DYNAMIC · SPECTRUM · ALLIANCE

SOLVING THE SPECTRUM CRUNCH

DYNAMIC SPECTRUM MANAGEMENT SYSTEMS

October, 2023

The Dynamic Spectrum Alliance (DSA) is a global, cross-industry, not for profit organization advocating for laws, regulations, and economic best practices that will lead to more efficient utilization of spectrum, fostering innovation and affordable connectivity for all.

We invite you to find out more at **www.dynamicspectrumalliance.org**

Follow the DSA on Twitter: **@DynamicSpectrum**

This material has been funded by the Foreign, Commonwealth & Development Office - Government of the United Kingdom; however, the views expressed do not necessarily reflect the UK Government's official policies.

Lead author:
Michael Calabrese

Michael A. Calabrese is a graduate of Stanford Law and Business Schools (JD/MBA) and of Harvard College. He directs the Wireless Future Program at New America's Open Technology Institute, a non-profit think tank based in Washington, D.C and is a DSA Member. He develops and advocates policies to promote ubiquitous, fast and affordable wireless broadband connectivity, including the reallocation of prime spectrum for unlicensed access, next generation Wi-Fi, and dynamic spectrum sharing.

Calabrese has served on the U.S. Department of Commerce Spectrum Management Advisory Committee (CSMAC) since 2009 and as an Invited Expert on President Obama's Council of Advisors on Science and Technology (PCAST) spectrum reform working group during 2011-2012. Calabrese has previously served as Vice President of New America (2003-2010), General Counsel of the U.S. Congress Joint Economic Committee, director of domestic policy at the Center for National Policy, and as a counsel at the national AFL-CIO.

CONTENTS

EXECUTIVE SUMMARY

As demand for wireless connectivity continues to surge, the use of databases and automated spectrum management systems to coordinate more intensive and efficient spectrum sharing has emerged as a critical regulatory tool. Regulators in a growing number of countries have authorized automated and even dynamic spectrum coordination systems (DSMS) to manage frequency assignments in shared bands and to protect incumbent operations (including military and public safety systems) from harmful interference.

Ofcom, the U.K. regulator, stated in the agency's 2016 Framework for Spectrum Sharing: "Geolocation databases are making it easier for devices to identify spectrum that is available for sharing while protecting the operation of existing services. . . . the fundamental principle is not frequency specific and can be extended to a broader range of frequencies" beyond enabling access to unused TV White Space channels. More recently, in its 2022/2023 Plan of Work, Ofcom stated that it will be studying "the potential role automated assignment databases could play in meeting future spectrum management challenges".

In the United States, the Federal Communications Commission (FCC) has authorized commercial spectrum management systems to coordinate sharing in four frequency bands, three of which have operated successfully for years. The U.S. Congress in 2018 mandated development of a National Spectrum Strategy that includes examining "existing and planned databases or spectrum access systems designed to promote spectrum sharing."

And in Europe, in June 2021 the EU's Radio Spectrum Policy Group issued an opinion urging more innovation and experimentation in spectrum sharing: "The RSPG seeks to nudge a change of mindset: all considerations in the field of spectrum by policy makers, spectrum managers, users and industry should be done by pursuing better spectrum efficiency through more spectrum sharing, including by following the principle of 'use-it-or-share-it'."

The reliance on automated databases to facilitate more advanced and low-cost telecommunications has a long and storied history that extends from the replacement of manual switchboard operators to the Domain Name Service (DNS) databases that serve as the essential circulatory system of the Internet itself. These advances have proven so beneficial in promoting universal and affordable communication they are taken for granted today. Although the use of databases as a tool for spectrum management is a more recent development, it has proven no less compelling as a means of achieving large-scale, low-cost, and virtually real-time access to communications capacity that would otherwise go unused.

The use of databases to coordinate spectrum assignments has evolved but is nothing new. The basic steps are exactly the same as in a manual coordination process. What is new are more frequency-agile devices and improvements in the computation power needed to efficiently run advanced propagation analysis and algorithms that coordinate devices and users in near real-time.

There is no question that today we have the technical ability to automate frequency coordination and thereby lower transaction costs, use spectrum more efficiently, speed time to market, protect incumbents from interference with certainty, and generally expand the supply of wireless connectivity that is fast becoming, like electricity, a critical input for most other industries and economic activity.

While spectrum database coordination is nothing new, it has in recent years evolved from manual, to automated, to dynamic – applying automation and propagation modeling to static licensing data. This evolution has progressed from the manual, database-informed coordination of fixed links and satellite earth stations; to database-assisted coordination of point-to-point links on a semi-automated basis (e.g., in the 70/80/90 GHz bands); to the fully-automated frequency coordination of unlicensed sharing of vacant TV channels (TV White Space); to the dynamic coordination of a three-tier hierarchy of sharing by Spectrum Access System databases across the 3550-3700 MHz band with U.S. Navy radar (CBRS: the Citizens Broadband Radio Service).

Most recently, regulators have begun authorizing Automated Frequency Coordination (AFC) systems that enable the operation of next-generation radio local area networks (RLANs) utilizing Wi-Fi 6E at standard power, both outdoors and indoors, across most of the 6 GHz band. During 2023 the United States and Canada are expected to approve the commercial deployment of multiple AFC systems to manage the deployment of Wi-Fi 6E – outdoors and at standard power (up to 4 watts EIRP) – across 850 MHz (900 contiguous MHz in Canada) on a shared basis with more than 50,000 high-power fixed microwave links. Similar authorizations are pending in Brazil, South Korea and the Kingdom of Saudi Arabia. In June 2022 EU regulators approved a work item to study the feasibility of higher power RLAN operations (up to 4W EIRP) in the lower 6 GHz band by utilizing a "dynamic spectrum access coordination function" that is expected to provide similar capabilities to the AFC systems being certified in the U.S. and Canada.

