

Article

Dynamic Spectrum Allocation in the C-Band: An Overview

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Abstract

The rapid growth of wireless communication demands has led to heightened competition for limited spectrum resources, with traditional allocation methods proving insufficient to meet evolving needs. In response, DSA has emerged as a promising strategy, allowing secondary users to access underutilised portions of the spectrum, particularly in bands primarily allocated for satellite communication, such as the 3.4–4.2 GHz range. DSA offers a flexible solution by enabling the secondary use of the underutilised spectrum while protecting primary users like terrestrial FSS/SS. This paper surveys state-of-the-art DSA techniques and introduces the concept of DSUE to quantify real-time spectrum reuse effectiveness under coexistence constraints. Emphasis is placed on integrating FSS ground station parameters—such as location, antenna orientation, and sensitivity—into intelligent spectrum management frameworks. The review also evaluates ML/AI-driven resource allocation and interference mitigation approaches that enhance coexistence performance. By structuring a DSUE-aware environment, this study provides technical direction for harmonising terrestrial wireless mobile broadband and satellite systems, enabling more efficient, adaptive, and interference-aware spectrum sharing.

Keywords: DSA; DSUE; FSS; ML/AI; SS

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1. Introduction

In traditional spectrum allocation policies, PU are granted exclusive access to fixed frequency bands [1]. However, this conventional approach has led to a spectrum scarcity issue, leaving limited available bandwidth to accommodate emerging communication needs. Furthermore, studies on spectrum usage reveal that many PUs occupy their assigned bands for only a small portion of the time and area, resulting in the significant underutilisation of the spectrum.

In recent years, the demand for wireless communication has surged, often outpacing the availability of designated frequency bands. Amid this increasing pressure, innovative approaches to spectrum management have gained prominence, particularly in the context of DSA. This technique allows secondary users to access frequency bands that are primarily allocated to license holding technologies—like satellites, radars, and aerospace communications—specifically within the 3.8–4.2 GHz range. This approach allows multiple users or technologies to reuse or share radio resources, improving spectrum efficiency and increasing throughput without requiring new spectrum resources [2].

In South Africa, terrestrial wireless mobile networks are essential for bridging the digital divide caused by vast geography, low population density in remote rural provinces,

and economic disparities. Fiber deployment across regions like Limpopo, Kwazulu Natal, the Eastern and Northern Cape is often not cost-effective due to rugged terrain and sparse settlements [3], making 4G/5G wireless solutions a more scalable and practical alternative. Major MNOs typically focus on profitable urban metros for network upgrades, leaving rural and low-income communities underserved despite their growing need for connectivity to support eHealth, eGov, digital agriculture, education, and mobile finance. Wireless access enables broader socio-economic inclusion by expanding access to government services, job markets, remote learning, and entrepreneurship. Furthermore, national policies such as the ICASA's spectrum obligations in [1,4] mandate universal service coverage, which wireless technologies can fulfil efficiently—especially when combined with spectrum sharing models like TVWS, LSA, or CBRS. These frameworks also empower smaller operators and municipalities to deploy affordable, community-based networks. Thus, terrestrial wireless mobile infrastructure is not merely a technical solution but a strategic tool for inclusive development and equitable digital access.

By intelligently identifying and utilising underused spectrum resources, DSA aims to enhance spectrum efficiency, a critical requirement given the finite nature of frequency allocations. This review explores the mechanisms through which DSA can be adopted and implemented in satellite environments, as critically examining its potential to mitigate spectrum scarcity while ensuring that PUs, as considered in [5–7], maintain their operational integrity. Ultimately, the analysis in [2,8–10] revealed that effectively leveraging DSA could establish a more robust communication framework, fostering both technological advancement and improved user experiences in an increasingly congested spectrum landscape. These claims are generating research interests in a successful setup of 5G and FSS coexistence while considering antenna evolution in 5G NR in terms of MIMO and RIC configurations. Figure 1 shows the outline of the paper.

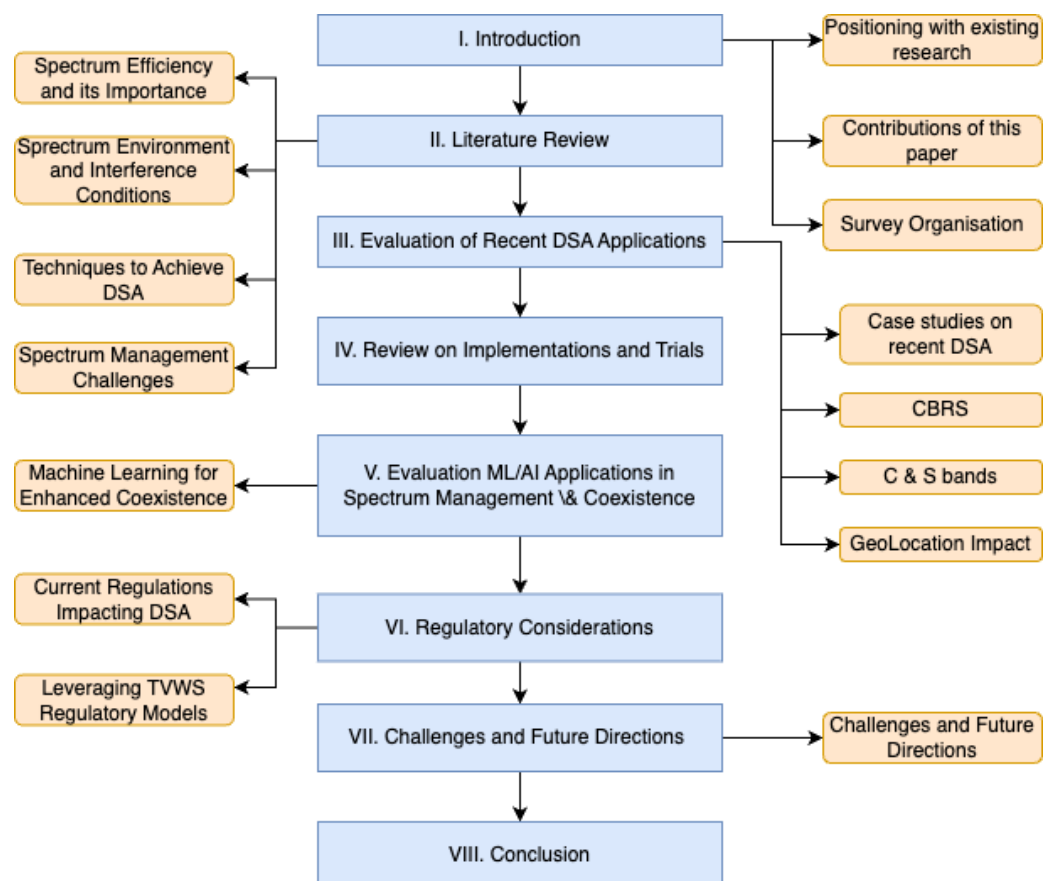


Figure 1. Structure of the paper.

1.1. Positioning Within Existing Surveys

Existing literature in Table 1 on DSS has laid a strong foundation across several dimensions, including spectrum coexistence, resource allocation, and policy development. For example, coexistence mechanisms and interference mitigation strategies have been thoroughly classified for cognitive radio networks in TVWS [10,11]. Surveys such as [12,13] provide insights into inter-technology coexistence frameworks and models like CBRS and LSA, while Moubayed et al. and Patil et al. in Refs. [2,8] highlight opportunities and challenges for spectrum sharing in 5G and B5G environments.

A strong body of research has also emerged around ML/AI applications for dynamic spectrum access and radio resource allocation. These include supervised and reinforcement learning-based mechanisms for efficient spectrum assignment and automation [14–16]. Several works point to ML as a crucial tool for enhancing the intelligence and adaptability of spectrum management frameworks [2,8], though most of this research has focused on terrestrial coexistence among traditional wireless mobile broadband systems. However, there is limited literature that specifically addresses the coexistence between terrestrial wireless mobile networks (such as 4G, 5G NR) and terrestrial ground satellite receivers. The need to safeguard these incumbent services while leveraging dynamic spectrum access calls for new models of interference characterisation and intelligent spectrum management. Therefore, this paper positions itself to fill this gap by investigating ML/AI-driven resource allocation approaches to enable efficient coexistence in DSS environments while ensuring the protection of FSS/SS-receiving ground stations. This approach integrates real-time learning, geolocation databases, and regulatory-aware constraints into the coexistence and spectrum reuse framework.

Table 1. Checklist summary of spectrum sharing literature on techniques and technologies and their coverage.

Reference	Coexist.	ML-RA	PU Prot.	Inter-Tech.	Reg.	LSA	CBRS	TVWS	Sat/Radar
(2020) [2]	✓	✓	✓	✗	✓	✗	✗	✗	✗
(2015) [11]	✓	✗	✗	✓	✗	✗	✗	✓	✗
(2019) [12]	✓	✓	✓	✓	✓	✓	✓	✓	✗
(2016) [10]	✓	✗	✗	✓	✗	✗	✗	✗	✗
(2024) [8]	✓	✓	✓	✓	✓	✓	✓	✗	✗
(2020) [14]	✓	✓	✓	✗	✗	✗	✗	✗	✗
(2021) [15]	✓	✓	✗	✗	✗	✗	✗	✗	✗
(2022) [16]	✓	✓	✗	✗	✗	✗	✗	✗	✓
(2018) [13]	✓	✓	✓	✓	✓	✓	✗	✓	✓
(2017) [17]	✓	✓	✗	✓	✓	✗	✗	✗	✓
(2019) [18]	✓	✗	✓	✓	✓	✗	✗	✓	✗
(2020) [19]	✓	✓	✓	✗	✓	✗	✓	✗	✗

1.2. Contributions of This Paper

This paper contributes to the body of knowledge by proposing a systematic approach for extracting and incorporating the physical and technical parameters of FSS and SS ground stations into DSS environments. Specifically, it addresses the critical challenge of protecting satellite downlink transmissions from interference caused by nearby terrestrial mobile networks. The study outlines methods for identifying relevant FSS/SS parameters such as antenna orientation, elevation angle, sensitivity thresholds, and geographic location that must be integrated into spectrum management frameworks. Leveraging these parameters, the paper introduces ML/AI-driven models that enable the real-time adjustment of terrestrial network transmission power, antenna beamforming patterns, and spectrum access decisions based on proximity and alignment with satellite ground receivers. This dynamic,

data-informed approach enhances the coexistence between terrestrial and satellite systems by minimising harmful interference while maximising spectral efficiency. Ultimately, the paper provides a foundation for intelligent, location-aware, and adaptive interference management policies that support the scalable deployment of mobile broadband systems. The contributions can be listed as

- A comprehensive review of DSA techniques involving coexistence between PU and SU.
- A detailed discussion on the spectrum environment factors and interference challenges.
- ML/AI insights to enhance spectrum management considering antenna technologies.
- Evaluation of recent DSA implementations.
- Review on trials and regulatory factors.
- Proposal of future directions.

