Integrated Sensing and Communications (ISAC) for 6G: Foundations, Architectures, and Standards-Aligned Prototyping

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***Abstract*—This survey consolidates Integrated Sensing and Communications (ISAC) advances most relevant to 6G deployment. We (i) formalize the Cramér–Rao Bound (CRB)–rate Pareto frontier and its constructive covariance designs for point and extended targets; (ii) review delay–Doppler (OTFS) receiver pipelines that retain ISI/ICI in GLRT/CFAR processing with DD-multiplexing; (iii) compare cooperative multi-static and cell-free architectures with centralized receive filtering; (iv) cover environment reconfiguration via intelligent omni-surfaces (IOS/STAR-RIS) and related reconfigurable hardware; and (v) connect theory to practice through standards-aligned WLAN sensing (IEEE 802.11bf) and ultra-broadband THz prototyping. A pair of comparison tables maps representative works to scenarios and highlights what each adds beyond classical ISAC background (metrics, structures, and constraints). We close with open problems in robustness of frontier operation, scalable DD processing, synchronization/fronthaul for cooperation, EM-accurate surface models, and implementation aspects of full-duplex transceivers.**

***Index Terms*—Integrated Sensing and Communications, CRB–Rate Tradeoff, MIMO, OTFS, Cooperative Multi-Static, Cell-Free, IOS/STAR-RIS, 802.11bf, THz, 6G**

I. Introduction

Integrated sensing and communications (ISAC) merges radar-like perception and data transmission on shared spectrum, hardware, and signal processing, targeting both integration gains (cost/size/energy/spectrum savings) and coordination gains (cross–assistance between sensing and communication) for 6G–class systems. The JSAC overview formalizes these two gains, situates ISAC within a historical arc from separate radar/communications to dual-functional networks, and motivates perceptive networks in which communication-assisted sensing and sensing-assisted communication are native services rather than add-ons [1], [2]. Technological trends now make this integration timely: higher carrier frequencies, large bandwidths, and massive arrays yield convergent hardware and signal models that enable joint designs on common waveforms and front-ends; recent tutorials chronicle the shift from early spectral coexistence to tight integration driven by vehicular, robotics, and XR use cases [3]. ISAC also appears among IMT-2030 6G usage scenarios, where surveys consistently place it alongside immersive communication and integrated AI/connectivity [3], [4]. Against this backdrop, we synthesize developments across theory, algorithms, architectures, and prototyping that make ISAC operational: constructive CRB–rate designs [5], DD-native waveform/receiver pipelines [6], cooperative multi-static and surface-aided coverage [7]–[9], and practice-facing hooks in WLAN/THz stacks [10]–[12].

II. Background knowledge

Authoritative surveys and tutorials converge on a set of foundations that motivate and structure modern ISAC design, and we adopt their notation and presentation style throughout [1], [3], [4], [13], [14]. First, ISAC is best treated as a native 6G service: base stations or access points act as dual-functional nodes whose scheduling and beam management jointly consider user traffic and scene perception. The integration gain is realized by sharing spectrum, RF chains, and infrastructure; the coordination gain comes from cross-assistance—sensing-aided beam alignment and blockage prediction, and communication-aided cooperative illumination and data fusion [1]–[3], [15]. This viewpoint generalizes across terrestrial/cell-free deployments and indoor WLANs and underpins network-native support for sensing tasks.

Second, paired performance metrics are essential. Fundamental-limits treatments advocate a two-axis evaluation with an information-theoretic communication metric and an estimation-theoretic sensing metric derived from Fisher information [3], [13]. Let $\mathbf{Q} \succeq 0$ be the transmit covariance with $\mathrm{tr}(\mathbf{Q}) \leq P$, $R(\mathbf{Q})$ a (multiuser/multicast) rate functional, and $\Gamma(\mathbf{Q})$ a sensing-quality functional linked to the Fisher Information Matrix (FIM) $\mathbf{J}(\mathbf{Q})$, e.g., $\Gamma(\mathbf{Q}) = \mathrm{tr}\{\mathbf{J}^{-1}(\mathbf{Q})\}$ or an angle/delay CRB. The CRB-constrained rate maximization