Spectrum coordination systems have demonstrated the ability to facilitate licensed, unlicensed and lightly-licensed sharing regimes. Regulators now have the models, technologies and established commercial providers needed to authorize automated coordination systems that best fit the NRA's policy goals, which will vary depending on the nature of the incumbent service, the propagation characteristics and size of the band, the nature of the shared-access use, and other factors.

Dynamic spectrum management systems (DSMS) are known by different names in different frequency bands. They can also be more or less dynamic with respect to inputs. However, the basic steps are the same and the outcome is determined by the rules and framework adopted by each national regulatory authority (NRA). DSMS facilitate spectrum sharing by carrying out at least the following core functions:

- Protect incumbent licensees or other users from interference caused by entrants with lower priority (and, in some cases, coordinate among users with the same priority).
- Provide authoritative and in some bands virtually real-time decisions on requests to transmit or assign usage rights.
- Enforce the use of authorized devices.
- Monitor spectrum assignments and, in some cases, actual usage.

The basic building blocks and sequential steps of an automated frequency coordination system include the following informational inputs and core functions:

- **Rules and policy guidance,** including exclusion zones and terms of use, promulgated by the regulator (NRA);
- **Incumbent information,** primarily from licensing databases;
- **A registry of eligible shared-access users and devices,** including information on geolocation, operating parameters and verification of device certification;
- **Static and dynamic inputs on the spectrum environment,** which can include GIS data (such as terrain and clutter) and sensing data;
- **Analysis of the impact of emissions on interference,** applying propagation and interference models to the available data on users and the environment;
- **Coordination and Protection algorithms that translate the rules,** environmental inputs, and interference analysis into objective answers to requests to transmit;
- **A communications interface that allows shared-access users to directly and regularly renew grants, share information,** and receive any subsequent changes to their authorization.

Use of DSMS yields substantial benefits to industry, regulators and consumers alike. Compared to manual or even database-assisted coordination, automated frequency coordination:

- **expands and speeds access to unused spectrum, facilitating more intensive use of the resource,**

- **better protects incumbent licensees,**
- **lowers access costs** for operators and regulatory costs for NRAs,
- **protects incumbents with greater certainty** and ensures consistent outcomes,
- **accounts quickly for changes in use of the band** or even changes in the NRA's rules.

DSMS technology can also be leveraged to provide additional capabilities that include:

- monitoring and collecting data on actual use of the band;
- coexistence optimization, which helps devices minimize mutual interference (relevant in particular where secondary users have no interference protection);
- enforcement assistance (including the ability to identify and shut down errant devices);
- facilitate secondary market transactions;
- collect any usage or regulatory fees authorized or required by the NRA;
- provide a portal for incumbents and/or users to report corrections or updates to licensing data, operating parameters, or to report incidents of interference.

Looking ahead, increasing consumer demand for data-intense applications on user devices, coupled with the potential benefits of 5G and IoT networks, are motivating regulators to consider how DSMS can unlock unused capacity in occupied-but-underutilized bands. This report highlights several bands under active consideration for sharing managed by DSMS, as well as the potential for database-assisted sharing in satellite bands, such as among NGSO satellite constellations.

6 GHz for License Exempt Use at Standard Power: As mentioned above, the United States and Canada are on track to certify multiple automated frequency coordination (AFC) systems during 2023 to manage license-exempt RLANs operating at standard power (SP) both outdoors and indoors across at least 850 MHz between 5925 and 7125 MHz. AFCs will ensure that outdoor and standard power deployments avoid harmful interference to any of the tens of thousands of point-to-point microwave links and other incumbents in the band. At this writing, adoption of rules that would permit SP operations under AFC control are actively pending in Brazil, South Korea and Saudi Arabia as well. The European Commission has tasked a working group to study the feasibility of adding an authorization for RLANs to operate at SP in the lower portion of the 6 GHz band (5925-6425 MHz), where only very low-power and indoor-only use is currently authorized.

3.8-4.2 GHz for local shared licensing: The United Kingdom and several EU states are among a growing number of NRAs adopting local shared licensing initiatives that coordinate access to unused spectrum, most commonly in the 3.8 – 4.2 GHz C-band. In the U.K., Ofcom's framework for Shared Access Licenses (SALs) enables both mobile and fixed wireless networks (point-to-multipoint) to coordinate shared use of vacant channels on a co-primary basis with incumbent FSS earth stations and fixed point-to-point licensees. Although both very small-area licenses (50-meter radius) and medium-power base station licenses (in rural areas only) – over 1,600 as of year-end 2022 – are coordinated manually, Ofcom is exploring how to automate the SAL licening process.

In the U.S., the FCC is considering the authorization of additional DSM systems to facilitate shared access by unlicensed, licensed, and lightly-licensed entrants in underutilized bands, including:

37-37.6 GHz and 42-42.5 GHz: The lower 37 GHz band has already been allocated for coordinated shared use on a co-primary basis by commercial and federal government users. The FCC proposed in May 2023 to authorize coordinated local shared use of the currently unused 42 GHz band for terrestrial broadband, possibly under the same shared access rules as the lower 37 GHz band. The precise sharing rules and role of a spectrum management system for coordinating shared access licenses remains under consideration.

