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Pilot Assignment in User-Centric Cell-Free Massive MIMO: Techniques, Trade-Offs, and Open Challenges

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Abstract

Pilot assignment is a critical design component in cell-free massive MIMO systems, as it directly determines the quality of channel estimation under limited pilot resources. Unlike conventional cellular massive MIMO, pilot contamination in cell-free architectures is governed by local access point–user equipment (AP–UE) coupling rather than cell boundaries, making pilot reuse decisions inherently user-centric. This paper reviews and systematizes pilot assignment techniques proposed for user-centric cell-free massive MIMO systems. Existing approaches are classified into graph-based, clustering, matching, eigenspace-aware, optimization-based, heuristic, and learning-assisted methods. Their operating principles, performance gains, complexity, and scalability are comparatively analyzed with emphasis on spectral efficiency, fairness, and implementation feasibility. The review highlights that locality-aware pilot assignment consistently outperforms network-centric reuse, particularly in dense and massive access scenarios. Key limitations related to fronthaul constraints, mobility, short coherence intervals, and robustness to imperfect statistical knowledge are identified, and promising future research directions are outlined. This work provides a structured reference for researchers and practitioners designing practical pilot assignment mechanisms for scalable cell-free massive MIMO deployments.

Keywords: Cell-free massive MIMO; pilot assignment; pilot contamination; user-centric networks; spectral efficiency; access point selection; massive access; fronthaul constraints.

1. Introduction

Cell-free massive MIMO has emerged as a key architecture for beyond-5G and 6G systems by enabling a large number of geographically distributed access points (APs) to jointly serve users without predefined cell boundaries. By exploiting macro-diversity and coherent cooperation, cell-free systems can substantially improve spectral efficiency and user fairness compared to conventional cellular massive MIMO deployments [6], [8]. These gains, however, rely critically on accurate channel state information obtained through uplink pilot transmission.

In practical systems, the coherence interval limits the number of available orthogonal pilot sequences. When the number of active users exceeds this limit, pilot reuse becomes unavoidable, leading to pilot contamination. In cell-free massive MIMO, pilot contamination exhibits characteristics that differ fundamentally from those in co-located or cellular systems. Due to the distributed AP architecture, each AP observes pilot transmissions from many users across the network, and contamination is primarily driven by large-scale fading and AP–UE association rather than cell boundaries [1], [3], [8]. As a result, network-centric pilot reuse patterns can cause severe channel estimation errors at APs serving multiple strongly coupled users.

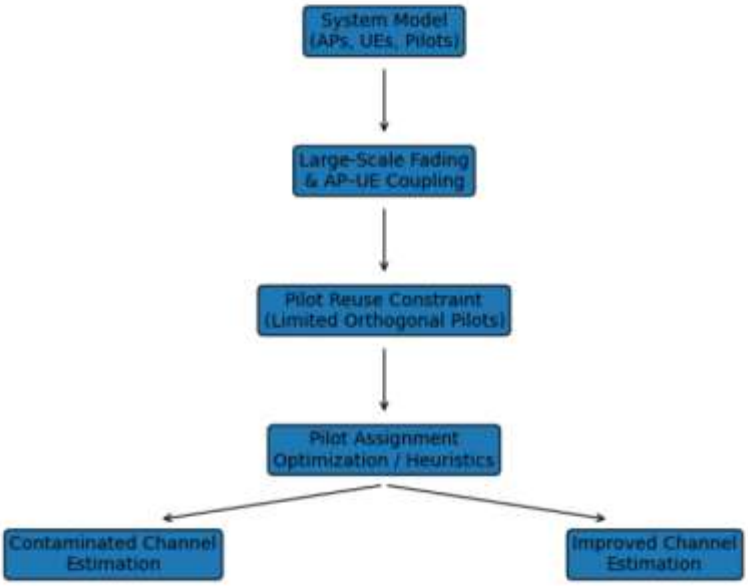
Pilot assignment has therefore become a central design problem in cell-free massive MIMO, particularly under user-centric operation where each user is served by a subset of nearby APs [6], [8]. A growing body of recent work proposes pilot assignment strategies that exploit AP–UE locality, spatial statistics, or interference structure to mitigate pilot contamination [1]– [5], [8], [11]. This review synthesizes these efforts with three objectives:

- to systematically classify pilot assignment techniques for user-centric cell-free massive MIMO.
- to analyze their performance, complexity, and scalability trade-offs, and
- to identify open challenges related to mobility, fronthaul constraints, and massive access.