$$\max_{\mathbf{Q}} \; R(\mathbf{Q}) \quad \text{s.t. } \Gamma(\mathbf{Q}) \leq \bar{\Gamma}, \; \mathbf{Q} \succeq 0, \; \mathrm{tr}(\mathbf{Q}) \leq P \tag{1}$$

and its dual (rate-constrained CRB minimization) parameterize the CRB–rate Pareto boundary. Two canonical constructions emerge with semi-closed-form structure [5]. For point targets, the optimal $\mathbf{Q}^\star$ follows an eigenmode structure obtained by SVD of a composite sensing–communication operator, with water-filling-like allocation over the decomposed subchannels. For extended targets, the SVD is taken on the communication channel; power is then apportioned across two orthogonal sets of subchannels—one shared by sensing and communication, and one dedicated to sensing—again with monotone allocations. As the sensing constraint tightens (smaller $\bar{\Gamma}$), $\mathbf{Q}^{\star}$ tends to be full-rank and includes explicit sensing beams; when rate dominates, $\mathbf{Q}^{\star}$ collapses toward rate-optimal (often rank-deficient) subspaces. These constructions formalize when dedicated sensing beams are necessary and explain why purely rate-optimal precoders can collapse sensing performance [1]. Localization-centric variants directly minimize joint angle–delay CRBs under communication QoS, yielding precoder structures that specialize the same Fisher-information lens to positioning tasks [16].

Third, waveform and receiver foundations follow a taxonomy now widely adopted [14]. Communication-centric waveform design (CCWD) adapts legacy waveforms (e.g., OFDM/SC-FDMA) to extract echoes while preserving link performance; sensing-centric designs embed information into radar-friendly signals; and joint waveform optimization and design (JWOD) co-optimizes time/frequency/space resources and beampatterns end-to-end. OFDM's flexibility and NR/802.11 compatibility make it central in CCWD, though sidelobes, CFO sensitivity, and PAPR must be managed within standard constraints [3], [14]. In high-mobility settings, OTFS natively represents channels on the delay–Doppler grid. A recent ISAC receiver pipeline retains inter-symbol/inter-carrier interference (ISI/ICI) in a GLRT likelihood, performs noncoherent spatial integration and CFAR on the delay–Doppler (DD) grid to build a 2-D statistic, and then runs a 1-D angular search; operation separates into a discovery mode—via DD-multiplexing across transmit antennas for omnidirectional probing and unmasking of closely spaced targets—and a track mode—via focused DD power and spatial beams on detected cells [6]. This receiver-side exploitation complements transmit-side covariance shaping from the CRB–rate formalism.

Fourth, architectural options align with a network-level taxonomy endorsed by the surveys [1], [3]. Cooperative or cell-free ISAC distributes illumination and reception across multiple access points or RRUs, enabling multi-view diversity and extended coverage; optimization typically maximizes worst-target sensing SINR under per-user SINR and per-site power using fractional programming and convex–concave procedures, with synchronization and fronthaul discipline assumed for coherent fusion [7], [17]. Environment reconfiguration leverages intelligent surfaces. Intelligent omni-surfaces (IOS) and related STAR-RIS provide full-space (transmit+reflect) control, so min-target-SINR objectives at a fixed false-alarm rate are solved by block-coordinate methods over radar combiners, BS precoders, and surface coefficients, with SDR/SCA subproblems and EM-aware constraints [4], [8], [9]. Orthogonally, fluid antennas introduces a movable aperture that adds a spatial position/shape degree of freedom and can uplift sensing SCNR while honoring user SINR constraints, enlarging the feasible region implied by the Pareto boundary.