10 GHz, 12.2-12.7 GHz, 12.7-13.25 GHz: The FCC is also considering the use of DSMS to facilitate the coordination of more intensive sharing of underutilized upper-mid-band spectrum for fixed point-to-point (PtP) and point-to-multipoint (PtMP) broadband use. Active proceedings are pending on two adjacent bands that together comprise more than 1000 MHz (from 12.2 to 13.25 GHz), as well as a proposal by rural broadband providers for coordinated sharing of 500 MHz of military radar spectrum in the 10-10.5 GHz band.

Finally, this report reviews a number of emerging technological advances that can further amplify the benefits of DSMS. These include more detailed, real-world GIS data (e.g., terrain, clutter, building heights and materials); real-time spectrum occupancy data; the growing sophistication of propagation and interference modeling; value-added, cloud-based database services; and the potential to incorporate more advanced AI and blockchain technology.

SOLVING THE SPECTRUM CRUNCH:
Dynamic Spectrum Management Systems

1. INTRODUCTION AND DATABASE BASICS

As this section details, although spectrum database coordination is nothing new, it has recently evolved from manual, to automated, to dynamic – adding automation and propagation modeling to static licensing data. A progression of regulatory innovation in database-assisted frequency sharing – including for licensed fixed links, unlicensed Wi-Fi and mobile/LTE – is described in Section 2 below. This technical evolution from manual to dynamic frequency coordination yields substantial and demonstrable benefits for regulators, industry stakeholders and end-users, as detailed in Section 3 below. As these benefits become better known – and as the demand for spectrum capacity becomes more pressing – additional bands (including 6 GHz and 3.8-4.2 GHz) have emerged as candidates for shared use via automated frequency coordination, as described in Section 4 below. Section 5 reviews some of the emerging technologies that promise to make DSMS even more efficient and cost-effective in the future.

Growing Global Support for Dynamic Spectrum Sharing

As demand for wireless connectivity has surged, the use of databases to coordinate more intensive and efficient spectrum sharing has emerged as a critical regulatory tool. Regulators and legislators in a number of countries have authorized automated and even dynamic frequency coordination databases to manage real-time assignments in shared bands and to protect incumbent operations (including military and public safety systems) from harmful interference.

In the United States, the Federal Communications Commission (FCC) has steadily developed experience and confidence in automated frequency coordination, which it first authorized in 2010 to manage opportunistic and unlicensed access to vacant broadcast TV channels (the TV White Spaces). In 2015 the FCC authorized the Citizens Broadband Radio Service (CBRS) that relies on automated Spectrum Access Systems (SAS) to coordinate commercial sharing of 150 MHz of prime mid-band spectrum with the U.S. military and fixed satellite service incumbents. And in mid-2023 the FCC is expected to approve the commercial deployment of multiple Automated Frequency Coordination (AFC) systems to manage the deployment of Wi-Fi 6E – outdoors and at standard power (up to 4 watts EIRP) – across 850 MHz of the 6 GHz band on a shared basis with more than 50,000 high-power fixed microwave links. The U.S. Congress has supported this trend, including in 2018 legislation that mandated development of "a national plan for making additional … bands available for unlicensed or license by rule operations," including examining "existing and planned databases or spectrum access systems designed to promote spectrum sharing."[1]

The European Union, which has already approved low-power, indoor-only operation of unlicensed RLANs (i.e., Wi-Fi 6E) in the 5925-6425 GHz band, is currently studying mechanisms to manage higher-power operations (up to 4 watts EIRP) both indoors and outdoors. The EU regulator (CEPT) has tasked a working group in its Electronic Communications Committee (WG ES45) to "[s]tudy the feasibility of introducing a dynamic spectrum access coordination function under which WAS/RLAN up to 4W could operate, while ensuring the protection of incumbent services (including their possible future deployment) in the 5945-6425 MHz frequency band and in adjacent bands."[2] The working group has tasked ETSI to study "database(s)management . . . including the questions regarding implementation, regulatory and technical conditions of those databases."[3]

More broadly, in June 2021 the EU's Radio Spectrum Policy Group issued an opinion urging more innovation and experimentation in spectrum sharing: "The RSPG seeks to nudge a change of mindset: all considerations in the field of spectrum by policy makers, spectrum managers, users and industry should be done by pursuing better spectrum efficiency through more spectrum sharing, including by following the principle of 'use-it-or-share-it'."[4]

Ofcom, the U.K. regulator, was an early adopter of TV White Space database coordination and is similarly considering automated frequency coordination in 6 GHz, as well as in 3.8-4.2 GHz and other bands for its innovative local shared licensing program. Ofcom stated in the agency's 2016 Framework for Spectrum Sharing: "Geolocation databases are making it easier for devices to identify spectrum that is available for sharing while protecting the operation of existing services. . . . the fundamental principle is not frequency specific and can be extended to a broader range of frequencies" beyond enabling access to TV White Space channels.[5] More recently, in its 2022/2023 Plan of Work, Ofcom stated that it will be studying "the potential role automated assignment databases could play in meeting future spectrum management challenges."[6]

In addition to coordinating frequency assignments and interference avoidance, DSMS technology offers the potential for additional functionality and efficiency far beyond what manual or database-assisted coordination can offer. Far greater efficiencies will also be possible as more granular and real-world data (terrain, clutter, three-dimensional mapping, etc.) are incorporated into the algorithms that a DSMS relies upon to grant, deny or modify requests for shared spectrum access on a virtually real-time basis while safeguarding incumbent users with priority rights. A number of these emerging technologies – including real-world GIS data, spectrum sensing and monitoring, and AI and blockchain database applications – are reviewed in Section 5.

