RESEARCH-ARTICLE

Saving Private Cellular: The Coordination Vaccum in CBRS

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ABSTRACT

FCC's introduction of the Citizens Broadband Radio Service (CBRS) has opened 150 MHz of mid-band spectrum for shared use, enabling enterprises and communities to deploy private cellular networks ranging from smart factories to rural broadband without purchasing expensive licenses. As these deployments continue to grow by the tens of thousands, there is an increasing need for fair and efficient coordination of the shared CBRS spectrum. However, there are no built-in mechanisms in the CBRS framework to coordinate spectrum use and ensure fairness. The lack of coordination mechanisms, limited visibility into underutilized spectrum, and the absence of any fairness models threaten the reliability and growth of private cellular ecosystem, where independent operators often interfere and compete inefficiently—undermining the very promise of shared spectrum. In this paper, we highlight fair and efficient coexistence among CBRS-based private cellular networks as an urgent and open research problem. We identify the key challenges, and propose a research agenda aimed at developing the architectures, protocols, and policies needed to realize a sustainable, cooperative shared spectrum ecosystem.

CCS CONCEPTS

• **Networks → Network architectures**; **Wireless access networks**; *Wireless access points, base stations and infrastructure.*

KEYWORDS

CBRS, private cellular networks, spectrum sharing, interference management

1 INTRODUCTION

Private cellular (LTE/5G) networks, independently deployed and operated by local communities or enterprises, are touted as key enablers of innovation and economic growth [18]. In industrial settings, they power smart factories, autonomous systems, and mission-critical applications that demand reliable, low-latency connectivity [11, 18]. In parallel, they offer a public benefit by enabling

affordable broadband in rural and underserved communities often ignored by commercial operators[2, 6, 21].

Private cellular networks have historically been hamstrung by one key barrier: spectrum. Securing licensed spectrum rights was prohibitively expensive and often out of reach for all but the largest operators. The FCC's **Citizens Broadband Radio Service (CBRS)** initiative changed the game. In 2015, the FCC established CBRS as a three-tier shared spectrum model that opened 150 MHz of the 3.5 GHz band for commercial use[12]. The spectrum is first reserved for Tier-1 users (protected US Navy incumbents) and Tier-2 users known as Priority Access Licensees (PAL) - (who pay for licensed access). The remaining spectrum (under Tier-3) is made available for **General Authorized Access (GAA)**, that can be used by small-scale organizations without any auctioned licenses or fees. This hierarchical structure is shown in Figure 1.

It is this GAA tier that has fueled the rapid rise of CBRS. By eliminating spectrum licensing costs, GAA has enabled enterprises, campuses, and rural operators to deploy private cellular networks independently of traditional carriers. Adoption has surged: over 270,000 new CBRS base stations (**CBSDs**) were deployed between 2021 and mid-2024, with roughly 95% operating under GAA sharing [5]. GAA represents a transformative shift—bringing prime mid-band spectrum within reach of any organization.

This opportunity exposes a new coordination problem. By design, GAA users share spectrum on an equal basis, which introduces the challenging situation of multiple independently managed networks operating in the same band and geographical area. Interference between neighboring CBRS deployments can significantly degrade the channel quality (and, thereby, network throughput) of users in overlapping coverage regions. Therefore, as the density of CBRS deployments increases, effective mechanisms are needed to coordinate the use of the shared GAA spectrum.

As of today, the CBRS framework leaves GAA coexistence largely to chance. Spectrum use in the GAA band is mediated by cloud-based coordination services known as Spectrum Access Systems (SAS), operated by a small set of FCC-certified commercial entities [8]. These SASes serve as neutral brokers of spectrum access, ensuring that lower-tier users do not interfere with incumbents or PAL users as shown in Figure 1. However, while they enforce protection for Tier-1 and Tier-2 users, they provide no interference guarantees among GAA users[13]. In fact, under current Part 96 regulations, SAS administrators have no authority to arbitrate or deny GAA spectrum requests on the basis of fairness or interference between GAA networks – they must grant access as long as higher-tier users are protected [7]. The FCC essentially encourages GAA operators to coordinate informally [13] to avoid interference, but provides no enforceable coordination primitives. As a result, when two or more operators crop up in the same vicinity, the system has no built-in way to prevent destructive competition for channels. Once a GAA base-station has been granted access to a channel, it may cling to it for an extended period of time (a channel grant can