This aims to explore the most effective methods for the ML/AI-based coexistence framework of DSA networks. The main research question to be answered is

“How can ML/AI-based opportunistic spectrum access systems enhance coexistence and access accuracy in the sub-6 GHz spectrum bands while addressing limitations and challenges of existing DSA frameworks?”

To address the above question, the following sub-questions will be answered:

1. What are the key limitations and challenges of current multi-network operator spectrum sharing in tiered coexistence frameworks in the different spectrum bands?
2. How can ML/AI algorithms such as DL and RL be applied to enhance spectrum access accuracy and coexistence in the sub-6 GHz bands in radically changing environment conditions in real-time?

1.3. Survey Organisation

The organisation of this survey, shown in Figure 1 is structured to comprehensively address DSA with a focus on coexistence between terrestrial wireless mobile networks and satellite ground stations such as FSS/SS. The literature review section follows, covering the importance of spectrum efficiency, the spectrum environment and interference conditions, techniques to enable DSA—including cognitive radio and database-assisted sharing—and the role of ML/AI in spectrum coordination. It also examines spectrum management approaches relevant to satellite systems. Subsequent sections evaluate recent DSA applications, enablers, and frameworks/models (CBRS, TVWS, LSA), and review regional implementations and trials. This is followed by an assessment of the ML/AI models used for coexistence and interference management. The survey then discusses implementation challenges and future directions, and concludes by summarising key findings and proposing research opportunities for intelligent, satellite-aware DSA frameworks.

2. Literature Review

Coexistence broadly refers to the ability of multiple wireless systems or technologies with similar priorities to operate in the same spectrum band without significantly negatively impacting each other’s performance.

While these contributions in Table 2 have made substantial progress in enabling efficient and flexible spectrum usage, they primarily focus on terrestrial coexistence scenarios or overlook the fine-grained protection mechanisms required for primary users in satellite bands. Notably, the growing interest in utilising the 3.8–4.2 GHz band for 5G NR highlights the increasing pressure on incumbent FSS ground stations, which require robust protection against harmful interference. Current approaches often lack detailed characterisations of interference at satellite receiver terminals and fail to incorporate predictive, location-aware interference mitigation using spectrum occupancy data.

Table 2. Summary of key literature on ML/AI (ML/AI)-based coexistence.

Reference/Journal	Year	Core Contributions	Focus
[2]	2020	Proposes ML models for spectrum-as-a-service (SaaS) and dynamic sharing.	SaaS and ML-driven DSS architecture.
[8]	2022	Presents intelligent SS for 5G/B5G using CR, ML/AI, and blockchain; outlines challenges and future research.	AI-enhanced spectrum management in 5G/B5G.
[14]	2020	Offers taxonomy and challenges in ML-driven dynamic spectrum management.	ML for DSA and interference-aware access.
[16]	2022	Surveys deep reinforcement learning for dynamic spectrum and resource management.	DRL for intelligent resource allocation.
[17]	2017	Surveys database-assisted spectrum sharing for satellite systems (GSO/NGSO) and coexistence.	Satellite–terrestrial spectrum sharing via databases.
[17]	2016	Discusses spectrum occupancy and interference maps for PU protection and DSS efficiency.	Interference-aware DSA planning and PU safeguarding.

This review paper addresses this critical gap by focusing on the coexistence of terrestrial wireless mobile broadband systems and FSS/SS ground stations. It aims to explore how spectrum databases and interference maps can be integrated with ML/AI-based decision systems to enhance dynamic resource allocation while ensuring the protection of incumbent satellite users to achieve a higher DSUE. By examining recent advances in PU protection, interference prediction, and adaptive learning for spectrum access, this review establishes a research direction that enables the intelligent, real-time management of spectrum access in shared bands involving ground satellite receivers. Ultimately, this contributes to the development of resilient, database-assisted coexistence frameworks suitable for both national regulators and mobile network operators seeking to deploy terrestrial wireless mobile broadband networks in shared environments.

DSA is a paradigm that allows for the flexible and opportunistic use of the radio spectrum, enabling multiple users grouped as primary and secondary users to share the same frequency bands dynamically. It is another spectrum sharing paradigm, which compared to other techniques, is dynamic, dependent on a definition of an algorithm to manage access with a level of fairness. DSA can significantly increase spectrum efficiency through coexistence techniques, allowing for the more effective utilisation of available spectrum resources. It refers to the real-time adjustment of spectrum utilisation in response to changing conditions, allowing for the more efficient use of available frequency bands.

2.1. Spectrum Efficiency and Its Importance

Spectrum efficiency refers to the optimal use of available spectrum resources [2]. Although this is a generic metric, this might appear high even when some of the bands are not in use. SUE then measures how efficiently an unused or underutilised spectrum is accessed and reused. Maximising utilisation efficiency is a fundamental goal of spectrum sharing [2]. DSUE enhances spectrum efficiency by ensuring that an available spectrum is not left idle. This is the dynamic, intelligent layer that fills in spectrum usage gaps to achieve maximum efficiency across users, time, space, and frequency.

The measure of the data rate achieved per unit bandwidth by Equation (1) is useful in realising the efficiency in a statically allocated spectrum, but not insightful because it does not consider time-sharing or coexistence with others. It is mainly a property of modulation, coding, and protocol efficiency. It defines the theoretical efficiency of each technology separately.

$$SE \triangleq \frac{\sum_{u \in \mathcal{U}} R_u}{B} \quad [\text{bits/s/Hz}], \quad (1)$$

where

- R_u : Data rate in bits per second (bps)
- B : Bandwidth in Hertz (Hz)

SUF refers to how fully the allocated spectrum is utilised over time and geography. It captures spectrum occupancy across space, time, and frequency. This is shown by Equation (2)

$$SUF = \frac{\text{Time used} \times \text{Geographic coverage} \times \text{Bandwidth used}}{\text{Total available spectrum resource}} \quad (2)$$

In comparison to spectrum efficiency in Equation (1), SUE is dynamic as it measures how effectively the system exploits the spatiotemporal availability of the spectrum subject to protection constraints. Our DSUE extends SUE with indicator functions that turn access on/off as the instantaneous uplink/downlink interference at protected FSS/SS receivers remains below thresholds. The basic SUE, Equation (3), is defined as the ratio of useful data throughput T to the allocated spectrum bandwidth B and time t to realise the SUF in Equation (2), expressed as

$$SUE \triangleq \frac{\int_{\mathcal{A}} \int_{\mathcal{T}} \mathbb{K}_{\{\text{spectrum active}(x,y,t)\}} dt da}{|\mathcal{A}| |\mathcal{T}|} \in [0, 1], \quad (3)$$

where

- $\mathcal{A}$: The geographical area of interest;
- $\mathcal{T}$: The observation time interval;
- $|\mathcal{A}|$: The total size (measure) of the area $\mathcal{A}$;
- $|\mathcal{T}|$: The total duration (measure) of the time interval $\mathcal{T}$;
- $\text{spectrum active}(x, y, t)$: Condition that is true if the spectrum is actively used at location (x, y) and time t ;
- $\mathbb{K}_{\{\cdot\}}$: Indicator function, equal to 1 if the condition holds (spectrum active), and 0 otherwise;
- $\int_{\mathcal{A}} \int_{\mathcal{T}} \cdot dt da$: The total space–time measure of active spectrum usage;
- Denominator $|\mathcal{A}| |\mathcal{T}|$: The maximum possible usage (if the spectrum was active everywhere and at all times).

Hence, $SUE \in [0, 1]$, where 0 indicates no usage and 1 indicates the full utilisation of the spectrum across the entirety of the space and time.

In a dynamic spectrum sharing scenario involving terrestrial wireless mobile networks and FSS/SS ground stations, this metric must be spatially and temporally adjusted to account for geographic restrictions around satellite receivers, as well as uplink and downlink separation. We introduce a location-aware efficiency term extending from Equation (3), denoted by η_{DSU} , defined as

$$\eta_{\text{DSU}} = \frac{\sum_{i=1}^N T_i(x_i, y_i)}{B \cdot t \cdot (A - A_{\text{protect}})} \quad (4)$$

where

- $T_i(x_i, y_i)$ is the throughput achieved by the user or base station i at spatial location (x_i, y_i) ;
- B is the total spectrum bandwidth available for dynamic access (3.4–4.2 GHz);
- t is the total transmission time observed;
- A is the total area under consideration;
- A_{protect} is the area excluded due to satellite protection constraints, such as exclusion zones around FSS ground stations.

Maximising SUE, Equation (3) must not compromise the operational integrity of the PU. The uplink interference from UE to the satellite receiver is spatially dependent and can be captured through interference coupling function $I_{\text{uplink}}(x_i, y_i)$, while downlink interference from gNB to the satellite receiver can be expressed as $I_{\text{downlink}}(x_j, y_j)$. We distinguish the uplink (I_{uplink}) and downlink (I_{downlink}) because mobile-to-satellite and gNB-to-satellite coupling paths differ in EIRP, height, and antenna patterns as shown in Figure 2; hence, they yield different protection-driven access masks. The resulting interference-aware DSUE can be further refined as

$$\eta_{\text{DSUE}} \triangleq \frac{\int_{\mathcal{A}} \int_{\mathcal{T}} (\sum_u R_u(x, y, t)) \mathbb{1}_{\{I_{\text{uplink}}(x, y, t) \leq I_{\text{th}}^{\text{FSS}}\}} \mathbb{1}_{\{I_{\text{downlink}}(x, y, t) \leq I_{\text{th}}^{\text{FSS}}\}} dt da}{B |\mathcal{T}| (|\mathcal{A}| - |\mathcal{A}_{\text{protect}}|)} \quad (5)$$

where

- $I_{\text{th}}^{\text{FSS}}$ is the interference protection threshold (e.g., -6 dB I/N);
- $\mathbb{1}_{\{\cdot\}}$ ensures that only locations satisfying interference constraints are included in the efficiency calculation;
- $R_u(x, y, t)$ is the achievable data rate for user u at position (x, y) and time t ;
- $\sum_u R_u(x, y, t)$ is the aggregate throughput from all active users at (x, y, t) ;
- $I_{\text{uplink}}(x, y, t)$, $I_{\text{downlink}}(x, y, t)$ is the uplink and downlink interference experienced by the FSS at (x, y, t) ;
- $I_{\text{th}}^{\text{FSS}}$ is the interference protection threshold defined for FSS receivers;
- $\mathbb{1}_{\{I_{\text{uplink}} \leq I_{\text{th}}^{\text{FSS}}\}}$, $\mathbb{1}_{\{I_{\text{downlink}} \leq I_{\text{th}}^{\text{FSS}}\}}$ are the indicator functions enforcing that only instances where both uplink and downlink interference are below the FSS threshold contribute to DSUE.