A. Wireline to Wireless: Database Coordination in Telecommunications

There is no question that today we have the technical ability to automate frequency coordination and thereby lower transaction costs, use spectrum more efficiently, speed time to market, protect incumbents from interference with greater certainty, and generally expand the supply of wireless connectivity that is fast becoming an input into every other industry. Despite these benefits, database coordination of shared spectrum access has also been greeted with a degree of skepticism and even resistance from licensees accustomed to exclusive use of spectrum. As Ofcom reported in its 2016 Statement: "Respondents to the consultation viewed geolocation databases as a promising enabler, and we were urged to expand the use of geolocation technology to bands beyond UHF... However, some raised concerns relating to the reliability of the databases, the accuracy of location information, and the ability of users to bypass the parameters set by the databases where devices are manually configured."[7]

While incumbent users of underutilized bands typically characterize dynamic spectrum management as a risky leap, the reliance on automated databases to facilitate more advanced and low-cost telecommunications has a long and storied history that extends from the replacement of manual switchboard operators with SS7 call-related networks relying on automated databases, to automated number porting database systems, to the Domain Name Service (DNS) databases that serve as the essential circulatory system of the Internet itself. These advances have proven so beneficial to promoting universal and affordable communication they are taken for granted today.

Similarly, the use of databases to coordinate spectrum assignments has evolved, but is nothing new. The basic steps are exactly the same as in a manual coordination process. What is new is surging consumer demand for wireless connectivity and hence the need to intensively share underutilized frequency bands. On the technical side, advances in computing power and cloud-based solutions have vastly improved the speed at which coordination can be conducted, as well as highly detailed geographic databases combined with clutter-aware propagation models, and transmitters and receivers capable of dynamically receiving information from databases. Once automated, frequency coordination databases can also become platforms for value-added services, such as radio resource management (RRM) and assurance services that go beyond simple link authorization or admission control.

i. The Longtime Reliance on Automated Databases for Wireline Telecommunications

Wireline telecommunication systems were the early beneficiaries of automated database coordination. Once upon a time, manual switchboard operators opened and closed phone lines by hand, as pictured just below. Over the course of a century this hands-on approach evolved into automated circuit switching and, by the late 1980s, into automated databases that could almost instantly vary the treatment of different calls based on the number and established algorithms. This progress culminated in the Signaling System 7 (SS7) architecture, which employed automated databases to support interoperable call initiation, routing, billing, and a variety of information-exchange functions, including call forwarding and wireless roaming, across the entire public switched telephone network (PSTN). The ITU recommended SS7 as an international standard in 1988 and it was swiftly adopted by major carriers worldwide.[8]

SS7 represented just one of a number of automated database networks that evolved to support efficient, low-cost, interconnected telephone connectivity worldwide.[9]

Figure 1: Manual switchboard operators (circa 1877) gave way over time to the automated call routing databases that characterized the SS7 signaling networks the ITU adopted as the international standard in 1988.

Among the most advanced today is the Local Number Portability (LNP) database which, in the United States, has been operated by a third-party contractor approved by the FCC since 1997 and overseen by a committee of major telecommunications providers. The United Kingdom's number porting system, also initiated in 1997, is similar.[10]

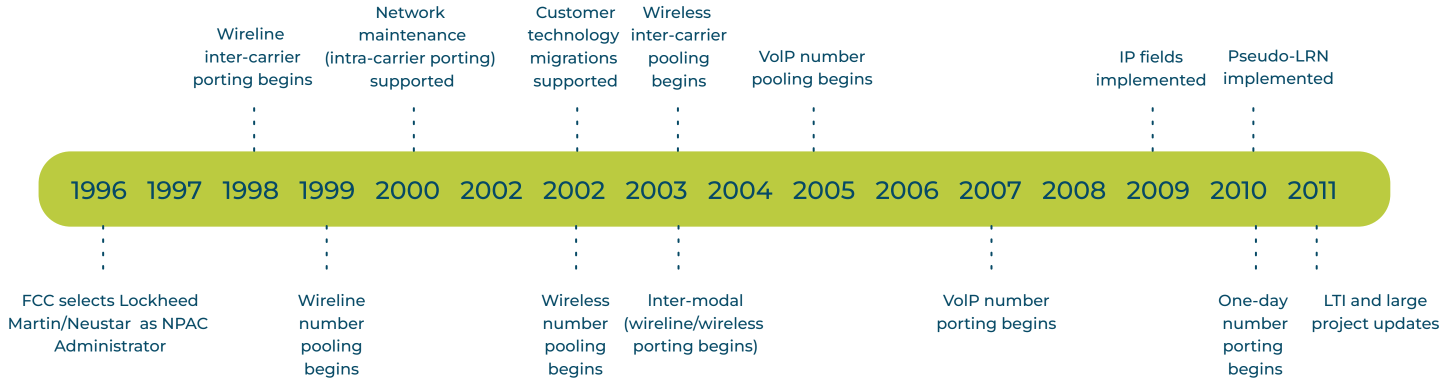


Figure 2: Phone number portability and forward call routing rely on automated database systems introduced in US and UK in 1997.[11]

Mobile communications have relied on automated and interconnected database coordination from the beginning of digital cellular voice and data services. GSM (Global System for Mobile communications), the standard developed by the European Telecommunications Standards Institute (ETSI), defined protocols for second-generation digital cellular networks. A common standard and interconnected databases allowed the subscribers of different operators to roam onto other GSM networks, including across borders and ultimately worldwide. In GSM networks, mobile call and SMS routing and roaming functions are managed by the mobile switching center, which in turn relies on the automated interaction of two key databases: the home location register (HLR) and the visitor location register (VLR). HLRs store details of every SIM card issued by the mobile operators, while VLRs are a database of information that allow operators to connect devices attempting to roam onto its network.[12]