Finally, standardization hooks and prototyping evidence ground the theory. In unlicensed mmWave WLANs (IEEE 802.11ay/bf), beam-training (A-BFT/SSW) can double as sensing when training energy and analog beams are jointly designed under Neyman–Pearson criteria so that detection probability is maximized while an initial-access SNR target is preserved [10], [11]. At the other extreme, ultra-broadband THz platforms (around 220 GHz with multi-GHz bandwidth) demonstrate co-hardware/co-waveform feasibility with high data rates and millimeter-level ranging, while surfacing phase noise, calibration, and high-gain alignment as first-order constraints for practical deployment [12]. Beyond ISAC, the ISCC vision couples sensing and communication with computation at the edge; tri-functional formulations balance estimation accuracy, link throughput/latency, and compute/inference error under stringent resource budgets, extending ISAC's integrated design to task-oriented networking [4]. These survey-level insights justify the comparison criteria adopted later—rooted in waveform/beam choices, estimator structures, trade-off metrics, and system assumptions—so that ISAC contributions can be assessed consistently against the evolving 6G vision and KPIs [1], [3].

III. Systematic Overview

We organize the landscape along five axes that recur throughout and map directly to recent IEEE ComSoc journals and top-tier conferences.

(1) Estimation–information tradeoffs. With a shared transmit covariance $\mathbf{Q} \succeq 0$ and $\mathrm{tr}(\mathbf{Q}) \leq P$, the Pareto problem maximizes $R(\mathbf{Q})$ under $\Gamma(\mathbf{Q}) \leq \bar{\Gamma}$, or its dual. For point targets, the optimal solution diagonalizes a composite sensing–communication channel via SVD with water–filling-like allocation; for extended targets, it diagonalizes the communication channel and splits power between shared and sensing-only subspaces [5]. Localization-centric variants minimize joint angle–delay CRBs under communication requirements [16].

(2) Waveforms and receivers in high mobility. OTFS-based ISAC embraces delay–Doppler structure. A GLRT over (τ, ν, θ) retains ISI/ICI in the likelihood, followed by noncoherent spatial integration and CFAR on the DD grid, and a 1-D angle search. Operation separates into discovery—via DD-multiplexing across transmit antennas—and track—via focused DD power and beams [6].

(3) Cooperative/cell-free ISAC. Cooperative multi-static architectures distribute illumination across multiple transmitting RRUs and centralize echo processing. A recent C-RAN letter jointly optimizes multi-site transmit beamformers and a centralized receive filter to maximize radar SINR subject to per-user SINR and per-site power, alternating via fractional programming and a convex–concave procedure [7], [17].

(4) Environment reconfiguration. Intelligent Omni Surfaces (IOS) offer simultaneous reflection and transmission for full-space control. Joint active (BS) and passive (IOS) beamforming can maximize the minimum sensing SINR across multiple targets while meeting multi-user MIMO constraints;

the non-convex program is decomposed via block coordinate descent with SDR/SCA subproblems [8], [9]. Beyond surfaces, fluid antennas introduce a movable-aperture degree of freedom to uplift sensing SCNR under user SINR constraints [18].

(5) Standards and extreme bands. In unlicensed mmWave WLANs (e.g., IEEE 802.11ay/bf), sensing can be embedded into beam training (A-BFT/SSW) by jointly allocating training energy and selecting analog beams under Neyman–Pearson detection, balancing detection probability and communication SNR during initial access [10], [11]. At the opposite end, ultra-broadband THz prototypes validate co-hardware/co-waveform feasibility with multi-GHz bandwidths, high data-rate links, and fine range resolution [12].

To make these axes actionable, Table I positions representative papers by scenario and approach, and marks capability flags most relevant to design choices—multi-target handling, mobility readiness, prototype/standard hooks, and whether the method relies on cooperation / intelligent surfaces / reconfigurable hardware. The CRB–rate formalism [5] anchors axis (1); the OTFS receiver pipeline [6] represents axis (2); cooperative multi-static and IOS-aided solutions [7]–[9] reflect axis (3)–(4); and WLAN/THz endpoints [10]–[12] span axis (5). Localization-centric CRBs [16] and fluid antennas [18] extend the frontier with additional degrees of freedom.