last up to 6 hours [19]). In the meantime, neighboring networks, managed by a different SAS, can be granted access to use the same channel, because neither the devices nor the SAS have a mandated mechanism to coordinate a better allocation. Similarly, there is no standard way for an operator to know if spectrum is underutilized nearby (e.g. if a neighbor's network is offline or idle) and to opportunistically use that free spectrum. The system's limited visibility and reactiveness (SASes only exchange spectrum usage information infrequently, e.g. once a day [15]) means that GAA spectrum can be stuck in a suboptimal allocation for extended periods.
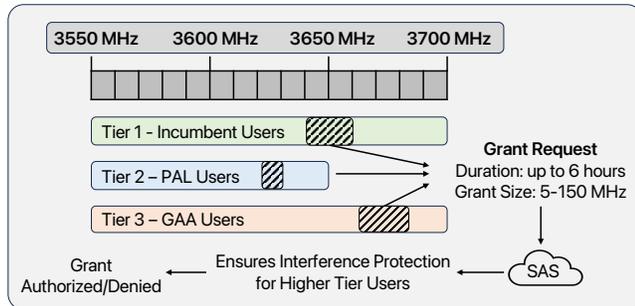
Figure 1: Overview of the CBRS ecosystem operating over 150 MHz of spectrum, with the SAS acting as a neutral broker to ensure that lower-tier users do not interfere with higher-tier users. Note that Priority Access License (PAL) users can only acquire license for and hence are restricted to the 3550–3650 MHz portion of the band.

This lack of coordination poses a fundamental threat to the promise of private cellular systems, where a crowded GAA scenario can devolve into a tragedy of the commons – well-intentioned operators stepping on each other's toes, or a few aggressive networks monopolizing spectrum to the detriment of others. Consider an industrial park where two companies set up independent cellular networks on CBRS: without coordination, they could unknowingly select overlapping channels, causing each other intermittent outages or reduced capacity that neither can easily diagnose or resolve. Worse, a "rogue" operator could deliberately or accidentally use a high-power, continuous transmission that hogs the band, and no regulatory mechanism currently exists to curtail it for the sake of fairness. Such scenarios undermine reliability (networks cannot guarantee service quality if a neighbor's actions are unpredictable) and trust in the ecosystem. Enterprises will be reluctant to adopt private cellular as a deployment choice if doing so is a gamble of spectrum contention with whoever sets up shop next door. We are already seeing early signs of this limitation. Operators report that the lack of any clear coexistence requirements for GAA has led to GAA-to-GAA interference issues in the field [10, 14]. Measurement studies confirm that co-channel interference between neighboring GAA networks can lead to substantial performance degradation, with throughput losses reaching as high as 25% compared to interference-free conditions [26].

New coordination mechanisms, that can enable efficient and fair use of GAA spectrum across neighboring CBRS deployments, are therefore urgently needed to support the next phase of private

cellular's growth. Early industry efforts are already underway (e.g. a voluntary Collaborative GAA Coexistence framework developed by the OnGo Alliance [22]), but these require unanimous participation and provide no recourse if an operator opts out. Moreover, these efforts rely on crude algorithms, based on static partitioning of CBRS band among overlapping deployments, that as we show in §3 can lead to severe under-utilization of the limited CBRS spectrum. Interference management is a well-studied problem in the context of commercial cellular networks but as we further highlight in §3, these solutions [3] assume centralized control by a single operator—an assumption that breaks in CBRS, where independent operators and SASs act without shared coordination or global state.

The goal of this position paper is *not* to propose a single definitive solution, but to articulate the problem space and sketch out a research agenda. We argue that the networking community should view multi-operator spectrum sharing in CBRS as a first-class problem: How should independent cellular networks discover each other and cooperate? How do we design algorithms that enable efficient and fair assignment of spectrum among different entities? What does "fair" spectrum assignment mean across disparate independently operated networks? What architectures – centralized via SAS, distributed between radios, or hybrid – can enable real-time coordination without unduly sacrificing the freedom and privacy of independent operators? The time is ripe to tackle these questions: the Private cellular revolution will either flourish with effective spectrum sharing norms – or falter in a tangle of uncoordinated interference.

2 DEFINING FAIR SPECTRUM SHARING

At the heart of spectrum sharing lies a deceptively simple question: *what does fairness mean when multiple independent networks contend for a common resource?* The status quo offers only partial answers. Beyond protecting higher priority Tier 1 and Tier 2 users, the CBRS framework leaves coordination among General Authorized Access (GAA) operators largely voluntary. While industry working groups such as the WINNForum and OnGo Alliance have proposed basic coexistence mechanisms (typically static, partition-based schemes that operators may opt into), they are quite rudimentary in nature [16, 22]. As a result, practical deployments still lack standardized, dynamic coordination primitives. We therefore begin with providing a systematic definition and benchmark for fairness in CBRS deployments.

