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Intelligent Reflecting Surfaces for 6G Millimeter-Wave Networks: Architecture, Channel Estimation, Beamforming, and Emerging Applications, Optimization, Security, and Multi-Operator Resource Sharing

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Abstract: The rapid evolution toward sixth-generation (6G) wireless communication systems necessitates the exploitation of millimeter-wave (mmWave) frequencies to support enhanced mobile broadband and ultra-reliable communications. However, mmWave signals suffer from severe propagation attenuation and vulnerability to physical blockages, severely limiting their effective coverage area. This paper explores the deployment of Intelligent Reflecting Surfaces (IRS) as a transformative, cost-effective paradigm to intelligently control the wireless propagation environment. By jointly investigating capacity optimization, physical-layer security, and multi-operator infrastructure sharing, we propose a comprehensive framework designed to mitigate mmWave limitations. A hypothetical evaluation methodology is outlined to demonstrate how dynamic IRS element allocation and passive beamforming can drastically improve spectral efficiency and network sustainability compared to traditional, non-IRS architectures. The sixth-generation (6G) wireless communication network is expected to provide ultra-high data rates, extremely low latency, massive connectivity, and intelligent communication services. Intelligent Reflecting Surfaces (IRS), also known as Reconfigurable Intelligent Surfaces (RIS), are programmable passive surfaces that manipulate electromagnetic waves to improve millimeter-wave communication by mitigating blockage and path loss. Sixth-generation (6G) wireless networks are expected to support very high data rates, ultra-low latency, massive connectivity, and intelligent communication services, while milli meter-wave (mmWave) operation is constrained by severe path loss, atmospheric absorption, and blockage susceptibility. Intelligent Reflecting Surfaces (IRSs), also referred to as Reconfigurable Intelligent Surfaces, offer a passive and cost-effective means of reshaping the propagation environment to improve mmWave communication by mitigating blockage and enhancing coverage. The merged literature reviewed here emphasizes three major IRS research directions: capacity and beamforming optimization, physical-layer security, and infrastructure sharing among mobile network operators (MNOs). A unified multi-module framework is also presented, combining channel estimation and blockage detection, joint beamforming optimization, and multi-operator element allocation, together with a hypothetical evaluation plan comparing IRS-assisted networks to conventional baselines.

Keywords: *Intelligent Reflecting Surfaces, 6G Millimeter-Wave Networks, Architecture, Channel Estimation, Beamforming, Emerging Applications, Optimization, Security, Multi-Operator Resource Sharing.*

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I. INTRODUCTION

- *Why Intelligent Reflecting Surfaces Matter for 6G Mmwave Systems*

- *From Passive Control to Smart Radio Environments*

Intelligent reflecting surfaces (IRSs) have shifted the conceptual center of wireless design from merely adapting to the propagation environment toward actively shaping it. Foundational reviews argue that future 6G systems will require controllable radio environments because conventional channel randomness becomes a bottleneck under dense connectivity, blockage sensitivity, and stringent energy-efficiency demands (Basar et al., 2019), (Pan et al., 2021). In this framing, IRSs are not just reflective panels but programmable electromagnetic interfaces that can tune

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phase, and in broader formulations also amplitude, frequency, and polarization, to influence how radio waves propagate (Basar et al.,2019), (Long et al., 2021). This reorientation is particularly relevant for millimeter wave (mmWave) systems, where high directivity and blockage can sharply reduce link robustness (Nemati et al., 2020), (Chen, Ma, et al., 2021). The literature therefore positions IRSs as a cost-effective physical-layer technology for improving coverage and energy efficiency while avoiding the full RF-chain burden of conventional active relays (Wu & Zhang, 2019), (Pan et al., 2021). The exponentially growing demand for high-data-rate multimedia access has driven the wireless research community to explore extremely high frequencies, particularly the millimeter-wave (mmWave) and terahertz bands, for the upcoming 6G networks (Yu et al., 2019). While these frequency bands offer massive available bandwidth, they are inherently limited by high path loss, atmospheric absorption, and a severe susceptibility to blockages from physical obstacles (Hashida et al., 2025). To maintain reliable communication links, contemporary networks have heavily relied on deploying massive multiple-input multiple-output (MIMO) systems and ultra-dense small cells (Zhao, 2019). However, this traditional network densification strategy inevitably incurs excessive hardware costs, massive energy consumption, and complex interference management challenges (Yu et al., 2020).

IRS comprises programmable reflecting elements that control phase, amplitude, polarization, and reflection direction with very low power consumption. Components include a base station, IRS controller and reflecting surface, and user equipment receiving direct and reflected signals. Signals transmitted by the base station are reflected by IRS elements with optimized phase shifts to strengthen reception. IRS extends coverage, redirects blocked signals, improves received power, and reduces transmit power.

Intelligent Reflecting Surfaces (IRSs) have recently emerged as a revolutionary technology capable of reconfiguring the wireless propagation environment via software-controlled reflection (Björnson, 2021). An IRS consists of a massive array of low-cost, passive reflecting elements that can independently alter the phase and amplitude of incident electromagnetic waves (Kudathanthirige et al., 2020). By intelligently coordinating these phase shifts, an IRS can create a highly focused reflection beam directed toward a specific user, thereby effectively bypassing blockages and establishing virtual line-of-sight communication links (Cui et al., 2019). The scope of this paper encompasses the optimal design of IRS-assisted 6G mmWave networks, focusing specifically on beamforming optimization, physical layer security, and multi-operator sharing mechanisms.

Despite the promise of next-generation wireless technologies, existing approaches remain insufficient to address the holistic challenges of 6G mmWave deployments. First, attempting to overcome mmWave propagation losses purely by uplifting the carrier frequency and increasing the number of active radio frequency (RF) chains introduces prohibitive hardware costs and massive power consumption (Yu et al., 2020)(Yu et al., 2019). Second, traditional physical layer security techniques, such as cooperative jamming and the transmission of artificial noise, consume excessive power and require complex active components, rendering them energy-inefficient for ubiquitous deployment (Yu et al., 2019). Finally, deploying separate, isolated network infrastructures for different mobile network operators (MNOs) leads to spatial conflicts, redundant capital expenditures, and severe inter operator interference (Hashida et al., 2025).

To address these critical shortcomings, this paper presents a novel approach to IRS-assisted mmWave networks. The primary contributions of this study are summarized as follows:

- We formulate a multi-module IRS integration framework that jointly optimizes the active transmit beamforming at the base station and the passive phase shifts at the IRS to overcome severe mmWave blockages.
- We propose a multi-operator IRS sharing model that dynamically partitions and allocates reflecting elements among competing operators to maximize system-wide spectral efficiency and ensure network fairness.
- We design a rigorous hypothetical evaluation plan to benchmark the proposed framework against conventional single-operator massive MIMO architectures in terms of energy efficiency and secrecy capacity.

The demand for high-data-rate multimedia access has motivated research into mmWave and terahertz bands for future 6G systems, since these bands provide wide bandwidth but also suffer from strong propagation loss and frequent blockage. Traditional responses to these challenges have included massive MIMO and ultra-dense small-cell deployment, but these approaches increase hardware cost, energy consumption, and interference management complexity. IRS technology has emerged as a software-controlled method for reconfiguring the wireless environment through large arrays of passive reflecting elements that can alter incident electromagnetic waves and create focused reflections toward intended users. By enabling virtual line-of-sight links, IRSs can bypass blockages and improve received signal quality in mmWave networks. The scope of the merged paper is centered on IRS assisted 6G mmWave network design with attention to beamforming optimization, physical-layer security, and multi-operator sharing. Existing approaches remain insufficient when considered holistically: simply increasing RF chains is costly and power-hungry, conventional physical-layer security methods such cooperative jamming and artificial noise are energy-inefficient, and separate operator infrastructures can produce redundant costs and severe inter operator interference. The paper therefore proposes an IRS-based framework intended to jointly address coverage, cost, security, and sharing.