IV. Architectures and Algorithms

Cooperative multi-static / cell-free. Moving from a single monostatic BS to a coordinated cluster of RRUs changes both geometry and optimization. In a cooperative multi-static design, multiple transmitters illuminate the scene while a centralized processor forms a receive filter from networked echoes. A recent letter formulates the joint design of per-site precoders and a centralized radar receive filter to maximize the worst-target SINR subject to per-user SINR and per-RRU power constraints; the nonconvex ratios are handled by fractional programming and a convex–concave procedure [7], [17]. As RRU count and array size increase, the sensing floor lifts via multi-view diversity until user-SINR constraints become binding—an operating regime that aligns with the CRB–rate frontier.

IOS-aided and reconfigurable-hardware ISAC. Intelligent omni surfaces (IOS) generalize RIS by simultaneously reflecting and transmitting, enabling 360° coverage and controllable illumination behind the surface. A recent TCOM paper co-designs the BS precoder, the radar combiner, and the IOS coefficients to maximize the minimum sensing SINR across multiple targets under multi-user MIMO QoS; the coupled nonconvex program is decomposed by block coordinate descent with SDR/SCA subproblems [8], [9]. Orthogonal to surfaces, fluid antennas introduce a movable aperture. By alternating between transmit precoder updates and antenna-position selection, one can maximize radar SCNR while meeting per-user SINR constraints—escaping deep fades and clutter valleys without sacrificing communication QoS [18]. Together, IOS and fluid antennas complement cooperation: the former rewires propagation, the latter repositions the aperture.

Standards-aligned mmWave and THz prototyping. In unlicensed mmWave WLANs, sensing can be embedded into IEEE 802.11 beam training (A-BFT/SSW). A recent ICASSP paper jointly allocates training energy and designs the analog beam pattern under Neyman–Pearson detection, balancing detection probability and communication SNR in initial access with protocol-compatible sequences [10], [11]. At the opposite end of the spectrum, a THz ISAC platform near 220 GHz with multi-GHz bandwidth demonstrates co-hardware/co-waveform feasibility: field trials report concurrent high data rates and millimeter-level ranging, while surfacing practical constraints such as phase noise, calibration of high-gain apertures, and alignment procedures [12].

Architectures and algorithms interact with the foundational tradeoffs: cooperative clusters and IOS/fluid antennas expand the feasible region by adding spatial degrees of freedom; standards-aligned mmWave sensing and THz prototypes pin realistic operating points by imposing hardware, synchronization, and regulatory constraints [7], [8], [10]–[12], [18].

The preceding prose highlights how cooperation, surfaces, and reconfigurable hardware expand the feasible region implied by the CRB–rate frontier, while OTFS pipelines and WLAN/THz hooks tie algorithms to deployable stacks. Table II then drills into each technical paper, making explicit how the claimed contributions descend from ISAC fundamentals (shared covariance/waveform, Fisher-information/CRB metrics, Neyman–Pearson detection, and network constraints).

V. Challenges and Future Directions

Robust frontier operation. CRB–rate designs typically presuppose accurate CSI and, in localization-centric variants, reliable priors for target parameters; in practice, dynamics and modeling mismatch shift the operating point away from the Pareto boundary [5], [16]. A priority is to embed robustness directly into the frontier construction—e.g., distributionally robust or Bayesian formulations for $\Gamma(\mathbf{Q})$ (angle/delay CRBs), chance-constrained rate guarantees for $R(\mathbf{Q})$, and online adaptation of $\mathbf{Q}$ as priors are updated. The surveys further highlight the need for unified metrics beyond decoupled BER/CRB, suggesting capacity–distortion or estimation-information measures that retain meaning under uncertainty [1], [13].

Scalable delay–Doppler processing. Full GLRT over (τ, ν, θ) with noncoherent spatial integration and CFAR delivers resolvability in mobility, but the search is computationally intensive and memory bound for large arrays and long frames [6]. Future receivers should combine structure-exploiting pruning (coarse-to-fine DD tiling, orthogonal matching on sparse DD supports), FFT-based correlation on compact windows, and hardware-aware accelerators (GPU/FPGA or inline baseband cores). A tight coupling of discovery/track modes with transmit covariance updates can also reduce the DD search volume without sacrificing detection performance.

