x)\in[0,1]$ and $\int_{\mathbb{R}^2}(1-u(x))\mathrm{d}x < \infty$, the PGFL for the point process Φ is given by
$$\mathbb{E}\left\{\prod_{x\in\Phi} u(x)\right\} = \exp\Big(-\int_{\mathbb{R}^2}(1-u(x))\lambda(x)\mathrm{d}x\Big). \tag{9}$$

For the conventional case of a PPP, the derivation of the characteristic function of the aggregate interference using the PGFL usually yields analytically tractable results. This is because according to Slivnyak's theorem, the reduced Palm distribution of the PPP is the same as its ordinary distribution. In other words, by removing a point from the PPP, the remaining process is the same as the original point process with the same intensity. Therefore, the PGFL for the PPP can also be expressed as (9).

Based on the aforementioned, the connection between this subsection and the survey is established through the following key aspects:

- *Spatial point processes & rationale:* This survey comprehensively covers all point processes that have been employed in ISAC frameworks based on SG. To elucidate the impact of point processes on ISAC performance metrics, it is crucial to have a clear understanding of each framework's spatial model. This overview provides

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a concise yet exhaustive summary of all point processes featured in the survey, along with their salient characteristics. It also clarifies the rationale and challenges of using each point process in ISAC frameworks.

- *Interference statistical characterization:* The statistical characterization of interference presents a significant challenge in conventional cellular networks, particularly those that employ ISAC technology. Typically, interference power is affected by various factors, including the random spatial distribution of nodes, shadowing, and fading. However, with the increasing adoption of ISAC technology, the statistical characterization of interference power distribution becomes even more complex when considering random antenna gains, random RCS, and clutter interference. This survey comprehensively examines the impact of aggregate interference on the system-level performance of ISAC networks. To facilitate the reader in quantifying the challenges posed by the additional random variables, this overview provides detailed descriptions of i) the most commonly used tools for statistically characterizing aggregate interference in ISAC networks and ii) the complexities that arise from including additional terms, which make the statistical characterization of interference more intricate.

B. Sensing and Communication Systems

To enhance the readability and clarity of the paper, a brief overview of the main characteristics of sensing and communication is provided[3]. Wireless communication and radar sensing have traditionally developed as distinct technologies. However, their underlying similarities have increasingly motivated research into their integration and coexistence. The driving forces for investigating the coexistence of sensing and communication are the result of two independent processes [74]:

1) The technological advances that have made it possible to use very high carrier frequencies for communication purposes, traditionally used in radar applications, in conjunction with the massive antenna arrays that are currently available;
2) The demanding requirements for reduced hardware costs and power consumption imposed by the upcoming 6G networks.

As a result of the convergence of these technologies, several benefits are expected, the most important of which are the reduction of electromagnetic pollution, efficient use of power and spectrum, improved wireless communication and sensing performance, and the introduction of novel applications. According to the research priorities and architectures studied, three main types of ISAC networks have been identified [75], which are also illustrated in Fig. 3.

- Sensing-assisted communication (SAC);
- Communication-assisted sensing (CAS);
- Joint communication and sensing (JCAS).

[3]A more detailed discussion for sensing and communication systems fundamentals can be found in [73].

The main objective of SAC is to increase the reliability of communication links using environmental information obtained from radar sensing. As a result environment characterization is achieved, which facilitates medium-aware communication through predictable propagation. This environmental knowledge enhances channel estimation accuracy especially at the millimeter-wave (mmWave) band, while reducing overhead by eliminating redundant estimations across multiple UEs through shared sensing-based acquisition. The additional information provided by sensing can be used in various communication techniques such as beam training, beam alignment, power adaptation, especially in high-mobility environments [76].

CAS focuses on how the sensing functionality can be enhanced by exploiting the operation of a communication system. In particular, conventional networks rely on distributed sensors and remote estimation for data fusion and control. In contrast, 6G perceptive networks enable device-free wireless sensing, integrating sensing and communication on a single platform, namely CAS. For example, communication signals reflected from objects can be used to detect or track objects without the need for additional sensors. This approach provides another degree of freedom in scenarios where sensing must be performed under non-line-of-sight (NLoS) propagation conditions. The CAS distortion is clearly affected by both the estimation errors occurring during SP and reconstruction errors arising in the coverage probability (CP) [76].

In JCAS, a single transmitted signal is used for both communication and sensing functionalities, an approach that is highly efficient and cost-effective. The implementation of JCAS technologies and services in a multi-functional network would be one of the pillars in a 6G network that is expected to transform wireless communication by providing ultra-high data rates, extremely low latency, massive device connectivity, and ultra-high reliability and availability. Clearly, in JCAS networks, the main objective is to design and optimize the signal waveform, system, and network architecture equally for both functions. This approach is in contrast to others, i.e., CAS, SAC, in which the research focus is on how the secondary functionality can be used to improve the primary functionality, without significantly affecting its operating principles.

The level of integration between sensing and communication systems can range from simple coexistence to deeper integration [73]. Specifically, at the lowest levels, communication and sensing coexist, but spectrum or hardware are not shared. Deeper integration levels involve sharing spectrum and hardware, taking advantage of the existing communication infrastructure for sensing. Further integration involves scenarios in which the same waveform is used for both functions and a unified signal processing framework is employed. In addition, in even deeper integration, communication signals are reused for sensing, reducing overhead and energy consumption, to enable 6G applications that require robust communication, precise sensing, and accurate localization capabilities. Therefore, in scenarios where functionalities coexist and share resources, but the design objective is typically to achieve target sensing and target communication performances simultaneously, often with compromises, the term "JCAS" is used. On the other hand, when the system is optimized holistically under a unified

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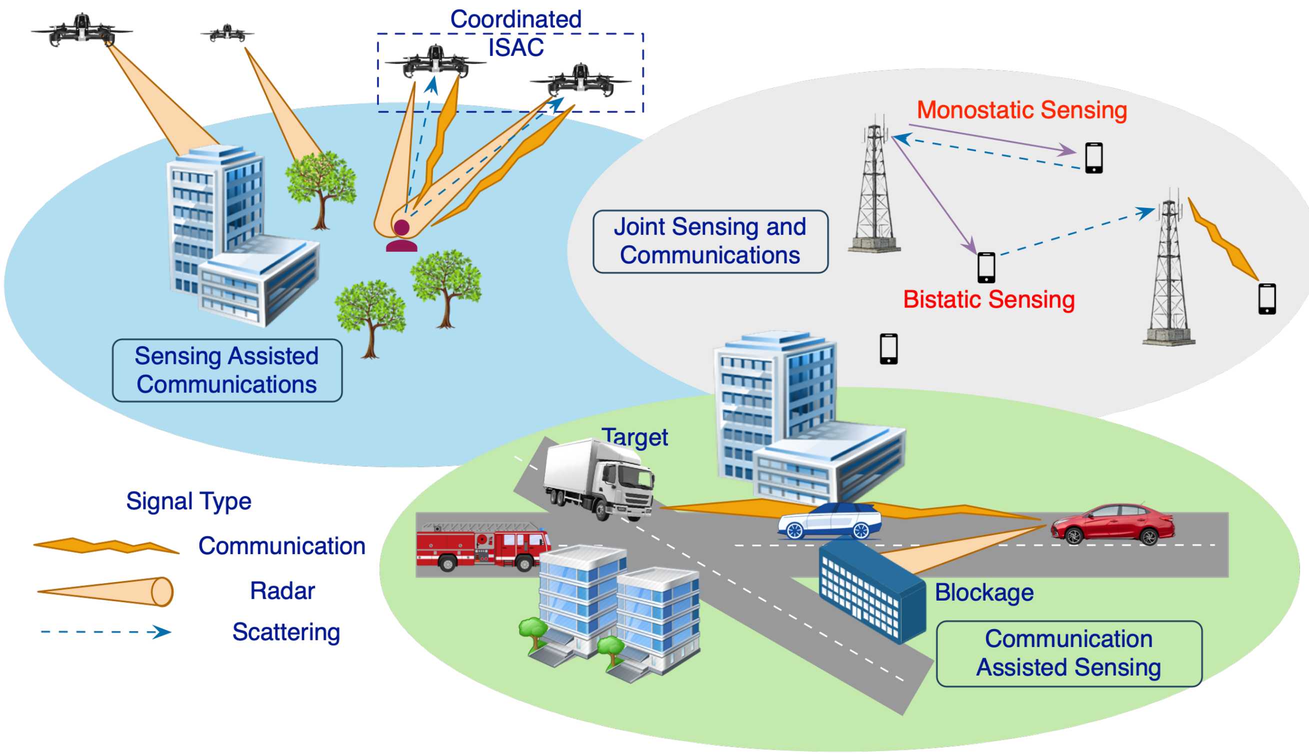

Fig. 3: Types and configurations of sensing and communication networks.

performance metric (or set of tightly coupled metrics), the term "ISAC" is employed [77].

Regarding the physical placement of the transmitter and receiver for sensing, various types of sensing configuration have been proposed: monostatic, bistatic, monostatic sensing with coordination, bistatic sensing with coordination [78], which are also illustrated in Fig. 3. In monostatic phased-array radar, the transmit and receive arrays are co-located, often utilizing the same antenna array for both transmission and reception. A key challenge in this scenario is related to interference from the transmit array affecting the receive array, which must be mitigated [42]. In bistatic phased-array radar, the transmit and receive arrays are located at separate locations, and thus reduced interference is expected. However, additional information is required because the angles of departure and arrival differ. In coordinated monostatic sensing, a sensing organizer, such as an access point, manages and synchronizes the transmissions of one or more devices performing monostatic sensing. The key challenges in this case include mutual interference management, synchronization, and scalability issues. Similarly, in coordinated bistatic sensing, the sensing organizer coordinates multiple sensing receivers and ensures that their operations are effectively coordinated [78]. In this case, in addition to the challenges of coordinated monostatic sensing, increased computational overhead must be supported.

In ISAC systems, resource allocation, in space, time, frequency, and power directly determines how effectively a given waveform can be optimized to perform both high-fidelity sensing and reliable data transmission [79]. Available bandwidth governs communication throughput and reliability as well as sensing range resolution. Spatial resources, in terms of beam-directionality and shape, and power allocation dictate communication throughput and coverage, while affect sensing volume coverage. Finally, time resources, including symbol duration and pilot overhead, influence Doppler resolution and latency, directly impacting communication latency and throughput and sensing detection range and velocity resolution. These resources must be jointly optimized to achieve optimal ISAC performance.

C. Key Performance Metrics

In this subsection, the most important key performance metrics that have been used in the context of sensing and communication analysis using SG tools are presented.

- **Communication CP:** This is the most common performance metric used in communication- and sensing-enabled networks. It is also referred to as *success probability*. It is formally defined as the probability that the communication SINR at the receiving node exceeds a target threshold γ required for successful demodulation of the communication signal and it is expressed as

$$P_c = \mathbb{P}[\mathrm{SINR}_{\mathrm{com}} > \gamma]. \tag{10}$$

The SINR threshold γ is set with respect to the achievable communication capacity requirement, given by $B\log_2(1+\mathrm{SINR}_{\mathrm{com}})$, where B is the transmission

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bandwidth. The definition in (10) has been used in [63, 70, 80–84].

- **Communication Average Data Rate:** Let $\Phi_{\rm bs}$ denote the PPP that models the spatial locations of BSs with density λ_{bs}. Then, the communication average data rate is given by $R_c = \mathbb{E}_{\Phi_{\rm bs}}[\log(1+{\rm SINR}_{\rm com})]$, where $\mathbb{E}_{\Phi_{\rm bs}}[\cdot]$ denotes expectation with respect to the point process $\Phi_{\rm bs}$.
- **Communication area spectral efficiency (ASE):** Let K denote the number of users served in each cell. Then, the communication ASE is analytically expressed as $T_c^{\rm ASE} = \lambda_{bs} K R_c$ [85].
- **Sensing Average Data Rate:** Let $\Phi_{\rm bs}$ denote the PPP that models the spatial locations of the BSs. Then, the target's average radar information rate based on the sensing SINR ${\rm SINR}_{\rm sen}$ is given by $R_s = \mathbb{E}_{\Phi_{\rm bs}}[\log(1+{\rm SINR}_{\rm sen})]$.
- **Sensing ASE:** Let J denote the number of targets detected in each cell. Then, the sensing ASE is given by $T_c^{\rm ASE} = \lambda_{bs} J R_s$ [85].
- **Potential Spectral Efficiency:** A key performance metric for the design of ISAC networks is the potential spectral efficiency (PSE), which is the network information rate per unit area (measured in bps/m^2) that corresponds to the minimum tolerated signal quality for reliable transmission.
    1) *Communication PSE:* Conventionally, the communication PSE of the communication system is defined as
    $$R_c = \lambda_{bs}\log_2(1+\gamma_c)\mathbb{P}[\gamma_0 > \gamma_c], \tag{11}$$
    where γ_c denotes a target threshold for reliable communication and γ_0 is the received SINR at the typical UE.
    2) *Radar PSE:* The communication PSE of the communication system is defined as
    $$R_r = \lambda_{bs}\log_2(1+\gamma_r)\mathbb{P}[\gamma_i > \gamma_r], \tag{12}$$
    where γ_r is a target threshold for reliable decoding and γ_i is the received SINR at the i-th BS.