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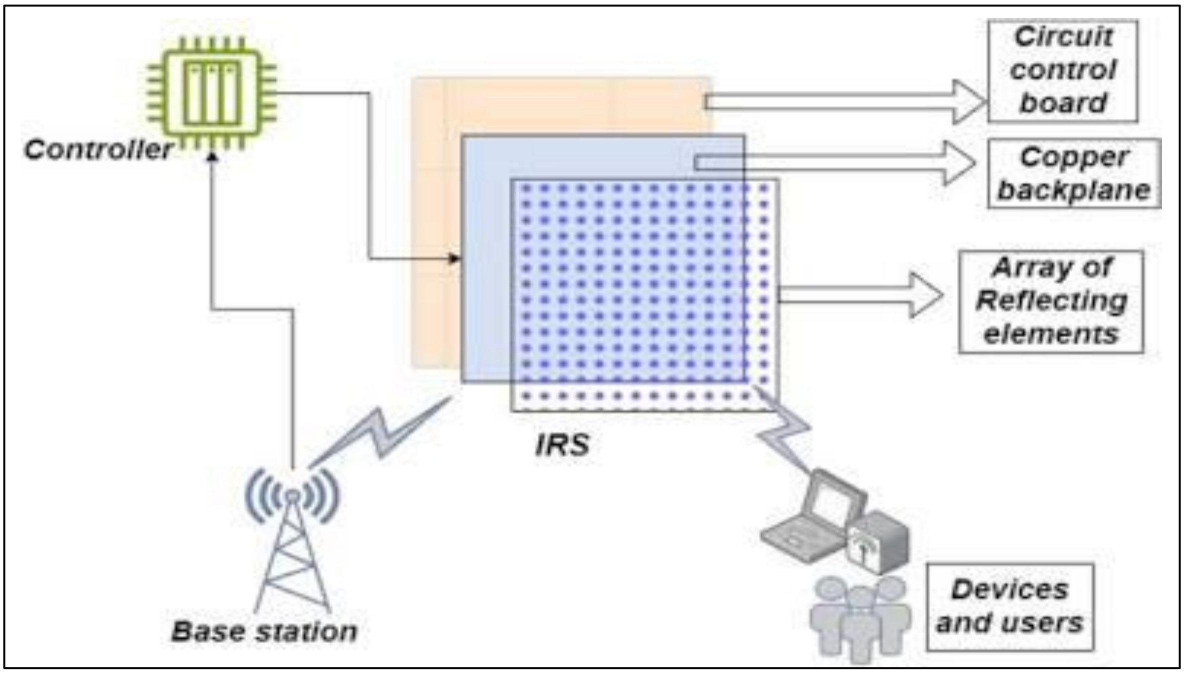

Fig 1 Internal Hardware Layering of an IRS

➢ *Scope, Objectives, and Review Focus*

This review focuses on how IRSs support 6G mmWave networks through hardware design, beamforming, channel estimation, and emerging services. The selected literature shows that performance gains depend not only on the presence of a surface, but on the interaction between architecture, CSI acquisition, and optimization strategy (Wu & Zhang, 2019), (Zhou et al., 2022). It also indicates that the technology's relevance extends beyond communication throughput to sensing, localization, vehicular networking, and other 6G functions (Hu et al., 2023), (Z. Chen, Ma, et al., 2021), (Zhu et al., 2022). The goal of the present synthesis is therefore to connect the physical principles of IRS operation with the systems-level conditions under which they become practically meaningful. That connection provides the basis for the subsequent discussion of hardware architectures, algorithmic design, and unresolved research constraints.

II. RELATED WORK

The integration of Intelligent Reflecting Surfaces into future wireless networks has garnered immense traction within both academia and industry (Zhao, 2019). The existing literature can be broadly classified into three distinct categories based on the primary optimization objective and deployment scenario. These categories include capacity and beamforming optimization, physical layer security, and infrastructure sharing paradigms.

The first category focuses heavily on capacity enhancement and joint beamforming optimization. The core idea in this domain is to maximize the spectral efficiency of the network by jointly designing the active beamformer at the access point and the passive phase shifts at the IRS (Yu et al., 2020)(Yu et al., 2019). Strengths of these approaches include mathematically rigorous closed-form derivations of achievable rates and diversity orders (Kudathanthirige et al., 2020). However, a major weakness is that many of these studies focus on idealized, single-user multiple-input single-output (MISO) scenarios without explicitly addressing the unique blockage dynamics of mmWave frequencies (Yu et al., 2019). In contrast to these foundational studies, our work directly incorporates mmWave blockage models and extends the optimization framework to multi-user, multi-operator environments.

The surrounding literature can be grouped into three broad categories: capacity and beamforming optimization, physical-layer security, and infrastructure sharing. In the first category, many studies focus on maximizing spectral efficiency through joint design of the active beamformer at the access point and passive IRS phase shifts, with mathematically rigorous derivations of rates and diversity orders. A limitation of much of this work is that it often idealized single-user MISO scenarios and does not explicitly address mmWave blockage dynamics. The present work extends this line by incorporating mmWave blockage models and multi-user, multi operator environments. In the second category, IRSs are used to enhance physical-layer security by configuring phase shifts so that the legitimate receiver is strengthened while signals at eavesdroppers are destructively interfered with. This strategy is described as more energy-efficient than traditional active jamming approaches. However, existing physical-layer security work is noted to be poorly integrated with broader network management issues such as inter operator interference in shared environments. In the third category, recent studies explore IRS use in diverse scenarios such as laser-based optical wireless communication and multi-MNO sharing to reduce reductant infrastructure costs. The main benefit of infrastructure sharing is lower deployment cost and more sustainable 6G operation. A key weakness of prior sharing models is oversimplified interference modeling when

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different operators control separate IRS portions. To address this, the merged paper emphasizes a more granular, element-level partitioning mechanism to mitigate cross-operator interference while preserving spectral efficiency.

The second category revolves around utilizing IRSs to enhance physical-layer security (PLS). The fundamental concept here involves adjusting the phase shifts of the reflecting units to simultaneously strengthen the signal at the legitimate receiver and destructively interfere with the signal at potential eavesdroppers (Cui et al., 2019). This approach is highly praised for being far more energy-efficient than traditional active jamming methods (Yu et al., 2019). Nevertheless, a notable weakness of current PLS research is its lack of integration with broader network management problems, such as interoperator interference in shared environments. Our proposed framework bridges this gap by merging PLS optimization objectives with collaborative multi-operator resource allocation.

The third category explores infrastructure sharing and novel deployment environments. Recent research has investigated the application of IRS in diverse settings, including laser-based optical wireless communication to overcome beam-blockage (Hamad et al., 2024), and multi-MNO sharing to reduce redundant infrastructure costs (Hashida et al., 2025). The core strength of sharing IRS infrastructure is the significant reduction in deployment costs and the enhancement of sustainable 6G networks (Hashida et al., 2025). However, the weakness lies in the oversimplification of the interference models when multiple operators simultaneously control different subsets of the IRS. Building upon these concepts, our work introduces a more granular, element-level partitioning mechanism that explicitly mitigates cross-operator interference while maintaining high spectral efficiency.

III. IRS FUNDAMENTALS AND ENABLING HARDWARE ARCHITECTURES

➢ *Reflective, Transmissive, Hybrid, Active, and Semiactive Designs*

Recent surveys distinguish several IRS realizations, each with different system implications. The most established configuration is the reflective IRS, in which incident energy is redirected toward users on the same side of the surface (Zenget al., 2021), (Panet al., 2021). Transmissive IRSs extend the concept by allowing signals to pass through the surface and serve users on the opposite side, while hybrid designs combine reflection and transmission in a single platform (Zenget al., 2021). More recent overviews also discuss active and semiactive RISs, where signal reception, amplification, or limited processing may be incorporated to address the performance limits of purely passive operation (Basar et al., 2024), (Shojaeifard et al., 2022), (Zhang & Dai, 2023). These distinctions matter because the literature does not treat "IRS" as a single fixed device class; rather, it is an umbrella term for a family of reconfigurable surfaces that trade off simplicity against capability (Basar et al., 2024), (Pan et al., 2021).