A more recent advance in the evolution of automated database coordination is the Internet's Domain Name Service (DNS). DNS is a database that connects domain names to IP addresses. More specifically, DNS is a distributed database, comprised of DNS servers that collectively keep track of the names and corresponding IP addresses of various domains and hosts on the internet. No single DNS server maintains the entire database; each gives authoritative information for domains which it administers, or delegates to other servers further down the hierarchy for those it does not. This allows local control of segments of the overall database while still facilitating rapid interconnection across the entire Internet through a hierarchy similar to the IP routing hierarchy.

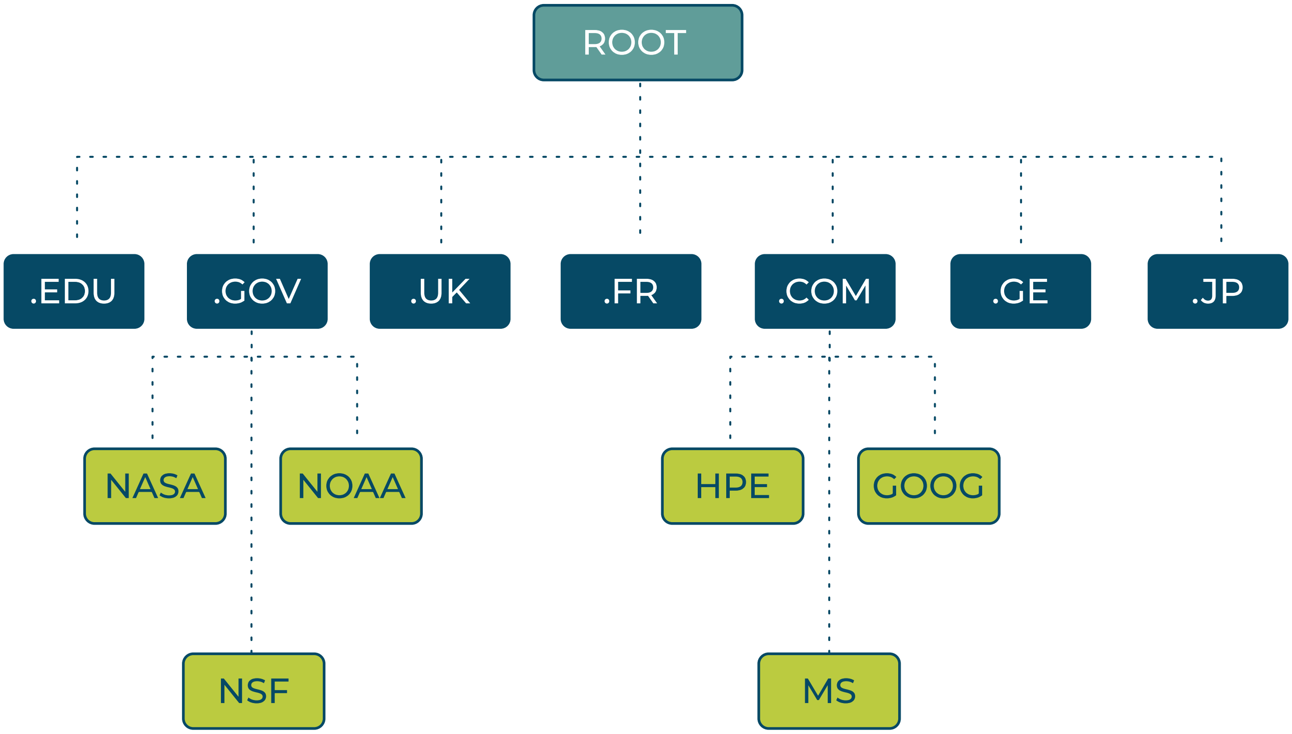


Figure 3: The Internet's Domain Name Service (DNS) is a distributed database process that connects domain names to IP addresses to facilitate the routing of Internet traffic.[13]

ii. The Longtime Use of Databases to Assist the Coordination of Shared Spectrum Bands

Although the use of databases as a tool for spectrum management is a more recent development, it has proven no less compelling as a means of achieving large-scale, low-cost, and virtually real-time access to communications capacity that would otherwise go unused. While auctions are now widely used to assign exclusive-use licenses over a very large geographic area for mobile networks (IMT), most spectrum is shared among users that can coexist and make more efficient use of a band through a cooperative coordination process. In some bands databases facilitate coordination among licensees of the same type, while in other bands the coordination is among site-based users licensed for different services.

Fixed terrestrial point-to-point links (PtP) and fixed satellite services (both FSS earth stations and the GSO satellites transmitting to them) are prime examples. For decades most coordination and approval of licenses for fixed, site-based licenses (such as FSS earth stations and terrestrial PtP links) has relied on an essentially manual coordination process informed by the national regulator's licensing database. A leading example is the coordination model used since 1996 in the United States to coordinate point-to-point microwave links in FSS bands. Today this coordination is database-assisted, as described further in the next section, but it is not as automated, dynamic or low-cost as it could be if the goal was to make more intensive and efficient use of these shared bands, some of which are notably underutilized.