Granularity of Fairness. The first question is that of granularity: at what level should fairness be enforced? Should resources be allocated in proportion to the number of users served by each CBRS base-station, or equally across operators that may deploy one or more base-stations, or equally across individual base-stations (or cells)? We discuss and unpack these alternatives, and why we think cell-level fairness is the most promising foundation for GAA coexistence.

1. User-based fairness: One might allocate spectrum proportional to the number of users (UEs) served by each CBRS network (as also proposed in a prior work [4]). However, this creates a perverse incentive: an operator could inflate its share simply by deploying dummy SIM cards. Ensuring truthful reporting of user counts is

unrealistic in a multi-operator setting, especially given competitive pressures.

2. Operator-based fairness: Alternatively, we could treat each operator as a unit, dividing spectrum equally among them. While this creates a "fair playing field", it ignores deployment scale. A small farm network with a handful of devices [9] and a MSO (Multiple Service Operator) operator with dozens of CBRS base-stations [20] would receive equal spectrum shares, resulting in extreme under-provisioning for the larger deployment which has legitimately invested more in the CBRS infrastructure.

3. Cell-based fairness (a viable middle ground): A more viable middle ground is fairness at the granularity of the cell or base station (CBSD). Each CBSD receives a fair share of spectrum relative to the number of other CBSDs in the area. This avoids the pitfalls of user-based fairness (gaming with dummy SIMs) and operator-based fairness (penalizing large, legitimate deployments). Gaming by deploying extra CBSDs is significantly harder: CBSD installation requires FCC/SAS registration, operator investment, and physical deployment, and SASs could cap per-operator CBSD entitlements if necessary. The notion of enforcing fairness at the granularity of cells further aligns with the co-existence protocols proposed in the CBRS working documents from industry bodies [16, 22].

Dimensions of Fairness. When assessing fairness, it is not enough to consider how much spectrum a cell is allocated (quantity); we must further consider the utility of the allocated spectrum (quality). A cell that has many interference-impacted users (located in the coverage region of a neighboring cell) would derive far more value from exclusive access to a single clean channel, than from multiple shared channels whose quality has been degraded due to interference. Any defensible notion of fairness must therefore combine these two dimensions of quantity and quality of allocated spectrum, and consider the resulting user *performance* (in terms of achieved data rate, throughput, or user experience).

Fairness and Spectrum Efficiency. The coexistence protocol proposed in CBRS working documents equally divides the GAA spectrum among participating cells that have overlapping coverage. In other words, each cell gets a static share of spectrum, that is clean and free from interference. While such static spectrum partitioning ensures perfect fairness among participating cells, it can result in unnecessary wastage of spectrum. When neighboring cells have no interference-impacted users (i.e. when the users at the cells would experience similar performance irrespective of whether their allocated channel is isolated or shared by the neighboring cell), strictly partitioning spectrum between the two cells is an overkill that wastes spectrum. Both cells can derive greater benefits from sharing the entire spectrum, as opposed to being statically allocated only half of it. Given the GAA spectrum in CBRS is a scarce resource to begin with, an ideal spectrum coordination mechanism must avoid such unnecessary wastage, while still ensuring fairness among participating cells.

Benchmarking "Spectrum-Efficient Fairness". We combine the principles above to benchmark our notion of spectrum-efficient fairness. We begin with the baseline of equally dividing spectrum among participating cells. This gives us a benchmark for perfect fairness. But beyond this, to achieve spectrum efficiency, the system should dynamically facilitate as much reuse of the spectrum across cells as possible, in a manner that strictly improves performance of

the participants (i.e. users at each cell) over the baseline, without degrading any user's performance. In other words, no user at any cell should ever be worse off than under static partitioning.

The design challenge, then, is clear: how do we maximize spectrum usage while guaranteeing that each deployment's performance is never worse than the static partitioning baseline? Answering this requires mechanisms that adapt allocations to real interference and demand conditions, while still offering predictable fairness guarantees.