Equation (1) is static (PHY/MAC efficiency per Hz), whereas Equations (3)–(5) are dynamic because activation depends on time-varying occupancy and interference constraints. This formulation captures the essence of coexistence-aware spectrum efficiency, accounting for the impact of spatial exclusion zones, uplink/downlink directional interference, and throughput contributions from dynamically allowed users, thereby enabling an accurate representation of the dynamic spectrum utilisation efficiency in shared FSS with 5G environments, as depicted in Figure 2, showing the satellite ground station receiving from a space transmitter and also receiving interfering signals from both the gNB and UE.

Satellites' transmission power is relatively lower than the power levels of wireless mobile networks; hence, the possible degradation mechanisms to influence Equation (5) and ultimately Equation (2) are considered as below:

1. **Aggregate interference:** The cumulative interference from multiple base stations or user devices transmitting concurrently. Even if each SU transmission is compliant individually, their aggregate power may exceed the interference-to-noise (I/N) threshold required by FSS receivers.
2. **ACI:** 5G NR signals operating near FSS downlink frequencies can leak energy into adjacent satellite bands due to imperfect filters and nonlinearities, especially if no guard band is maintained between the two systems.
3. **Oobe:** SU transmissions may cause unintended radiation beyond their allocated channel, which can desensitise satellite receivers that have very low noise floors, impacting their ability to detect weak satellite signals.
4. **CCI:** In cases where DSS permits co-channel use (e.g., through database-assisted spectrum access), direct overlap in time–frequency–space can lead to significant signal degradation or loss at the satellite ground station.
5. **Beam misalignment and antenna side lobe coupling:** The use of high-gain, beamforming antennas by 5G and 4G base stations or UE may inadvertently illuminate satellite

receivers, especially when side lobes or reflected beams align with FSS antennas, increasing interference risk.

6. Near-field interference: If SUs are deployed too close to FSS ground stations, line-of-sight interference paths can bypass natural attenuation and clutter, resulting in elevated interference levels even from low-power devices.

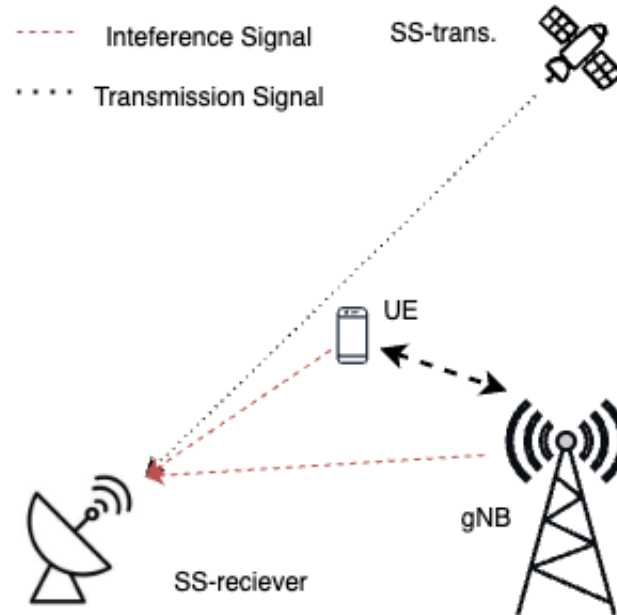


Figure 2. Terrestrial satellite and wireless mobile network coexistence environment.

Interference types, discussed in [12], which can be applied in an example considering an FSS and 5G NR environment, are considered in calculating the DSUE and are listed in Table 3.

Table 3. Types of interference between 5G and FSS systems.

Interference Type	Description
Uplink-to-downlink	5G uplink transmissions (e.g., UE → gNB) interfering with satellite downlink reception at FSS ground stations.
Downlink-to-downlink	5G base station downlink (gNB → UE) emissions overlapping with FSS satellite downlink signals at the Earth station.
Intra-system harmonics/OOBE	Spurious emissions from the 5G system outside its allocated band affecting adjacent satellite bands.
Aggregate emissions	Combined emissions from a large number of SUs) operating near FSS sites (urban deployments are particularly critical).
Directional/beam interference	High-gain antennas with electronically steered beams unintentionally pointing towards FSS antennas.
Reflected/scattered interference	Indirect paths due to building reflections or terrain scattering that deliver interfering signals to FSS receivers.

2.1.1. DSUE Capacity Shift

Using an FSPL model to isolate the effect of the interference margin, the minimum separation distance r that satisfies an FSS interference threshold I_{th} scales exponentially with the margin.

$$\begin{aligned}
 EIRP + G_{rx} - [32.45 + 20 \log_{10}(f_{MHz}) + 20 \log_{10}(r_{km})] &= I_{th} \\
 \Rightarrow r_{km} &= C \cdot 10^{M/20}, \quad C \text{ constant for fixed } (EIRP, G_{rx}, f, I_{th}).
 \end{aligned} \tag{6}$$

Remark 1. An increase of 1 dB in the interference requirement increases the exclusion radius by $10^{\frac{1}{20}} \approx 1.122$, which translates into an exclusion area growth proportional to r^2 , which is about +25.9%.

$$C_{\text{cell}} \approx \text{SE} \cdot B \cdot \left(1 - \frac{A_{\text{excl.}}}{A_{\text{service}}}\right) \quad (7)$$

Thus, from Equation (7), which shows the change in cell capacity as the exclusion area changes, if $A_{\text{excl.}}$ rises from 1.00 to 1.26 km² inside a 10 km² service area, the fractional capacity drops by ≈ 2.66 pp, directly translating a 1 dB protection change to a throughput losses.

2.1.2. DSUE Degradation

A key implication of the 1 dB interference margin analysis is that even seemingly minor protection adjustments translate into large geometric and capacity effects: a 1 dB tighter margin expands the exclusion radius by $\approx 12\%$ and the protected area by $\approx 25.9\%$. This sensitivity highlights several concrete design levers. First, beamforming null placement, vertical down-tilt, and adaptive power control can recover 1–2 dB at the FSS receiver, shrinking exclusion areas by up to 40% and reclaiming a significant spectrum for secondary use. Second, channelisation strategies—such as selecting carriers with lower out-of-band leakage or enforcing stricter ACLR masks—directly reduce effective EIRP toward the FSS, thereby relaxing protection distances without sacrificing throughput in other directions. Third, scheduling becomes a spatio-temporal mitigation tool: uplink allocations near exclusion boundaries (I_{uplink}) can be suppressed or power-limited, while downlink beams (I_{downlink}) can be dynamically steered away from FSS azimuths, trading modest spectral efficiency for robust coexistence. Finally, policy enforcement is embodied through DSUE’s indicator functions, where access is algorithmically permitted only if both uplink and downlink interference estimates remain below the FSS protection threshold. Together, these levers demonstrate how small numerical shifts in an interference margin cascade into real design choices, linking physical-layer adjustments, spectrum masks, and scheduling policies to enforce coexistence guarantees.

Because a 1 dB protection margin swing inflates the exclusion area by $\approx 26\%$ shown in Table 4, beamforming null placement and down-tilt may enable the recovery of even 1–2 dB at the FSS receiver, thereby materially shrinking the EZs. Likewise, tighter ACLR/OOBE filtering or opportunistic uplink/downlink scheduling near the boundary can claw back a comparable margin to stabilise DSUE. These design factors operationalise how seemingly small margin shifts alter exclusion radii and capacity as shown by Table 4.

Table 4. Impact of Δ interference margin tightening on exclusion design metrics.

Δ Margin (dB)	Radius Factor (r/r_0)	Area Increase	Capacity Drop
+1 dB	1.12	+26%	$\approx -20\%$
+2 dB	1.28	+64%	$\approx -40\%$

For a typical suburban $\alpha \approx 3.5$, we obtain $R_{\text{ex}} \propto \lambda^{1/(\alpha-2)} \approx \lambda^{0.67}$; hence, the protected area $A_{\text{protect}} = \pi R_{\text{ex}}^2 \propto \lambda^{1.33}$ grows super-linearly with BS density. Plugging this scaling into the DSUE definition,

$$\eta_{\text{DSUE}}^* = \frac{\sum_i T_i(x_i) \mathbb{1}_{\{I_{\text{uplink}} \leq I_{\text{th}}\}} \mathbb{1}_{\{I_{\text{downlink}} \leq I_{\text{th}}\}}}{B t (A - A_{\text{protect}}(\lambda))}, \quad (8)$$

Equation (8) reveals two coupled degradations as λ increases: (i) the usable area ($A - A_{\text{protect}}$) shrinks as $A - \Theta(\lambda^{1.33})$, and (ii) throughput terms T_i near the boundary

drop which, due to tighter beamforming, power control, and scheduling, needs to be kept $I_{\text{uplink}}, I_{\text{downlink}}$ below the threshold.

2.1.3. Impact of 5G BS Density on DSUE with Typical FSS Parameters

Consider a representative C-band FSS Earth station with a $G/T = 20$ dB/K. For a $B = 36$ MHz transponder, the receiver noise floor is

$$N = kT_{\text{sys}}B \quad (9)$$

where $T_{\text{sys}} \approx 100$ K, yielding $N \approx -133$ dBW. The deployment of 5G NR base stations is modelled as a Poisson point process (PPP) of density λ (sites/km²), with each BS contributing effective interference $P_{\text{tx}}G_{\text{BS} \rightarrow \text{ES}}L(r)^{-1}$ at the Earth station outside an exclusion radius R_{ex} .

Under standard shot-noise analysis with pathloss exponent $\alpha > 2$, the aggregate interference observed at the FSS terminal scales as

$$I_{\text{agg}}(\lambda, R_{\text{ex}}) \approx K\lambda R_{\text{ex}}^{2-\alpha} \quad (10)$$

where $K = \frac{2\pi P_{\text{tx}}G_{\text{BS} \rightarrow \text{ES}}}{\alpha-2}C_{\text{PL}}$ encapsulates the transmit power, antenna coupling, and propagation constants. The protection constraint $I/N \leq (I/N)_{\text{th}}$ then implies

$$R_{\text{ex}}(\lambda) \gtrsim \left(\frac{K\lambda(I/N)_{\text{th}}}{kT_{\text{sys}}B} \right)^{\frac{1}{\alpha-2}} \quad (11)$$

For a suburban pathloss exponent $\alpha \approx 3.5$, the exclusion radius grows with density as $R_{\text{ex}} \propto \lambda^{0.67}$, so the protected area $A_{\text{protect}} = \pi R_{\text{ex}}^2 \propto \lambda^{1.33}$ increases super-linearly with the base station density. Substituting the DSUE metric in Equation (5), two degradations emerge as λ rises:

1. The usable area $(A - A_{\text{protect}})$ shrinks approximately as $A - \Theta(\lambda^{1.33})$;
2. Throughput terms T_i near the exclusion boundary diminish due to stricter beam and power control constraints.