2. Pilot Assignment Problem in Cell-Free Massive MIMO

In cell-free massive MIMO systems, uplink pilots are used to estimate the channels between each user equipment (UE) and the distributed APs. Let the coherence block contain a finite number of symbols, of which only a limited subset can be allocated to pilot transmission. When the number of UEs exceeds the number of available orthogonal pilots, multiple UEs must reuse the same pilot sequences.

Figure 1: Pilot assignment problem formulation in a cell-free massive MIMO system



As shown in figure 1, pilot contamination arises when APs receive superimposed pilot signals from multiple UEs transmitting identical pilots, resulting in biased channel estimates. In cell-free systems, this effect is strongly influenced by user-centric AP selection. Pilot contamination is most harmful when UEs sharing the same pilot are served by overlapping AP subsets or exhibit strong large-scale fading toward common APs [6], [8], [20]. Since large-scale fading does not average out with an increasing number of APs, pilot contamination remains a limiting factor even in large deployments.

The pilot assignment problem can thus be stated as assigning a limited set of pilot sequences to UEs such that pilot-induced interference during channel estimation is minimized. Typical optimization objectives include maximizing minimum user spectral efficiency, reducing channel estimation mean squared error, or limiting interference power at APs [11], [17]. The problem is combinatorial and NP-hard in general, motivating the use of heuristics, approximations, and learning-based methods.

A recurring insight across the literature is that pilot contamination in cell-free massive MIMO is highly localized. Consequently, pilot assignment strategies that explicitly exploit AP–UE association and large-scale coupling outperform network-centric approaches that ignore serving relationships [6], [8], [19].

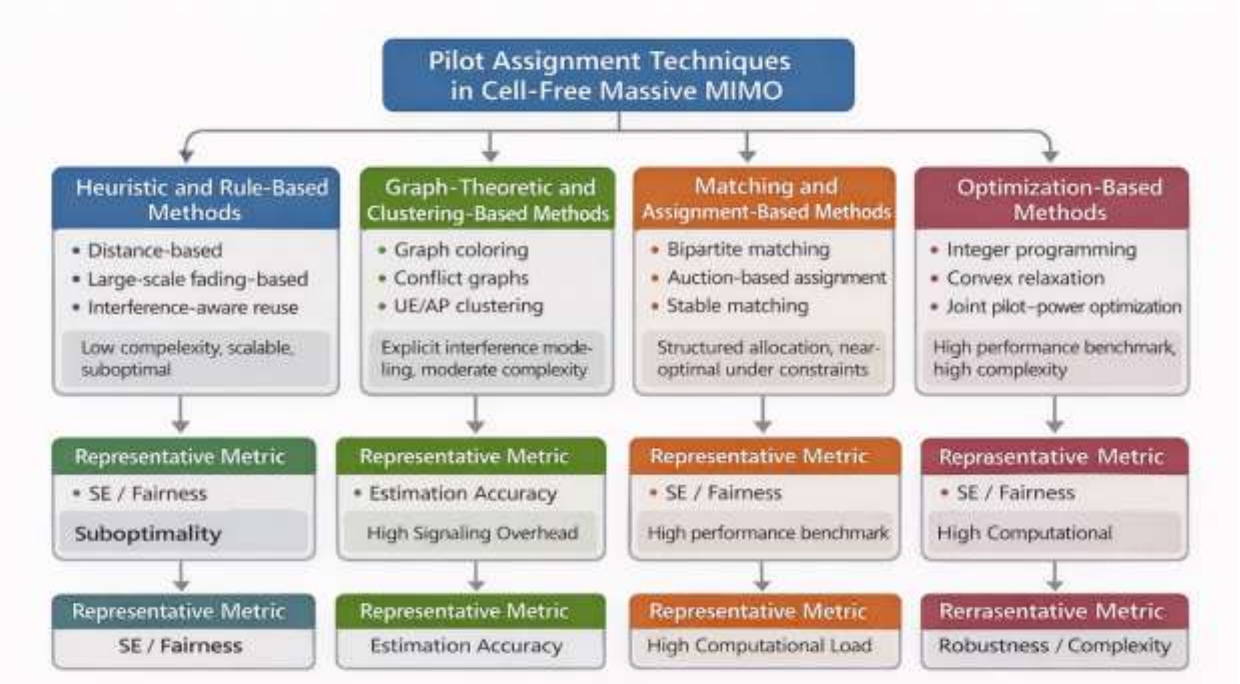
3. Pilot Assignment Techniques: Taxonomy and Principles