  In the context of ISAC networks, the definitions in (11) and (12) have been used in [57].
- **Energy Efficiency (EE):** EE is a key performance metric in communication and sensing enabled networks and typically accounts for both the spatial locations of network entities and the number of these entities. Therefore, it is of great research interest to optimize the density and spatial locations of nodes to maximize the energy efficiency of the network. The EE is defined as a function of the communication and sensing rates and is given by
  $$EE = \frac{R_c + R_r}{P}, \tag{13}$$
  where P denotes the total consumed power. In the context of ISAC networks, the definition in (13) and (12) has been employed in [57].
- **JCAS Coverage Probability:** Let $\Phi_{\rm UE}$ and $\Phi_{\rm s}$ denote the PPPs modeling the spatial locations of UEs and sensing objects, respectively. Formally, the JCAS coverage probability is defined as the *joint* fraction of UEs and sensing objects whose corresponding SINR is above some corresponding threshold and it can be expressed as
  $$P_{c,{\rm JCAS}}(\gamma_{\rm com},\gamma_{\rm sen}) = \frac{\lambda_{\rm UE}\mathbb{P}^0_{\Phi_{\rm UE}}[{\rm SINR}_{\rm com} \geq \gamma_{\rm com}]}{\lambda_{\rm UE}+\lambda_{\rm s}} + \frac{\lambda_{\rm s}\mathbb{P}^0_{\Phi_{\rm s}}[{\rm SINR}_{\rm sen} \geq \gamma_{\rm sen}]}{\lambda_{\rm UE}+\lambda_{\rm s}}, \tag{14}$$
  where $\mathbb{P}^0_{\Phi_{\rm s}}$ and $\mathbb{P}^0_{\Phi_{\rm UE}}$ denote the Palm measures associated with the point processes $\Phi_{\rm s}$ and $\Phi_{\rm UE}$, respectively. In the context of JCAS enabled networks, this definition has been employed in [84] and in [86] to characterize the meta-distribution.
- **JCAS Ergodic Rate:** The JCAS ergodic rate is defined as the *joint* spatial average of the corresponding rate functions. JCAS ergodic rate is expressed as
  $$E_{c,{\rm JCAS}} = \frac{\lambda_{\rm UE}}{\lambda_{\rm UE}+\lambda_{\rm s}}\mathbb{E}^0_{\Phi_{\rm UE}}[\log(1+{\rm SINR}_{\rm com})] + \frac{\lambda_{\rm s}}{\lambda_{\rm UE}+\lambda_{\rm s}}\mathbb{E}^0_{\Phi_{\rm s}}[\log(1+{\rm SINR}_{\rm sen})], \tag{15}$$
  where $\mathbb{E}^0_{\Phi_{\rm UE}}[\cdot]$ and $\mathbb{E}^0_{\Phi_{\rm s}}[\cdot]$ denote expectation with respect to the point process $\Phi_{\rm UE}$ and $\Phi_{\rm s}$, respectively. This definition has been used in [84].
- **$\mathcal{L}$-conditional Positioning CP:** Under the condition of $\mathcal{L}$ BSs participating in the positioning process of an ISAC-enabled network, the positioning coverage is defined as the probability that the received signal strength-based Cramer-Rao Lower Bound (CRLB) $\underline{\mathcal{C}}$ is not greater than the threshold value ϵ. The definition of the $\mathcal{L}$-conditional positioning coverage probability is given by
  $$P_p(\epsilon|\mathcal{L}) = \mathbb{P}[\underline{\mathcal{C}} \leq \epsilon]. \tag{16}$$
- **$\mathcal{L}$-localizability Probability:** The $\mathcal{L}$-localizability in an ISAC network can be defined as the probability that the SINR of the $\mathcal{L}$-nearest BS is greater than the threshold γ. In other words, the $\mathcal{L}$-localizability probability is defined as the probability that at least $\mathcal{L}$ BSs participate in the positioning process. Based on a simple SINR metric, it is mathematically expressed as
  $$P_L(\mathcal{L}|\gamma) = \mathbb{P}\left[\frac{P_t h_{\mathcal{L}} r_{\mathcal{L}}^{-\beta}}{\sum_{i=\mathcal{L}+1}^{\infty} P_t h_i r_i^{-\beta} + N_0} \geq \gamma\right], \tag{17}$$
  where $h_{(\cdot)}$ denotes the small-scale fading channel coefficient power gain, β denotes the path-loss exponent P_t is the transit power of the BSs and N_0 denotes the average power of received noise.
- **Positioning Coverage Rate:** The coverage rate in the positioning process of an ISAC-enabled network is defined as
  $$P_p(\epsilon) = P_p(\epsilon|L_P)P_L(L_P|\gamma) + \sum_{l=3}^{L_P-1} P_p(\epsilon|l)f_L(l|\gamma) + (1-P_L(3|\gamma))u(\epsilon - N_L), \tag{18}$$
  where L_P denotes the maximum number of BSs that can participate in the positioning process, $u(\cdot)$ denotes the step function, N_L denotes a sufficiently large value

and $f_L(\mathcal{L})$ is the PMF of exact $\mathcal{L}$ BSs involved in the positioning process. It should be also noted that the case where $l < 3$ corresponds to the unlocalizable scenario, as shown in [60].

- **Communication Coverage Rate:** The coverage rate in the communication process of an ISAC-enabled network is defined as

$$P_c(\epsilon_c) = \mathbb{P}[\mathrm{SINR}_{\mathrm{com}} \geq \epsilon_c], \tag{19}$$

where ϵ_c denotes a communication coverage rate target threshold.

- **ISAC Coverage Rate:** The coverage rate of the ISAC process in an ISAC-enabled network is defined as

$$P_{p\&c}(\epsilon, \epsilon_c) = \mathbb{P}[\underline{\mathcal{C}} \leq \epsilon, \mathrm{SINR}_{\mathrm{com}} \geq \epsilon_c]. \tag{20}$$

Considering the coupling effects between the positioning and communication process of an ISAC-enabled network, $P_{p\&c}(\epsilon, \epsilon_c)$ can capture the probability that the positioning and communication bounds are jointly lower and higher than ϵ and ϵ_c at any point in the ISAC network, respectively. In the context of ISAC enabled networks, localization-based performance metrics have been used in [60].

- **Rate CP:** The rate coverage probability is an SINR-based metric and is defined as the probability that the downlink rate of the typical UE is above a target rate threshold τ_r. Mathematically, it is expressed as

$$P_{rate}(\tau_r) = \mathbb{P}\left[\frac{K}{K_0} B \log_2(1 + \mathrm{SINR}) \geq \tau_r\right], \tag{21}$$

where K_0 is the number of UEs in the coverage area of the typical BS and K denotes the number of associated UEs of the typical BS. Note that the definition is conditioned on the existence of K_0 UEs in a given coverage area. The definition in (21) has been employed in [87].

- **Sensing Outage Probability:** The sensing outage probability is defined as the probability that a target cannot be detected successfully by BS. In other words, the signal-to-clutter-plus-noise ratio (SCNR) cannot exceed a certain threshold required for successful target detection. The definition has been used in [87].

- **Radar Detection CP:** The radar detection coverage probability is a key performance metric employed in most JCAS- and ISAC-related scenarios. The performance metric can be formulated on the basis of i) SCNR, ii) signal-to-clutter-plus-interference-plus-noise ratio (SCINR), and iii) SINR.

radar detection coverage probability is defined as the probability that the SCNR from a radar target is above a predefined threshold γ. The metric is used to capture the likelihood of a radar target being detected by a monostatic or bistatic radar based on the SCNR metric and can be expressed as

$$P_{\mathrm{rm}}(\gamma) = \mathbb{P}[\mathrm{SCNR} \geq \gamma]. \tag{22}$$

In the context of JCAS networks, the definition in (22) has been used in [88]. A definition similar to that in (22), which is referred to as successful detection probability, has also been used in [87]. In [80], the definition shown in (22) is referred to as sensing coverage probability.

The definition of the radar detection coverage probability can be extended by further considering the aggregate interference from nodes with the JCAS network, i.e., an SCINR-based metric. In this case, the radar detection coverage probability can be defined as the probability that SCINR is above a predefined threshold γ, i.e.,

$$P_{\mathrm{rm}}(\gamma) = \mathbb{P}[\mathrm{SCINR} \geq \gamma]. \tag{23}$$

The definition presented in (23) has been used in [83]. However, considering clutter interference in performance analysis usually makes the statistical characterization of aggregate interference intractable, even if the PPP is used to model the spatial locations of entities in a JCAS network. When considering an appropriate point process for modeling a cluttered environment, such as *cluster point process*, the calculation of the Laplace transform of the aggregate interference power distribution may result in high analytical complexity. To overcome this issue and maintain analytical tractability, clutter interference can be considered negligible compared to aggregate interference from nodes. In this case, the radar detection probability is defined as the probability that the radar receiver detects a real target. Equivalently, this means that the SINR-based metric for the radar receiver should exceed a predefined threshold necessary to detect the target, given that the target actually exists.

In the context of JCAS networks, the SINR-based radar detection probability has been used in [70, 81, 89, 90]. In [91], the SINR-based radar detection probability was alternatively referred to as successful ranging probability. In [65], the above definition is referred to as successful sensing probability.

- **Radar False Alarm Probability:** The radar false alarm probability is defined as the probability that the radar receiver falsely detects a target that does not exist. In the context of JCAS networks, a definition similar to the one above has been used in [64, 81].

- **Joint radar Detection and Communication CP (JRDCCP):** JRDCCP has been proposed as an extension of the definition of communication coverage and radar detection probabilities for JCAS networks. Formally, JRDCCP is defined as the probability of detecting a target with a given false alarm probability at the radar function while achieving a sufficient communication SINR. The key idea here is that interference from communication vehicles affects also the radar function and vice versa. Assume a communication SINR threshold θ and a threshold γ related to the radar function. γ related to the radar function. Then, the mathematical definition of JRDCCP is given by

$$P_{\mathrm{JRDCCP}}(\theta, \gamma) = \mathbb{P}\left[\mathrm{Pr_s} + \mathrm{Pr_c} + \mathrm{I} \geq \theta, \frac{\mathrm{Pr}_c}{\mathrm{Pr}_s + I} \geq \gamma\right], \tag{24}$$

for a given false alarm probability $\mathcal{P}_{FA}(\theta) = \mathbb{P}[\mathrm{Pr}_c + I \geq \theta]$, where Pr_c denotes the power for the communication

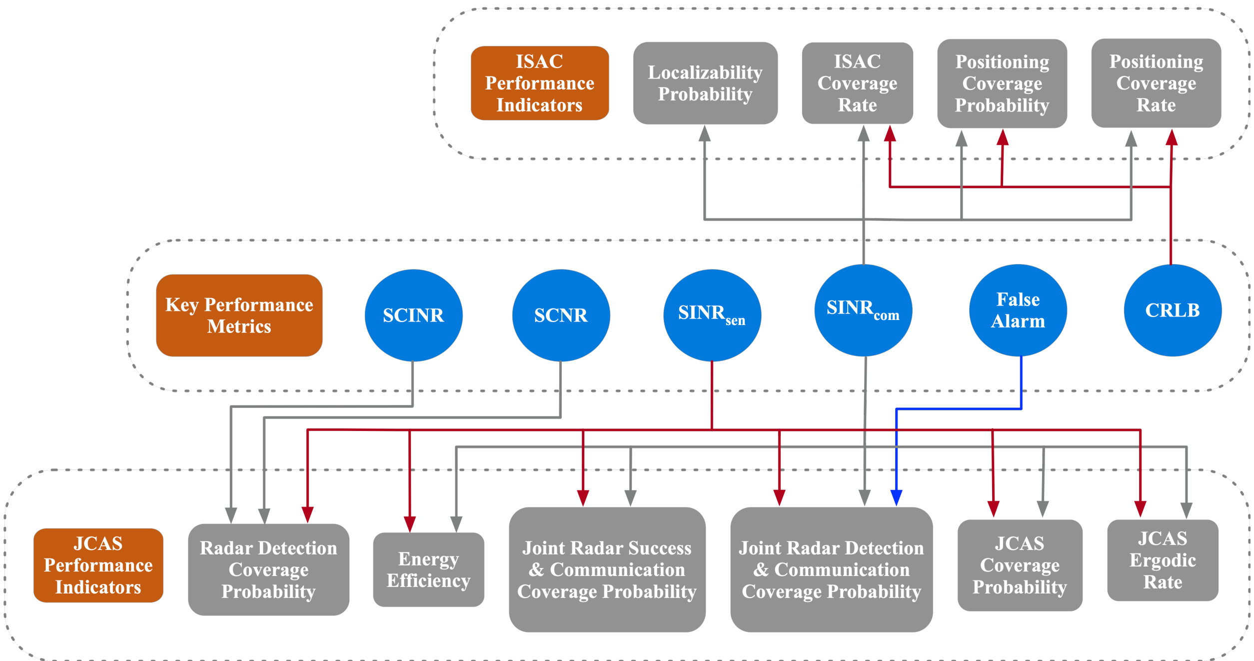

Fig. 4: Major key performance indicators and metrics.

link, Pr_s denotes the power for the radar link and I denotes the interference power from vehicles in the opposite direction of the road. The definition considers the probability of radar detection for a false alarm probability while ensuring a sufficient SINR for the communication function. The threshold γ is selected to meet the false alarm probability requirement, and then the JRDCCP metric is obtained for a given communication SINR threshold θ. The definition in (24) has been used in [81].

- **Joint radar Success and Communication CP (JRSCCP):** JRSCCP has been proposed as an extension to the definition of success probability for JCAS networks. Formally, JRSCCP is defined as the probability of simultaneously achieving sufficient SINRs on both the radar and communication functions. Its analytical expression is given by

$$P_{\text{JRSCCP}}(\theta,\theta') = \mathbb{P}\left[\frac{\text{Pr}_c}{\text{Pr}_s + I} \geq \theta, \frac{\text{Pr}_s}{\text{Pr}_c + I} \geq \theta'\right], \tag{25}$$

where θ and θ' denote the communication and radar SINR target thresholds, respectively. The definition in (25) has been used in [81]. In [92], the definition in (25) is used, but is referred to as the ISAC coverage rate. However, the CRLB metric of the ISAC network is not considered and therefore the definition in (25) differs significantly from the definition presented in (20).