Therefore, with $R_{\text{ex}} = 1$ km at $\lambda_0 = 5/\text{km}^2$, Equation (8) shows that doubling the BS density to $10/\text{km}^2$ inflates R_{ex} to ≈ 1.6 km, a $2.56\times$ increase in protected area. Consequently, the DSUE denominator expands while the numerator weakens, pulling η_{DSUE}^* downward unless compensated by null-steering, down-tilt, tighter ACLR/OOBE control, or conservative edge scheduling. This demonstrates quantitatively how a rising BS density materially stresses coexistence and necessitates advanced interference management.

2.2. Managing DSA

Effectively implementing DSA techniques for avoiding DSUE degradation necessitates a comprehensive understanding of both the technological and economic implications of spectrum-sharing methodologies. By enhancing SUE in frequency bands where satellites operate as PUs, DSA presents an innovative solution to address the increasing demand for wireless bandwidth. As highlighted in the analysis of shared spectrum economics, stakeholders must optimise SU bandwidths to fully capitalise on the available opportunities for spectrum sharing. Thus, integrating DSA techniques could yield substantial economic benefits while simultaneously accommodating the exponential growth of user traffic in critical frequency bands. In order to contextualise these opportunities, the enabling mechanisms that underpin DSA can be systematically classified into map-based, sensing-based, and learning-driven approaches, each offering distinct methods for ensuring efficient coexistence and PU protection, as outlined in Table 5.

Table 5. Classification of DSA enablers with C-band implications.

Category	Description	Examples	C-Band Implications
Map-based	Centralised, rule-based access using geo-databases, and protection zones	TVWS database, CBRS SAS, LSA repositories	Enables the protection of FSS Earth stations through exclusion zones and geolocation licensing; supports light licensing for local 5G deployments.
Sensing-based	The real-time detection of incumbents or other users through distributed sensing	Energy detection, LBT (NR-U/LTE-U), cooperative sensing	Limited effectiveness in C-band due to low FSS signal detectability; requires hybrid sensing database models to reliably protect satellite incumbents.
ML/AI-based	Predictive, adaptive spectrum management using learning-based models	RL for power/beam control, ML/AI for spectrum prediction, FL for MNO coordination	Enhances coexistence by dynamically adapting power, beams, and spectrum allocation in dense 5G deployments; supports multi-MNO sharing while ensuring FSS protection.

2.3. Classification of DSA Enablers

The enabling techniques for spectrum sharing, often collectively referred to under the umbrella of DSA, can be systematically classified into three categories: map-based, sensing-based, and ML/AI-based. Each category employs distinct mechanisms to ensure coexistence and PU protection, ranging from sensing-driven CR approaches to rule-based enforcement and adaptive ML/AI coordination. Table 5 summarises this classification with specific relevance to C-band coexistence, highlighting how historical learnings from TVWS and CBRS inform the design of harmonised sharing frameworks. When applied to the C-band, this taxonomy underscores the need for tailored coexistence strategies that not only safeguard FSS operations but also sustain the scalability of dense terrestrial wireless mobile network deployments. These enablers, while originating in broader spectrum sharing frameworks such as TVWS, CBRS, and LSA, provide the foundation for harmonised coexistence in the C-band, where the protection of satellite incumbents while achieving higher DSUE remains the central regulatory and technical challenge.

2.3.1. Map-Based Approaches

Map-based enablers rely on geo-location databases, spectrum maps, or predefined EZs. These have devices which query centralised entities for permissible operating parameters. These approaches emphasise regulatory enforcement and the deterministic protection of incumbents.

2.3.2. Sensing-Based Approaches

Sensing-based methods dynamically detect incumbent signals in real time. Techniques include energy detection, cyclostationary analysis, and cooperative sensing across multiple nodes. These methods have been widely discussed in classical CR literature and remain relevant for unlicensed coexistence [20–22].

2.3.3. ML/AI-Based Approaches

These approaches enhance DSA by enabling predictive and adaptive decision making. RL can be used for interference-aware scheduling, FL can be used for cross-MNO

coordination, and DL can be used for spectrum occupancy prediction. These techniques go beyond reactive sensing or static maps by leveraging historical and contextual data to manage coexistence in near real-time.

2.4. Dynamic Adaptation for Increased DSUE

In the realm of satellite communication, DSA techniques play a crucial role in optimising SUE, particularly in frequency bands where satellites operate as PUs. Among the enabling approaches, spectrum sensing allows SUs to detect unoccupied frequency bands and opportunistically access them without causing harmful interference to PUs. This capability enhances SUE and fosters innovation in applications such as disaster recovery and emergency communication, where timely access to bandwidth can save lives by providing a level of guaranteed connectivity. Techniques such as energy detection and dynamic frequency selection further support the identification of available spectrum resources and adaptation to the dynamic nature of satellite service demand, thereby improving DSUE to achieve a better SUF. Nevertheless, sensing-only approaches face inherent limitations, as they do not provide enforcement mechanisms to address erratic behaviour or penalise non-compliant SUs. This underscores the importance of complementing sensing with map-based and regulatory-driven approaches, which ensure accountability and long-term coexistence. As elaborated in [4], these advancements have the potential to significantly increase economic benefits for MNOs by optimising shared bandwidth in saturated frequency bands, thereby underscoring the transformative impact of DSA on satellite communications bands. Notably, the historical evolution of satellite technology, highlighted in [23], has paved the way for these DSA techniques, demonstrating their essential role in enhancing global connectivity through efficient data transmission and supporting crucial sectors such as telecommunications and navigation.

One way to enable DSA is through a SaaS architecture where users can access radio resources on demand. This model is particularly relevant for terrestrial wireless communication networks and ground satellites aiming to coexist in C-bands and higher bands.

Navigating the complex landscape of regulatory and technical considerations is paramount for the successful implementation of DSA systems, especially in bands dominated by satellite communications. Effective regulation is necessary to balance the competing interests of satellites as PUs and SUs are looking to exploit the same spectrum. The establishment of clear EZs is crucial to mitigate interference, particularly when considering the sensitivity due to variations in PU antenna characteristics, which can significantly influence the assessment of sharing opportunities [24,25]. Furthermore, the technical feasibility of DSA hinges on robust protocols that must ensure seamless coordination between operators. This includes addressing the overhead costs associated with implementing DSA protocols, which can impact the net benefits derived from spectrum sharing. As satellite communication continues to evolve, it is imperative to create regulatory frameworks that facilitate innovation while safeguarding the integrity of existing services [26].

2.5. Spectrum Environment and Interference Conditions

The effectiveness of DSA mechanisms heavily depends on an accurate understanding of the surrounding radio environment and the interference conditions within it. Central to this understanding is the ability to dynamically monitor and adapt to spectrum usage in real time. According to [27], real-time bandwidth monitoring plays a critical role in guiding the optimal transmission strategy for SUs. Spectrum reconstruction techniques, as discussed in the same study, further enhance this by enabling the adaptive adjustment of system parameters in response to environmental variations. These techniques facilitate the rapid

analysis of channel availability and propagation characteristics, thereby mitigating the risk of DSUE degradation and supporting the preservation of DSUE capacity under coexistence.

The spectrum environment consists of both static and dynamic inputs. Static inputs typically include GIS data, such as terrain profiles and clutter classification, which influence signal propagation and coverage. Dynamic inputs, on the other hand, include real-time spectrum sensing/monitoring data that provides current usage and occupancy levels and a rapid description of environmental characteristics [27]. By combining these inputs, interference and propagation models can be applied to conduct a comprehensive impact analysis of emissions across the environment, allowing the direct quantification of both DSUE degradation and DSUE capacity.

A foundational principle in DSA systems is the protection of PUs from the harmful interference of SUs as depicted in Equation (5) in the pursuit of higher DSUE and maintained capacity, introducing SU networks such as BS and UEs. As noted in [28], SUs are required to operate in a non-interfering manner and cannot claim protection from interference generated by PUs. This regulatory condition underpins many coexistence and spectrum-sharing protocols. Effective interference mitigation strategies are therefore necessary to ensure that SU transmissions remain below defined thresholds, especially in densely populated or mission-critical spectrum bands. These require the adoption of robust coordination protocols among sharing players due to the sensitivity of the sharing players in terms of interference protection and guaranteed access to the licensed bands [29].

2.6. Techniques to Achieve DSA

Spectrum sensing, as in Table 5, identifies the available spectrum by detecting the presence or absence of PUs [30], utilising methods such as energy detection, cooperative sensing, and database-assisted approaches like the SAS in CBRS. Spectrum decision involves selecting the optimal frequency band based on channel conditions, interference, and QoS requirements, often leveraging machine learning models for intelligent decision making. Spectrum-sharing coordinates multiple users within the same band through underlay, overlay, and interweave approaches, integrating access mechanisms like TDMA, FDMA, and spatial division. Finally, spectrum mobility ensures seamless transitions when PUs reclaim the spectrum, facilitating dynamic reallocation and uninterrupted connectivity. These interdependent techniques form the foundation of DSA, enabling efficient the coexistence of licensed and unlicensed users while optimising spectrum utilisation in wireless networks.

Traditional Methodologies in DSA Coexistence Management

Traditional methodologies for developing regulations to manage coexistence often rely on static interference models, fixed separation distances, and predefined protection contours. These approaches, while effective in some scenarios with static environment effects, will exhibit shortcomings resulting in a poor DSUE. Traditional frameworks typically use static interference thresholds and rigid operational parameters that do not adapt to the dynamic and evolving spectrum usage patterns. This leads to either the over-protection of PUs, wasting valuable spectrum space, or insufficient protection, causing harmful interference. These methods rely on conservative assumptions about interference scenarios, such as worst-case power levels, antenna patterns, and geographic separation. This approach does not account for localised variations in deployment scenarios or real-time environmental factors, which can lead to a very low SUE in Equation (3). Traditional systems do not incorporate real-time environmental features such as terrain variations, urban density, or weather conditions that could significantly impact signal propagation and interference. Manual analysis and fixed policies can delay regulatory responses to changing spectrum

demands, hindering the deployment of 5G networks while maintaining FSS protections. With the increasing number of devices and users, traditional interference management methods struggle to scale effectively in densely populated regions or globally distributed FSS networks.