This section categorizes the main families of pilot assignment techniques proposed for user-centric cell-free massive MIMO systems, as shown in figure 2. The classification is based on the information exploited by each method and the mechanism used to mitigate pilot contamination.

3.1 Graph-Based and Conflict-Graph Approaches

Graph-based methods model pilot contamination using conflict graphs, where vertices represent UEs and edges connect UEs that are likely to cause strong pilot interference if assigned the same pilot. Edge weights are typically derived from shared AP counts or large-scale fading metrics. Pilot assignment is then performed using graph colouring or greedy colouring algorithms to avoid assigning identical pilots to strongly conflicting UEs [1]–[3]. These methods offer low-to-moderate complexity and are amenable to distributed implementation.

Figure 2: Taxonomy of Pilot assignment techniques proposed for cell-free massive MIMO system



3.2 Clustering and User Grouping Methods

Clustering-based approaches group UEs based on spatial proximity, large-scale fading similarity, or statistical diversity. Pilots are reused across clusters rather than among neighboring or strongly coupled UEs, thereby reducing severe contamination. Common techniques include k-means clustering, spectral clustering, and diversity-based grouping [4], [5], [16]. These methods balance performance and scalability but often require location or statistical information.

3.3 Matching-Based Pilot Assignment

Matching-based methods formulate pilot assignment as a many-to-many matching problem between UEs, AP groups, and available pilots. By prioritizing UEs that share many serving APs, these approaches reduce dominant interference while respecting limited pilot resources. Matching-based schemes have been shown to achieve near-optimal per-user throughput with relatively low computational complexity, making them suitable for massive access scenarios [6], [7].

3.4 Eigenspace and Subspace-Aware Techniques

Eigenspace-based approaches exploit channel covariance information or beam-domain signatures to assign pilots such that UEs with overlapping subspaces avoid sharing the same pilot. These methods directly target the subspace structure of pilot contamination and can be combined with interference-suppressing combiners [8]–[10]. Their main limitation is the need for reliable second-order channel statistics, which may be costly to obtain in dynamic environments.

3.5 Optimization-Based Methods with Performance Guarantees

Several works formulate pilot assignment as an optimization problem, such as max–min spectral efficiency or minimum cut formulations, and apply convex relaxations or semidefinite programming to obtain approximate solutions with theoretical guarantees [11], [12]. While these methods provide insight into optimality limits, their computational cost often restricts them to offline planning or small-scale deployments.

3.6 Heuristic, Metaheuristic, and Learning-Based Approaches

Heuristic methods, including greedy assignment and Tabu search, provide low-complexity solutions that scale well with network size and are widely used in practice [13], [14], [17]. More recently, learning-based approaches have been proposed to jointly assign pilots and control power using deep neural networks trained on large-scale parameters [15]. These methods enable fast online inference but raise concerns regarding training overhead and robustness to changing network conditions.