- **Beam Misalignment Probability:** According to 5G NR, the key task of beam alignment is to establish an appropriate beam pair before data transmission [93]. The candidate beam pair is determined on the BS side based on the synchronization signal block (SSB) measurement reported by the user. Missed reception of SSBs and untimely beam switching will cause beam misalignment. Therefore, beam misalignment refers to the cases where the beams are not aligned at the UE and BS sides. In the context of ISAC networks, beam misalignment can be caused by:

1) *Imperfect sensing:* Insufficient resolution of the radar function may cause an estimation error resulting in inaccurate beam alignment [63].
2) *Association timeout:* Frequent beam switches induce a long time delay that is intolerable for latency-sensitive services, referred to as association timeout [63].
3) *Blockage:* The SSB transmission is blocked by nodes, objects, or scatterers [94].
4) *Mobility:* The MT moves too fast and the scheduled SSB has not been received before reaching the beam or cell boundaries [94].

Considering imperfect sensing and association timeout, the beam misalignment probability can be defined as

$$P_{\text{bm}} = P_{\text{err}} + P_{\text{to}}, \tag{26}$$

where P_{err} denotes the probability of imperfect sensing and P_{to} denotes the probability of association timeout in the ISAC network. The definition presented in (26) has been adopted in [63].

Now, assume that mobility- and blockage-related issues lead to beam misalignment. Assuming that no sensing information can be acquired, the beam misalignment probability is defined as

$$P_{\text{bm}}^{\text{no-sen}} = P_{\text{mm}}^{\text{no-sen}} P_{\text{ub}} + (1 - P_{\text{ub}}), \tag{27}$$

where P_{mm} denotes the mobility-induced misalignment probability and P_{ub} denotes the probability of unblocked line-of-sight (LoS) transmission of SSB. Assuming that

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assistance from sensing information is available, the beam misalignment probability is defined as

$$P_{\mathrm{bm}} = P_{\mathrm{rm}} P_{\mathrm{ub}}, \tag{28}$$

where P_{rm} denotes the resolution-related beam misalignment probability. The definitions presented in (27) and (28) have been used in [94].

The main performance metrics presented in this subsection and their relationship to key performance indicators are summarized in Fig. 4.

To conclude this section and enable a meaningful comparison of the various contributions presented in this survey, all ISAC performance metrics studied under the SG framework should be clearly defined. Accordingly, in the final part of this overview, we have: (i) reviewed the ISAC performance metrics examined in the literature, (ii) discussed key differences among them, and (iii) identified the specific research works within the survey that address each metric.

III. System Models Comparison & Discussions

The scope of this section is to present the main system models investigated in Sections IV and V, accompanied by a brief description of their technical characteristics. To this end, two tables have been prepared, namely Table III and Table IV. In order to help the readers get a quick yet clear view of the spatial models presented in Table III, in the following, we refer to the key characteristic of each point process employed, i.e.,

- *HPPP:* Random number of entities with a fixed deployment density on a (usually) infinite area.
- *Cluster Processes (TCP, MCP):* The daughter points arise from the parent points and are clustered around them within a fixed radius.
- *Cox point process:* A Poisson line process is first formed with a given density. Subsequently, the points are deployed on the lines according to a PPP.
- *MHCP (Type I or II):* The key idea is to start from a simple HPPP. Then, we remove the points that have a neighbor within a predetermined distance.
- *β-GPP:* By considering a Kernel function for the points' spatial location, β parameter is used to adjust the repulsion intensity.

To understand the main objectives and novelties of the research performed in the area of sensing and communication systems analyzed by SG, in Table III, an attempt is made to categorize the system models studied. It is noted that the references included in each row of the last column of this table are characterized by the same system model as depicted in the first column. A general observation that emerges from this table is that three main types of networks have been considered, namely terrestrial, aerial, and vehicular. Interestingly, a wide range of system models have been explored in the literature, where SG principles have been used effectively to model the spatial distributions of various network elements, such as BS, UEs, targets, link path blockages, and scatterers. These models enable a realistic representation of spatial interactions and heterogeneity in modern wireless networks, facilitating a tractable analysis of key performance metrics, including coverage and sensing accuracy.

Some further comments related to the findings that are tabulated in this table are the following:

- 3D point process models are very rarely used, even in aerial communications scenarios, despite the fact that this type of models have an important practical interest;
- The general scenario where the positions of all network elements, e.g., BSs, users, targets, blockages, scatterers, are modeled using spatial point processes has not been studied;
- In most cases, PPP has been employed, usually for mathematical simplifications purposes;
- The impact of randomly distributed blockages has not been thoroughly investigated in the existing studies;
- In several studies, the main contribution was related to beamforming (coordinated or not) issues, e.g., beam alignment, interference cancellation (or mitigation);
- In most cases, radar clutter is not taken into account despite the fact that it is responsible for detection errors, false alarms, and interference in ISAC systems;
- Clutter interference can accurately be modeled through cluster point process which has been largely ignored in the existing studies;
- In many cases, the same time and frequency resources have been used for both sensing and communication;
- The existing literature includes only a few works employing multicarrier schemes, and an even smaller number explores NOMA-based implementations;
- There are cases, where time (or frequency) division approach is employed;
- A very limited number of studies focus on CAS scenarios, despite the fact that this type of systems are very important especially in V2X applications, where enhanced environmental awareness is expected;
- The impact of large-scale fading, i.e., shadowing, is not taken into account, despite the fact that it is a critical factor in both aerial and vehicular communications;
- In almost all system models investigated, independent point process have been considered despite the fact that Poisson cluster processes, e.g., MCP and TCP, and DPP are particularly useful in modeling more realistic spatial distributions where certain spatial correlation between points exist.

Key insights can also be derived from Table IV, which can be summarized as follows.

- An important part of the research has omitted antenna patterns from the analysis;
- The impact of interference has been considered in the presented analysis;
- In some cases, the effects of blockage and/or clutter have been investigated;
- Several studies have ignored propagation conditions with respect to the presence or absence of a LoS component;
- Small-scale fading has been taken into account is most cases, at least for the communication functionality;

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TABLE III: Presentation of the main system models

Spatial Model of Network Entities	System Model Aspects and Contributions	Time/Bandwidth Allocation	Refs
BS, users, and targets follow PPP in 2D	1: Cooperative ISAC, coordinated beamforming, cooperative sensing 2: Cooperative sensing, cooperative communications, CRLB investigation, cluster size optimization in conjunction with power allocation 3: The impact of network deployment density is studied on the JCAS SIR performance	1,2: Same time and frequency blocks for communication and sensing 3: Communication and sensing occur in separate time-frequency resources	[85] [95] [96] [86]
BS and users follow PPP in 2D, while targets are UAVs distributed in a circle at height h	1: Maximize the energy efficiency 2: Zero-forcing precoding is employed under a multi-user MIMO (MU-MIMO) network	All BSs share the same transmission bandwidth	[57]
Users and undesirable scatterers follow independent PPP, BS or AP position is fixed	1: MmWave system with beamwidth investigations, in which antenna misalignment is studied 2: Explore/exploit duty cycle, the transmitted power, (bistatic) radar bandwidth and pulse repetition interval for maximizing the network throughput 3: MmWave system that takes into account the impact of clutter, antenna models RCS and interference	1,3: Sensing and communication are carried out simultaneously in different frequency bands 2: Time division approach is employed	[83] [88] [97]
BS and users follow independent PPP	1: Evaluating the ergodic sensing rate constrained by the maximum communication rate, and the ergodic communication rate constrained by the maximum sensing rate 2: Success serving probability is defined for both the communication and the sensing tasks based on mutual information	1: Communication and sensing occur in separate time-frequency resources 2: Sensing and communication are carried out simultaneously in different frequency bands	[60] [98] [99]
Sensing infrastructure and fusion centers follow Matern cluster process (fusion centers are parent process following PPP and sensing infrastructure are daughter process uniformly distributed around the fusion center)	Sectored antenna are assumed, delay upper bound of the sensory data transmission is investigated	Time division approach is employed	[65]
BS follow PPP, blockage follow Boolean line process, users and sensing targets are mutually independent point processes	Multi-carrier waveform is assumed, shared waveform, directional beamforming, and monostatic sensing	Communication and sensing occur in separate time-frequency resources	[84]
BSs follow PPP, while sensing targets and users distances from BS have been evaluated using a probabilistic approach	The distance-dependent blockage model is adopted, which integrates the effects of LoS, NLoS, and target reflection cascading paths	Time division approach is employed	[100]
BSs, mobile terminals and blockers follow PPP	1: MT are moving in a straight line, and beam misalignment is investigated 2: THz, MT are moving in a straight line, minimization of beam misalignment is performed, coverage probability is investigated	Orthogonal resources in time and frequency	[94] [101] [63]
Macro BS and small BSs follow independent PPP, UEs and targets also follow independent PPPs	1: RIS-aided NOMA scheme is investigated, interference comes from other BSs 2: The performance of RIS-NOMA is compared with that of RIS-OMA	Time division approach is employed	[62]
Primary and secondary network transmitters follow independent PPP, each blockage follows an independent stationary point process	In a cognitive network, a sense and predict approach is used to maximize the ASE of secondary networks	Time division approach is employed	[102]
BSs are distributed according to β-GPP, the points of interest are distributed according to PPP	Full duplex, self interference between radar and communication antennas, a cooperative multi-point radar detection technique is proposed	Time division approach is employed	[70]
APs are distributed as PPP and tagged user and sensing targets are assumed at the origin	THz communication study, in which the human body blockage has been investigated	Three waveform design schemes are compared frequency-division ISAC, time-division ISAC, and fully-unified ISAC	[103]
APs are distributed according to PPP, UEs are uniformly distributed on a circle around the transmitters	CSMA/CA-based channel access mechanism is used, the sensing performance is analyzed in terms of the maximum unambiguous range	Time division approach is employed	[104]
BSs and radars are distributed according to independent PPPs, users are distributed uniformly and independently	Dynamic transmission strategy is proposed in a bistatic detection architecture	Resource blocks are assigned in both communication and sensing	[105]
BSs are distributed according to the PPP communication mode UEs are distributed uniformly and independently at random in the Voronoi cells of the BSs	Full duplex is assumed and successive interference cancellation is proposed	Resource blocks are assigned in both communication and sensing	[89]
Road infrastructure, vehicles, and obstacles follow a superimposed generalized PPP in 2D	Cooperative JCS cooperative detection model, calculate the probability of successful JCS detection and communication	Same time and frequency blocks for communication and sensing	[90]
Vehicles and roadside units follow independent PPPs in a two-lane vehicular network	1: ISAC performance evaluation in SG, Monte-Carlo, and ray-tracing frameworks 2: Introduction of joint coverage and detection performance metrics for ISAC, cooperative detection with interference cancellation	Same time and frequency resources for sensing and communication	[106] [81]

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TABLE III: Presentation of the main system models investigated (continued from previous page).

System Model	Main Contributions	Time/Bandwidth Allocation	Refs
BSs and UEs follow independent PPPs in 2D	Joint consideration of power and spectrum allocation for ISAC, design of an adaptive beamwidth strategy for communication	Time division or frequency division approach is employed	[80]
BSs, UEs, and UAVs follow independent HPPPs in 2D	Cooperative ISAC for UAV surveillance, optimization of network configurations for sensing and communication performance	Same time and frequency resources for communication and sensing	[87]
BSs follow cellular structure in 2D, UAVs follow independent PPPs in 2D and there are uniformly distributed buildings (obstacles)	Co-design of communication and bistatic radar sensing for UAV network resilience; novel RCS estimation method	Non-overlapping spectrum allocation between communication and sensing	[64]
UAV with radars and UAV for communications follow independent 2D HPPPs	Closed-form expressions for successful ranging probability and transmission capacity	Spectrum overlay multiple access and time-division multiple access	[91]
Vehicles and roadside units follow a Cox PPP	Joint communication and computation-assisted sensing analysis with age of information as a key performance metric	Same time and frequency resources for sensing and communication	[71]
Vehicles follow a 1D Matérn hard-core process of type II	Design of a dual-beam ISAC scheme enabling 360^o radar detection and directional communication	Same time and frequency resources for sensing and communication	[107]
BSs, users and sensing targets follow independent HPPPs in 2D	Design of cooperative beamforming to mitigate interference	Same time and frequency resources for sensing and communication	[108]
Sensing targets follow a spatial HPPP in 2D	1: UAV trajectory optimization for ISAC with SAR, considering energy efficiency 2: UAV trajectory optimization for communication-assisted radar sensing	Same time and frequency resources for sensing and communication	[109] [110]
Vehicles follow a 1D PPP	1: Derivation of closed-form expressions for cooperative detection range 2: A CAS scenario is investigated for automotive radars	1: Shared spectrum allocation between radar and communication 2: Frequency division approach is employed.	[111] [112]
UAVs, UEs, targets, and blockages follow independent HPPPs in 2D	Analytical expressions for the communication coverage probability and successful detection probability are provided under the impact of blockage	Not specified	[113]

- Multiple antenna studies have been reported, but their number is relatively limited;
- In most studies, the presented approach is multiple access scheme agnostic;

In light of the remarks and observations mentioned above, it is evident that research interest shifts towards investigating the impact of realistic antenna patterns and MIMO technology on ISAC performance. In fact, as the number of antennas in large-scale MIMO ISAC systems increases, more precise and narrower beams can be formed for communication and sensing purposes. The exploitation of multiple antennas in ISAC systems not only improves the average data rate in communication but also enhances the accuracy of localization and tracking. As ISAC progresses towards exploiting more complicated UPA antennas, the antenna array design of ISAC networks needs to support great flexibility and therefore it should be carefully considered for realistic performance evaluation. However, it is surprisingly to observe that only [87] has considered the geometrical characteristics of a UPA antenna. In fact, the integration of realistic 3D antenna patterns or UPAs into the performance evaluation of ISAC systems renders the obtained system insights marginal due to the inherent high analytical complexity that typically arises. This observation is further substantiated by the fact that only [72] moves beyond the HPPP spatial model while additionally accounting for beamforming capabilities and more realistic and complex antenna patterns, compared to the commonly assumed flat-top approximation. As the research trend increasingly shifts towards MIMO ISAC technology, there is a growing expectation of additional research beyond the HPPP spatial model, while simultaneously striving to strike a balance between accuracy and analytical complexity. To address this challenge, the interaction between SG and optimization tools is anticipated to play a central role.