2.7. RIC, RIS, and MIMO Applications

Improved technologies to enhance efficiency on the physical layer have been discussed and investigated in theory in [31,32], where advanced wireless technologies such as RIS, RIC, and MIMO antennas serve as key enablers for interference mitigation and efficient spectrum utilisation. RIS, composed of programmable surfaces, can dynamically steer radio signals away from FSS Earth stations and synthesise RF nulls, thereby minimising electromagnetic leakage into protected satellite zones without reducing the 5G transmission power. RIC, a component of the Open RAN architecture, leverages ML/AI algorithms to implement real-time radio resource optimisation, enabling proactive beam and power control, policy enforcement around exclusion zones, and adaptive interference avoidance strategies. Meanwhile, massive MIMO systems facilitate spatial multiplexing and beam-forming, allowing for highly directional transmissions and interference nulling that limit the exposure of FSS receivers to unwanted signals. The integration of these technologies supports intelligent and fine-grained control over the propagation environment, enabling the coexistence of high-capacity 5G deployments with incumbent satellite operations. However, achieving effective protection for FSS also necessitates accurate geolocation data, real-time coordination mechanisms, and standardised coexistence frameworks, particularly in dense or heterogeneous network scenarios.

2.8. Spectrum Management Challenges in DSA Systems

Designing and implementing spectrum management in centralised DSA systems presents significant challenges due to the inherent complexities of monitoring, scalability, and privacy. Spectrum monitoring and infrastructure limitations are pronounced, as traditional monitoring relies on costly and geographically constrained infrastructure like spectrum observatories. Centralised systems require accurate, real-time data on dynamic spectrum usage, which is complicated by the need for efficient data collection from resource-constrained devices in large-scale deployments. Scalability poses another obstacle, as the central controller endures substantial computational and communication loads, impeding system expansion to support extensive user bases and wide areas.

PU privacy is equally critical, as centralised systems often require sensitive PU information, such as location and operational status, to allocate the spectrum effectively. Protecting this data against unauthorised access and potential misuse demands robust security measures for the central controller, introducing further computational overheads. Striking a balance between PU privacy and optimal spectrum utilisation is challenging, as overly stringent privacy protections may compromise spectrum sharing efficiency, while lax measures could expose sensitive PU data.

Emerging solutions address these issues through innovative approaches. Crowdsourcing leverages the sensing capabilities of mobile devices to reduce monitoring costs and expand geographical coverage [33]. Intelligent task scheduling algorithms optimise resource usage for efficient crowdsourced monitoring, complemented by incentive mechanisms to ensure user participation. Advanced PU privacy measures, such as smart antennas and location uncertainty schemes, enhance privacy without sacrificing spectrum efficiency. Additionally, ML/AI techniques offer transformative potential, enabling accurate channel prediction, RL for decision making, and FL to preserve data privacy in collaborative model training. These advancements, particularly relevant to 5G NR and FSS coexistence,

underline the need for adaptive and secure spectrum management strategies in centralised DSA systems.

2.9. Challenges of Implementing DSA

Protecting the PUs from harmful interference is the most important factor in achieving a successful DSA. This is ensuring that the SU does not interfere with the PU. This requires careful spectrum sensing and access management [34] which can be achieved by exchanging activity information in coordinated schemes, but remains a challenge in uncoordinated schemes.

SUs must accurately detect the presence of PUs to avoid interference, but reliable detection can be subject to system complexity and the increased costs of enhanced sensing/measurement techniques [35]. Consequently, the trade-offs on sensing/measurement capabilities due to the complexity of the system can lead to threats at the MAC layer, such as the hidden node problem, and sub-optimal false alarm and detection probability issues can affect the PHY [36]. Additionally, the time it takes to sense and detect an idle channel reduces the effective data transmission time.

Traditional interference coordination and cancellation methods rely on accurate CSI estimations, which may be difficult to obtain in DSA networks, mainly because they are of different priority and rely on different regulatory frameworks due to their difference in technology. This ultimately leads to the lack of a centralised control framework due to the impossibility of sharing CSI and activity information. When a centralised control is achieved, scalability becomes an issue due to heavy computational and communication overheads in a dynamic allocation system environment. The vast harvesting of CSI and activity information also presents security threats to the PU system, which can lead to the deduction of PUs' locations, status, and activity profile.

The economic challenges facing DSA in the C-band and adjacent 5 GHz ranges extend beyond technical feasibility to issues of cost, incentives, and business viability. Deployment requires additional CAPEX in the form of SAS, geo-location databases, and DSA-capable BS. For established MNOs, these costs are marginal compared to existing infrastructure but still introduce risk if efficiency gains fail to yield proportional revenue. For new entrants; however, DSA significantly lowers entry barriers by avoiding the high costs of exclusive spectrum licences, creating competitive opportunities but also revenue threats for incumbents.

From a regulatory perspective, regulators must balance incentives and penalties through administrative fees that encourage efficient use and use punitive charges to discourage inefficient occupation or hoarding. Economic feasibility is defined by CAPEX/OPEX trade-offs: while DSA reduces upfront spectrum acquisition costs, operators incur higher coordination and interference-management expenses. In developing regions, DSA provides a cost-effective path to broadband expansion with minimal upfront investment, but regulators must safeguard incumbent incentives to avoid under-investment. Conversely, in high-revenue markets, incumbents may resist DSA if exclusive licensing remains more profitable, underscoring the importance of aligning equipment costs, regulatory compliance, and market incentives to ensure adoption.

Ultimately, the economic feasibility of DSA hinges on the balance between efficiency-driven pooling models and the business strategies of established operators. As spectrum pooling and shared-access frameworks expand, careful policy design is required to ensure participation from all stakeholders, prevent monopolistic behaviour, and maintain a fair distribution of costs and benefits across incumbents, new entrants, and regulators.

Spectrum pooling can be understood as the basis of spectrum sharing in DSA with multi-operators, which can also be the genesis of exacerbated discussions and legal battles

between the monopoly operators, or them teaming up to reject DSA in the C-band due to historical battles with regulators, as seen in South Africa in [37,38].

New technologies present complex challenges in protecting PU within DSA. Massive MIMO is an advancement in antenna technology used in 5G networks to significantly improve spectral efficiency, capacity, and coverage. It involves deploying a large number of antenna elements at the base station to simultaneously serve multiple users using spatial multiplexing. Although currently used in n77 and n79 bands and in mmWave frequencies, this technology employs complex signal processing techniques to achieve carrier aggregation and beamforming to deliver higher throughputs and increase spectral efficiency. These increase the complexity of calculating and deducing the transmission power to be considered in protecting the PU.

Multi-Objective Problem

Maximising DSUE while considering the above challenges presents a multi-objective optimisation problem because it involves reconciling conflicting goals across the two communication systems. Terrestrial wireless mobile networks aim to maximise spectral efficiency, coverage, and user throughput through dense deployments and dynamic spectrum use. The FSS/SS, operating with high sensitivity and stringent interference thresholds, must be protected from harmful interference in Table 3 originating from terrestrial wireless mobile transmissions. These conflicting objectives introduce trade-offs like increasing transmission power or coverage, which can enhance mobile performance but risks violating satellite protection criteria, while enforcing larger EZs around satellite ground stations ensures interference avoidance but restricts wireless mobile networks' access to valuable spectrum space.

Given these challenges, the coexistence problem is best framed as a multi-objective optimisation goal. Advanced data-driven techniques such as ML/AI, DRL, and game-theoretic strategies promise to handle the complexity and adaptivity required in such scenarios. These methods can be employed to learn and predict optimal transmission configurations that yield Pareto-efficient outcomes, ensuring high spectral efficiency for the terrestrial wireless mobile networks while adhering to the strict protection criteria of satellite ground stations. This enables the design of intelligent, real-time spectrum management frameworks that support sustainable coexistence within shared spectrum environments.

2.10. Overview of Spectrum Management Challenges in Satellite Bands

The coexistence of RF networks is categorised in function of the need for coordination between the involved networks according to spectrum usage and opportunities. Coordinated approaches require information collection exchange and analysis among the coexisting networks to increase spectral efficiency. They are uncoordinated when minimal or no information exchange is required to increase spectral efficiency, but the networks tune and adjust their operating parameters for a better coexistence with neighbouring networks. Uncoordinated methods re-adjust their operating parameters by observing the spectrum usage of the other RF system. Together, they constitute a resource allocation scheme extended with a consideration of the environment. Table 2 in [10] presents the pros and cons of the most common spectrum sharing methods. They can be further classified into four domains: time, frequency, code, and space domains, depending on the domain they allocate resources in. The spectrum in which the network is deployed drives the type of sharing to be employed. In the C-band, infrastructure-based and sharing-rule-based methods promise to be easy to implement with minimal changes to existing standards for primary users. Compared to other methods, these two methods have overheads of considering the environmental changes and primary user activity.

Satellite receivers have been operating in the C-band from 3.4 to 4.2 GHz for downlink connectivity. The use of the C-band for 5G services poses potential interference risks to FSS VSAT systems that operate in close proximity, typically within 1–2 km [39–41].

The existence of 5G signals and satellite signals in this band will lead to mainly co-channel interference, inter-modulation interference, and adjacent channel interference. OOB can arise due to the FSS operating just below 3800 MHz. The high-power levels in 5G devices can saturate sensitive receivers in FSS VSAT systems, even if they only operate in adjacent bands. These 5G signals in nearby frequencies and locations can block or desensitise satellite receivers, making them less effective at detecting weak satellite signals.

The FSS ES LNB amplifier operates linearly only up to a certain power level of the incident signals. In the traditional operating range of the LNB of 3400–4200 MHz, the incident signals could be from the 5G BS, the satellite downlink, or both. As the incident power increases, the amplifier transitions from linear to nonlinear behaviour and eventually saturates, resulting in the complete loss of incoming signals. Satellite signals received by the LNB have much lower power than the higher-powered 5G terrestrial signals, potentially causing the saturation of satellite antenna LNBs and disrupting FSS C-band receivers [39].

3. Recent DSA Applications with Coexistence

While early work on DSA was largely synonymous with CR, the regulatory and commercial DSA frameworks deployed today (TVWS, LSA, CBRS) have diverged into structured, database-driven or license-tiered models. TVWS access is coordinated via geo-location databases and the PAWS to protect incumbent DTT services. Likewise, the CBRS in the 3.5 GHz band employs a three-tiered SAS and ESC to ensure incumbent protection while maximising spectrum utilisation, complemented by LTE-U and LAA mechanisms that dynamically offload traffic into an unlicensed spectrum. These lessons from TVWS and CBRS frameworks inform coexistence strategies in the C-band, where protecting FSS/SS ground stations against terrestrial wireless mobile network interference requires similarly dynamic, database-driven, and tiered spectrum management approaches. Although DSA is used as an umbrella term, we distinguish between CR-based opportunism and regulatory DSA implementations. CR provided the conceptual foundation for opportunistic access, real-world DSA frameworks have evolved into regulatory-backed implementations with distinct mechanisms and governance models, as summarised in Table 6.