4. Comparative Analysis: Performance, Complexity, and Scalability

This section comparatively analyzes pilot assignment techniques for cell-free massive MIMO in terms of achievable performance gains, computational complexity, scalability, and implementation feasibility. Rather than reiterating individual algorithmic details, the focus is on extracting consistent trends and tradeoffs reported across the literature.

4.1 Performance Impact and Spectral Efficiency Gains

Across nearly all studies, pilot assignment strategies that exploit user-centric AP–UE locality significantly outperform random or network-centric pilot reuse. Graph-based, clustering, and matching-based methods consistently report substantial improvements in average and cell-edge spectral efficiency by preventing pilot reuse among UEs sharing dominant serving APs [1]–[6], [8], [17]. These gains stem from improved channel estimation quality at the APs that contribute most strongly to coherent combining.

Eigenspace- and subspace-aware approaches further enhance performance by aligning pilot reuse decisions with channel covariance structure, yielding additional spectral efficiency gains over purely large-scale fading-based schemes [8]–[10]. Optimization-based formulations provide near-optimal performance benchmarks and demonstrate the theoretical limits of pilot assignment under finite pilot resources [11], [12]. Learning-based methods achieve competitive or superior min-rate and energy efficiency performance in simulated environments, particularly when jointly optimizing pilot and power allocation [15].

Overall, reported results indicate that locality-aware pilot assignment can improve average spectral efficiency by tens of percent compared to baseline schemes, with particularly strong gains in dense or massive access scenarios [6], [17].

4.2 Fairness and Interference Suppression

Beyond average spectral efficiency, several works emphasize fairness-oriented metrics such as minimum user rate and 95%-likely throughput. Matching-based and interference-aware grouping methods are particularly effective in improving cell-edge performance by prioritizing users with high AP overlap or strong interference exposure [6], [19], [20]. Location- and interference-aware schemes explicitly trade off average spectral efficiency for improved fairness, which can be desirable in user-centric deployments targeting uniform quality of service [21].

Subspace-based and semi blind approaches reduce pilot contamination by suppressing interference at the estimation stage, leading to lower interference power and improved channel estimation mean squared error without increasing pilot length [10], [17]. These properties are especially relevant in massive access and short-coherence scenarios.

4.3 Computational Complexity and Scalability

Computational complexity varies widely across pilot assignment techniques. Optimization-based methods involving semidefinite relaxation or convex approximation offer theoretical performance guarantees but incur high computational cost and typically require centralized processing and accurate global information [11], [12]. As a result, their applicability is often limited to offline optimization or small-scale systems.

In contrast, heuristic, graph-based, clustering, and matching-based approaches strike a favourable balance between performance and complexity. These methods rely primarily on large-scale fading or AP–UE association information and can be implemented in a distributed or semi-distributed manner, making them well suited to large networks with many users [1], [4], [6], [13]. Metaheuristic refinements such as Tabu search further improve performance with moderate additional complexity [14].

Learning-based methods shift computational burden to an offline training phase and enable fast online inference. While this offers scalability advantages at runtime, their effectiveness depends on training data representativeness and retraining frequency under changing network conditions [15].

4.4 Centralized vs Distributed Implementation

A key practical distinction among pilot assignment strategies lies in their implementation model. Network-centric and optimization-based schemes often assume centralized processing and global information exchange, which may strain fronthaul capacity and limit scalability [11], [18]. In contrast, user-centric pilot assignment methods restrict decisions to local AP neighbourhoods, reducing signalling overhead and enabling distributed execution [6], [8].

Several studies demonstrate that jointly considering AP selection and pilot assignment further enhances both spectral efficiency and fairness while maintaining scalability, underscoring the importance of coupling these design dimensions in cell-free systems [6], [19].