3 SPECTRUM SHARING MECHANISMS AND HOW THEY FALL SHORT

In this section, we review how both industry and academic efforts have approached spectrum sharing (either in CBRS or more generally for cellular networks), and scope for a better design. To ground this discussion, we simulate a simple scenario (depicted in Figure 2) in an open-source cellular simulator [23]. In this scenario, we deploy two CBSDs [1], each operating at 47 dBm — the most common power level observed in real-world CBRS deployments, with nearly 76% of the total deployments operating at this power level [5]. The two CBSDs (referred to as Cell 1 and Cell 2) are placed 1.5 km apart. Cell 1 serves five users, four of whom lie in the interference zone (i.e. the coverage region that overlaps with Cell 2, and is therefore impacted by interference). Cell 2 serves ten users, most of whom are located outside the interference zone. We implement several representative resource-allocation schemes and evaluate their impact across four user classes: Cell 1's interference-impacted and non-interference-impacted users, and Cell 2's interference-impacted and non-interference-impacted users. The results are summarized in Table 1.
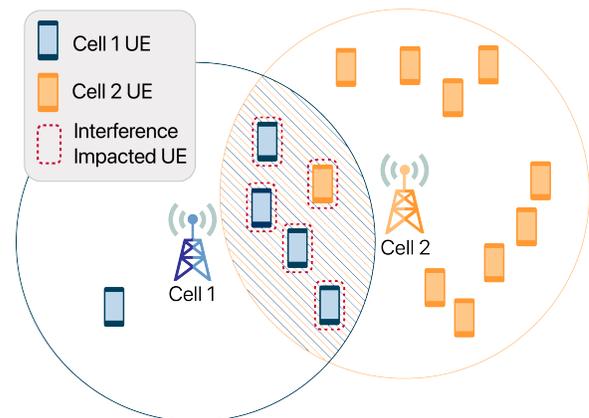
Figure 2: Deployment setup for the toy scenario. Users enclosed by the dotted boundary represent interference-impacted users located in the overlapping coverage region, while the remaining users experience interference-free conditions.

Static Partitioning. As mentioned in §2, the prevailing practice is either no coordination at all or a form of static spectrum partitioning where operators voluntarily agree to divide the available GAA band among themselves [22]. We start with simulating the

latter – an equal split of spectrum between the two cells. The first row in Table1 reports the average throughput experienced by each of the four categories of users with this scheme. We use this to benchmark the lower bound on performance under a fair division, and evaluate how subsequent schemes perform relative to this baseline. As discussed earlier, this scheme is overly conservative and wastes spectrum by avoiding any reuse or sharing across cells. In our example scenario, at least one Cell 1 user and most of Cell 2 users can comfortably reuse the same frequency channels without experiencing interference from the other cell. Static partitioning disallows such reuse.

Full Frequency Reuse. We next simulate the opposite extreme, where there is no coordination at all, and every cell is free to reuse the entire band. The resulting increase in bandwidth allocation increases the overall throughput non-interference-impacted users (by 59% at Cell 1 and 100% for Cell 2). However, the interference-impacted users suffer severely due to the degradation in the quality of channels allocated to them: average throughput for these users drops by 45% and 68% at Cell 1 and Cell 2 respectively, when compared to our static partitioning benchmark. Even though both cells get the same amount spectrum, the end outcome is unfair to the cell that has higher fraction of interference-impacted users (and unfair to these specific users). This underscores the importance of allocating good quality spectrum (our second dimension of fairness in §2).

F-CBRS. F-CBRS [4], the only other academic work on CBRS spectrum sharing, extends the notion of static partitioning by unequally dividing spectrum among participating cells, in proportion to the number active users at each cell. It assumes truthful reporting of user counts — an unrealistic expectation among competing operators. More importantly, it discards interference awareness - i.e. what number of users are actually impacted by interference. In our example, F-CBRS's user-count-based partitioning skews the allocation toward Cell 2, which hosts ten users compared to Cell 1's five. Consequently, Cell 2 receives two-thirds of clean (or isolated) spectrum. This increases the throughput of users at Cell 2. Cell 1, on the other hand, receives a smaller share of the spectrum, causing both classes of its users (interference-impacted and non interference-impacted) to suffer roughly 33% degradation in throughput.