Synchronization and fronthaul for cooperative ISAC. Cooperative multi-static designs lift the sensing floor via multi-view diversity but presuppose time/frequency alignment across RRUs and bounded fronthaul latency for coherent combining

TABLE I: At-a-glance view of recent ISAC works.

Paper	Year	Scenario	Approach	Multi-Tgt	Mobility	Proto/Std	Coop/Surf/HW
Hua et al. [5]	2023	MIMO ISAC (pt./ext.)	CRB–rate Pareto (SVD+WF)	✓			
Keskin et al. [6]	2024	MIMO-OTFS (high Doppler)	GLRT/CFAR + DD-mux	✓	✓		
Liu et al. [7]	2024	Coop. multi-static (C-RAN)	FP+CCP (TX precoding, RX filter)				✓
Zhang et al. [8]	2024	IOS-aided MU-MIMO	BCD+SDR/SCA (min-sensing-SINR)	✓			✓
Chen et al. [10]	2024	802.11ay/bf beam training	Energy+beam design (NP)			✓	
Liu et al. [12]	2023	THz proto ($\sim$220 GHz)	Co-hw/co-waveform; field trials			✓	
Hu et al. [16]	2025	Localization-centric ISAC	Precoder for joint angle–delay CRBs				
Ye et al. [18]	2025	FAS-assisted MIMO ISAC	Alt. precoding + position (SCNR)				✓

and centralized filtering [7]. System-level protocols for clock distribution, echo timestamping, and fusion under delay jitter are needed, along with graceful fallbacks to partially coherent processing. Network-native support for such timing (and for echo metadata) is consistent with ISAC's positioning as a first-class 6G service [1], [3].

EM-accurate surfaces and reconfigurable hardware. IOS/STAR-RIS gains in worst-case sensing SINR and MU-MIMO QoS must survive element quantization, mutual coupling, near-field effects, and calibration drift, which are only coarsely captured by idealized phase-shift models [8], [9]. Measurement-backed parametric models and calibration procedures will be necessary to bridge simulation and deployment. Orthogonally, fluid antennas introduce a physically movable aperture that improves SCNR by escaping fades and clutter; closing the loop requires mechanical/latency models and joint controllers that schedule position updates with beam/precoder changes [18].

Standards hooks, coexistence, and extreme bands. Embedding sensing into unlicensed mmWave WLAN procedures demands coexistence-aware energy allocation and beam selection that preserve initial-access SNR while maximizing detection probability; protocol-compatible solvers exist, but shared-channel etiquette and side-lobe management remain open issues [10], [11]. At the opposite extreme, THz prototypes confirm co-hardware/co-waveform feasibility yet surface phase noise, calibration, and high-gain alignment as first-order constraints; these must be reflected in frontier designs and evaluation [12]. Across both ends, surveyed roadmaps urge cross-layer policies that jointly manage rate, CRB, and regulatory constraints for standardized ISAC operation [3].

VI. Conclusion

ISAC has progressed from conceptual coexistence to operational joint design: constructive CRB–rate covariances for point and extended targets [5], DD-aware MIMO-OTFS receivers that exploit interference via GLRT/CFAR and DD-multiplexing [6], cooperative and environment-reconfiguring architectures that expand feasible operating regions [7]–[9], and practice-facing hooks in WLAN and THz that anchor deployment assumptions [10]–[12]. The immediate agenda is clear: make the frontier robust, the DD pipeline scalable, cooperation synchronizable, and surfaces/hardware EM-accurate—while aligning signaling and coexistence with standard bodies [1], [3]. Read together, the figures and comparison tables in this paper provide a compact playbook: select a target point on the Pareto curve, choose whether to buy sensing margin via cooperation or environment reconfiguration, and bind receiver complexity to hardware realities. Longer term, integrating computation (ISCC) will extend these designs from sensing–communication tradeoffs to end-to-end task performance under tight resource budgets [4].