Table 6. Comparison of TVWS, CBRS, and unique 5G—satellite coexistence challenges in the context of spectrum sharing.

Aspect	TVWS	CBRS (3.5 GHz)	5G–Satellite Coexistence (C-Band)
Control Mechanism	Geo-location database with PAWS protocol	Centralised SAS with ESC	Hybrid: database-driven coordination, beamforming constraints, exclusion zones around Earth stations
Regulatory Model	Light licensing, regulator-approved databases	Three-tiered licensing structure	Strict ITU/regional satellite protection rules; coordination across borders; spectrum rights already allocated to FSS incumbents
Incumbent Protection	EZ and database coordination	SAS dynamically enforces incumbent protection and triggers spectrum evacuation	Requires the continuous protection of FSS ES with high sensitivity; protection of passive services in adjacent bands; stricter interference thresholds

Table 6. *Cont.*

Aspect	TVWS	CBRS (3.5 GHz)	5G–Satellite Coexistence (C-Band)
DSA Nature	Database-driven, regulator-certified coordination	Centralised, hierarchical coordination	Multi-layer: regulatory-driven protection, sensing/monitoring, and ML/AI-driven adaptation needed for real-time coexistence
Unique Challenges	Rural coverage, device availability	Dynamic tier coordination	Cross-border interference; satellite downlink vulnerability to aggregate interference; large exclusion zones reduce terrestrial capacity; coexistence requires balance of DSUE degradation vs. DSUE capacity

3.1. C and S Bands and Other Bands

The ITU-R Sector and 3GPP both play significant roles in the evolution and standardisation of DSA, from TVWS to 5G NR, while also considering coexistence with FSS. The ITU-R establishes the global regulatory framework for spectrum allocation by distinguishing between primary and secondary services, where SU must tolerate interference from primaries. They play complementary roles in enabling DSA: while ITU-R defines the global regulatory and protection framework, 3GPP develops the technical standards and system-level implementations. Table 7 summarises their distinct but aligned contributions.

Table 7. Comparison between the contributions of ITU-R and 3GPP to DSA and FSS coexistence.

Aspect	ITU-R	3GPP
Scope	Defines a global regulatory framework for spectrum allocation and coexistence.	Specifies technical standards and architectures for LTE, 5G NR, and beyond.
Spectrum Role	Identifies IMT bands (3400–4200 MHz) and sets protection rules for incumbents.	Implements spectrum-sharing methods.
Coexistence Tools	Provides interference models (e.g., I/N ratio, ITU-R P.452, S.465 antenna patterns).	Integrates LBT, duty cycling, and beamforming in standards.
Process	Uses the WRC process to update rules, allocate new bands, and refine protection thresholds.	Defines deployment scenarios (UMa, UMi, RMa), channel models, and DSS system integration.
Practical Example	Ensures coexistence of IMT with FSS through separation distances and I/N limits.	Aligns with SAS frameworks, enabling multi-tiered spectrum access and PU protection.

3.2. Geo-Location Usage in Network Management

Geo-location databases, as presented in [13,17], play a fundamental role in enabling DSA by facilitating spectrum sharing while protecting PUs. These databases are used to determine localised spectrum availability by acquiring and managing information about service providers and incumbents, as seen in models like TVWS and LSA. By maintaining detailed records of PU locations, types, and operating schedules, geo-location databases ensure that SUs avoid causing harmful interference, often by enforcing exclusion zones. Systems such as the SAS for CBRS rely on registered device locations to dynamically allocate spectrum resources while coordinating between PUs and SU. The operational aspects involve building and maintaining secure, collaborative databases capable of sharing real-time information across multiple services. Furthermore, advancements such as integrating spectrum sensing and developing REMs are being explored to enhance the precision and responsiveness of geo-location databases, making them even more critical in future dynamic spectrum sharing ecosystems. Thus, geo-location databases serve as a cornerstone in managing spectrum access, ensuring efficient usage and the robust protection of primary services across modern DSA frameworks.

Despite the limited opportunities, actions have been taken towards exploring new unencumbered frequency bands for the use of wireless activities. Meanwhile, the idea of

spectrum sharing has started to attract a great deal of interest from both academia and industry. Hence, DSA is then proposed to enable spectrum sharing between PUs and SUs to mitigate the above mentioned spectrum scarcity problem.

There are two significant spectrum initiatives in South Africa for enabling DSA [24]: (1) TV bands: Low-power unlicensed users are permitted by ICASA to access the unused channels in the TVWS. A database-driven approach is mandated by ICASA in these bands. To obtain the spectrum access permission, the unlicensed devices must register with a database that informs the spectrum availability. (2) 3.5 GHz band: Similar to the CBRS in the USA promulgated by the FCC for dynamic spectrum sharing between government and commercial users in the range of 3.5–3.7 GHz (referred to as 3.5 GHz band) [26,42]. This sharing paradigm allows CBSDs, which are also called SUs, to opportunistically use the 3.5 GHz band licensed to satellite and radar systems, in locations and times where the PUs are not using this band.

4. Review on Implementations and Trials

Countries have adopted different technical, regulatory, and operational approaches to ensure that 5G NR can expand without causing harmful interference to incumbent FSS/SS systems.

The international DSA trials summarised in Table 8 demonstrate a range of regulatory and technical strategies adopted to enable the coexistence of terrestrial 5G networks and incumbent FSS operations in the C-band (3.4–4.2 GHz). Countries such as the United States and Canada led structured, phased rollouts with formal spectrum clearance, the relocation of FSS services, and strict out-of-band OOB controls. Malaysia, South Korea, and Japan implemented coexistence guidelines that included guard bands, exclusion zones, beamforming constraints, and geographic coordination databases to protect satellite ground stations.

Table 8. Comparison of international DSA trials involving FSS coexistence.

Country	Band (GHz)	PU/SU	Regulation Developed	PU Protection Measures	DSA Trial Outcomes	ML Used
Malaysia	3.5–4.2	FSS/5G	Yes (MCMC Guidelines)	- Exclusion zones - Power limits near FSS - PSD limits based on ITU-R	Successful pre-deployment trials validated coexistence assumptions	No
South Korea	3.5–3.8	FSS/5G	Yes	- Guard band (100 MHz) - Stringent OOB limits - Beamforming and adaptive antennas	Successful, with ongoing adjustments for urban deployment	No
Japan	3.4–3.8 (5G); 3.8+ (FSS)	FSS/5G	Yes (MIC Guidelines)	- Site-specific coexistence agreements - Dynamic geo-database use - Antenna tilt and relocation	Effective with localised constraints; hybrid use approved	Partial
India	3.4–3.6 (5G); 3.7–4.2 (FSS)	FSS/5G	Yes (TRAI strategy)	- Exclusion zones - Mandatory coordination for large FSS stations	Conservative deployment; full DSA not yet realised	No
Canada	3.45–3.65 (5G); 3.8+ (FSS)	FSS/5G	Yes (ISED phased plan)	- Guard bands - Cross-polarisation discrimination (XPD) - Geographical separation	Successful urban trials (e.g., Toronto); ongoing migration	No
United States	3.7–3.98 (5G); 4.0+ (FSS)	FSS/5G	Yes (FCC Auction 107)	- FSS relocation to upper C-band - OOB limits, filters, siting restrictions - Ground station tech upgrades	Highly structured, commercial deployments active	No

In contrast, India adopted a more conservative approach by deferring aggressive 5G rollout near the FSS infrastructure and emphasising mandatory coordination. Despite different regulatory environments, all countries shared a common goal of minimising

interference to satellite downlinks through physical separation, power control, and coordination protocols.

The comparative evidence from the trials [43,44] strengthens the proposed DSUE framework by considering regulatory and technical constraints to measurable coexistence outcomes. From trials, CBRS achieves high DSUE through automated SAS coordination with minimal EZ, whereas TVWS suffers DSUE degradation due to wide PU protection areas. The Malaysia C-band field trials further demonstrate that DSUE is highly sensitive to mitigation parameters. Thus, the DSUE framework not only unifies these diverse observations but also provides a quantitative basis for comparing how sharing models and empirical trials translate into usable spectrum efficiency under C-band coexistence.

Importantly, the trials did not report the significant integration of ML/AI techniques in real-world deployments, although presenting a 100% accuracy in predicting interference zones. Extending this to DSUE, ML/AI can enable predictive EZ management, adaptive UE power/beam control, and demand forecasting, highlighting a research opportunity. Future work could build upon these frameworks by introducing ML-driven spectrum management and interference mitigation strategies that dynamically adapt to real-time satellite and mobile network conditions.

5. Evaluation ML/AI Applications in Spectrum Management and Coexistence

Coexistence studies in dynamic spectrum-sharing environments utilise a variety of mathematical methods to manage interference and allocate spectrum efficiently. In typical terrestrial scenarios—such as coexistence between Wi-Fi, LTE, or 5G networks—models like stochastic geometry, game theory, and optimisation are employed to characterise and optimise network behaviour under interference constraints. However, when FSS or other satellite ground receivers are introduced into the spectrum environment, these modelling approaches require significant adaptation due to the stringent protection requirements, highly sensitive receiver front-ends, and directional antenna characteristics inherent to satellite systems.

ML/AI represent positive advancement in terms of addressing limitations by dynamically learning and adapting to the diverse and complex coexistence scenarios. ML/AI algorithms can extract meaningful features from large datasets, such as spectrum usage, signal power, geographic and topographic characteristics, and temporal patterns. This allows for more granular and scenario-specific interference management. The systems can model and predict the interference levels in real-time, accounting for changing environmental factors and device deployments. This enables adaptive protection measures for FSS while maximising 5G NR spectrum efficiency. Complementing the systems with satellite monitoring systems data and environmental historical data, context-aware regulatory insights can be extracted to develop tailored policies for the specific characteristics of each deployment scenario. Techniques like RL can optimise coexistence strategies by continuously learning from operational feedback, balancing interference protection and spectrum utilisation dynamically. By addressing these limitations of traditional methodologies, ML/AI provides a pathway to develop more robust, adaptive, and efficient coexistence frameworks, ensuring harmonious 5G NR and FSS operation in shared spectrum environments like the 3.6–4.2 GHz band.

Machine Learning for Enhanced Coexistence

ML/AI can play a significant role in optimising dynamic spectrum sharing between 5G NR and FSS, since this is mainly a regional specific problem, with unique challenges all round. This necessitates careful planning, coordination, and dynamic adaption to the environmental changes per region.