In virtually every case, frequency coordination databases facilitate spectrum sharing by carrying out at least the following core functions:

- Protect incumbent licensees or other users from interference caused by entrants with lower priority (and, in some cases, coordinate among users with the same priority);
- Provide authoritative and in some bands virtually real-time decisions on requests to transmit or assign usage rights;
- Enforce the use of authorized devices;
- Monitor spectrum assignments and, in some cases, actual usage.

The next step in the evolution of spectrum coordination has been to fully automate the process of spectrum coordination. As explained in the next section, in any automated frequency coordination system the basic steps are the same and the outcome is determined by the rules adopted by each national regulatory authority (NRA). However, compared to manual or even database-assisted coordination, automated frequency coordination speeds access to spectrum, lowers costs, promotes more intensive use, better protects incumbent licensees, ensures consistent outcomes, and accounts quickly for changes in use of the band or even changes in the NRA's rules.

In addition, database coordination creates an opportunity to achieve more intensive and efficient use of a band by incorporating detailed GIS data (e.g., on terrain and clutter) and even dynamic data (e.g., from spectrum sensing) that reflect the real-world spectrum environment on a very localized basis and thereby support far more sophisticated propagation and interference modeling. As more countries adopt database techniques, operators serving multiple adjacent NRAs could also coordinate between conflicting rules, converting what are often effectively radio "DMZs" into productive use.

B. Dynamic Frequency Coordination Systems: The Basics

Spectrum coordination databases have demonstrated the ability to facilitate a variety of regulatory frameworks, including licensed, unlicensed and lightly-licensed sharing regimes. Regulators now have the models, technologies and proven commercial providers that allow them to either create or authorize a DSMS that best fit the NRA's policy goals. The DSMS framework will vary depending on the nature of the incumbent service, the propagation characteristics and size of the band, the nature of the shared-access use, and other factors. In all cases the grant provided by a DSMS is equivalent to a time-bounded authorization (or license) to transmit. At a high level, the shared-access frameworks enabled by automated frequency coordination systems adopted by one or more NRAs, and profiled in this report, currently include:

- **Coordinated, licensed sharing:** Examples include traditional fixed link coordination in 70/80/90 GHz and the FCC's current rulemaking on potential database-coordinated sharing by fixed point-to-multipoint deployments in the 12 GHz, 37-37.6 GHz and 42 GHz bands.
- **Opportunistic, unlicensed use of unused spectrum by frequency and location:** Examples include TV White Space databases (which enable use of locally-vacant TV channels) and the AFC systems that will soon manage RLAN use outdoors and at standard power across most of the 6 GHz band in the U.S., Canada and other countries.
- **Two-tier Licensed Shared Access based on geographic areas and database assist:** More than a dozen European and other NRAs are implementing opportunistic sharing through the coordination of local shared access licenses, with a primary focus on the 3.8-4.2 GHz C-Band occupied (but grossly underutilized) by fixed satellite earth stations. The future use of automated coordination is being considered in some cases, depending in part on usage.
- **Three-tier shared access, combining licensed and opportunistic use:** In the United States, CBRS is managed by a dynamic SAS that governs private sector sharing of U.S. Navy radar spectrum at 3550-3700 MHz to accomodate a mix of licensed and lightly-licensed use. In the United Kingdom, TV White Space is managed in tiers by a dynamic geolocation database, sharing broadcast spectrum (primary) with wireless microphones (secondary) and opportunistic unlicensed sharing for TVWS devices (tertiary).

The basic building blocks and sequential steps of an automated frequency coordination system include the following informational inputs and core functions:

- Rules and policy guidance, including exclusion zones and terms of use, promulgated by the regulator (NRA);
- Incumbent information, primarily from licensing databases;
- A registry of eligible shared-access users and devices, including information on geolocation, operating parameters and verification of device certification;
- Static and dynamic inputs on the spectrum environment, which can include GIS data (such as terrain and clutter) and sensing data;
- Analysis of the impact of emissions on interference, applying propagation and interference models to the available data on users and the environment;
- Protection algorithms that translates the rules, environmental inputs, and interference analysis into objective answers to requests to transmit;
- Calculation engine: The database applies the rule-derived algorithms in response to requests for a spectrum grant;
- A communications interface that allows shared-access users to directly and regularly renew grants, share information, and receive any subsequent changes to their authorization.

Putting this all together, we see that DSMS is simply a means of scaling and automating the process that the regulator (with or without the assistance of third parties) authorizes for any band that does not need to be exclusively licensed. Just like manual coordination for fixed point-to-point links, for example, there is a request for an assignment, analysis of licensing data, the application of the rules to available inputs, and a decision communicated. However, whereas a more manual or even database-assisted coordination process can be expensive, slow, limited in its granularity, and prone to inconsistent results, an automated calculation engine can produce near-real-time and consistent outcomes at very low marginal cost.

Dynamic Spectrum Coordination System: How it Works

The starting point for the automated coordination process outlined above is, of course, the NRA's rules and policy guidance – including any subsequent revisions. This begins with the maxim that shared-access users "shall first do no harm" to incumbent services. The goal is minimal impact on incumbent operations, although the trade-offs between degrees of protection and spectrum efficiency should be determined by the NRA for each band and reflected in the rules. Importantly, the rules do not require technical implementation details, which can be delegated (subject to NRA approval) to one or multiple AFC operators or, ideally, to an expert multi-stakeholder group that includes relevant experts and industry representatives.[15]

With rules in place, one or more DSMS operators are typically authorized by the NRA to develop and manage the system. As discussed further below (Section 3), NRAs have options that range from contracting with a sole-source DSMS to qualifying and certifying multiple, competing DSMS operators. In either case the DSMS operator(s) develop the algorithms that translate the NRA's rules into objective answers to requests for a spectrum frequency assignment. Testing is typically required and the NRA can invite public comment, which allows a range of stakeholders to surface concerns, ideas and suggestions.