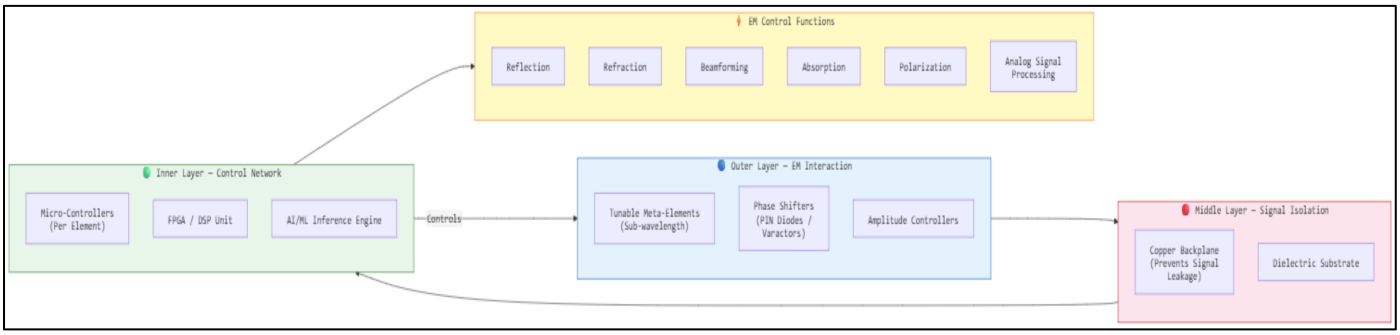

Fig 2 IRS Hardware Architecture — Three-Layer Structure

➢ *Meta Surfaces, Patch Arrays, and Surface-Wave-Assisted Platforms*

Hardware architecture also determines the electromagnetic model used in analysis. Surveys of near-field IRS communications highlight patch array-based and meta surface-based designs as two central branches, with different channel models and different scaling behavior in spherical-wave propagation (Muetal.,2024). In parallel, surface-wave-assisted RISs are described as a design dimension that uses the surface itself as an intelligent propagation medium rather than as a purely passive reflector (Shojaeifard et al., 2022). This broadens the notion of controllability beyond phase-only reflection and creates an architecture space that includes dynamic meta surface antennas and stacked components (Basar et al., 2024). The key implication is that hardware structure is inseparable from algorithm design: channel models, beamforming rules, and training procedures all depend on whether the device behaves as a conventional reflector, a transmissive sheet, or a surface-wave-enabled propagation platform (Mu et al., 2024), (Basar et al., 2024).

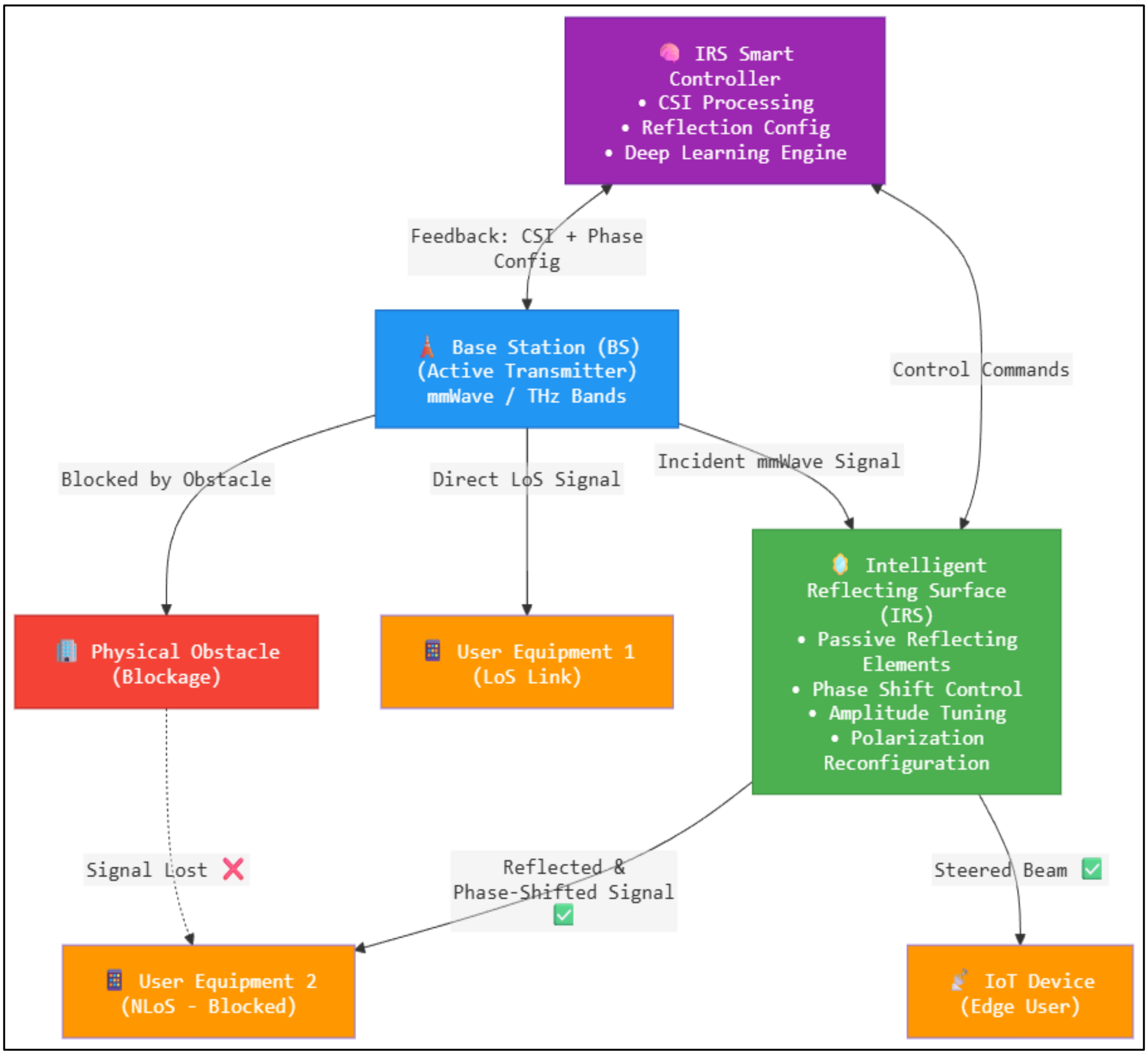

Fig 3 IRS-Assisted 6G mmWave Network — System Architecture

➢ *Energy, Cost, and Deployment Trade-Offs*

The principal attraction of IRSs is their promise of high array gain with low power consumption and low cost (Pan et al., 2021), (Zhang & Dai, 2023). The passive nature of many IRSs removes the need for transmit RF chains, which is why joint active-passive designs can emulate the performance of more antenna-rich systems with fewer active components at the access point (Wu & Zhang, 2019). Yet the same passivity that lowers cost also limits controllability and makes performance sensitive to channel conditions, especially when direct links are already strong (Zhang & Dai, 2023). The literature on hardware architectures therefore converges on a central trade-off: more complex surfaces may mitigate multiplicative fading and improve functionality, but they also weaken the original promise of ultra-low-cost deployment (Zhang & Dai, 2023), (Basar et al.,2024). For 6G planning, this means deployment analysis must weigh energy efficiency against calibration burden, design flexibility, and the degree to which the environment can be realistically controlled.