ML/AI plays a pivotal role in enhancing the coexistence, employing SAS frameworks by effectively managing interference and considering the distances from PUs. By leveraging ML/AI algorithms, SAS frameworks can dynamically adapt their resource allocation strategies based on real-time environmental conditions, thereby improving spectrum efficiency and minimising interference. One approach involves utilising supervised learning techniques to predict interference levels based on historical data and environmental parameters such as distance from PUs, signal strength, and traffic patterns. By training models on past interference scenarios and their corresponding outcomes, SAS frameworks can make informed decisions on channel assignment and power control to mitigate interference while maximising spectrum utilisation. Regression models like polynomial regression or support vector regression can predict channel conditions for users across different technologies and bands [2].

Channel condition prediction: Regression models like polynomial regression or SVR can predict channel conditions for users across different technologies and bands. This information enables 5G NR networks to select high-quality channels in various frequency bands, facilitating a flexible, on-demand spectrum-as-a-service architecture. RL agents can learn to make optimal decisions regarding spectrum sharing, maximising rewards for efficient spectrum utilisation. These agents can use predicted channel conditions as input to allocate suitable channels for user requests.

The main object in coexistence is to allow new technologies access to the spectrum while guaranteeing the protection of the PU. The authors in [41,45,46] emphasised interference management as a critical aspect of the system. Both 5G NR and FSS are to operate in the licensed bands and must avoid causing harmful interference to each other. Technical and regulatory bodies like the ITU, WINF, and 3GPP play a critical role in standardisation, developing frameworks that define technical specifications, interference thresholds, and operational procedures to ensure harmonious coexistence between different technologies [41,45]. These technical specifications address the directionality of the antennas, power levels, and operating bands for different coexistence scenarios. FSS Earth stations typically utilise highly directional antennas pointed towards the satellite, while BSs might use more omnidirectional antennas. This difference in antenna characteristics can be exploited to manage interference by carefully planning BS locations and antenna beam directions [45]. BSs can transmit at higher power levels compared to some unlicensed devices. This necessitates careful power control mechanisms and potentially larger separation distances to protect FSS receivers from interference.

Works like [25] employ neural networks, including RBFNN and GRNN, to mitigate the interference between 5G and FSS systems operating in adjacent frequency bands. However, challenges persist, such as adapting these methods to advanced 5G technologies like beamforming and MIMO, which fundamentally reshape the interference landscape. Similarly, studies such as [47] explore the potential of Q-learning and auction-based approaches for dynamic channel allocation in the CBRS band, but highlight the computational complexity associated with real-time operations under high load conditions. Furthermore, hierarchical reinforcement learning, as discussed in [48], demonstrates its utility in balancing the quality of service QoS for diverse traffic types, including ultra-reliable low-latency communications URLLCs and enhanced mobile broadband eMBB.

Although there is not an exhaustive pool of studies into DSUE as a metric, the authors in [18] have shown that Q-learning in particular surpasses conventional static policies in DSA. The studies using LTE traffic traces have demonstrated that ANN-based predictors improve spectrum utilisation efficiency. When applied to C-band coexistence, these techniques can be adapted for dynamic EZ management, promising to yield DSUE gains of 15–20% through adaptive boundary adjustments.

In a similar way, DRL has enabled the joint optimisation of beamforming and power control for terrestrial base stations. As discussed in the literature review, the approach dynamically mitigates interference while maintaining throughput, reducing interference power at PU receivers by approximately $\approx 12\%$ compared to static allocation schemes [19]. However, scalability and throughput degradation for eMBB traffic under heavy loads remain significant hurdles. Collectively, these studies underscore the transformative potential of ML/AI in fostering coexistence but also emphasise the need for scalable, adaptable, and efficient algorithms to meet the evolving demands of 5G and beyond.

6. Regulatory Considerations

ICASA is the national custodian of the frequency spectrum and regulator of wireless communication technologies in South Africa. As the custodian, ICASA sells over licenses to MNOs to facilitate their communications. In licensed bands, the MNOs implement access policies to allocate access to their customers through their infrastructure of radios distributed all over the country. With the adoptions of 4G, LTE, 5G, B5G, the regulator has been stretched by big MNOs requesting more spectrum to grow and maintain their business and the ICT industry as a whole in the forefront comparing to the rest of the world.

With the short-comings of the two transitions mentioned in [49,50], emphasis and explorations have been added to opportunistic access technologies, with CSIR leading the path with TVWS technology [51]. Recently, with the successful roll-out of the technology, ICASA has increased the scope to follow the international trends of adopting coexistence and opportunistic access in unlicensed bands with 5G technologies [52]. The undertaking with the TVWS roll-out has potentially proven success in creating an opportunistic access environment in a band, which can help expand and augment wireless communications while increasing spectral efficiency. In 2023, ICASA presented a proposal for a regime to formulate opportunistic spectrum management in the S and C frequency bands [53]. The proposal aims to establish mechanisms for the resident new and old technologies to coexist fairly in the two bands.

Navigating the complexities of spectrum management in satellite bands presents a myriad of challenges, particularly as demand for terrestrial and satellite communications continues to escalate. Satellite services operate predominantly within designated frequency bands, where they must contend with both regulatory limitations and the operational requirements of ground-based systems. The coexistence of multiple users, particularly in the 3.8–4.2 GHz range, exacerbates the challenge of interference, necessitating sophisticated management strategies. Notably, the integration of DSA technologies could dramatically enhance spectrum efficiency, allowing for greater flexibility in the allocation and utilisation of frequencies, as highlighted in the call for the increased C-Band carrier aggregation bandwidth from 300 MHz to 800 MHz. As satellite communications evolve, particularly in response to burgeoning data demands, the shift towards shared spectrum frameworks is paramount, offering potential economic benefits to mobile network operators by optimising spectrum use. Hence, addressing these spectrum management challenges is vital for the sustainable growth of satellite communications and the efficacy of emerging DSA technologies.

6.1. Current Regulations Impacting DSA Implementation in Satellite Bands

The implementation of DSA in satellite bands, particularly within the 3.8–4.2 GHz range, is significantly influenced by current regulatory frameworks that prioritise the protection of primary users, especially satellite operators. Regulations mandate strict exclusion zones to mitigate interference risks that could arise from secondary users in these bands [54]. Consequently, MNOs face challenges in optimising spectrum utilisation due

to these restrictions, which can stifle investment in shared networks and limit potential economic benefits. Moreover, the complexity of inter-operator coordination in deploying DSA poses further obstacles, requiring regulatory bodies to evaluate the efficacy of existing protocols [8]. In balancing innovation with incumbent rights, regulators must develop transparent guidelines that facilitate DSA while ensuring that satellite communications remain robust. Such a regulatory landscape is essential for fostering the necessary investment and technological advancements in these critical spectrum bands.

Similarly, the considerations in 5G NR and FSS coexistence is similar to the TVWS considerations, wherein the primary incumbent is the TV broadcasting network, and is to be protected at all time. Although, in this instance, both technologies will be licensed, the primary incumbent is to be guarantee protection at all times. The FCC, for the CBRS, employed an SAS to manage the spectrum sharing, ensuring incumbent protection, and coordinating the access of the secondary users by interacting with the incumbent databases [55]. This SAS monitors interference levels between the different devices/transmissions and allocates power transmission levels for each, guided by the standards in [56]. Standardisation also considers fairness in the sharing between secondary users and interoperability between different technologies.

6.2. Leveraging TVWS Regulatory Models for 5G NR vs. FSS Coexistence in the 3.6–4.2 GHz Spectrum

The development of regulatory frameworks for TVWS devices by bodies such as the FCC in the United States and ETSI/Ofcom in Europe provides valuable lessons for facilitating 5G NR and FSS coexistence in the 3.8–4.2 GHz band through dynamic spectrum sharing. The FCC's approach, which categorises devices into fixed, Mode II, and Mode I (sensing-only) types, allows for flexibility in device deployment based on operational requirements. However, the reliance on geolocation databases for interference protection, along with detailed separation distances and protection contours, ensures robust incumbent protection [57]. In contrast, the ETSI/Ofcom framework in Europe adopts a more unified approach to WSD regulation, emphasising geolocation databases and conservative power limits based on worst-case density estimates to safeguard incumbents. These frameworks illustrate the importance of balancing innovation and spectrum efficiency with rigorous protections for incumbent users, a principle that can guide international coexistence strategies for 5G NR and FSS [58].

In South Africa, ICASA have also developed regulations that could inform coexistence management in this spectrum. ICASA has implemented TVWS guidelines focusing on geo-location databases to protect broadcasters while maximising secondary access opportunities. Similarly, CSIR has been instrumental in conducting trials and establishing technical standards for WSDs in the region. For the 3.8–4.2 GHz band, such approaches can be adapted to incorporate advanced geolocation systems tailored for FSS protection while allowing flexible 5G NR deployments. By leveraging lessons from TVWS regulation, including the potential use of spectrum sensing as a supplementary tool and fostering international collaboration on database harmonisation for cross-border spectrum management, regulators can create robust frameworks for dynamic spectrum sharing. This will support equitable spectrum utilisation while safeguarding critical satellite services.

All three regulators approach emphasises predefined separation distances, and protection contours with transmission power management to ensure incumbent protection [58]. Although CBRS and LSA incorporate sensing to complement the geolocation database, sensing can easily complicate the management algorithms by catering for sensor malfunctions and other technical issues.

7. Challenges and Future Directions

As DSA frameworks evolve to support increasingly dense and heterogeneous networks, new challenges emerge, particularly due to the integration of advanced antenna technologies such as massive MIMO, RIS, and RIC. While these innovations improve spectral efficiency and beamforming capabilities, they also increase the complexity of interference management and coexistence protection, especially in shared bands involving incumbent services like FSS. Massive MIMO and RIS enable highly directional transmissions, but their real-time dynamic behaviour can create unpredictable interference footprints, challenging conventional protection zones. Guaranteeing protection for incumbent users now requires environment-aware, adaptive models that can dynamically account for changing radiation patterns and propagation conditions. Furthermore, RIS-aided beam steering adds a layer of reconfigurability that cannot be easily modelled using traditional static interference assumptions.

A few possible advancements facilitate DSA involving PUs and SUs, mainly achieving absolute protection for the PU with the introduction of MIMO, RIC, and beamforming, which necessitates intricate computation to decision making. One future direction involves the need for a database-enabled model to address the challenges of protecting primary users from interference caused by unlicensed spectrum users and ensuring equal spectrum access opportunities for new users [8]. This emphasises a need for a central store for PU sites and operational parameters or limits to enhance an SAS logic to manage the SU operational parameters, limits, and consideration of protection zones. This further poses a need for influence on MIMO and RIC operational parameters and beamforming algorithms to achieve the dynamic protection of the PU; fair spectrum allocation within SUs and protection between SUs.