On another front, while the links between LOS and NLoS connections, primarily determined by the presence of obstructions, significantly contribute to ISAC performance metrics, their combined impact has scarcely been examined. Indeed, while LoS/NLoS links strongly influence user association policies and communication performance, their impact on radar functionalities and sensing coverage necessitates a more nuanced investigation. In this regard, RIS-empowered ISAC may assume a pivotal role in scenarios where sensing targets lack LoS connections or possess weak LoS links, thereby revealing novel and insightful information in large-scale SG frameworks. Similarly, while environmental clutter substantially determines the SCNR metric in radar functionality, it is evident that clutter interference is rarely considered. However, suppression of echoes reflected by clutters remains a primary objective in ISAC systems. The design and development of SG-based schemes that simultaneously suppress clutter interference while employing advanced spatial point processes to realistically model network entities remain a critical challenge.

As shown in Table III, the HPPP has been widely used in the SG framework to model the positions of BSs, UAVs, users, targets, and blockages within ISAC networks. The works [85, 86, 95, 96] have considered three distinct PPPs to model the locations of BSs, users, and targets. This approach offers both analytical tractability and model robustness. This is because altering the position of the typical receiver within an infinite PPP-based spatial model does not impact the model's performance. In an attempt to simplify the mathematical analysis at the expense of reduced robustness, the works [83, 88, 97] modeled users and scatterers as two independent

TABLE IV: Technical features and channel characteristics in existing literature ("c" and "s" stand for communication and sensing, respectively, and "non FT" stands for non flat-top antenna pattern).

Reference	HPPP	Antenna Pattern	Interference	Blockage/Clutter	LoS/NLoS	Small-scale Fading	MISO / SIMO / MIMO	Multiple Access Scheme
[60]	✓	✗	✓	Blockage	✗	✓(c)	✗	✗
[85]	✓	✗	✓	Clutter	✗	✓(c)	MISO	✗
[57]	✓	✗	✓	Clutter	✗	✓(c,s)	MISO	✗
[65]	✗	✓	✓	✗	✗	✓(c,s)	✗	✗
[96]	✓	✗	✓	✗	✗	✓(c)	MISO	✗
[100]	✓	✗	✓	Blockage	✓	✓(c,s)	✗	✗
[114]	✓	✗	✓	✗	✗	✓(c)	MISO	CoMP-CDM
[62]	✓	✗	✓	✗	✓	✓(c,s)	MIMO	NOMA
[115]	✓	✗	✓	✗	✗	✓(c,s)	✗	✗
[88]	✓	✓	✗	Clutter	✗	✗	✗	✗
[84]	✓	✓	✓	Clutter	✓	✓(c,s)	✗	✗
[70]	✗	✓	✓	✗	✓	✓(c,s)	✗	✗
[83]	✓	✓(non FT)	✓	Clutter	✓	✓(c,s)	✗	✗
[82]	✓	✓	✓	✗	✗	✓	✗	✗
[102]	✓	✗	✓	Blockage	✗	✓	✗	✗
[63]	✓	✓(non FT)	✓	Blockage	✗	✗	✗	OFDM
[94]	✓	✗	✗	Blockage	✗	✗	✗	✗
[81]	✓	✗	✓	✗	✗	✓(c,s)	✗	✗
[72]	✗	✓(non FT)	✓	✗	✗	✓(c,s)	MIMO	OFDM
[90]	✗	✗	✓	✗	✓	✓(c,s)	✗	✗
[64]	✓	✓(non FT)	✗	✗	✗	✗	✗	CDM
[91]	✗	✗	✓	✗	✗	✓(c,s)	✗	SOMA/TDMA
[80]	✓	✗	✓	Clutter	✗	✓(c,s)	✗	TDMA/FDMA
[87]	✓	✓	✓	Clutter	✓	✓(c,s)	MISO	✗

point processes while the positions of the BSs were considered predetermined. Although the infinite-point process is suitable for conducting large-scale performance evaluation of ISAC networks, it cannot capture finite 2D or 3D networks where a predetermined number of entities is employed in a finite region. Although [70] used the β-GPP point process to model the location of the BSs, the performance analysis was limited to the typical radar target while no point process was used for blockages. Finally, only [65] has used the MCP to capture the spatial correlation between the fusion centers and the sensing infrastructures. Similarly, the works in [81, 90, 106, 111, 112] have used HPPP to model vehicle spatial locations, while only [107] and [71] have used the 1D-MHCP and Cox point process, respectively, to model vehicle locations. Although 1D-MHCP is more accurate in modeling vehicle locations compared to oversimplified PPP, PLP is the most accurate point process to model vehicles on roads modeled as straight lines. However, the resulting Cox point process often leads to an intractable analysis. In fact, the technical challenges come from the spatial coupling between the vehicular nodes induced by the underlying PLP. Consequently, the expressions for the performance metrics consist of nested integrals, which can reveal limited system-level insights.

With respect to the architectures that have been investigated, two main categories have been identified, namely terrestrial and vehicular/aerial networks. Based on these categories, the reviewed works are summarized in Section IV (Terrestrial Networks) and Section V (Vehicular/Aerial Networks).

IV. Terrestrial Networks

In order to better understand the commonalities and differences between the reviewed works, the contributions have been classified into ISAC, JCAS, and SAC systems.

A. Integrated Sensing and Communication

1) Cooperative ISAC: The exploitation of cooperation in the performance evaluation of ISAC networks has been widely considered in the literature. Once the performance of cooperative ISAC networks has been demonstrated at the system level, optimization techniques can be applied in terms of key parameters such as transmit power [85] or cluster size in cooperative ISAC networks [116]. In such cases, key design insights to improve the performance of ISAC networks are revealed.

In [85], a cooperative ISAC network was proposed using coordinated beamforming for interference nulling. The distribution of BSs, users, and targets was modeled as a PPP. The performance of the considered scheme was evaluated using the ASE criteria for both sensing and communication operations. Interference nullification was shown to improve the average data and radar information rates. Such an approach is necessary to maximize the sensing ASE, but not always for the communication ASE. The fixed relationship between the number of service users and the BS transmit antennas was also revealed for optimal performance.

In [114], a cooperative architecture was proposed for ISAC-enabled networks, incorporating coordinated multipoint transmission (CoMP) along with multistatic sensing. To account for practical aspects, the impact of the allocation of antennas to BSs on cooperative sensing and cooperative communication performance was investigated. By modeling the spatial locations of the BSs as a 2D PPP, analytical expressions for the communication data rate and the CRLB were obtained. Subsequently, the paper focused on the sensing performance by investigating three localization techniques to assess their effects on ISAC network performance. After investigating key performance metrics, a performance boundary optimization problem was studied. The results verified that cooperative transmission and sensing in ISAC networks can effectively improve sensing and communication gains and strike a more flexible trade-off between sensing and communication performance. In addition, the proposed cooperative scheme shows superior performance improvement compared to centralized or distributed antenna allocation strategies, especially when using a large number of antennas.

In [116], a cooperative ISAC scheme was investigated, revealing critical cooperative dependencies in the ISAC network. Specifically, a coordinated beamforming approach was proposed for adaptive interference nulling, with each BS transmitting to multiple users and performing sensing operations. The study derived the expression for the sensing and communication ASE to analyze spatial resource allocation objectives, including spatial diversity gain, spatial multiplexing gain, and interference nulling. The BS, users, and target locations followed an HPPP. It was shown that interference nulling is not necessary to maximize communication ASE but is necessary to maximize sensing ASE.

In [95], a cooperative ISAC scheme was proposed that integrates CoMP joint transmission and multi-static sensing. By optimizing the size of the cooperative BS cluster, the performance of sensing and communication (S&C) performance was balanced. The network model included BSs, users, and targets, all modeled as independent PPPs. The authors quantified ISAC performance in terms of data rate and Cramér-Rao lower bound (CRLB), applying SG techniques. The simulation results indicated that the cooperative scheme outperforms the time-sharing scheme with more resources and larger backhaul capacity.

In [96], ISAC performance was quantified in terms of data rate and CRLB, applying SG techniques for analysis. In the network considered, each BS was assumed to support multiple transmit and receive antennas, with locations modeled as HPPP. Communication users and targets were also modeled as independent PPPs. By optimizing cooperative cluster sizes and power allocation, the data rate-CRLB region and the weighted sum of data rate and inverse CRLB were maximized. The CRLB expression showed that the deployment of (N) ISAC transceivers enhances the cooperative sensing performance according to the scaling law $(\ln^2 N)$. The simulation results presented showed that the proposed scheme improves the data rate and reduces the CRLB, outperforming conventional time-sharing schemes.

A common approach in all the aforementioned works is the exploitation of optimization tools. In particular, it was shown that proper optimization of the cooperative cluster size and power allocation can provide a balanced trade-off between sensing and communication performance. In [85, 116] the exploitation of interference nulling in mitigating interference in cooperative ISAC networks was investigated. Taking a step further, [95, 96] delved into the fundamental limits of cooperative ISAC networks by demonstrating a reduction in the CRLB metric. However, from an SG point of view, it is worth mentioning that oversimplified point processes were employed to model the spatial locations of nodes, such as the PPP. In light of this, it becomes clear that a more nuanced point process can be adopted to realistically model the spatial locations of nodes within the cooperative clusters, such as the MCP and the TCP.

2) RIS-assisted ISAC: Recently, RISs have received considerable attention due to their ability to mitigate blockage effect in ISAC networks. Nevertheless, in the context of SG, the implication of RISs remains shallow.

In [92], the gain in the coverage rate from RISs in ISAC networks was theoretically investigated. The BSs, equipped with multiple antennas and blockages, were modeled as PPP. RISs were deployed to enhance ISAC performance, with optimal densities of BSs and RISs identified for practical deployment. Using mmWave beamforming, user association policies, and conditional coverage rates were derived, with the marginal coverage rate calculated using distance-dependent thinning. The joint coverage rate improvement from 67. 1% to 92. 2% was shown with the deployment of RIS.

In [62], an analytical framework was introduced to evaluate downlink transmissions in MIMO IoT heterogeneous networks (HetNets) with ISAC capability. By modeling the spatial locations of the NOMA-enabled BSs and the UEs as independent PPPs and by further utilizing the RIS technology, approximate and asymptotic expressions for outage probability were derived for i) a scenario involving direct transmission from the BS to the typical blocked user, and ii) a scenario involving transmission via active RIS. In addition, approximate expressions for the ergodic rates, the system throughput, and the beam pattern for the sensing performance were also derived. The results emphasized the benefits of the proposed active RIS-non-orthogonal multiple access (NOMA) over conventional orthogonal multiple-access HetNets and revealed that an increase in the number of RIS elements significantly improves the proposed active RIS-NOMA outage performance.

Given the aforementioned, [92] illustrates the enhancement in the joint coverage rate achieved by considering the deployment density of RISs. Conversely, [62] focuses on demonstrating the impact of the number of RIS elements on i) the communication outage probability, ii) the ergodic rate, and iii) the sensing SINR. A common approach employed in both works is i) the exploitation of the Poisson process for modeling the spatial locations of RISs and ii) the nearest distance-based association scheme. Nevertheless, the two works show a notable disparity in a key aspect of the association scheme. Although the links between LoS and NLoS are implicitly incorporated in the performance analysis of [62], they are ignored during the user association procedure, a distinction not observed in [92], where such differentiation is explicitly acknowledged.

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3) Beamforming: Enabling beamforming capabilities in SG-based ISAC frameworks has started gaining considerable attention due to the potential of adapting the antenna pattern's beamwidth either for enhancing target detection or for enhancing communication performance. In fact, increasing the beamwidth during the detection phase increases the probability of detecting more targets. In contrast to this, small beamwidth values indicate narrower beams which are suitable for beamforming during the communication phase. The following works consider beamforming capabilities in the performance analysis.

In [65], the Matérn cluster process (MCP) was used to model the spatial locations of the sensing infrastructures and fusion centers in an ISAC network. Note that the fusion centers are collection points for sensing information. Detection and transmission occur on the same mmWave spectrum, with orthogonal sub-bands allocated to SIs to reduce intra-cluster interference. The service capability of sensory data transmission is analyzed, which is characterized by the successful sensing probability. In addition, the delay upper bound was investigated using stochastic network calculus, which was subsequently transformed into an SNR-based metric. An optimal power allocation strategy was proposed to minimize the transmission delay, balancing sensing quality and latency.

In [66], a digital twin (DT)-based model drift-adaptive resource reservation scheme for ISAC-enabled networks was proposed. The term model drift was defined as the degradation of the accuracy of a predictive model when the data distribution changes. Using SG tools, two spatial models were adopted for the location of ISAC devices and sensing targets. In the first model, the spatial locations of the ISAC devices and the sensing targets were modeled as independent 2D PPPs, while in the second model, the spatial locations of the ISAC devices and the sensing targets were modeled as PPP and TCP, respectively. The goal was to provide a statistical quality of service guarantee with minimal resource consumption for a sensing service. To this end, a DT was constructed in the network controller to collect the location of the sensor nodes and the targets. The simulation results showed that the proposed resource reservation scheme was able to reduce the resource under and over-provision under non-stationary network conditions.

In [103], a framework for THz ISAC networks was presented, which also considered blockage effects, antenna radiation, and association schemes. The system model involved the deployment of random access points via a 2D HPPP, with APs serving as transmitters and transceivers for communication and sensing. Analytical expressions for the CP and sensing probability were derived using the moment generating functions (MGFs) of aggregated interference. The network capacity analysis compared three THz ISAC waveform designs, showing that the high AP density maximizes communication and sensing coverage probabilities. The narrower beamwidth improves the average communication rate, while the average sensing rate initially increases and then decreases.