IV. BEAMFORMING, PRECODING, AND COVERAGE ENHANCEMENT IN MMWAVE NETWORKS

➢ *Joint Active and Passive Beamforming for Multiuser Downlink Systems*

The strongest system-level evidence for IRS value in mmWave networks comes from joint optimization of transmit and reflect beamforming. In a canonical multiuser downlink setting, minimizing access-point transmit power while satisfying users' SINR constraints can be achieved by coordinating active beamforming at the AP with passive phase shifts at the IRS (Wu & Zhang, 2019). This result is important because it shows that IRSs are not standalone replacements for base-station processing; their value emerges from coupling with conventional precoding. Related work on hybrid precoding extends the same logic to multiuser mmWave communication, where analog-digital base-station precoding and IRS phase shifts are jointly optimized to reduce mean-squared error between transmitted and received symbols (Pradhan et al., 2020). Taken together, these studies indicate that IRSs function best as part of an integrated beam control stack rather than as isolated reflectors (Wu & Zhang, 2019), (Pradhan et al., 2020).

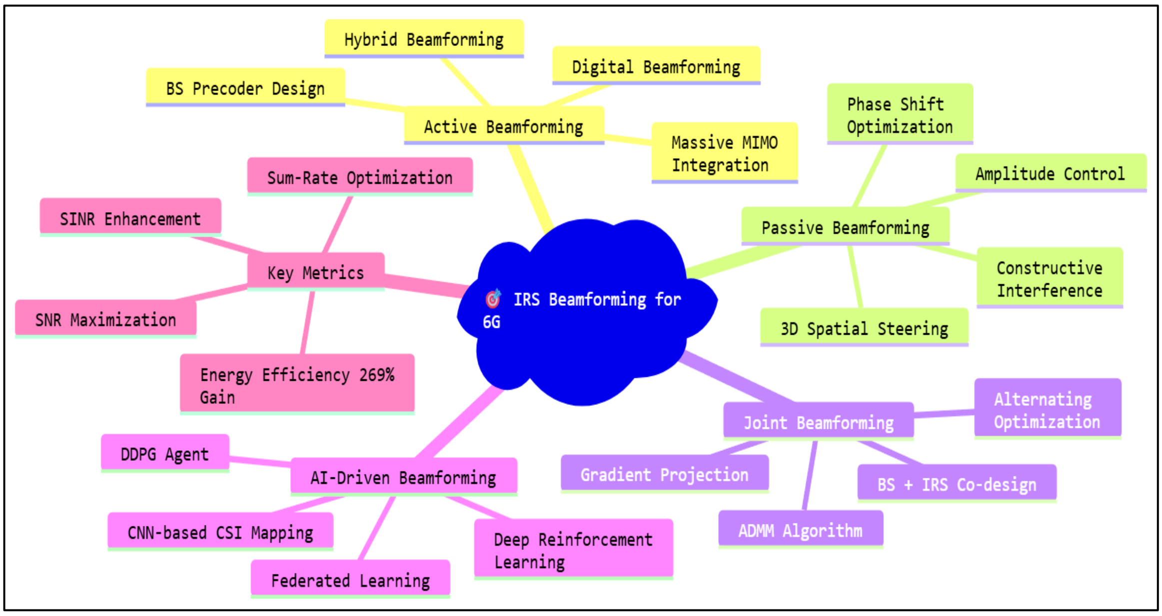

Fig 4 Beamforming Types in IRS-6G Systems

➢ *Hybrid Precoding and Mse-Minimizing Design Strategies*

Hybrid precoding is especially relevant in mmWave networks because it reflects the practical constraint that fully digital processing may be too costly or RF-chain intensive. The optimization literature addresses this by handling constant modulus constraints through gradient-based or manifold-based procedures, while preserving convergence guarantees where possible (Pradhan et al., 2020), (Lin et al., 2022). In the broader literature, similar joint design logic appears in passive beamforming algorithms that exploit estimated cascaded CSI to maximize spectral efficiency (Lin et al., 2022). This suggests that beamforming in IRS assisted networks is not merely a matter of maximizing received power; it often requires multi objective design that balances interference suppression, symbol fidelity, and hardware feasibility. The significance for 6G is that IRSs can reduce dependence on very large antenna arrays, but only if optimization can scale to realistic multiuser settings (Wu & Zhang, 2019), (Pradhan et al., 2020).

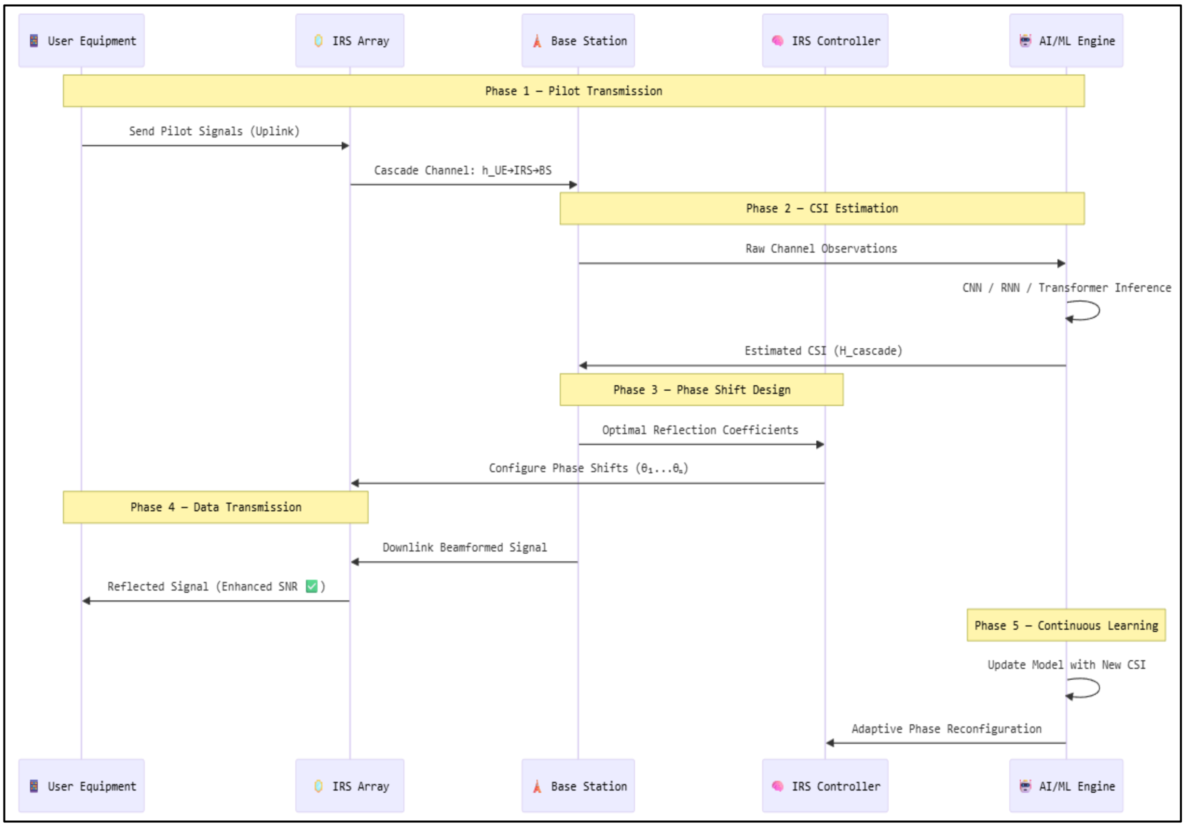

Fig 5 Channel Estimation Process — Sequence Flow

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➢ *Coverage, Sir Scaling, and Passive Reflector Density Effects*

At the network level, stochastic-geometry analysis shows that RIS deployment can substantially improve mmWave coverage and downlink SIR in large-scale cellular systems (Nemati et al., 2020). One important result is that the density ratio between active base stations and passive RISs strongly affects coverage gains (Nemati et al., 2020). This means that performance is not determined by the surface alone, but by spatial planning across the network. The same study further suggests that deploying passive reflectors can be as effective as adding more active antennas at base stations for coverage enhancement (Nemati et al., 2020). That finding aligns with the asymptotic beamforming analysis in single-cell systems, where very large IRSs can achieve strong passive beamforming performance and approximate massive-MIMO-like rate behavior with fewer active RF chains (Wu & Zhang, 2019). The literature therefore supports a consistent interpretation: IRSs are most valuable when network geometry, user distribution, and reflector density are jointly engineered rather than treated as separate design layers.