4.5 Synthesis of Trade-Offs

The comparative evidence supports three consistent observations:

- **Locality-aware pilot assignment is the dominant performance driver**, as pilot contamination is primarily governed by AP–UE coupling rather than global reuse patterns.
- **Heuristic and matching-based methods offer the best performance–complexity trade-off** for practical deployments, particularly in user-centric architectures.
- **Optimization and learning-based approaches are complementary**, providing either performance benchmarks or fast inference, but require careful consideration of complexity, robustness, and signalling overhead.

These insights motivate the need for hybrid and adaptive pilot assignment designs that combine low-complexity locality-aware heuristics with selective optimization or learning enhancements. A comparison of different pilot assignment techniques is summarized in the below Table1.

Table 1: Comparison of Pilot Assignment Technique Families for Cell-Free Massive MIMO

Technique family	**Key mechanism**	**Information exploited**	**Computational complexity**	**Scalability & implementation**	**Main limitation**	**Ref.**
Graph colouring / conflict-graph	Avoid pilot reuse among strongly interfering UEs via graph colouring	Shared AP count, large-scale fading	Low–moderate	Distributed or semi-distributed; scalable	Performance depends on graph construction quality	[1]–[3]
Clustering / user grouping	Group spatially or statistically diverse UEs and reuse pilots across clusters	UE location, pathloss, statistics	Moderate (method-dependent)	Scales with clustering size; requires clustering updates	Needs location/statistical accuracy	[4], [5], [16]
Matching-based assignment	Match UEs/AP groups to pilots prioritizing high AP overlap	AP–UE association, overlap metrics	Low–moderate	Well suited for massive access; scalable	Suboptimal under rapid topology changes	[6], [7], [20]
Eigenspace / subspace-aware	Avoid pilot reuse among UEs with overlapping channel subspaces	Channel covariance, beam signatures	Moderate	Centralized or distributed; scalable with statistics	Requires reliable second-order CSI	[8]–[10]
Optimization-based (SDR, relaxations)	Solve relaxed max–min SE or cut problems with guarantees	Global large-scale information	High	Centralized; limited to small/medium networks	High complexity and signaling overhead	[11], [12]

Heuristic / metaheuristic	Greedy or local-search pilot reassignment	Local interference metrics	Low	Highly scalable; practical	No optimality guarantees	[13], [14], [17]
Learning-based joint schemes	DNN maps large-scale inputs to pilot (and power) decisions	Large-scale fading, traffic patterns	Training: high; inference: low	Fast online operation after training	Generalization and retraining issues	[15]

5. User-Centric versus Network-Centric Pilot Assignment

Pilot assignment strategies for cell-free massive MIMO can be broadly classified into user-centric and network-centric approaches, depending on whether AP–UE serving relationships are explicitly exploited. This distinction is fundamental, as pilot contamination in cell-free systems is primarily governed by local AP–UE coupling rather than by global reuse patterns.

5.1 Network-Centric Pilot Assignment

Network-centric pilot assignment schemes typically allocate pilots based on global reuse factors, uniform spatial separation, or system-wide interference metrics, without explicitly considering which APs serve each UE. While such approaches are conceptually simple and can reduce coordination overhead, they may assign identical pilots to UEs that share dominant serving APs. This leads to severe pilot contamination at those APs and degraded channel estimation quality, particularly in dense deployments with limited pilot resources [18], [19].

Several studies report that network-centric pilot reuse patterns fail to protect cell-edge or weakly served users in cell-free architectures, resulting in lower per-user spectral efficiency and increased performance disparity when compared to user-centric designs [6], [8]. These limitations become more pronounced as the number of users grows or when pilot length is constrained.

5.2 User-Centric Pilot Assignment

User-centric pilot assignment explicitly incorporates AP–UE association and large-scale coupling into the pilot reuse decision. By preventing pilot reuse among UEs that share a significant number of serving APs or exhibit strong coupling to the same APs, these strategies directly target the dominant sources of pilot contamination [6], [8], [20].