Research is needed to analyse decisions on the spectrum, especially with migration to higher frequency bands considering the specific location-based deployment of technologies like B5G. This ties into the idea of localised licenses, where the value and pricing might vary geographically and temporally according to socio-economic factors, creating opportunities for DSA based on these factors. Several research efforts focus on DSA which adapts to network conditions and user needs [59]. Applying these dynamic approaches to incorporate temporal and localised licensing while respecting protection zones is a promising avenue. ML/AI techniques are being explored to facilitate automation and dynamic spectrum sharing [8,45,60–62].

DSA with temporal localised licenses and protection zones needs to focus on developing sophisticated management systems, possibly leveraging ML/AI, to ensure efficient spectrum utilisation while safeguarding PUs. It also requires defining clear operational rules and evaluating the practical implementation and performance of such dynamic licensing and protection mechanisms in various wireless network scenarios, including terrestrial and satellite systems [8].

Effective interference management is crucial as more technologies coexist within the same spectrum bands. Advanced techniques like ML/AI-based interference prediction, adaptive beamforming, and dynamic power control are being explored to address this challenge. Ensuring fair and efficient coexistence among diverse technologies remains a significant challenge. Coexistence mechanisms such as LBT, adaptive duty cycling, and dynamic spectrum allocation are being refined to improve DSS performance. Spectrum opportunities are often fragmented, complicating aggregation and utilisation. Techniques like carrier aggregation and spectrum stitching are being developed to address this issue, albeit at the cost of increased system complexity.

The success of DSS depends on harmonised regulatory frameworks and viable business models. Collaborative efforts between stakeholders, including regulators, operators, and industry players, are essential to ensure efficient spectrum sharing.

ML/AI are poised to revolutionise DSS by enabling intelligent and adaptive spectrum management. Techniques like reinforcement learning, deep learning, and federated learning can automate decision making, optimise resource allocation, and enhance interference mitigation in real time. To address these challenges, ML/AI present promising avenues. ML/AI techniques can be employed to predict interference, learn optimal beam configurations, and dynamically allocate resources in real time. Particularly, reinforcement learning and federated learning approaches are being explored to support adaptive spectrum management with limited centralised control. These models enable multi-MNO coordination under LSA or similar models by supporting short-term, geo-local licensing schemes.

Future research should focus on integrating spatial awareness, antenna state information, and spectrum demand forecasting into learning-based DSA algorithms. There is also a growing need for standardised metrics and datasets to evaluate ML/AI-driven spectrum sharing under realistic deployments. In addition, regulatory evolution must keep pace, potentially requiring real-time spectrum monitoring via geo-location databases and RIC-level orchestration to enforce interference protection guarantees.

Ultimately, the convergence of advanced antenna systems and intelligent spectrum management holds the potential to realise highly efficient, interference-resilient spectrum coexistence across 5G and beyond. Key research directions include

- The development of hybrid ML/AI-assisted databases for coordinated DSA;
- The integration of RIS/MIMO-aware propagation models for real-time interference estimation;
- Standardization of ML/AI-driven coexistence metric;
- Regulatory updates that support flexible, data-driven spectrum sharing.

8. Conclusions

In reviewing the spectrum management challenges in DSA systems from the perspective of spectrum sharing mechanisms, it is evident that traditional approaches face significant limitations in effectively balancing spectrum utilisation, scalability, and incumbent protection. Static spectrum-sharing mechanisms, reliant on fixed rules or predefined parameters, struggle to adapt to dynamic and complex scenarios, leading to inefficiencies in spectrum allocation and coexistence management. This review highlights several key findings for enabling efficient and interference-aware DSA:

1. **Coexistence feasibility:** Coexistence is feasible when technical safeguards—such as exclusion zones, antenna beam steering, power control, and spectrum coordination—are enforced. Ensuring that interference from gNBs and UEs does not exceed established interference-to-noise (I/N) thresholds at the FSS/SS ground station is critical. These thresholds are defined by the sensitivity and operating parameters of the satellite receivers.
2. **Spectrum utilisation efficiency:** Traditional spectrum efficiency metrics can be extended to DSUE by incorporating the probability and severity of interference events. This includes factoring in both spatial (proximity, antenna alignment) and temporal dimensions (time-varying traffic demand) of spectrum use. A reduction in spectral reuse due to interference mitigation measures must be captured in DSUE calculations, allowing for a more realistic assessment of spectrum productivity in shared environments.
3. **Dynamic environments and interference modelling:** In highly dynamic settings, such as urban deployments with moving UEs, interference patterns vary over time. Hence, real-time interference estimation—using models that consider antenna patterns, block-

age, terrain profiles, and directional gain is necessary. These models help determine how much usable spectrum remains available without degrading the performance of protected SS.

4. ML/AI integration: ML/AI techniques such as DRL and Q-learning can enhance DSUE as a multi-objective problem by enabling intelligent spectrum management. ML/AI can
 - Predict interference conditions and adjust transmission parameters proactively;
 - Classify zones of permissible transmission based on the satellite receiver's location;
 - Optimise beamforming and power control decisions in real time;
 - Assist in dynamic channel allocation that balances utilisation and protection constraints.

The adoption of DRL within simulated environments present a transformative approach to address these limitations. DRL enables DSA systems to learn optimal spectrum-sharing policies by interacting with the dynamic and realistic simulations of spectrum environments, incorporating features such as varying interference levels, user demands, and environmental conditions. By simulating diverse scenarios, DRL can optimise spectrum usage in real time while safeguarding incumbent operations, enhancing both the effectiveness and adaptability of policy development. This methodology offers a promising pathway to create robust, data-driven spectrum-sharing frameworks, ensuring the efficient utilisation of shared resources in increasingly congested and competitive spectrum environments.

This review has examined the evolution and implementation of DSA as a solution to the growing demand for wireless capacity, spectrum scarcity, and the need for efficient coexistence mechanisms—particularly between emerging 5G NR systems and incumbent FSS. Global trials and deployments have demonstrated the viability of DSA frameworks and models such as TVWS, CBRS, and LSA, each adapted to regional spectrum management policies and regulatory landscapes. Notable efforts in the United States, South Korea, India, Malaysia, Canada, and Japan highlight the diversity of technical implementations and policy frameworks. These range from centralised SAS with tiered access control in CBRS to dynamic geo-location-based coordination in TVWS, and controlled spectrum leasing in LSA. The commercialisation of private 5G networks has further driven innovation in spectrum sharing, especially in enterprise and industrial verticals. In these setups, coexistence between multiple MNOs and incumbent services is no longer hypothetical but operational, necessitating intelligent and scalable spectrum management approaches. The challenge lies in ensuring FSS protection, particularly in the congested C-band 3.6–4.2 GHz, while facilitating efficient and equitable resource allocation among diverse operators with varying QoS requirements.

To address these challenges, recent advances suggest that ML/AI can play a pivotal role in real-time DSA decision making. Through intelligent spectrum prediction, interference mitigation, and adaptive resource allocation, ML/AI models—integrated with geo-location databases—can continuously monitor spectrum availability and dynamically allocate channels while respecting interference protection thresholds. Moreover, by incorporating socio-economic datasets such as national census information, these systems can prioritise access where it is most economically and socially beneficial, enabling context-aware spectrum governance. In future networks, DSA will depend not only on real-time technical indicators such as SINR and interference levels, but also on spatial, temporal, and economic context. This calls for a harmonised architecture combining spectrum sensing, centralised and distributed spectrum databases, cognitive radio techniques, and adaptive ML/AI models. Moreover, regulatory bodies must support this evolution by standardising interfaces, operational constraints, and data-sharing policies across MNOs and spectrum incumbents.

In conclusion, the path forward for dynamic and intelligent spectrum sharing lies in integrating advanced ML/AI models, economic prioritisation through geo-localised data, and flexible regulatory frameworks. Together, these will enable scalable, fair, and interference-protected coexistence in shared bands paving the way for inclusive and efficient spectrum use in 5G and beyond.

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Abbreviations

The following abbreviations are used in this manuscript:

3GPP	Third Generation Partnership Project
4G	Fourth Generation of Radio Networks
5G	Fifth Generation of Radio Networks
5G NR	5G New Radio
ANN	Artificial Neural Network
ACI	Adjacent Channel Interference
ACLR	Adjacent Channel Leakage Ratio
B5G	Beyond 5G
BS	Base Station
CR	Cognitive Radio
CBRS	Citizens Broadcast Radio Service
CBSD	CBRS Device
CAPEX	Capital Expenditure
CCI	Co-channel Interference
CSI	Channel State Information
CSIR	Council for Scientific and Industrial Research
DL	Deep Learning
DRL	Deep Reinforced Learning
DSA	Dynamic Spectrum Access
DSS	Dynamic Spectrum Sharing
DSUE	Dynamic Spectrum Utilisation Efficiency
DTT	Digital Terrestrial Television
EIRP	Effective Isotropic Radiated Power
eMBB	Enhanced Mobile Broadband
ES	Earth Station
ESC	Environmental Sensing Capability
ETSI	European Telecommunications Standard Institute
EZ	Exclusion Zone
FCC	Federal Communications Commission
FSS	Fixed Satellite Service
gNB	gNodeB

SINR	Signal-to-Interference-plus-Noise Ratio
FL	Federated Learning
FSPL	Free-space Path Loss
GIS	Geographic Information System
MAC	Medium Access Control
MIMO	Multiple-Input-Multiple-Output
MNO	Mobile Network Operator
OOBE	Out-of-Band Emission
VSAT	Very Small Aperture Terminals
LAA	License Assisted Access
LBT	Listen Before Talk
LSA	Licensed Shared Access
LTE	Long-Term Evolution
LTE-U	LTE-Unlimited
LNB	Low-Noise Block
ICT	Information and Communication Technology
ICASA	Independent Communications Authority of South Africa
IMT	International Mobile Telecommunications
ITU	International Telecommunication Union
ITU-R	The Radiocommunication Sector of the International Telecommunication Union
ML/AI	Machine Learning/Artificial Intelligence
NR	New Radio
NR-U	New Radio-Unlicensed
PAWS	Protocol to Access White Spaces
PHY	Physical Layer
PU	Primary User
QoS	Quality of Service
REMs	Radio Environment Maps
RIC	Reconfigurable Interface Controller
RIS	Reconfigurable Intelligent Surface
RF	Radio Frequency
RL	Reinforced Learning
SU	Secondary User
SUE	Spectrum Utilisation Efficiency
SUF	Spectrum Utilisation Factor
SVR	Support Vector Regression
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access
RBFNN	Radial Basis Function Neural Networks
GRNN	General Regression Neural Networks
SAS	Spectrum Access System
SaaS	Software-as-a-Service
SS	Satellite Services
TV	Televisions
TVWS	TV White Space
URLLC	Ultra Reliable and Low Latency Communication
WINF	Wireless Innovation Forum
WSD	White Space Device
UE	User Equipment
USA	United States of America

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