IRSs are programmable reflecting surfaces with elements that can control phase, amplitude, polarization, and reflection direction using very low power. A basic IRS-assisted system includes a base station, an IRS controller and reflecting surface, and user equipment receiving both direct and reflected signals. The working principle is to transmit signals from the base station to the IRS, where optimized phase shifts re applied so the reflected waves reinforce reception at intended users. In 6G mmWave networks, IRSs are important because they can extend coverage, redirect blocked signals, improve received power, and reduce transmit power. The main advantages identified across the sources are energy efficiency, improved coverage, better spectral efficiency, low hardware cost, enhanced reliability, and green communication support. Reported application areas include smart cities, loT, V2X, indoor communication, industrial automation, UAVs, and satellite communication. Passive beamforming is a central function of IRS operation because it aligns reflected waves to raise SNR, reduce interference, and improve throughput. Common challenges include channel estimation, optimization complexity, hardware imperfections, mobility, synchronization, and security.

The proposed framework is organized into three sequential modules: Channel Estimation and Blockage Detection, Joint Beamforming Optimization, and Multi-Operator Element Allocation. The first module continuously monitors CSI to detect physical blockages on the direct link between base station and users. After blockage detection, the second module computes the optimal active beamforming matrix at the transmitter and passive phase shift matrix at the IRS. The third module dynamically partitions IRS elements among MNOs according to real-time traffic demands and spatial fairness constraints.

V. CHANNEL ESTIMATION AND TRAINING OVERHEAD REDUCTION

➢ *Sparsity-Driven Estimation in Angular-Domain mmWave Channels*

Channel estimation is a central bottleneck because IRSs are passive, high dimensional, and involved in cascaded channels that are harder to measure than conventional direct links (Yuan et al., 2021), (Zhou et al., 2022). A recurring solution is to exploit the sparsity of mmWave channels in the angular domain (Linet al., 2022). One study formulates estimation as an 1-regularized problem with fixed-rank constraints and solves it through alternating minimization and manifold optimization (Lin et al., 2022). The same work also proposes a compressive sensing-based three-stage protocol to reduce computational complexity while preserving estimation quality (Lin et al., 2022). The broader methodological lesson is that IRS-assisted mmWave estimation is feasible because propagation itself is structured; sparse angular support can be converted into algorithmic savings if the estimator is designed around the geometry of the channel rather than around generic dense-matrix assumptions (Lin et al., 2022), (Chen et al., 2021).

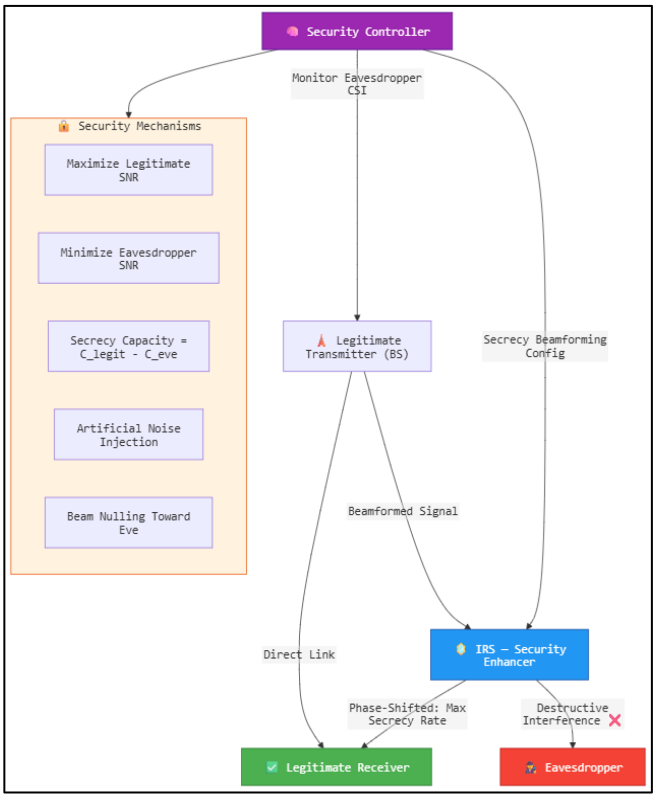

Fig 6 IRS Physical Layer Security Framework

➢ *Low-Pilot Cascaded Estimation for Multiuser IRS-Assisted Systems*

Pilot overhead becomes even more problematic in multiuser settings, where each user contributes a separate cascaded channel. A low-pilot strategy for multiuser mmWave massive MISO systems exploits the sparsity and correlation of cascaded channels across users, estimating full CSI in the first coherence block and then re-estimating

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only channel gains in subsequent blocks (Zhou et al., 2022). The same study uses a two-phase design: first, one typical user's cascaded channel is estimated using linear correlation among paths; then the remaining users' channels are inferred using partial BS-RIS channel information obtained earlier (Zhou et al., 2022). The value of this approach is methodological as well as practical, because it shows how temporal stability of geometry can be converted into reduced training cost (Zhou et al., 2022). In parallel, another recent study handles arbitrary IRS shapes through low-dimensional robust sparse matrix reconstruction, indicating that the estimation problem is becoming more realistic rather than simpler (Chu et al., 2024).A compact representation of the estimation pipeline is shown below.

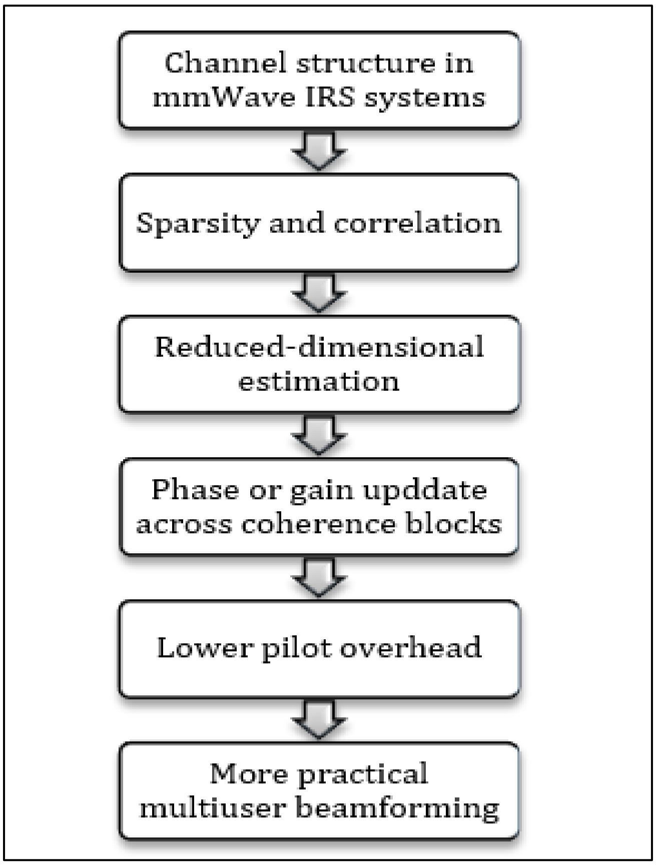

Fig 7 Estimation Pipeline

➢ *Adaptive and Learning-Based Estimators for Time-Varying Channels*

The estimation challenge intensifies when channels vary over time or the IRS geometry is no longer regular. To address this, adaptive estimators combine atomic-norm ideas, alternating optimization, and ADMM to recover direct and reflective channels jointly (Chu et al., 2024). The same study proposes a learning based solver built from fixed-point iteration and a cascaded deep-learning network that can adjust network depth to channel variation (Chu et al., 2024). This is noteworthy because it moves beyond static sparse recovery toward estimators that adapt complexity to the operating environment. The literature collectively suggests that future IRS deployment will depend on estimation algorithms that are both structure-aware and flexible enough to track nonstationary conditions (Yuan et al., 2021), (Chu et al., 2024). In other words, the practical bottleneck is no longer whether IRS channels can be estimated at all, but whether they can be tracked at scale with acceptable pilot cost and computational burden.