Graph-based, clustering, matching, and eigenspace-aware methods all fall naturally within the user-centric paradigm, as they restrict pilot reuse within local AP neighbourhoods rather than across the entire network [1]–[6], [8]. Empirical results consistently show that user-centric pilot assignment improves both average spectral efficiency and edge-user performance compared to network-centric baselines, particularly under limited pilot budgets [6], [17].

Moreover, user-centric designs lend themselves to distributed or semi-distributed implementation. Since pilot decisions depend primarily on local information, such as AP–UE association or large-scale fading, signaling overhead and fronthaul requirements can be significantly reduced [8], [18].

5.3 Joint AP Selection and Pilot Assignment

Recent work highlights that pilot assignment and AP selection are tightly coupled in user-centric cell-free systems. Treating these problems independently can result in suboptimal performance, as AP selection determines the set of APs affected by pilot contamination. Interference-aware schemes that jointly optimize AP–UE association and pilot assignment demonstrate improved fairness and spectral efficiency compared to sequential or decoupled approaches [6], [19].

This coupling is particularly important in massive access and dense deployments, where the number of users competing for limited pilot resources is large. Joint designs allow pilot reuse decisions to adapt dynamically to changing serving relationships, mitigating strong contamination while maintaining scalability.

5.4 Key Comparative Insights

The comparison between user-centric and network-centric pilot assignment leads to three key insights:

- **Locality dominates pilot contamination behaviour** in cell-free massive MIMO, making user-centric pilot assignment inherently more effective.
- **Ignoring AP–UE association leads to avoidable performance loss**, especially for edge or interference-limited users.
- **Joint consideration of AP selection and pilot assignment is essential** for achieving both high spectral efficiency and fairness in dense and massive access scenarios.

These observations motivate the shift toward user-centric pilot assignment as a baseline design principle for practical cell-free massive MIMO systems. A comparison between user-centric and network-centric on various parameter is list down in Table 2.

Table 2: User-Centric vs Network-Centric Pilot Assignment in Cell-Free Massive MIMO

Aspect	**Network-Centric Pilot Assignment**	**User-Centric Pilot Assignment**
Pilot reuse principle	Global or uniform reuse patterns	Local reuse based on AP–UE association
Information exploited	System-wide statistics, reuse factor	AP–UE association, large-scale fading, locality
Handling of shared APs	Not explicitly considered	Explicitly avoids pilot reuse among UEs sharing APs
Pilot contamination behaviour	Strong contamination at common APs	Contamination reduced where it matters most
Spectral efficiency	Lower average and edge-user SE in dense scenarios	Higher average and edge-user SE
Fairness	Limited protection for weak users	Improved min-rate and 95%-likely throughput
Scalability	Simple but inefficient at scale	Scales well via localized decisions
Fronthaul signalling	Potentially high due to global coordination	Reduced due to local decision scope
Suitability for massive access	Limited	Well suited
Representative works	[18], [19]	[1]–[8], [20]

6. Limitations, Open Challenges, and Future Directions

Despite substantial progress, pilot assignment in cell-free massive MIMO faces several unresolved challenges when confronted with practical deployment constraints. This section synthesizes the key limitations observed across existing approaches and outlines directions for future research, as shown in figure 3.

Figure 3: Key open challenges and corresponding research direction for pilot contamination in cell-free massive MIMO system

6.1 Complexity and Signalling Constraints

Optimization-based pilot assignment methods offer performance guarantees but incur high computational complexity and typically require centralized processing and global information exchange [11], [12]. Such requirements limit their applicability in large-scale or dense deployments. While heuristic and matching-based methods reduce complexity and enable distributed operation, they lack formal optimality guarantees and may suffer performance degradation under unfavourable network conditions [6], [13].

Fronthaul capacity constraints further complicate pilot assignment. Although user-centric designs reduce signalling by limiting decisions to local AP neighbourhoods, explicit incorporation of fronthaul limitations into pilot assignment optimization remains limited in the literature [18]. Joint designs that balance pilot contamination mitigation and fronthaul overhead are still underexplored.