Fermi. Interference management solutions for conventional (non-CBRS) cellular networks offer more dynamic alternatives that combine spectrum partitioning with reuse. These solutions, however, are designed for single-operator settings – where all cells that share the same frequency bands (and can therefore interfere) are owned and managed by the same operator. Fermi [3] is one such solution, where each participating cell specifies the amount of spectrum it can reuse based on how its users are split between interference-impacted and non-interference-impacted regions. The minimum among the specified amount of reusable spectrum is then shared across all participating cells . The remaining spectrum is cleanly partitioned among the cells in proportion to the number of interference-impacted users in each cell. So for our example, 20% of the GAA spectrum is shared by both cells. Of the remaining 80%, four-fifth is allocated to Cell 1 and only one-fifth is allocated to Cell 2. One can immediately see how such an allocation is unfair to Cell

2 users who get a much smaller share of spectrum, and experience up to 59% lower throughput than the static baseline.

The above unfairness stems from Fermi's decision to split the spectrum in proportion to the number of interference-impacted users, which might make sense in a single operator setting, but is ill-suited for CBRS where cells are independently operated. In fact, in extreme cases, Fermi's formulation can starve cells with no interference-impacted users entirely. A second limitation of Fermi stems from its conservative computation of how much spectrum can be reused across cells (e.g. it disallows a more nuanced, disproportional, pair-wise spectrum reuse when three or more cells interfere with one another – we omit detailed elaboration for brevity). Like Fermi, we also advocate dynamically combining spectrum reuse and partitioning. However, we'd like to do so in a manner that holds up to our cell-based fairness benchmark, and allows for greater spectrum reuse. In §4, we further highlight the unique challenges of realizing such interference-aware spectrum sharing mechanisms in multi-operator CBRS settings, when compared to Fermi's single-operator setting.

Co-op Oracle : An Ideal Upperbound. To reason about what an ideal coordination framework for CBRS could achieve, we define a conceptual upper bound called the ***Co-operative Oracle***. We begin from a simple fairness baseline where each cell receives an equal static share of spectrum. Using per-user telemetry reports indicating which users experience interference from which neighboring cells, the system constructs a global interference view showing how many users of each cell are impacted by each neighbor. Using this view, each cell determines what fraction of its static share can safely be made available for reuse, and with which cells, without harming its own users. This decision is made based on how each cell's static share is split across its users, and which cells interfere with those users. In our example, four-fifth of Cell 1's users face interference from Cell 2. So Cell 1 gets exclusive access to at least four-fifth of its spectrum share (which is four-fifth of the 50% spectrum allocated to Cell 1). Cell 2, similarly gets exclusive access to one-tenth of its 50% spectrum share. The rest of the spectrum shares can be reused across both cells to improve spectrum efficiency, without degrading baseline performance. Figure 3 visualizes this allocation. This simple coordination yields a fair and efficient outcome – each cell retains enough protected spectrum for their vulnerable users while maximizing reuse where possible. As shown in Table 1, unlike other schemes which improve performance for some users at the expense of others, Co-op Oracle consistently delivers gains across all classes (ranging from 11% to 88%) by balancing protection and reuse.

While Co-op Oracle illustrates the upper bound of what interference-aware coordination could achieve, however it also assumes full cooperation and truthful participation. In practice, such assumptions can be naive, and can possibly lead to unilateral exploitation. We next outline the key challenges that arise when attempting to realize this idealized coordination in practice.

4 OPEN CHALLENGES

Co-op Oracle , described above, represents an idealized mechanism where all operators cooperate fully and share truthful fine-grained

Variant	Cell 1 Impacted	Cell 1 Non-Interference Impacted	Cell 2 Impacted	Cell 2 Non-Interference Impacted
Static Partitioning	1.73	2.14	0.74	1.07
Full Frequency Reuse	0.96 (-45%)	3.41 (+59%)	0.24 (-68%)	2.14 (+100%)
F-CBRS	1.16 (-33%)	1.43 (-33%)	0.86 (+17%)	1.42 (+33%)
Fermi	2.55 (+48%)	3.33 (+56%)	0.31 (-59%)	0.74 (-31%)
Co-op Oracle	1.92 (+11%)	4.03 (+88%)	1.04 (+41%)	1.27 (+19%)

Table 1: Per-user throughput (Mbps) for different spectrum sharing schemes and user classes. Percentages in parentheses indicate change relative to the Static Partitioning baseline for each class of users.
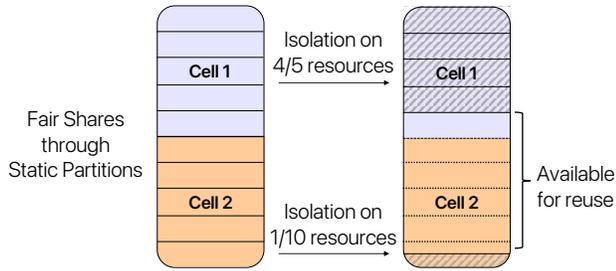
Figure 3: Resource split under Co-op Oracle system design. The isolated resources show the amount of resources reserved for interference protection, in proportion to the number of impacted users. The rest of the share of each cell is made available for reuse across cells

telemetry information (indicating the degree of interference experienced by users at each cell from each of the other cells). However, realizing such a mechanism requires overcoming several practical system and algorithm challenges that we describe below.