VI. BEYOND COMMUNICATIONS: POSITIONING, SENSING, AND NEW 6G USE CASES

➢ *IRS-Assisted Integrated Sensing and Communication at mmWave*

IRSs are increasingly studied as enablers of integrated sensing and communication (ISAC) rather than as pure connectivity devices. A distributed semi-passive IRS-based ISAC framework for mmWave SIMO systems allows location sensing and data transmission to occur on the same time-frequency resources (Hu et al., 2023). The proposed protocol divides each coherence block into channel estimation, ISAC, and pure communication periods, using estimated location information to support beamforming in subsequent blocks (Hu et al. 2023). This design is important because it demonstrates how sensing can reduce dependence on perfect CSI while still supporting communication performance close to perfect-CSI benchmarks (Hu et al., 2023). The result also reinforces a broader architectural theme: IRSs are most compelling when they help unify tasks that were previously treated as separate signal-processing problems.

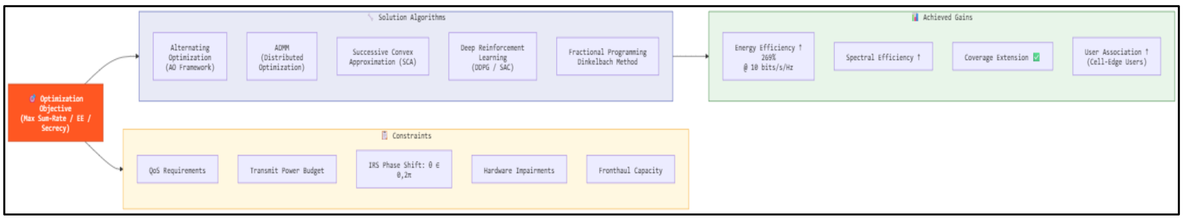

Fig 8 Optimization Framework for IRS-6G Systems

➢ *6G IoT Positioning and Millimeter-Level Localization*

Positioning is another domain in which IRSs may have disproportionate impact. A contemporary survey on 6G IoT positioning explains that RISs can intelligently manipulate radio waves and are well suited for accurate localization because of their channel structure and controllable propagation characteristics (Z. Chen, Ma et al., 2021). The survey classifies existing positioning work and emphasizes that 6G systems will increasingly integrate communication, intelligence, sensing, positioning, control, and computation (Z. Chen, Ma, et al., 2021). In the ISAC study, the sensing procedure achieved millimeter-level positioning accuracy, illustrating the practical relevance of that survey's framing (Hu et al., 2023). The connection between the two is more than thematic: it suggests that IRS-enabled localization could be especially valuable in dense loT systems where high accuracy and energy efficiency are both required (Z. Chen, Ma, et al., 2021), (Huet al., 2023).

- *Vehicular, Terahertz, UAV, and Energy-Harvesting Scenarios*

Beyond positioning, surveys of vehicular and terahertz systems show that IRSs are being mapped onto multiple 6G scenarios. In vehicular communications, IRSs are viewed as a low-cost means to mitigate blockage in mmWave and THz bands while improving signal strength, physical-layer security, and positioning accuracy (Zhu et al., 2022). In THz communications, IRSs are presented as a way to address severe propagation loss and blockage, with applications spanning mobile communications, secure links, UAV settings, and MEC (Chen et al., 2021), (Chen, Ma, et al.,2021). Hardware surveys also identify energy harvesting, aerial networks, and next-generation multiple access as promising application domains (Basar et al.,2024). These converging lines of evidence imply that IRSs should be understood as a general smart-connectivity platform rather than as a niche mmWave add-on. Their value lies in reusing the same programmable surface to support communication, sensing, localization, and mobility-oriented services across heterogeneous 6G scenarios (Zhu et al., 2022), (Basar et al., 2024).

The joint optimization problem is non-convex because of the unit-modulus constraints on passive IRS elements. To manage this difficulty, the framework uses alternating optimization combined with manifold optimization, which is presented as a way to obtain high-quality suboptimal solutions with manageable computational overhead. For sharing, the paper favors dynamic spatial partitioning over time-division multiplexing because 6G latency requirements make simultaneous reflection preferable to time-slot synchronization delays. The proposed evaluation uses a standardized urban microcell dataset with dense obstacles to emulate severe mmWave blockage conditions. The framework is benchmarked against three baselines: a conventional massive MIMO system without IRS, an IRS-assisted system with random phase shifts, and a single-operator IRS deployment. The main performance metrics are sum-rate spectral efficiency, energy efficiency in bits per Joule, and achievable secrecy rate with randomly distributed eavesdroppers. Initialize the system by acquiring CSI for legitimate users and potential eavesdroppers in the multi-MNO environment. Monitor the network for mmWave blockages and allocate a dedicated IRS subset to the affected operator according to current load and priority. Apply a manifold optimization algorithm to determine the optimal passive phase shift matrix for the allocated IRS elements so as to maximize SNR at intended receivers. Update the active transmit beamformer iteratively until network spectral efficiency converges to a stable maximum.

VII. RESEARCH GAPS, CHALLENGES, AND FUTURE DIRECTIONS

- *Channel State Information Acquisition and Pilot Contamination*

Despite strong promise, CSI acquisition remains the dominant challenge. Multiple reviews identify CSI estimation as one of the most fundamental barriers to IRS enabled systems because the IRS is passive and the cascaded channel is high dimensional (Yuan et al., 2021), (Pan et al., 2021). The multiuser estimation literature shows that overhead can be reduced through sparsity and channel correlation, but these gains depend on quasi-static geometry and carefully designed training protocols (Zhou et al., 2022). This creates a practical tension: the more dynamic the network, the less reusable the estimated structure becomes. Pilot contamination and training inefficiency are therefore not peripheral issues but central design constraints for scalable deployment (Yuan et al., 2021), (Zhou et al., 2022). Future work will likely need to combine geometry aware pilot design, user clustering, and learning-based tracking to make IRS assistance viable in dense 6G traffic conditions (Chu et al., 2024).