In [99], the theoretical performance of ISAC networks was studied, where BS and UE were modeled as independent HPPPs. Each UE accesses the nearest BS to form a Voronoi tessellation, and each BS has its corresponding sensing target. Each target is randomly located in a disk region with the corresponding BS as the center. The paper introduced the success serving probability as a unified analytical framework based on mutual information for both communication and sensing. The study highlighted the importance of beamforming and the distribution of sensing targets in optimizing ISAC network performance.

In [57], an analytical framework was introduced to analyze the performance of sensing and communication in dense ISAC networks. The locations of the BSs, users, and targets were assumed to be modeled as PPPs. Closed-form expressions were obtained to evaluate PSE and EE. Moreover, based on the derived results, an optimization problem for optimal BS density was formulated and validated through Monte Carlo simulations. It was revealed that the optimal BS density for ISAC networks is lower than that for communication-only networks, improving the coverage radius and energy efficiency, especially in low transmit power regions.

In [60, 98], the fundamental limits of the performance of ISAC were evaluated under resource constraints. A generalized SG framework was proposed in which the location of BSs and users are modeled using an HPPP. BSs perform positioning and communication functions during downlink transmissions, while users access positioning pilots from the nearest BSs for self-positioning while receiving communication data from the nearest BS. Theoretical results related to the coverage rate highlighted the impact of the BS density on ISAC performance, showing an improvement in the coverage rate from 1. 4% to 39. 8% as the BS density increases from 1 km^2 to 10 km^2.

It is noteworthy that the works [65, 66, 99] explore simplified or scaled-down beamforming capabilities by employing straightforward sectorized antenna patterns. In contrast, [99] adopts an antenna pattern based on the pyramidal shape, accommodating both azimuth and vertical beamwidth. Conversely, [57] employs a realistic precoding vector during the performance analysis of dense ISAC networks. Notably, while [60] also uses a sectorized antenna pattern, it delves deeper into beamforming procedures by incorporating realistic beamforming vectors in the definition of SINR metrics. Lastly, in contrast to the works of [57, 65, 66, 99], the work in [103] demonstrates the influence of the azimuth beamwidth on the average communication and sensing rates.

4) Blockages: Surprisingly, although the effect of blockages substantially determines the performance of ISAC networks, its impact remains shallow. Indeed, in [100], the coverage performance of ISAC networks was examined under blockage effects. In this context, a general analytical model was proposed that utilizes time-division duplexing to avoid mutual interference. The locations of BSs were modeled as PPP, while for simplicity, sensing targets were considered as point scatterers, primarily detectable under LoS conditions. The performance metrics used included the communication SINR and sensing coverage probability. It was shown that increasing the BS density improves the coverage probability when the BS density is lower than the blocking density. Moreover, an optimal BS density was identified for maximizing

This article has been accepted for publication in IEEE Communications Surveys & Tutorials. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/COMST.2025.3594560

coverage probability, with blocking providing favorable gains by reducing interference.

Based on the aforementioned, while [100] provides a comprehensive analysis of the impact of blockages on ISAC performance, specifically examining rectangular blockages of random length and width, it is evident that further investigation of the blockage effect is necessary. Notably, while antenna patterns were not explicitly considered at the BSs, a thorough examination of the impact of directional links, coupled with the incorporation of 3D blockage effects, will yield novel design insights.

5) Resource Allocation: Many works investigating ISAC networks have demonstrated the impact of resource allocation, i.e., time, frequency, power, and beam direction, on the performance of ISAC systems. Since ISAC inherently refers to a *shared* waveform for communication and sensing functions, the impact of shared resources on i) ISAC performance and ii) the trade-off between communication and sensing needs considerable attention. The following works address the impact of resource allocation on ISAC performance.

In [89], a large full-duplex ISAC-enabled cellular network was studied to efficiently reuse the scarce spectrum. By modeling the spatial locations of the BSs and UEs as independent PPPs, the detection probability at the BS was investigated based on the received SINR metric. To this end, both self-interference cancellation and successive interference cancellation schemes were utilized to successfully decode communication and sensing signals at the BS. Numerical results revealed that after a certain level of residual self-interference, decoding/detection is not viable, while the sensitivity of both radar and communication modes was demonstrated.

In [61], the age of information (AoI) in massive mobile sensing networks was investigated considering channel fading, path loss, and ISAC-enabled network topology, as well as the problem of shared spectrum interference. By modeling the spatial locations of the receivers and the sensing nodes as independent PPPs, the upper and lower bounds of AoI were derived, and the relationship between AoI and mobile speed, spatial density, and channel access probability was demonstrated through simulations. The numerical results demonstrated that the average AoI decreases as the average speed of the interferers increases under a last-come-first-served discipline.

In [105], a dynamic transmission strategy was proposed in which the quantity of radar mode detection is traded for quality as a countermeasure to the fact that interferers in radar mode in ISAC-enabled networks have direct links. By modeling the spatial locations of the BSs and radars as independent PPPs, we investigated and compared the performance of both the radar and communication modes with and without a dynamic transmission strategy with the performance of a conventional radar-only network. The numerical results revealed that the dense deployment of low-cost passive radars offers superior detection for farther targets, especially compared to a radar-only network.

In [115], a distributed ISAC network was investigated in which ISAC users were randomly distributed in a circular area using an HPPP. These ISAC users share a common bandwidth and transmit power and simultaneously transmit communication and sensing signals that interfere with each other. Performance was evaluated in terms of coverage and detection probabilities, which were obtained in closed form. Extensive simulations confirmed the accuracy of the derived results, highlighting the fundamental performance limits and trade-offs in distributed ISAC networks.

Based on the aforementioned, the works [89, 115] consider both frequency and power allocation. However, in contrast to [89], the authors in [115] delve deeper into the investigation of the trade-off between sensing and communication when resource allocation is considered. The authors in [61] assume a shared spectrum resource allocation, while [105] further adopts a time allocation, leading to a time-frequency resource allocation. Surprisingly, the impact of beam allocation in ISAC performance and fundamental trade-offs between sensing and communication functions has not been investigated.

B. Joint Communication and Sensing

1) Time Division: Time division approach is widely adopted in JCAS systems, as it reduces interference and allows simplified waveform designs. In [88], a JCAS system was investigated, focusing on bistatic/passive radar deployments with directional beams to identify MUs and establish communication links. The distribution of the scatterers was modeled as an HPPP. Performance metrics include network throughput, radar detection efficiency, and joint radar and communication reliability. Based on SG tools, an optimization of the JCAS parameters, e.g., exploration/exploitation of a time management scheme, radar bandwidth, transmit power, and pulse repetition interval, was performed to maximize throughput. Monte Carlo simulations validated the theoretical results, highlighting the trade-offs between detection success and clutter density, achieving a peak JCAS reliability of 70% for bistatic configurations.

In [104], the performance of a JCAS network was investigated, in which nodes switch between radar and communication modes in an uncoordinated time division manner. The nodes followed a CS-based medium access protocol, and their locations are modeled as a PPP. Key contributions included the development of an analytical framework for evaluating CSMA-based JCAS networks, the modeling of interference from uncoordinated transmissions, and the analysis of sensing performance in terms of the maximum unambiguous range. The study also derived closed-form expressions for the mean access probability and the aggregated network throughput density, which were validated through extensive simulations. These findings help to characterize both radar and communication performance in large-scale JCAS networks.

In [117], the performance of a time-sharing JCAS network was studied, where the nodes (distributed as HPPP) switch between radar sensing and data transmission modes. The study proposed approximation methods to evaluate various performance metrics, such as the maximum detectable radar range under a desired false alarm probability, packet loss rate, and per-node throughput, providing information on resource allocation strategies, such as communication packet length and radar update rate. The trade-offs between radar and communication performance in a shared bandwidth scenario were highlighted. To this end, it can be inferred that, in order to support throughput-intensive applications, JCAS nodes may allocate fewer time slots to radar operations. When longer search durations are permitted, narrower beams can be employed for user detection, thereby increasing the likelihood of accurately locating MUs. This highlights a fundamental aspect of the trade-off inherent in the joint radar-communication network: enhanced detection performance comes at the cost of significantly reduced data transmission capacity.

2) MmWave: MmWave communications are well-suited for JCAS systems, owing to their distinctive characteristics, i.e., the large available bandwidth and high antenna directivity, which enhance the quality of the direct link. In [70], the coexistence of full-duplex JCAS systems in mmWave HetNets with repulsive node distributions was investigated. The study developed an analytical framework using SG to model these networks, considering the spectrum sharing and radar sensing capabilities of the BSs. Specifically, the BS distribution was modeled as a β-GPP. In this context, a cooperative multi-point radar detection technique with three hard-decision combining rules (OR, Majority, AND) was proposed, and analytical expressions for detection performance were provided. Repulsive BS deployment was shown to improve detection performance by reducing interference, and temporal interference correlation significantly affects network performance.

In [97], an SG-based framework was used to analyze the performance of a mmWave JCAS system. The system included a sensing subsystem for radar detection of MUs and a communication subsystem using directional antennas. Both functions were operated simultaneously to reduce delay and improve beam alignment. The network was modeled with MUs and scatterers whose distribution follow PPP, and JCAS nodes in hexagonal cells acting as monostatic radars and BSs. The performance of the system was evaluated in terms of CP and detection probability, with parameters of interest the MU and clutter density, RCS fluctuations, radar search duration, antenna directivity, and bandwidth. Radar sensing was shown to significantly affect overall performance, with the duration of radar search being critical to maximizing the average system throughput. Therefore, although mmWave signals experience higher path loss and are more susceptible to blockages, these properties can actually benefit network performance by reducing overall interference. Moreover, mmWave signals are highly sensitive in blockage, rendering SG a viable approach to modeling spatial distributions in practical deployments. Furthermore, the extensive bandwidth available at the mmWave frequencies not only facilitates higher communication data rates but also improves radar range resolution, thus increasing the system's capability to discern between closely spaced targets or users.

3) Multicarrier: Multi-carrier signals, for example OFDM, are highly beneficial in JCAS networks since they may offer high resolution of time and frequency dynamically [118]. These waveforms enable frequency-domain parameter estimation at the symbol level, reducing inter-symbol interference and allowing joint analysis of sensing and communication within the receiver framework. In [84], a rigorous analytical framework was presented and used to characterize the joint performance of communication and parameter estimation JCAS networks with a shared multi-carrier waveform. The BSs and sensing objects were modeled as stationary, ergodic point processes. Performance metrics included coverage probability and ergodic rate, derived using mutual information and Fisher information matrix. The concepts of CP and ergodic rate were extended to radar settings using mutual information. In addition, methods were developed to obtain bounds on the Laplace transform of shot noise processes, while a new analog of Hölder's inequality was introduced. Closed-form bounds and approximations for JCAS coverage and rate were provided and validated through numerical case studies, highlighting the trade-offs between sensing and communication performance. The sensing SINR was shown to improve with BS density, while interference affects sensing more than communication.

In [86], a fine-grained analytical framework for JCAS networks was proposed by deriving the meta distribution of the SIR. The locations of BSs, UEs, and sensing objects were modeled as independent HPPPs. The performance of the system was evaluated in terms of the conditional JCAS coverage probability and the complementary cumulative distribution function (CDF) of the SIR meta-distribution. An important outcome of the paper was the investigation of the impact of interference from simultaneous transmissions.

OFDM signals can be jointly optimized for communication and ranging performance through careful pilot placement, power allocation, and subcarrier configuration. This dual capability makes OFDM a prime candidate for multi-functional JCAS systems, especially in mmWave environments where bandwidth and directionality are favorable.

4) MU-MIMO: SG is critically important in MU-MIMO communication scenarios with JCAS systems. More specifically, SG allows us to capture the spatial randomness of users and targets and more accurately analyze the interference of both functionalities. In [69], a novel framework was introduced to analyze the probability of success in JCAS systems using the DPP. The distribution of BS and MU was modeled with the DPP, which captures repulsion among nodes. The performance of the system was evaluated using the success probability, based on the received SINR. The proposed framework was shown to provide a rigorous closed-form analysis of success probability, providing insight into the trade-offs between sensing performance and communication reliability. Concluding, in practical deployments, BSs are deliberately spaced to minimize overlap and reduce interference—behavior that is effectively captured by the DPP model.

C. Sensing Assisted Communications

1) Beam-alignment: In SAC, the radar functionality may be employed for improving link reliability using beam-alignment. In particular, beam alignment technology is very important in high-frequency sensing and communication systems In [94], focusing on THz/mmWave networks, a beam alignment scheme was proposed utilizing SSB-based sensing to assist beam switching. By modeling the spatial locations of the BSs, UEs, and blockers as independent PPPs and determining the optimal design of the SSB pattern, a closed-form resource allocation was derived that is independent of the density and mobility of the nodes. The numerical results revealed that the proposed scheme significantly reduces the probability of beam misalignment in highway and urban scenarios.

In [101], a time-frequency resource allocation technique for sensing signal mapping schemes that maximize the coverage probability of the ISAC-THz networks with reduced sensing costs was proposed. By modeling the spatial locations of the BSs, mobile terminals, and blockers as independent PPPs, the trade-off between coverage performance and sensing accuracy was demonstrated. It should be noted that sensing information is used to avoid misalignment of the beam. To this end, a narrow beam design was adopted, and the optimal trade-off between sensing assistance and its cost was obtained as a resource allocation-based optimization problem. The results revealed that a wider coverage requires more sensing resources, and the high frequency significantly limits the unambiguous sensing range. However, this paper does not present an efficient mechanism for configuring sensing signals, unlike the approach outlined in [94].