Telemetry Collection. The first challenge stems from obtaining the required telemetry information. Industry efforts [16] have defined some basic reporting requirements to support simple coexistence schemes such as static partitioning (e.g., CBSD location and antenna parameters) that enable creating an interference graph across cells, but exclude more nuanced information about the degree of interference experienced by individual users from different cells (that is needed for effective interference-aware coordination). Collecting this information requires different cells to coordinate, such that per-user performance can be measured in the absence and presence of transmissions from each cell.

While LTE and 5G-NR expose interfaces for such fine-grained cross-cell interference measurements [24, 25] that systems like Fermi can exploit, realizing similar capabilities in the CBRS ecosystem is much more challenging. Unlike traditional cellular systems, CBRS deployments span networks owned by different operators and overseen by different SAS administrators, with minimal shared control or time synchronization. Running coordinated measurements across these administrative boundaries is therefore a challenge. Moreover, collecting such data at extremely fine granularity, is impractical in many real-world CBRS deployments: networks are resource-constrained, located in remote regions and hence cannot support frequent or per-user telemetry reporting.

One possible solution is to rely on approximate representations, using aggregated or periodically sampled measurements with

coarse-grained cross-cell coordination to estimate interference patterns, rather than real-time reports per user. The key is to balance accuracy with overhead. We should aspire to design algorithms that are *uncertainty-aware*, capable of making robust decisions even when data is coarse, delayed, or partially missing.

Scheduling and Allocation. Even with a reasonably accurate interference view, mapping channels to operators (and ultimately users) remains a challenging problem in itself. CBRS spectrum, spanning a bandwidth of 150 MHz, is allocated at discrete granularity of 5 MHz channels. So the first difficulty lies in realizing *fractional sharing*: how to divide channels fairly when allocations are partial (e.g., "half a channel") through some sort of time-slicing or coordinated reuse. A second challenge is channel selection itself: different channels may yield different performance across operators depending on propagation characteristics and path loss, making the mapping from operators to specific frequencies non-trivial. The mapping of channels must attempt to prioritize *contiguity* as well: allocations scattered across disjoint frequencies can degrade throughput and complicate radio configuration.

Lastly, the system should be generalizable. §3 exemplified the outcome that an ideal coordination mechanism Co-op Oracle can achieve for a simple example with two cells having overlapping coverage. Another algorithmic challenge is to extend such an approach to general scenarios with more than two cells, where different users of each cell experience varying degrees of interference from different cells. How can we take these varying degrees of interference into account to maximize pair-wise reuse of spectrum between cells when scheduling and allocating channels?

Avoiding Manipulation and Incentivizing Cooperation. Building coordination around operator-reported telemetry inevitably opens the door to strategic behavior. A system like Co-op Oracle relies on the principle that if an operator's spectrum can be reused without harming its users, it should make that spectrum available to neighbors. Yet in a competitive environment, this expectation may be unrealistic. An operator can easily inflate its number of interference-impacted users—either by over-reporting or by deploying additional SIMs in contested regions—to reduce the amount of spectrum it must share. A promising direction is to embed incentives for cooperation within the ecosystem. Efficient spectrum use demands that operators not only coexist but also benefit from helping one another. Mechanisms that reward networks for sharing spectrum could align self-interest with collective efficiency. The broader research challenge is to formalize this incentive structure. How do we build an ecosystem such that cooperation becomes the rational strategy even in a competitive, multi-operator environment?

Compatibility with Existing Ecosystem. The CBRS architecture has matured under the guidance of WINNForum [17], with well-defined interfaces. Any new coordination layer must therefore coexist with these legacy mechanisms—respecting higher tier protection mechanisms and other such principles. A central systems question is how to layer dynamic coordination atop this static foundation: what can be implemented within current SAS APIs, what requires standardization, and how to evolve the ecosystem without destabilizing existing deployments or requiring impractical levels of changes to the status quo.

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