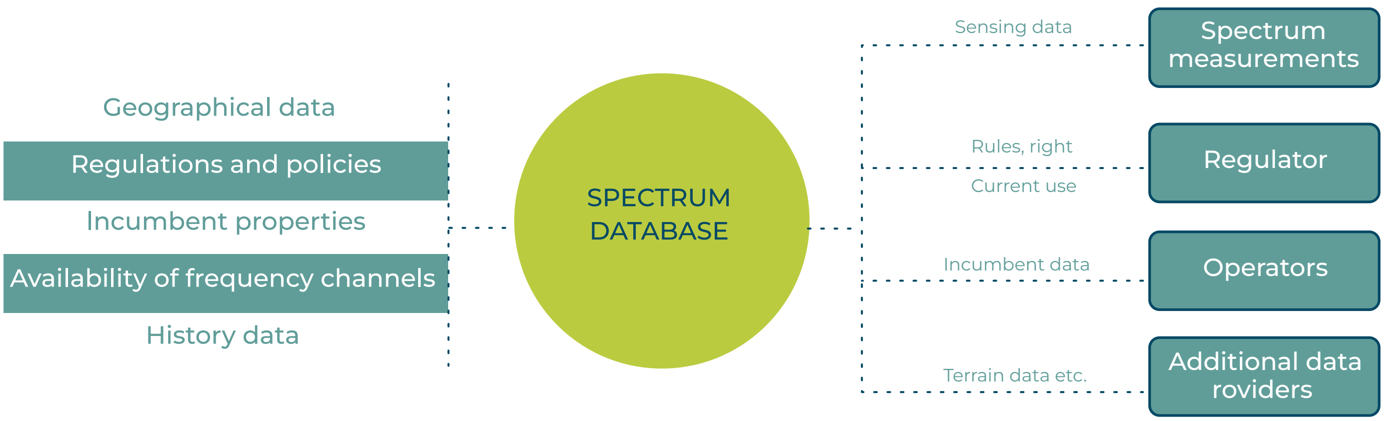


Figure 4- A general spectrum database model. (Source: M. Höyhtyä, et al.) [16]

An essential component of any coordination process is complete and accurate licensing information on incumbent operations. Database operators will regularly ingest the NRA's licensing data on the protected service(s) and must do so frequently enough to capture new licensees or changed operating parameters. The frequency of these updates will vary by band. Baseline parameters of the incumbent systems, such as the interference tolerance of receivers and the coverage area of base stations, are also critical inputs into the AFC's analysis and response to requests from secondary users.

Unfortunately, collecting incumbent information can be problematic when "the regulator might have some but not all the data, or not to the level of detail needed for the protection calculations," as the European Council of Postal and Telecommunications (CEPT) observed in its report on a framework for TV White Space database management.[18] The NRA may need to require incumbents to report additional information,[19] as well as to verify the accuracy of licensing data, or at least give incumbents the choice of taking this 'self-help' measure or instead face increased risk of interference. At the same time, it's important to minimize the burden and require all stakeholders to report only information necessary to facilitate sharing without interference. The ECC report also notes there may be privacy and cost considerations, but in implementations to date these have been judged to be minor and manageable.[20]

The DSMS operator may be required to collect a similar set of information from shared-access users as part of granting any request for permission to transmit.

These secondary users, whether lightly-licensed or unlicensed, must generally register through an online self-registration portal and provide general information (e.g., contact information, location, certified devices to be used) as well as whatever technical operating parameters the DSMS requires to apply its algorithms. Registration is also an opportunity for the database operator to set up a payment mechanism for any fees authorized by the NRA, including (at the regulator's option) a licensing or spectrum use fee.[21]