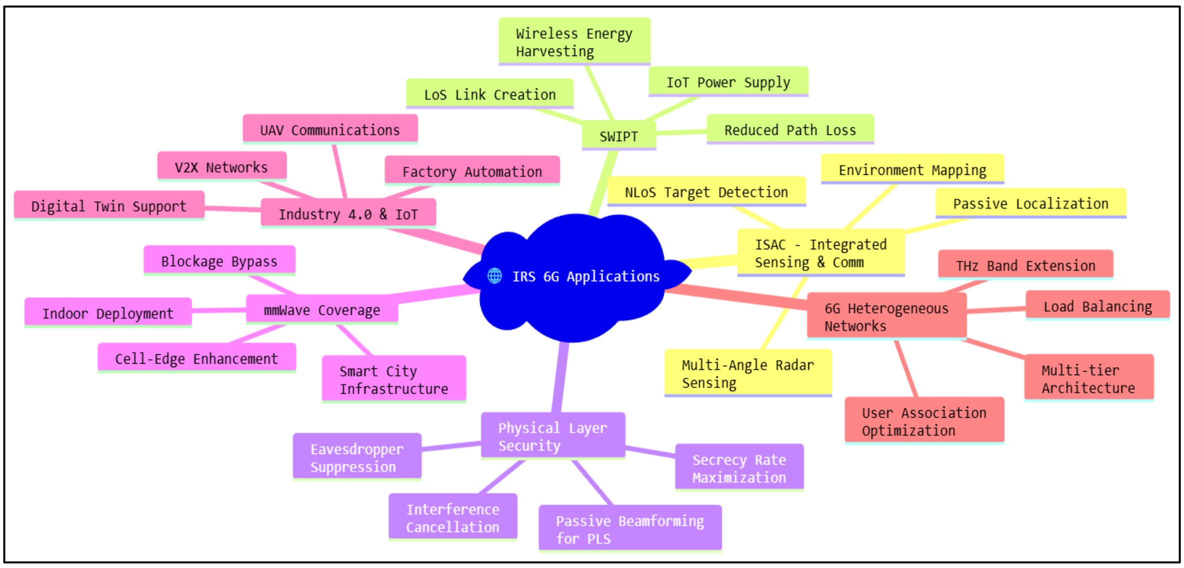

Fig 9 Emerging Applications of IRS in 6G

➢ *Passive Information Transfer, Robust Design, and Hardware Non-Idealities*

A second challenge concerns the limits of passive operation itself. Reviews explicitly identify passive information transfer and low-complexity robust system design as unresolved physical-layer issues (Yuan et al., 2021). The "critical problem" analysis goes further by warning that multiplicative fading can suppress the visible gain of passive RISs when direct links are strong (Zhang & Dai, 2023). This is why active and semiactive designs have begun to attract attention: they may mitigate the performance ceiling of fully passive surfaces, albeit at the cost of higher hardware complexity and power consumption (Zhang & Dai, 2023), (Basar et al., 2024). Hardware non-idealities also matter because emerging architectures include sensors, amplification units, transmission capability, and stacked components, all of which complicate calibration and robust control (Basar et al., 2024). The field therefore faces a familiar systems problem: the more capabilities added to the surface, the more the theoretical elegance of passive control gives way to implementation difficulty.

➢ *Near-Field Propagation, Beam Training, and Scalability Limits*

A final set of challenges arises in near-field regimes and large-scale deployments. Near-field IRS communications require spherical-wave models rather than far field approximations, and surveys show that patch array-based and meta surface based designs have distinct scaling laws and effective degrees of freedom (Mu et al., 2024). The same literature proposes two-stage hierarchical beam training and low-complexity element-wise beamforming, which indicates that beam search complexity remains a core obstacle (Mu et al., 2024). Scalability is also constrained by the fact that the performance gains of large surfaces depend on whether the propagation environment actually supports the assumed scaling behavior (Wu & Zhang, 2019), (Mu et al., 2024). For 6G planners, this means that the next research frontier is not simply larger IRSs, but more realistic models for near-field operation, distributed control, and network-wide coordination. Without those advances, IRS deployment may remain impressive in analysis but difficult to scale in heterogeneous real networks.

VIII. METHOD/APPROACH

To fully realize the potential of IRS in 6G mmWave networks, we propose a structured, multi-module framework designed to handle the complexities of high-frequency propagation and multi-operator demands. The framework is divided into three sequential modules: Channel Estimation and Blockage Detection, Joint Beamforming Optimization, and Multi-Operator Element Allocation. The first module continuously monitors the channel state information (CSI) to detect physical blockages in the direct link between the base station and the users. Once a blockage is detected, the second module is triggered to compute the optimal active beamforming matrix at the transmitter and the passive phase shift matrix at the IRS. Finally, the third module dynamically partitions the IRS elements among different MNOs based on real-time traffic demands and spatial fairness constraints.

The key design choices in this framework are rooted in the need to balance computational complexity with optimal performance. The joint optimization of active and passive beamforming results in a highly non-convex problem due to the unit-modulus constraints of the passive IRS elements (Yu et al., 2019). To address this, we choose to employ an alternating optimization technique combined with manifold optimization, which has been shown to yield high-quality suboptimal solutions with manageable computational overhead (Cui et al., 2019). Furthermore, for the multi-operator sharing mechanism, we opt for dynamic spatial partitioning of the IRS elements rather than time-division multiplexing. This rationale is driven by the strict latency requirements of 6G networks, as spatial partitioning allows simultaneous reflection for multiple operators without introducing time-slot synchronization delays (Hashida et al., 2025).

To validate the efficacy of the proposed approach, we formulate a comprehensive hypothetical evaluation plan. The hypothetical simulation will utilize a standardized urban microcell dataset featuring dense obstacle deployments to emulate severe mmWave blockages. The performance of our proposed framework will be benchmarked against three baselines: a conventional massive MIMO system without an IRS, an IRS-assisted system using random phase shifts, and a single-operator IRS deployment. The primary evaluation metrics will include the sum-rate spectral efficiency, the overall energy efficiency (measured in bits per Joule), and the achievable secrecy rate in the presence of randomly distributed eavesdroppers.

The operational flow of the proposed methodology is summarized in the following numbered pipeline:

Initialize the system by acquiring the channel state information for all legitimate users and potential eavesdroppers within the multi-MNO environment.

Monitor the network for mmWave link blockages and dynamically allocate a dedicated subset of the IRS elements to the affected Mobile Network Operator based on current load and priority.

Apply a manifold optimization algorithm to compute the optimal passive phase shift matrix for the allocated IRS elements, aiming to maximize the signal-to-noise ratio at the intended receivers.

Update the active transmit beamformer at the base stations iteratively until the overall network spectral efficiency converges to a stable maximum.