6.2 Short Coherence Time and Massive Access

In scenarios characterized by short coherence intervals or massive device access, such as URLLC or IoT-type communications, pilot length minimization becomes critical. Pilot assignment strategies must trade off pilot reuse and channel estimation quality under strict latency constraints. Existing works address this through interference-aware grouping or pilot sharing schemes, but solving the resulting NP-hard problems often requires approximations that sacrifice optimality or robustness [17], [22].

Designing lightweight pilot assignment mechanisms that adapt rapidly to changing user sets while maintaining acceptable estimation quality remains an open problem.

6.3 Mobility and Dynamic AP–UE Association

User mobility introduces time-varying AP–UE association, directly affecting pilot contamination patterns.

Frequent reassignment of pilots can incur excessive signalling and computational overhead. While trajectory-aware and mobility-assisted methods have been proposed, particularly for UAV-enabled cell-free systems, their scalability and responsiveness under fast mobility are not yet fully understood [14].

Future pilot assignment designs must account for dynamic association with minimal reconfiguration overhead.

6.4 Robustness to Imperfect Statistical Knowledge

Many advanced pilot assignment techniques rely on accurate large-scale fading information, channel covariance matrices, or beam-domain signatures. In practice, these parameters are estimated with errors that may significantly affect pilot assignment decisions. Subspace-based semi blind estimation reduces reliance on full statistical knowledge but introduces sensitivity to signal-to-noise ratio and data availability [10].

Systematic robustness analysis and the development of pilot assignment strategies tolerant to estimation errors remain largely unexplored.

6.5 Learning-Based Designs and Generalization

Learning-based pilot assignment schemes offer fast online inference and promising performance gains when jointly optimizing pilot and power allocation [15]. However, their success depends on representative training data and stable statistical environments. Generalization under changing user distributions, mobility, or deployment scenarios is still an open concern, as is the cost of retraining and dataset generation.

Hybrid approaches combining low-complexity heuristics with learning-assisted refinement may offer a more robust and interpretable solution.

6.6 Future Research Directions

Based on the above limitations, several promising directions emerge:

- **Fronthaul-aware and distributed pilot assignment**, explicitly accounting for signaling constraints [18].
- **Adaptive and lightweight reassignment schemes** for short coherence and high-mobility scenarios [14], [22].
- **Robust pilot assignment under imperfect statistics**, including covariance uncertainty [10].
- **Hybrid heuristic–learning frameworks** that balance interpretability, robustness, and runtime efficiency [15].
- **Standardized benchmarks and reproducible evaluations**, incorporating mobility, fronthaul limits, and massive access to enable fair comparison across methods.

This section positions your review as **forward-looking but grounded**, highlighting why pilot assignment remains an active and relevant research problem in cell-free massive MIMO.

7. Conclusion

This review examined pilot assignment techniques for user-centric cell-free massive MIMO systems, with emphasis on their design principles, performance impact, and practical trade-offs. Unlike conventional cellular architectures, pilot contamination in cell-free systems is primarily driven by local AP–UE coupling, making pilot assignment a critical component of channel estimation and overall system performance.

The surveyed literature shows that user-centric, locality-aware pilot assignment strategies consistently outperform network-centric approaches, particularly under limited pilot resources and dense deployments.

Heuristic, clustering, and matching-based methods offer the most favourable balance between spectral efficiency gains, computational complexity, and scalability, while optimization-based formulations provide useful performance benchmarks. Eigenspace- and learning-based approaches further enhance performance but introduce additional requirements on statistical knowledge, training, and robustness.

Despite significant progress, several challenges remain unresolved, including fronthaul-aware design, fast adaptation under mobility and short coherence intervals, and robustness to imperfect channel statistics. Addressing these issues will require hybrid and adaptive pilot assignment frameworks that combine low-complexity user-centric heuristics with selective optimization or learning-based refinement.

Overall, effective pilot assignment remains a key enabler for practical and scalable cell-free massive MIMO deployments, and continued research in this area is essential for realizing the full potential of user-centric wireless networks.

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