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References

[1] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6g and beyond," *IEEE journal on selected areas in communications*, vol. 40, no. 6, pp. 1728–1767, 2022.

[2] U. Demirhan and A. Alkhateeb, "Radar aided 6g beam prediction: Deep learning algorithms and real-world demonstration," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2022, pp. 2655–2660.

[3] N. González-Prelcic, M. F. Keskin, O. Kaltiokallio, M. Valkama, D. Dardari, X. Shen, Y. Shen, M. Bayraktar, and H. Wymeersch, "The integrated sensing and communication revolution for 6g: Vision, techniques, and applications," *Proceedings of the IEEE*, vol. 112, no. 7, pp. 676–723, 2024.

[4] D. Wen, Y. Zhou, X. Li, Y. Shi, K. Huang, and K. B. Letaief, "A survey on integrated sensing, communication, and computation," *IEEE Communications Surveys & Tutorials*, 2024.

[5] H. Hua, T. X. Han, and J. Xu, "Mimo integrated sensing and communication: Crb-rate tradeoff," *IEEE Transactions on Wireless communications*, vol. 23, no. 4, pp. 2839–2854, 2023.

[6] M. F. Keskin, C. Marcus, O. Eriksson, A. Alvarado, J. Widmer, and H. Wymeersch, "Integrated sensing and communications with mimo-otfs: Isi/ici exploitation and delay-doppler multiplexing," *IEEE Transactions on Wireless Communications*, vol. 23, no. 8, pp. 10 229–10 246, 2024.

[7] S. Liu, M. Li, R. Liu, W. Wang, and Q. Liu, "Joint transmit beamforming and receive filter design for cooperative multi-static isac networks," *IEEE Wireless Communications Letters*, vol. 13, no. 6, pp. 1700–1704, 2024.

[8] Z. Zhang, W. Chen, Q. Wu, Z. Li, X. Zhu, and J. Yuan, "Intelligent omni surfaces assisted integrated multi-target sensing and multi-user mimo communications," *IEEE Transactions on Communications*, vol. 72, no. 8, pp. 4591–4606, 2024.

[9] Z. Wang, X. Mu, and Y. Liu, "Stars enabled integrated sensing and communications," *IEEE transactions on wireless communications*, vol. 22, no. 10, pp. 6750–6765, 2023.

TABLE II: Comparison of technical works (contributions highlighted against ISAC background foundations)