In [63], the analysis presented in [94] and [101] is extended to also take into account the network coverage. More specifically, in [63], a joint SSB and reference signal-based sensing (JSRS) scheme was proposed to assist beam alignment in THz networks based on 5G beam management. By modeling the spatial locations of BSs, UEs, and blockers as independent PPPs, the analytical expression for communication coverage probability for the JSRS-enabled network was obtained. The expression was used for evaluating the network's ability to reduce beam misalignment and quantify the coverage improvement. The expression also guides the network density deployment and beamwidth selection. In terms of sensing operation, the time-to-frequency allocation ratio that minimizes the sensing error-induced beam misalignment was obtained by solving the formulated optimization problem. The numerical results demonstrated that the proposed JSRS scheme is effective and highly compatible with the 5G air interface.

A common observation in all the aforementioned contributions is that beam misalignment can significantly affect the performance of both sensing and communication functionalities. Moreover, the probability of beam misalignment depends on the central frequency, the SSB bandwidth, and the number of BS beams.

2) Beamwidth: The design of antenna beamwidths is a key factor in enhancing the system's performance. In [119], the performance of an ISAC-enabled network was investigated in terms of achievable throughput, where the nodes utilize the radar functionalities to direct highly directional beams to MUs for communication services. By modeling the spatial locations of the clutter scatterers as PPPs, radar scanning was performed to detect and localize MUs/targets in the presence of discrete clutter scatterers. Subsequently, radar information was utilized to analyze radar operational metrics and realize high communication throughput. The numerical results demonstrated the impact of the radar duty cycle and beamwidth on the performance of the ISAC-enabled network in terms of communication throughput.

In [83], an analytical model for mmWave radar-assisted communication systems was presented, considering undesirable clutter, RCS fluctuations, and interference from the transmitting nodes. MUs and clutter scatterers were distributed as a PPP. The network consisted of hexagonal small cells, each with a BS-mounted radar at the center, in which the beamwidth trade-offs were investigated. The system performance was evaluated using the coverage probability and radar detection probability criteria. It should be noted that, in addition to the framework presented in [119], the antenna misalignment error has also been considered. Key results highlighted the importance of beamwidth design trade-offs, showing that careful selection can eliminate beam training overhead and improve system performance. In sensing-assisted communication systems, the trade-off of beamwidth is a fundamental design consideration that directly impacts both sensing accuracy (by increasing / decreasing spatial resolution) and communication performance (by increasing / decreasing coverage area). Moreover, the misalignment error caused by an imperfect radar-based localization becomes negligible when the beamwidths of both the radar and communication subsystems are appropriately selected, effectively reducing the need for beam training.

D. Main Observations and Discussion

By comparing the novel advances presented in this section, the following key observations have been identified. Despite the fact that a very large number of works have integrated both optimization and SG tools into the ISAC paradigm [63, 85, 88, 92, 94, 96, 101, 114], the use of AI and ML tools remains remarkably unexplored. It is also worth-noting that investigations related to beamwidth and beam-alignment are mainly focused to SAC scenarios. Furthermore, the performance of ISAC systems in near-field scenarios is not investigated, despite the fact that the mmWave/THz technologies are expected to extend the near-field region and thus increase spatial resolution in ISAC. Furthermore, although it is undoubtedly a key 6G enabling technology, the effect of RISs on the performance of ISAC networks has hardly been explored [62, 92], while the key performance limitations have not been investigated at all. Finally, it is surprising to observe that despite the fact that, with recent advances in ISAC technology, 3GPP-based mobility modeling has become more essential than ever, no research work has performed a performance comparison of different mobility schemes, similar to [58]. By closing this Section, we can conclude that:

- Although some initial steps have been taken to investigate the impact of blockages and RIS on the performance of terrestrial ISAC networks, exploration of fundamental performance limits has not been reported. This is because designing a RIS-assisted SG framework to investigate the fundamental performance limits of an ISAC network is particularly challenging, even if the HPPP is employed to model the spatial locations of the network's entities. Consequently, system-level insights and design guidelines remain limited.
- Surprisingly, few works have addressed the impact of realistic antenna patterns, such as the 3D 3GPP antenna

This article has been accepted for publication in IEEE Communications Surveys & Tutorials. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/COMST.2025.3594560

pattern, within the context of SG-based frameworks. Although the 3dB beamwidths for both azimuth and elevation angles play a pivotal role in ISAC performance, further investigation is necessary. The primary challenge lies in the statistical characterization of both the random azimuthal and elevation angles of the nodes relative to the deployment region. Consequently, the resulting angles required to define the 3D 3GPP-based antenna pattern may not exhibit a uniform distribution.

V. Aerial/Vehicular Networks

For the scenario of aerial or vehicular communication networks, the contributions are also classified in the ISAC, JCAS, and SAC scenarios.

A. Integrated Sensing and Communication

1) Monostatic/Bistatic Sensing: Although monostatic sensing at a single BS is attractive because of the presence of a common shared clock and the simplified signal processing techniques, bistatic sensing between BSs has also attracted considerable research interest to seamlessly integrate sensing into communications. The main reason is that it requires almost no change to the current network infrastructure. The following works investigate monostatic/bistatic sensing functionalities.

In [108], the coverage performance of air-ground ISAC downlink networks was analyzed. Specifically, the communication coverage probability was evaluated while taking into account interference during sensing. The work incorporated cooperative beamforming to improve sensing accuracy and compared HPPP models with lattice models to establish lower and upper performance bounds.

In [109], ISAC was studied for UAV-borne synthetic aperture radar (SAR) systems, focusing on minimizing power consumption while maintaining communication and sensing performance. It considered an aerial network where the sensing targets were distributed using a PPP. A trajectory optimization framework was proposed to reduce propulsion power under sensing and communication constraints, with an emphasis on power consumption and average rate.

In [87], the performance of downlink perceptive mobile networks was investigated for autonomous and cooperative UAV surveillance. The system model considered an aerial network operating in the mmWave band, where BSs, UAVs, and ground UE were modeled as a 2D PPP. Key performance metrics included coverage probability and successful detection probability, while mutual interference and resource contention between sensing and communication functions were analyzed, providing a basis for network optimization. It proposed a cooperative sensing strategy that combined monostatic and bistatic sensing techniques to improve the reliability of UAV surveillance. The simulation results verified the framework and highlighted the advantages of cooperative sensing over individual approaches.

In [120] a cooperative air-ground OFDM-ISAC network model is proposed, where ISAC-enabled BSs are spatially distributed according to a 2D homogeneous PPP to serve terrestrial users and sense aerial targets. Cooperative beamforming strategies are considered, including zero-forcing and maximum ratio combining, in order to mitigate interference. The communication and sensing performance of the system is analyzed using metrics such as coverage probability, spectral efficiency, detection probability, and the Cramér-Rao bound. The results showed that performance depends on the BS and target height, with trade-offs between sensing and communication influenced by the system parameters.

Based on the aforementioned, it is easy to observe that the works [87, 108, 109] consider monostatic sensing functionalities in a UAV-assisted system. In contrast to [108] and [87], the work in [109] assumes UAV mobility. However, [87] extends beyond monostatic sensing by further considering bistatic sensing in a comprehensive performance analysis. Subsequently, a detailed comparison between monostatic and bistatic sensing with respect to the ability to perform UAV surveillance is conducted. Moreover, while [87] assumes that BSs are equipped with UPA antenna models, the antenna patterns in [108] and [109] have been totally ignored in the analysis of ISAC-based performance metrics. In light of the aforementioned, it becomes quite obvious that further performance comparisons between monostatic and bistatic sensing functionalities in the context of SG are required to obtain meaningful insights for ISAC networks at system-level.

2) Resource Allocation: In vehicular ISAC networks, few works have been identified to investigate the impact of resource allocation on the performance of ISAC-based performance metrics or the trade-offs between sensing and communication functionalities.

In [107], a dual-beam ISAC scheme was proposed for vehicular networks to provide 360° radar detection and directional communication simultaneously. The study developed an analytical framework based on SG using MHCP to model vehicle positions and assess detection probability and communication coverage probability, considering incident and reflected interference. It investigated two power allocation optimization problems to improve detection performance without degrading communication performance. The simulation results confirmed the accuracy of the analytical models and demonstrated the benefits of the proposed power allocation schemes in improving the average detection probability.

In [72], an intervehicle communication scheme was investigated to schedule communication and vehicle sensor signals. Using 1D-MHCP to model the spatial locations of vehicles, an analytical framework was proposed to statistically characterize the mutual interference among multiple vehicles. The interference mitigation scheme was evaluated in terms of interference probability, duration, and the achievable detectable density. Going one step further and recognizing the different performance requirements of communication and sensing functions, a joint resource allocation problem was investigated. Subsequently, the optimization problem mentioned above was solved using an algorithmic approach. The results demonstrate a notable improvement in the proposed ISAC-based interference mitigation scheme compared to the benchmarks.

In [81, 106], a full-duplex ISAC downlink system was investigated for automotive scenarios. The system model considered

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a vehicular network with vehicles traveling in the direction of the typical vehicle, interfering vehicles traveling in the opposite direction, and RSUs distributed on three parallel lines following three independent PPPs. Key performance metrics included coverage probability, false alarm probability, and detection probability. The framework was validated through Monte Carlo simulations, which highlighted trade-offs between sensing and communication functions. The work explored the optimization of network node performance and density to maximize joint performance. It also extended the analysis to account for mutual interference between sensing and communication, considering both perfect and imperfect interference cancellation.

While [107] investigates optimization problems for power allocation with respect to the ability to improve the average detection probability, it does not provide any insight about trade-offs between sensing and communication functionalities of vehicular ISAC networks. In addition, while [81] also investigates a power allocation optimization problem, it additionally reveals insights into the trade-offs between the sensing and communication functionalities. In contrast to both [107] and [81], the work in [72] extends beyond the investigation of power allocation by comprehensively investigating a joint resource allocation problem by considering both power and subcarrier allocation. Subsequently, insights on the trade-off between sensing and communication performance are revealed. It is worth mentioning that all the aforementioned works exploit optimization tools to optimize ISAC performance metrics. However, the fundamental trade-offs between sensing and communication performance in vehicular ISAC networks within the context of SG remain largely unexplored.

3) Blockage Effect: Surprisingly, the impact of blockages on the performance of UAV ISAC networks has barely been explored. Indeed, in [113], the communication coverage and successful detection probabilities were investigated in UAV-enabled ISAC systems. The main novelty of the paper is the fact that the impact of blockages on propagation paths was considered for deriving probability distributions for UAV-user and UAV-target distances. PPP were used to model the 2D dimensions of the UAVs, users, targets, and blockages. The analytical framework presented was used to examine how the density, height, and height of the blockage influence the performance of the system, demonstrating that the strategic deployment of the UAV can effectively compensate for blockage-induced degradation.

While [113] captures the length, orientation, and height of the typical blockage and demonstrates the impact of blockages on the ISAC performance metrics of UAV networks, more research demonstrating the impact of 3D blockages in the performance of UAV ISAC networks is essential to come to safe conclusions about the impact of 3D blockages at the system level.

B. Joint Communication and Sensing

1) Cooperative Detection: Cooperative detection enables multiple nodes to collaboratively sense and share information, to enhance target detection, tracking accuracy, and environmental perception. However, there are various challenges, including synchronization, data sharing overhead, latency, security, and complex data fusion.

In [111], JCAS systems were analyzed for cooperative detection in vehicular networks. The system modeled vehicle positions using a 1D PPP and focused on improving spectrum utilization and mitigating interference. The paper derived closed-form expressions for the average cooperative detection range under different scenarios with varying numbers of vehicles. JCAS systems were shown to improve spectrum sharing and detection efficiency through JCAS. Analytical results validated the proposed framework and highlighted its effectiveness in evaluating cooperative detection performance.

In [90], the performance of cooperative detection in JCAS vehicular networks was investigated. Using geographic information system data, road obstacles were statistically modeled and the effects of shading and SG obstacles were evaluated using a generalized PPP. Key performance metrics included the probability of successful cooperative detection under LoS and NLoS conditions. The paper also explored simulation-based deployment optimization strategies to improve detection reliability and communication efficiency and emphasized the adherence to urban roadway structure standards to ensure practical relevance. Finally, it focused on obstacle detection as a primary service in the downlink and demonstrated the potential of JCAS to enable coordinated detection and infrastructure optimization in urban vehicular networks. It is important to be noted that the dimensions of the objects that have been employed in the analysis presented in [90] are based on real data.

In [121], the performance of JCAS systems for multi-radar cooperative detection in drone surveillance was investigated. Radars were deployed on a 2D plane to detect drones in a 3D space, forming clusters with a fusion center. The distribution of fusion centers followed an HPPP, whereas other radars followed an independent PPP. The performance of the considered scheme was studied in terms of detection volume and successful communication probability. An optimal power allocation between radar and communication was shown to maximize the detection volume.

2) Bistatic: Bistatic radar plays a central role in ISAC by leveraging spatially distributed nodes to enhance sensing performance, support cooperative detection, reduce interference, and maximize spectrum efficiency

In [110], JCAS was studied for cellular-connected UAVs used as bistatic SAR platforms to sense randomly distributed objects using PPP. A trajectory planning algorithm was proposed to optimize UAV flight paths to minimize propulsion energy while ensuring the required sensing resolutions. Key performance metrics included power consumption, with simulations that demonstrated energy savings of up to 55% compared to the shortest-path approaches.

In [64], a distributed communication and sensing system was codesigned to improve the resilience of UAV networks. The system model considered an aerial network with UAV locations modeled as a PPP, while the system reliability and the resilience of the UAV network were investigated. The study analyzed a JCAS framework that incorporates bistatic radar functionality to improve collision avoidance. A novel RCS

TABLE V: Summary of the key results of the reviewed literature.