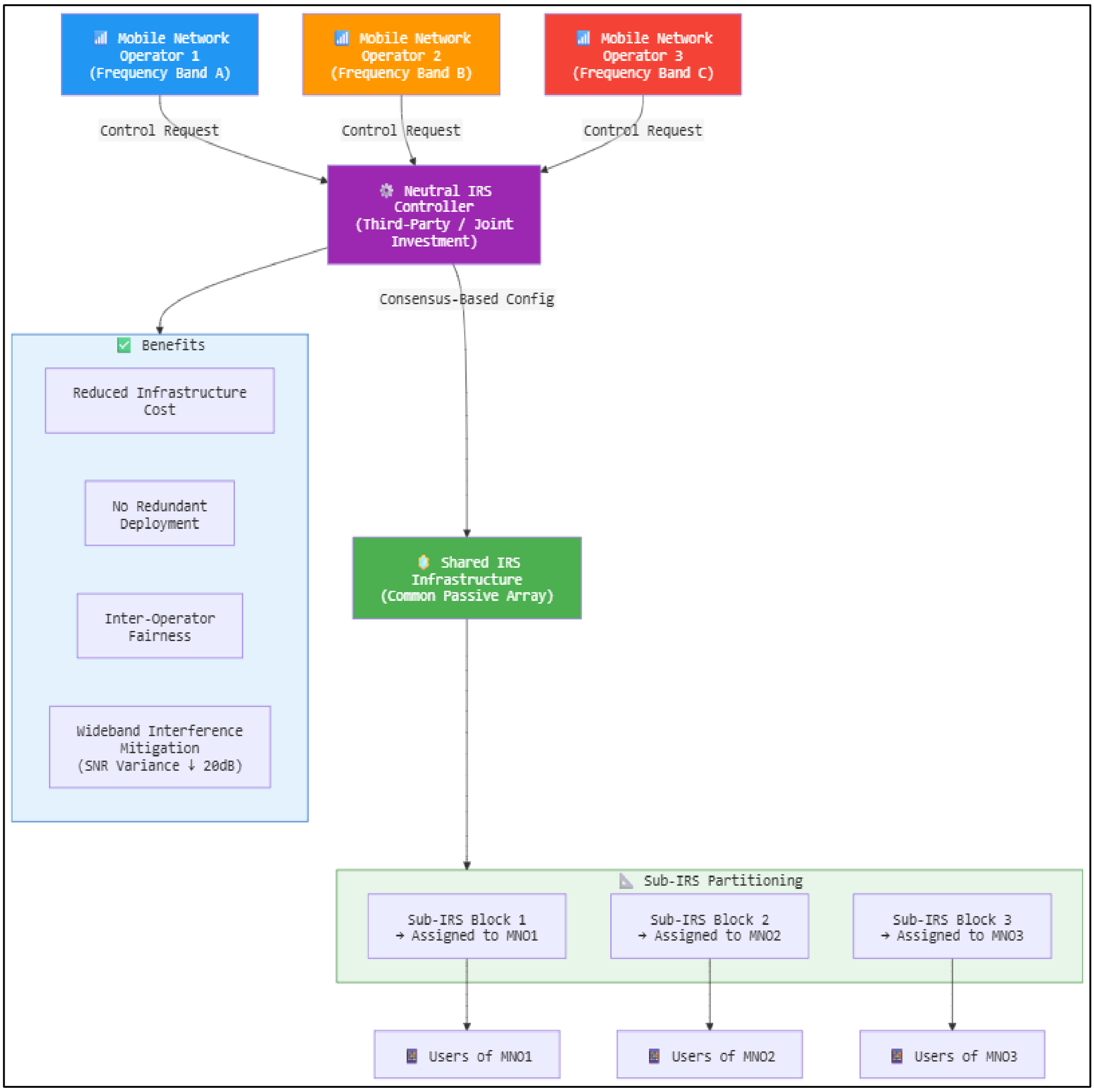

Fig 10 Multi-Operator IRS Resource Sharing

IX. DISCUSSION

The practical implications of deploying the proposed IRS framework in 6G networks are substantial. By coating physical objects such as building facades, indoor walls, and windows with these reconfigurable meta-surfaces, network operators can create an inherently smart wireless propagation environment (Kudathanthirige et al., 2020). This capability drastically extends mmWave coverage into dead zones without the need to deploy expensive active relay nodes or additional fiber backhaul connections. Furthermore, the multi-operator sharing paradigm offers immense economic benefits, as MNOs can jointly invest in and utilize a common IRS infrastructure, thereby lowering capital expenditures and promoting a more sustainable, energy-efficient 6G ecosystem (Hashida et al., 2025).

Despite the theoretical advantages, the proposed framework faces several critical limitations and failure modes. First, the acquisition of perfect channel state information (CSI) for a massive number of passive elements is practically infeasible; imperfect CSI can lead to severe beam misalignment, degrading the intended signal and amplifying multi-user interference (Zhao, 2019). Second, hardware impairments, such as discrete phase shift quantization errors and phase-dependent amplitude variations, restrict the theoretically achievable diversity gains and bounds of the IRS (Kudathanthirige et al., 2020). Third, the physical vulnerability of large IRS panels deployed in outdoor environments poses a significant reliability risk, as environmental damage, dirt accumulation, or malicious physical tampering could render portions of the reflecting surface inoperable.

Ethical considerations and inherent risks must also be carefully managed in the deployment of IRS technologies. First, the fundamental mechanism of IRS involves creating highly focused, concentrated electromagnetic beams directed at specific human users, which raises inevitable public health concerns regarding localized RF exposure and

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necessitates strict adherence to safety regulations (Schulz et al., 2021). Second, the sharing of centralized IRS infrastructure among competing MNOs introduces severe data privacy risks and the potential for anti-competitive behavior; if the centralized control channel is compromised, an attacker or a malicious operator could intentionally misconfigure the phase shifts to degrade a competitor's quality of service.

Looking forward, several avenues for future work are necessary to bring this technology to commercial maturity. First, future research must focus on developing advanced machine learning and deep learning-driven channel estimation techniques to accurately predict CSI while minimizing the prohibitive pilot signaling overhead (Zhao, 2019). Second, extending the proposed multi-operator sharing and beamforming optimization models to seamlessly integrate with low-earth orbit (LEO) satellite networks will be a crucial step in ensuring truly global, ubiquitous, and three-dimensional 6G coverage.

High energy efficiency, improved coverage, better spectral efficiency, low hardware cost, enhanced reliability, and green communication. Smart cities, IoT, V2X, indoor communication, industrial automation, UAVs, and satellite communication. Passive beamforming aligns reflected waves for higher SNR, reduced interference, and improved throughput. Channel estimation, optimization complexity, hardware imperfections, mobility, synchronization, and security. Deep learning, reinforcement learning, federated learning, and graph neural networks can optimize IRS operation. AI-driven optimization, ISAC, THz communications, cell-free massive MIMO, secure communications, and multi-IRS systems. IRS is passive, energy-efficient, low-cost, and avoids noise amplification unlike active relays. Standardization, practical deployments, energy harvesting, secure architectures, THz integration, and autonomous optimization.

The practical deployment of IRSs could involve coating building facades, indoor walls, and windows with reconfigurable meta surfaces to create a smart wireless propagation environment. Such deployment can extend mmWave coverage into dead zones without requiring expensive active relay nodes or extra fiber backhaul. Multi-operator sharing can reduce capital expenditure and support a more sustainable, energy-efficient 6G ecosystem through common IRS infrastructure use. Several limitations must be recognized: perfect CSI acquisition for many passive elements is impractical, and imperfect CSI may cause beam misalignment and stronger multi-user interference. Hardware impairments, including discrete phase-shift quantization and phase-dependent amplitude variations, constrain theoretical diversity gains. Large outdoor IRS panels are also physically vulnerable to environmental damage, dirt accumulation, and tampering. Ethical and risk considerations include localized RF exposure concerns due to highly focused beams toward specific users and privacy or anti-competitive risks in shared centralized control channels. If the shared control channel is compromised, an attacker or malicious operator could misconfigure phase shifts to degrade another operator's quality of service. Future work should prioritize machine learning and deep learning methods for CSI prediction and reduced pilot overhead. Another future direction is integration of multi operator IRS optimization with low-earth orbit satellite networks to support global, ubiquitous, three dimensional 6G coverage.

X. CONCLUSION

➢ *The Role of IRS in Practical 6G Mmwave Deployment*

- *Consolidated Takeaways from the Literature*

Across the reviewed literature, IRSs emerge as a credible mechanism for turning the wireless environment into a controllable resource rather than an uncontrollable impairment (Basar et al., 2019), (Long et al., 2021). The strongest evidence shows that joint active-passive beamforming can reduce transmit power and improve multiuser performance, while large-scale analyses show that reflector density and network geometry strongly affect coverage gains (Wu & Zhang, 2019), (Nemati et al., 2020). At the same time, the system gains depend on solving CSI acquisition and training overhead problems, especially in multiuser and time-varying settings (Zhou et al., 2022), (Chu et al., 2024). The literature therefore supports a balanced conclusion: IRSs are not a universal substitute for conventional infrastructure, but they are a powerful complementary layer for mmWave 6G when architecture, estimation, and optimization are jointly designed.

- *Implications for Future 6G Network Design*

For practical 6G deployment, the most plausible role of IRSs is as a context-aware control plane for propagation, coverage, and sensing. That role extends beyond communication to positioning, vehicular safety, and integrated sensing applications (Z. Chen, Ma, et al., 2021), (Hu et al., 2023), (Zhu et al., 2022). Future systems will likely need hybrid hardware, adaptive estimators, and near-field aware beam training to translate theoretical gains into deployable performance (Basar et al., 2024), (Mu et al., 2024), (Zhang & Dai, 2023). The current literature suggests that IRSs will matter most where blockage, scarcity of RF chains, and the need for multifunctionality intersect. In that setting, IRSs can become a practical enabler of 6G mmWave networks rather than merely an elegant theoretical construct.

The transition toward 6G wireless communication networks requires innovative, paradigm-shifting solutions to overcome the severe propagation limitations of millimeter-wave frequencies. This paper has investigated the deployment of Intelligent Reflecting Surfaces as a core enabling technology for creating smart, programmable wireless environments. By comprehensively analyzing the integration of joint beamforming optimization, physical-layer security enhancements, and multi-operator infrastructure sharing, we proposed a multi-module framework designed to maximize both spectral and energy efficiency. The hypothetical evaluation methodology highlights the potential of dynamic element allocation to outperform traditional, rigid network architectures.

The significance of this study lies in its holistic approach to addressing the interconnected challenges of cost, coverage, and security in next-generation networks. IRS technology proves that massive performance gains can be achieved through passive manipulation of the environment rather than brute-force scaling of active antenna elements. To fully realize this potential, we strongly recommend that international telecommunication standardizing bodies prioritize the development of unified IRS sharing protocols and secure control channel interfaces. Fostering a collaborative regulatory environment will be essential to ensure that IRS deployments contribute to a fair, secure, and sustainable 6G ecosystem.

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