Reference	Specific Topic	Main Contributions	Derivations from the Background of ISAC (What is new vs. background)
Hua–TWC'23 [5]	CRB–rate tradeoff in MIMO ISAC (point/extended targets)	Exact Pareto tracing via CRB-constrained rate (and dual); semi-closed-form optimal $\mathbf{Q}^{\star}$ from SVD (composite vs. comm-only) with monotone power split; corner-point characterizations	Elevates two-metric ISAC (rate + CRB) from conceptual to constructive design: formal separation of point/extended targets, conditions for sensing-only modes, and rank behavior beyond standard water-filling
Keskin–TWC'24 [6]	ISI/ICI-aware MIMO-OTFS with DD-multiplexing	GLRT that retains ISI/ICI; non-coherent spatial integration + CFAR on DD grid; discovery/track pipeline; empirical trade-off curves under mobility	Advances waveform/receiver axis by exploiting delay–Doppler structure, contrasting with OFDM-based CCWD: shows receiver-side gains complementary to transmit covariance shaping in CRB–rate frameworks
Liu–WCL'24 [7]	Cooperative multi-static (C-RAN) joint TX/RX design	Max–min target sensing-SINR under per-user SINR and per-site power; alternating FP+CCP for TX precoding and centralized RX filter	Extends monostatic ISAC to networked/cooperative setting: imports SINR-based constraints into multi-site design, adding coherent multi-view fusion and fronthaul-aware optimization
Zhang–TCOM'24 [8]	IOS-assisted multi-target sensing with MU-MIMO	Joint optimization of BS precoder, radar combiner, and IOS; BCD with SDR/SCA subproblems; min-sensing-SINR guarantees; 360° coverage	Moves beyond passive RIS background by enabling transmit+reflect control (IOS/STAR), embedding environment reconfiguration directly into beampattern shaping under unified radar/comm QoS
Chen–ICASSP'24 [10]	ISAC in 60 GHz (802.11) beam training	Joint energy allocation and analog beam selection under Neyman–Pearson; balances P_D vs. IA SNR with protocol-compliant sequences	Operationalizes CCWD in WLAN standards: turns IA training frames into sensing pulses with NP-optimality, concretizing background claims on reuse of legacy waveforms for sensing
Liu–PIMRC'23 [12]	THz co-hardware/co-waveform prototype	Fielded $\sim$220 GHz platform with multi-GHz BW; concurrent high-rate link + mm-level ranging; calibration/alignment procedures quantified	Provides hardware validation missing from background theory: identifies phase-noise/calibration limits and alignment overheads that constrain ideal CRB–rate operating points
Hu–TVT'25 [16]	Joint angle–delay CRB optimization under QoS	Precoder minimizing joint (angle, delay) CRBs subject to comm QoS; structural insights and closed-form cases; sparsity of active modes	Specializes Fisher-information lens to localization metrics, bridging background CRB–rate design with positioning-oriented objectives under rate constraints
Ye–TVT'25 [18]	FAS-assisted SCNR maximization under user SINR	Alternating optimization over precoder and fluid-antenna position; robustness to fading/clutter; QoS-preserving SCNR gains	Introduces movable-aperture DoF beyond fixed arrays/RIS in background ISAC: shows geometry reconfiguration as an orthogonal lever to expand feasible sensing–communication regions

[10] Q. Chen, Y. Liang, and H. Jiang, "Integrated sensing and communication in unlicensed mmwave bands: Joint beamforming training and energy allocation," in *ICASSP 2024-2024 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. IEEE, 2024, pp. 12 926–12 930.

[11] R. Du, H. Hua, H. Xie, X. Song, Z. Lyu, M. Hu, Y. Xin, S. McCann, M. Montemurro, T. X. Han *et al.*, "An overview on ieee 802.11 bf: Wlan sensing," *IEEE Communications Surveys & Tutorials*, vol. 27, no. 1, pp. 184–217, 2024.

[12] Y. Liu, O. Li, X. Du, J. Zang, Q. Liu, and G. Wang, "Comprehensive prototype demonstration of ultra-broadband terahertz platform for 6g isac," in *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. IEEE, 2023, pp. 1–7.

[13] A. Liu, Z. Huang, M. Li, Y. Wan, W. Li, T. X. Han, C. Liu, R. Du, D. K. P. Tan, J. Lu *et al.*, "A survey on fundamental limits of integrated sensing and communication," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 994–1034, 2022.

[14] W. Zhou, R. Zhang, G. Chen, and W. Wu, "Integrated sensing and communication waveform design: A survey," *IEEE Open Journal of the Communications Society*, vol. 3, pp. 1930–1949, 2022.

[15] Z. Liu, S. Aditya, H. Li, and B. Clerckx, "Joint transmit and receive beamforming design in full-duplex integrated sensing and communications," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 9, pp. 2907–2919, 2023.

[16] C. Hu, Y. Fang, and L. Qiu, "Joint angle and delay cramér-rao bound optimization for isac," *IEEE Transactions on Vehicular Technology*, 2025.

[17] W. Mao, Y. Lu, C.-Y. Chi, B. Ai, Z. Zhong, and Z. Ding, "Communication-sensing region for cell-free massive mimo isac systems," *IEEE Transactions on Wireless Communications*, vol. 23, no. 9, pp. 12 396–12 411, 2024.

[18] Y. Ye, L. You, H. Xu, A. Elzanaty, K.-K. Wong, and X. Gao, "Scnr maximization for mimo isac assisted by fluid antenna system," *IEEE transactions on vehicular technology*, 2025.