Area of Interest	Network Type	Key Result	Reference
Spatial Resources	Terrestrial	1) The optimal communication trade-off for ASE maximization tends to use all spatial resources for multiplexing and diversity gain without interference nulling. 2) For sensing objectives, sufficient antenna resource allocation tends to eliminate inter-cell interference.	[85]
BS Density	Terrestrial	1) Increasing the BS density from 1 km^{-2} to 10 km^{-2} can increase the ISAC coverage rate from 1.4% to 39.8%. 2) The sensing function performs best at high BS densities, while the communication performance is optimized at moderate BS densities. 3) Even at low BS densities, interference remains a more significant factor in the performance of sensing than in communication. 4) With the increase of the constrained sensing rate, the ergodic communication rate improves significantly, but the reverse is not obvious. 5) The small distance resolution and the high data rate are the two main constraints on the maximum achievable coverage probability with optimized power and spectrum allocations. 6) We should not pursue resolution redundancy too much in practical applications of JSAC, since maintaining redundancy in sensing will cripple the joint performance of JSAC. 7) If we want to improve the maximum coverage probability by increasing the small distance resolution in sensing or decreasing the high data rate in communication, the latter option may be a better choice. 8) If there is some information about the target density in practical applications, the corresponding optimal BS density can be set. If there is no information about the target density in practical application, the density of BS can be set as 150 to 200 points/km^2. 9) Repulsive BS deployment improves detection performance by reducing interference.	[60],[84], [80],[70]
	Terrestrial with Aerial Targets	1) The optimal dual-function radar-communication BS density for the ISAC network is different from the classical communication-only network, and this optimal value becomes smaller as the target altitude increases. 2) A few BSs are sufficient to achieve optimal performance at very high altitudes.	[57]
Blockage Density	Terrestrial	1) Blockages can have a positive effect on coverage, especially in improving communication performance. 2) There is an optimal BS density when the blockage is of the same order of magnitude as the BS density, maximizing communication or sensing coverage probability.	[100]
BS Height	Aerial	1) Both the communication CP and radar detection CP initially rise and then fall as BS density increases, each reaching their peak at different density levels. 2) Sensing performance can also be improved by using more OFDM subcarriers and symbols or by lowering the sensing target height.	[120]
RU Height and Density	Vehicular	1) Optimal deployment height of infrastructure is 7 m. 2) The infrastructure deployment interval is 150 to 300 m according to the probability requirement of successful cooperative detection, which complies with the Chinese and European transport standards.	[90]
Antenna Beamwidth	Terrestrial	1) The beamwidth of the communication antenna exhibits a trade-off where a narrow beam provides higher gain and reduces interference, but increases the effect of misalignment error. 2) There exists an optimal search duration and a main lobe spread parameter of the communication antenna at the optimal search duration value. 3) While maintaining the same beam alignment quality, sensing-aided networks can use narrower beams to extend network coverage.	[83, 94]
Effect of RISs	Terrestrial	A joint coverage rate improvement is achieved with RIS deployment.	[92]
Cooperative vs. Standalone Sensing	Terrestrial	1) The use of N ISAC transceivers results in an improved average cooperative sensing performance across the network, following the $\ln 2N$ scaling law. 2) The scaling law is less pronounced compared to the N^2 performance improvement achieved when the transceivers are equidistant from the target. 3) Cooperative transmission and sensing in ISAC networks can effectively improve the sensing and communication gain. 4) The cooperative scheme shows superior performance improvement compared to centralized or distributed antenna allocation strategies, especially when more antennas are available.	[96, 114]
	Aerial	1) Cooperative sensing can achieve a large performance improvement over standalone sensing by utilizing the spatial diversity gain of multiple collaborating BSs. 2) Multiple illuminators provide additional robustness for detection. 3) The detection performance of multiple illuminators can be improved if the detection of the same target by different illuminators is independent.	[64, 87]
Multiple Access Technique	Aerial	1) TDMA outperforms SOMA in terms of successful ranging probability. 2) SOMA outperforms TDMA in terms of transmission capacity. 3) SOMA can outperform TDMA in terms of both successful ranging probability and transmission capacity when the node density of active UAV-radars is larger than the node density of UAV-communications.	[91]
Safety Critical Applications (Collision Avoidance)	Aerial	A distributed communication and sensing system can improve the resilience of UAV networks.	[64]
Interference	Vehicular	ISAC-based schemes can effectively mitigate mutual interference among multiple vehicles.	[72]

estimation method was proposed to address the challenges of modeling complex-shaped objects. The work combined radio network planning and link budget estimation with Monte Carlo simulations to evaluate radar detection performance. SG methods were used to estimate collision probability without extensive flight-hour simulations. The numerical results confirmed robustness to RCS pattern nulls, demonstrating the suitability of the system for safety-critical applications such as collision avoidance. It is worth noting that in [64] Doppler shifts have been analytically investigated, while in [110] a trajectory planning has been carried out, with respect to power consumption, which is very important for UAV-assisted communications.

3) Multiple Access: Multiple access schemes in JCAS systems are crucial to enable multiple users or devices to simultaneously share spectrum and resources for both communication and sensing tasks. These schemes must support not only data transmission but also high-resolution sensing, often in dynamic environments. In [91], the coexistence of UAV radar and communication networks was analyzed under different multiple access protocols. It considered an aerial network operating in the mmWave band, with UAV-mounted BSs and radars modeled as PPPs. Spectrum overlay multiple access (SOMA) and time division multiple access (TDMA) protocols were studied, and closed-form expressions for performance metrics such as successful range probability and transmission capacity were derived. The analysis showed that SOMA outperforms TDMA in both successful ranging probability and transmission capacity when the density of active UAV radars exceeds that of UAV communications. By comparing multiple access schemes, the paper highlighted the trade-offs between radar and communication performance and provided insights into optimizing UAV network configurations for JCAS systems.

C. Sensing Assisted Communications

In [112], in a communication-sensing scenario, the authors proposed a framework to take advantage of V2X communication to efficiently allocate spectrum resources. The spatial distribution of interfering radars was modeled as PPP and interference is evaluated for different radar types. Moreover, the minimum spectrum required for zero-interference was analyzed, and simulations confirmed that the proposed approach achieves near-zero interference while optimizing spectrum usage. Generalizing the results of [112], in [80], the locations of BSs, STs, and sensing and communication targets were modeled using three independent homogeneous PPPs in a 2D plane. More specifically, in [80], the performance of JCAS for large-scale networks was analyzed, focusing on downlink sensing-assisted beamforming and adaptive resource allocation. The system model considered a vehicular network operating at 77 GHz. The paper evaluated the coverage probability as a function of the user and BS densities, the required high data rate and small distance resolution, and the allocation ratios of power and spectrum. The sensing system detected the environment and obtained user positions, followed by adaptive beamforming to improve communication efficiency. Using SG, interference in sensing and communication was modeled separately and joint coverage probability expressions were derived. The analysis highlighted the trade-off between small distance resolution and high data rate as key constraints to maximize coverage probability with optimized power and spectrum allocation. It also showed that different BS densities should be considered for different scenarios, and the relationship between the user and the BS densities could serve as a reference for practical applications.

D. Main Observations and Discussion

Comparing the various contributions in this section, the following observations have been identified. In V2X networks, SG has been employed to model the position of the vehicles, thus adopting 1D spatial models. Despite the fact that dynamic network conditions have been assumed, the impact of Doppler effect and/or outdated channel state information and/or beam misalignment have not been thoroughly investigated, i.e., only in [64] the Doppler effects have been taken into account. In addition, blockage induced by other vehicles is also a parameter not included in the presented analysis. As far as aerial networks are concerned, all studies have focused on aerial-to-ground scenarios. In particular, air-to-air communications and/or space-air-ground integrated networks (SAGINs) have not been taken into consideration. An important observation in this type of networks is that raising the BS height enhances sensing performance but degrades communication quality, highlighting a tradeoff between communication and sensing capabilities. Moreover, for analytical simplification purposes, the network entities, e.g., aerial BSs or UAV-targets, are considered spatially distributed in a 2D plane. However, in practical scenarios, the aerial nodes are expected to be distributed in specific aerial highways in the 3D space. In closing, additional concluding remarks can be reported:

- Shadowing phenomena resulting from random variations in mean power levels have not been considered;
- The impact of randomly distributed scatterers in space is not considered for the sensing or communication functionalities;
- In particular, scenarios with combined UAV-supported V2X communication have not been investigated;
- Similarly to terrestrial ISAC networks, the impact of blockages in vehicular and aerial ISAC networks has barely been investigated;
- Although the inclusion of antenna patterns and beamforming capabilities has been extensively considered in the performance evaluation of aerial networks by exploiting optimization tools, their implication within the context of an SG-based framework remains unexplored. This is because the consideration of 3D antenna patterns and beamforming vectors in the definition of SINR-based metrics can lead to extremely intractable analysis. Therefore, the derivation of simplified, yet accurate, expressions for performance metrics in ISAC networks assisted by UAVs should be expected.

VI. Key Results, Open Problems, Future Directions, and Standardization

This section presents a comprehensive summary of key findings and attempts to identify research challenges and future research directions for ISAC systems. First, key findings are presented for communication and sensing networks in the context of SG. Next, key research challenges and future directions are discussed in an effort to bridge the research gap between ISAC and SG toward the vision of a unified SG-based ISAC framework.

A. Key Results

Given the diverse methodological approaches and conceptual frameworks of the reviewed works, drawing uniform comparisons is inherently complex and should be approached with caution. To this end, an effort to synthesize some important findings is presented in Table V. It is noted that the references included in each row of the last column of this table are associated with a specific area of interest depicted in the first column. Specifically, according to the area of interest presented in the table, we are led to the following remarks:

- Using the SG-based analytical results, meaningful insights have been obtained about the density of deployment of RUs, BSs, and blockages, and their effect on the performance of communication and sensing networks is demonstrated. For example, interference plays a more critical role in affecting the performance of sensing systems than it does in communication systems. Moreover, in practical JSAC systems, excessive increase in the sensing resolution or redundancy should be avoided, as it can consume the resources needed for communication and ultimately degrade the overall performance of the system.
- The trade-off between communication and sensing functionalities in ISAC networks while considering spatial resources and antenna beamwidth design has been examined, and key design guidelines are provided. For example, when aiming to enhance the maximum coverage probability, reducing the high data rate in communication may be more effective than increasing the sensing resolution for short distances.
- Blockages can enhance communication performance by reducing interference under certain conditions. Optimal coverage is achieved when BS and blockage densities are of similar magnitude, highlighting the importance of environmental factors in JSAC system design.
- As a key enabling technology for 6G, RISs have been exploited to enhance the JCAS coverage rate of this kind of networks.
- Antenna beamwidth and alignment are important factors, especially for SAC systems. More specifically, the beamwidth of a communication antenna involves a fundamental trade-off: narrower beams offer higher gain and better interference suppression but are more sensitive to alignment errors. Moreover, in SAC, it is possible to maintain beam alignment quality while employing narrower beams, thereby effectively extending network coverage.
- Performance comparison has been carried out between multiple access schemes and between cooperative and standalone sensing. For example, the cooperative scheme outperforms both centralized and distributed antenna allocation strategies, with the performance advantage becoming more pronounced as the number of available antennas increases.
- ISAC technology has been used for collision avoidance in UAV networks.
- ISAC-based schemes have been shown to be effective in minimizing interference.

Based on the above, it is clear that a notable research interest is directed towards: 1) the effect of deployment density of network entities in the ISAC performance, 2) the effect of directional antenna patterns on the performance of ISAC networks, and 3) the role of enabling technologies and multiple access schemes in mitigating interference and enhancing performance in ISAC networks. Table V provides a comprehensive summary of the most valuable insights obtained from journal articles[4].

B. Open Problems and Future Research Directions

There are still many open research challenges and future directions that require critical attention to drive further progress and meet the required performance goals in communication and sensing enabled networks. In the following, we discuss the identified key open challenges and provide research directions that require further investigation.

1) Novel Spatial Point Processes: The literature review revealed a strong trend in the use of HPPP to model the spatial locations of network entities. Despite its undoubtedly great potential to maintain analytical tractability, the HPPP has certain limitations. For example, when a predetermined or known number of nodes is deployed in a finite region, the HPPP is definitely not an appropriate choice, and the Binomial Point Process (BPP) should be utilized instead. Note that BPP has not yet been used to analyze the performance of ISAC networks. The BPP can accurately approximate the spatial locations of i) terrestrial UEs in the near-field region of an ISAC-enabled BS, ii) UAVs in 2D aerial lanes and iii) UAVs in 3D aerial corridors [122, 123] (as it can be seen in Fig. 5). Nevertheless, BPP is a non-stationary point process, and therefore it may result in an intractable performance analysis, especially for UAV-enabled ISAC networks. If one is interested in modeling the positions of UAVs in aerial corridors while maintaining a minimum safety distance [124], the MHCP is an appropriate choice (see Fig. 5). For terrestrial networks, the scatterers around a sensing target that cause clutter interference can be reasonably modeled using Poisson cluster processes (see Fig. 5). Finally, a relatively new communication system is SAGIN-ISAC that has recently attracted the interest of the academia [125]. For this type of networks Cox point processes can be used to model the satellite constellation (low or medium Earth orbit) [126].

[4]Each paper has its own focus, merits, and contributions. A paper not listed in Table V does not mean that the overall contribution of the paper is disparaged in any sense.

This article has been accepted for publication in IEEE Communications Surveys & Tutorials. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/COMST.2025.3594560

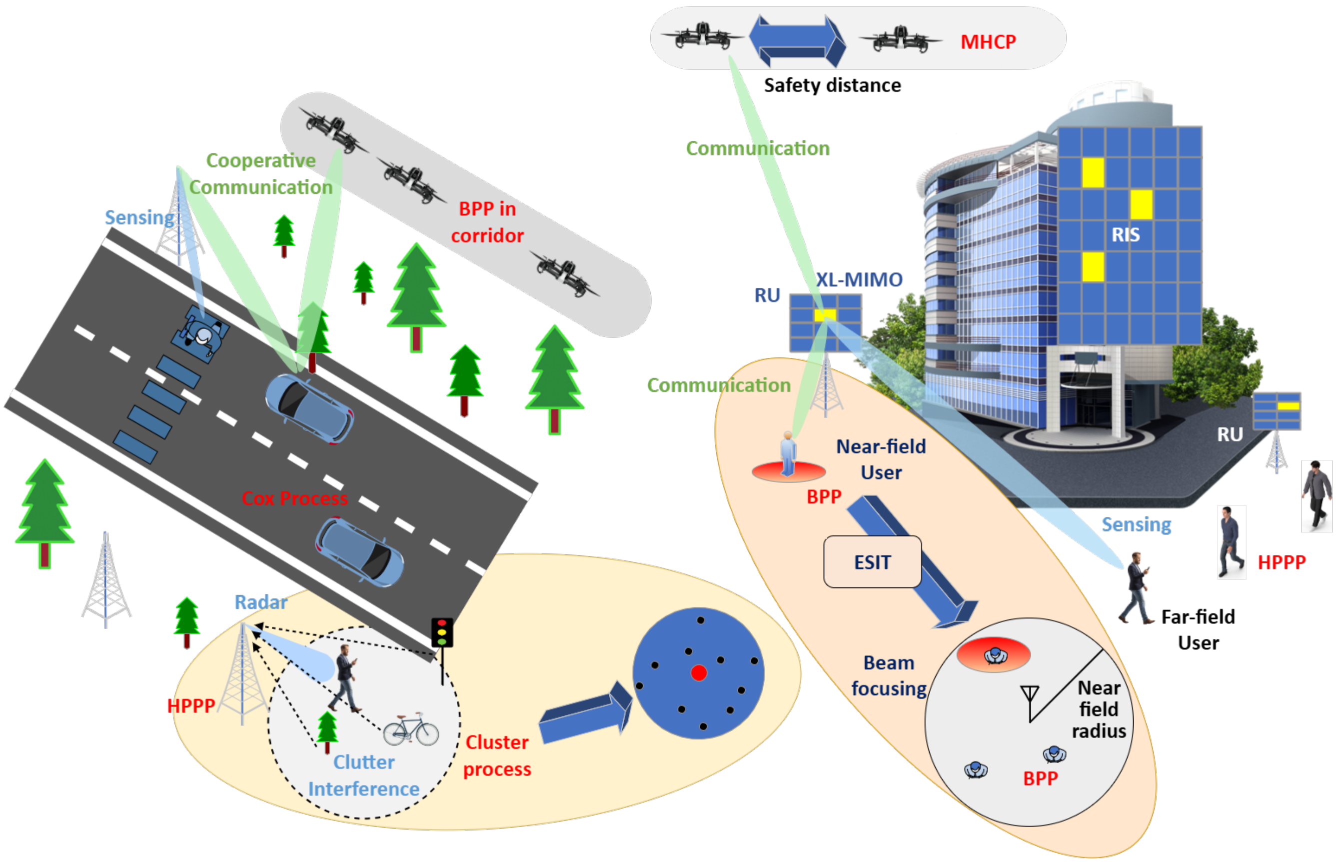

Fig. 5: Conceptualization of an SG-based framework for communication and sensing networks. The various spatial models are denoted with red font.

Currently, there is considerable research interest in investigating fundamental performance limits for terrestrial and aerial ISAC networks. However, the research is still in its early stages. The adoption of more realistic spatial point processes for modeling nodes in terrestrial ISAC networks and especially UAV-enabled can provide new insights for fundamental performance limits and key performance metrics. However, the adoption of more realistic spatial point processes may lead to complicated SG-based frameworks. Indeed, the choice of an appropriate spatial point process is not a straightforward task and should be used judiciously to balance the trade-off between complexity and accuracy. The vision of an SG-based spatial model for ISAC networks is presented in Fig. 5.

2) Electromagnetic Signal and Information Theory (ESIT): ESIT can be defined as physics-aware information theory and signal processing for communications [127]. In particular, ESIT deals with physically consistent schemes for the transmission and processing of information in communication networks with the use of radiating and capable of transmitting and/or receiving information electromagnetic surfaces.

Very few research studies have considered the promising capabilities of holographic surfaces and holographic MIMO to ISAC, which we refer to as holographic ISAC (HISAC). These studies demonstrate its potential to improve both sensing and communication performance through optimized beamforming strategies. However, research on HISAC is still in its early stages. In this context, SG can serve as a valuable tool for performing a system-level performance analysis of HISAC.

In addition, the large size of emerging antenna technologies, including RIS and holographic surfaces, as well as the potential use of high-frequency bands, makes communications in the near-field region feasible. Although ESIT and near-field communications are undoubtedly an exciting area of research in the context of ISAC technology [128–130], the research gap between SG theory and ESIT remains extremely large.

In fact, even the role of SG in the performance of near-field communications has barely been revealed [131]. The main research challenges that prevent the integration of SG in ESIT are related to the physical and electromagnetic properties of the antenna arrays.

- The fundamental performance limits in ESIT are strongly based on the characteristics of the antenna arrays, such as the number of elements, the type of aperture array (discrete or continuous) and the orientation of the array.
- The near-field distance-dependent path loss between a UE and an ISAC-enabled BS is strongly dependent on the elements of the antenna arrays.
- Both discrete and continuous apertures are now an integral part of the small-scale fading channel model. In fact, statistical channel models for near-field multipath fading that integrate the properties of continuous-aperture antennas remain an open problem. The main reason for

this is that the channel models for continuous aperture antennas are based on the Green function. However, the use of Green's function in scattering environments is extremely challenging [132].

As a result, no system-level performance analysis has been investigated by exploiting the spatial randomness of nodes in ISAC networks while considering the physical properties implied by ESIT. In this direction, new spatial models and channel statistics should be investigated to facilitate the derivation of expressions for key performance metrics. Under the umbrella of SG, possible future directions include the following:

- *Poisson bipolar networks:* While Poisson bipolar provides the only spatial model for capturing the orientation of antenna arrays, it may lead to a simple but reasonable step toward near-field ISAC performance analysis.
- *Association policy based on the maximum number of effective degrees of freedom:* Similar to the conventional minimum distance association criterion, novel association policies that integrate ESIT features, e.g. spatial multiplexing gain (degrees of freedom), are expected to provide new insights into fundamental performance limitations. Accordingly, the communicating UE may now associate with the BS providing the maximum number of degrees of freedom.

A vision of a hybrid near-field/far-field SG-based spatial model is illustrated in Fig. 6, where the locations of near-field communicating UEs can be modeled as a BPP around an ISAC-enabled BS. The BS can use beam focusing for communication and beamforming for sensing.

3) Networks with Extended Functionalities: Considering the demanding key performance indicators of future 6G networks along with recent advances in ISAC and power transfer capabilities, future 6G networks are expected to integrate SWIPT and ISAC. In this direction, new multi-functional networks that can simultaneously provide sensing, communication, and power capabilities are currently under remarkable investigation [133, 134]. In the context of SG, recent research focuses on frameworks for the joint integration of communication and energy harvesting functionalities [135, 136]. Inspired by existing ISAC-related performance metrics, such as the JCAS CP, a new performance metric may arise that goes beyond ISAC, namely the joint CP of communication, sensing, and energy harvesting. Formally, the proposed metric is defined as the probability of achieving the JCAS CP at a given node beyond some target thresholds, given that the energy harvested at the same node exceeds a predefined threshold required for circuit activation. Such kind of extended performance metrics share the vision of future multi-functional 6G networks and pave the way for the formulation of multi-functional SG-based frameworks. Accordingly, analytical expressions for the extended performance bounds will subsequently reveal novel insights and design guidelines for multi-functional 6G networks.

DT technology plays a crucial role in the operation and infrastructure management of 6G networks, enabling intelligent and flexible future communication systems [137]. Beyond infrastructure, 6G serves as a platform that fosters DT applications in diverse domains, including industrial IoT, smart cities, extended reality, e-health, and the metaverse, thus bridging the physical and digital worlds [138]. In [139], DT is integrated in network slicing for improved service provision and management, while an ISAC-based environment-aware offloading mechanism is also adopted to reduce latency in the Internet of Vehicle Systems. The combination of SG and ISAC is expected to enable DT to serve as a more accurate, efficient, and resilient virtual replica of the 6G network, ultimately improving network planning, operation, and user experience optimizations.

4) SG Meets AI in ISAC: As the complexity of ISAC networks continuously increases, AI and ML algorithms are becoming the dominant tools to obtain system-level insights into key ISAC network performance metrics. Although SG is limited by a fundamental trade-off between accuracy and complexity, AI is now complementing SG theory to overcome these limitations. ML methods can be used to develop adaptive algorithms that dynamically optimize network performance based on real-time conditions [140]. Future studies could explore hybrid strategies that employ predictive beamforming optimization [141], interference management in multiuser ISAC scenarios [142], channel estimation for the sensing and communication signals [143], assuming randomly spatially distributed nodes, targets, scatterers and/or blockages.

5) Channel Modeling: Several aspects of ISAC channel modeling have not been investigated in scenarios where spatial randomness is considered. For example, in most of the presented studies, channel behavior is considered to be slowly varying, even in V2X communications. However, in dynamic networks where MU tracking is performed, e.g., [144], SG tools can increase the reliability of performance results. In addition, in time-varying scenarios, the Doppler effect should not be ignored, as it can severely affect channel behavior [145]. Furthermore, the impact of random shadowing in ISAC scenarios or sensing-assisted communications has not been analytically investigated, e.g., [146, 147], especially by using SG tools. Finally, SG tools could be very helpful in presenting novel geometry-based stochastic channel models in ISAC scenarios [148]. Moreover, mobility models play a vital role in UAV (vehicular) communications as they provide a realistic representation of the dynamic movement patterns of UAVs (vehicles), which is essential for the accurate design, simulation, and evaluation of communication protocols and systems. Therefore, the investigation of mobility models for UAVs (e.g., [144]) and vehicular systems (e.g., [149]) through the lens of SG tools is expected to yield more realistic and theoretically supported results.

6) ISAC with Heterogeneous Technologies: Multi-sensor cooperative perception with diverse sensor types is a key challenge. Although many ISAC systems focus on a single sensor type, such as radar, future large-scale networks will utilize more diverse sensor technologies, such as cameras, light-emitting diodes (LEDs), lidars, or thermal imagers [150, 151]. SG methods can play a critical role in capturing how these different sensors, each with its own field of view, detection range, and clutter sensitivity, are distributed over large areas.

TABLE VI: Standardization activities on ISAC

Standardization body	**Recent deliverables that explicitly mention ISAC**	**Scope & milestone**
ETSI ISG ISAC	First Group Report *GR ISAC–001 "ISAC Use-Cases for 6G"* (Apr. 2025) [152]	Pre-standard study group defining use-cases, KPIs and evaluation methods for 6G ISAC; normative specifications planned for 2026–27.
3GPP	SA1 Technical Report **TR 22.837 "Feasibility Study on ISAC"** (Release 19) [153]	Stage-1 requirements captured in TR 22.837; parallel RAN study items on "NR Sensing" under way, targeting Rel-19 normative work in 2026.
IEEE 802.11	Draft **802.11bf "WLAN Sensing"** approved for Sponsor Ballot (May 2025) [154]	Adds MAC/PHY changes enabling < 30 cm range and Doppler estimation in Wi-Fi 7/8; publication expected early 2026.
ITU-R WP 5D	**Report M.2516** (2022) lists "Integrated Sensing and Communication" as an *IMT-2030 foundational technology trend* [155]	Frames ISAC as an official IMT-2030 capability, steering spectrum and evaluation-methodology discussions within ITU.
O-RAN Alliance	Research Report **RR-2023-01 "O-RAN Towards 6G"** identifies joint sensing and communications as a key RAN Intelligent Controller service [156]	Positions open-RAN architecture as a vehicle for network-native sensing functions.

For example, cameras can provide rich visual detail but only at certain viewing angles, while radar can penetrate certain obstacles but may be susceptible to specular reflections. By building a unified SG-based model that collectively represents the deployment and coverage areas of these sensors, the CP, detection reliability, and accuracy can be quantified. Key challenges include i) the determination of the best approach to cluster or schedule sensors to minimize blind spots and avoid redundant scanning, ii) the establishment of cooperative data fusion rules that account for varying accuracy and update rates, and iii) mitigation of heterogeneous interference or blocking effects. Investigating these issues with SG will provide critical design insights, which range from the identification of the different sensors deployment for optimal joint perception to managing the communication overhead of fusing sensor data at the network edge.

C. ISAC Standardization Landscape

As shown in Table VI, ISAC has already been incorporated into the formal agendas of key standardization bodies. Dedicated study items and draft specifications now extend to the cellular, wireless local area network (WLAN), and open radio access network (O-RAN) domains. Most organizations are converging on a 2026-2028 time frame for standardization activities. This industrial momentum provides concrete waveform parameters and KPI targets for ISAC systems.

VII. Conclusions

SG has long been a powerful tool for evaluating the performance of complex wireless networks. By modeling spatial locations through point processes, a reliable analytical performance evaluation can be performed and used to provide useful design insights. Despite the obvious usefulness of this tool in scenarios where the location of network elements is very important for performance evaluation, it has only recently been adopted in ISAC network studies. In this survey, a comprehensive analysis of the technical literature on SG was performed for sensing and communication analysis. The article started with a brief overview of the SG tools and the basic concepts of communication- and sensing-enabled networks. In this context, a subsection with performance metrics used in the literature was presented. Then, system models and key technical components used in the literature for terrestrial, vehicular, and aerial networks were reviewed, highlighting the main results achieved so far in JCAS, SAC, and CAS networks. Finally, the article identified open problems and future research directions in SG for ISAC.

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This article has been accepted for publication in IEEE Communications Surveys & Tutorials. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/COMST.2025.3594560

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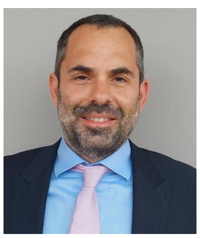

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