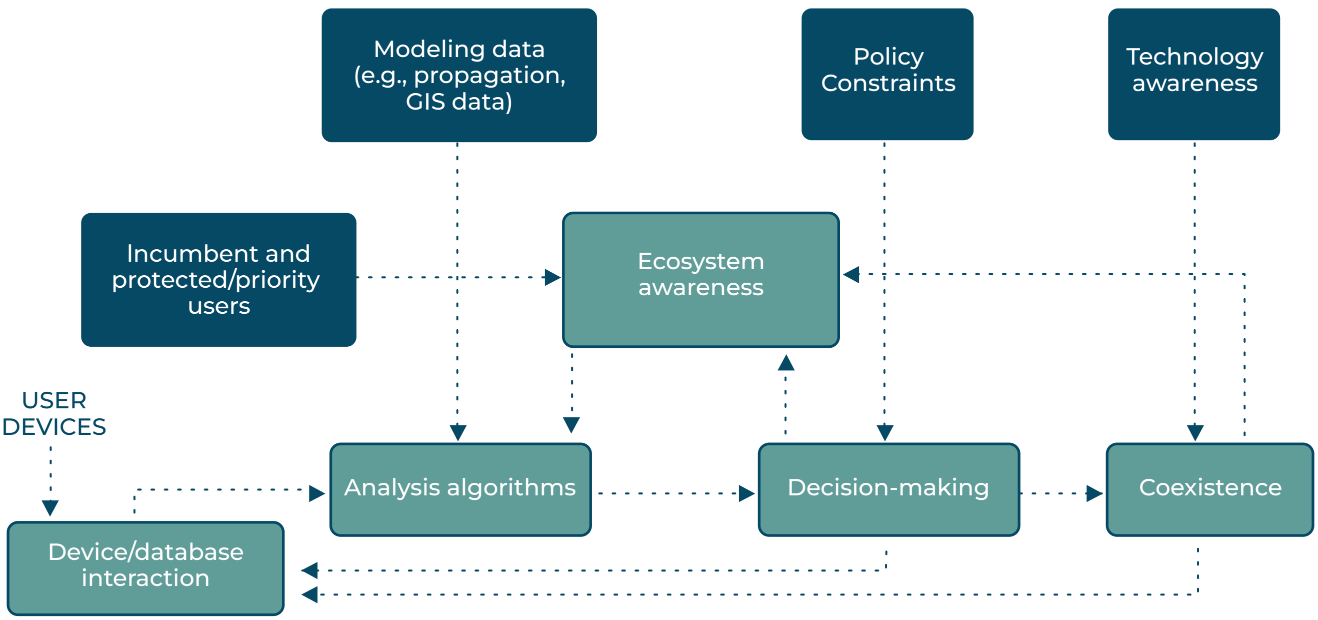


Figure 5: Conceptual architecture for an automated frequency coordination (AFC) system.

Importantly, DSMS operators will typically maintain a registry of access points and other devices certified by the NRA. The verification of device certification is critical to ensure that a grant to operate is not given to a device that is not compliant with the technical rules for the band. The NRA's device certification rules must prohibit users from modifying the hardware or software settings to circumvent the need to request and comply with time-limited assignments from an authorized DSMS.[22] Conversely, the NRA will need to adopt device certification standards that require that a device will not transmit on the band without a current grant from an approved database provider.

Another valuable and increasingly sophisticated set of inputs inform interference modeling and ecosystem awareness. The analysis algorithms for dynamic databases include models for propagation (path loss), device characteristics (e.g., out of band emission masks), and antenna patterns (e.g., a directional antenna has a far different impact than an omnidirectional). Propagation and interference models can have a major impact on the availability of shared spectrum. Propagation modeling can be limited to terrain (for example, the limited but widely-used Longley-Rice propagation model), or it can be more robust by factoring in clutter (structures, trees), building materials, building height, and other information. The results of coexistence studies between real devices and real incumbents, whether bench-tests or field measurements, may be used by an NRA as a foundation for determining what levels of interference are tolerable in a given situation. [23]

The more detailed and reliable the data, the more accurate (and typically the more robust) the grants of permission for shared-access usage will be.[24] For example, at low power, Wi-Fi or other broadband devices may be able to operate far more extensively if the DSMS algorithms take into account a 3D modeling of clutter, which can factor in not only the footprint of a building (at ground level) but also its height. Dynamic databases will increasingly integrate real-world GIS data, device location data, RF sensing data (if available), and the NRA's rules and policies into a Radio Environment Map (REM) that provides the most granular, efficient and reliable basis for granting or denying requests to operate on a secondary basis. This is discussed further in Section 5 below.

At this point, the DSMS database is certified and has the incumbent, user, environmental and other data it needs to immediately respond to requests for a frequency assignment. A network operator or individual device requests an assignment. Depending on the rules adopted, the operator's request could be for an assignment of one or more generic channels of bandwidth, for a specific frequency range, or for a list of available frequencies from which to choose. The coordination system will first verify the secondary user is registered and that the access point or other device seeking authorization is certified. Algorithms informed by the rules, the available modeling data, and the user's location and device characteristics are applied to the user's request. The calculation engine generates a list of allowed frequencies, associated transmit powers, an expiration of the grant, and any other parameters.[26]

In an automated coordination system, the result is immediately communicated back to the user. In some cases, the denial of a specific request is accompanied by an offer of an alternative channel or power level, depending on the design of the overall system. The need to have a coordination analysis reviewed and approved using NRA resources is eliminated. This speeds time to market and minimizes costs. Similarly, an automated coordination system can also facilitate secondary market transactions. The database can quickly match supply and demand, reduce transaction costs, and enforce conditions (e.g., NRA rules on license partitioning, term or power limits).[27]

The frequency assignment will typically be time-limited, requiring the network or device to periodically request a renewed or changed grant. The grant provided by the DSMS is therefore equivalent to a time-bounded authorization (or license) to transmit. The automatic expiration of a grant accommodates any changes in protection requirements for incumbents and can vary widely (from hours to weeks). A failure to renew is presumed to be due to inactivity and the grant expires. This automation allows the NRA to make the grant of a frequency assignment as geographically limited, or as short in duration, as it deems appropriate to protect incumbents and serve its overall policy purpose. These conditions can also change over time.

Beyond these basic functionalities, DSM systems have potential capabilities beyond the reach of a manual or even a database-assisted process. These fall into categories that include monitoring and collecting data on actual use of the band; coexistence optimization, which helps devices minimize mutual interference (relevant in particular where secondary users have no interference protection);[28] enforcement assistance (including the ability to identify and shut down errant devices);[29] and dynamic adjustments to the admission control parameters (in response, for example, to aggregate interference in a certain geographic area). The benefits of automated coordination to network operators and regulators is discussed further in Section 3 below, but leading examples include to:

- Optimize coexistence among secondary users, if relevant, based on NRA rules (for example, among unlicensed or other opportunistic users);
- Capture data and report on actual use of the band, as well as any anomalies that may inform future regulatory action;[30]

- Maintain the ability to identify and shut down a device or provider in cases of harmful interference or emergency;
- Facilitate secondary market transactions;
- Collect any usage or regulatory fees authorized or required by the NRA;
- Provide a portal for incumbents and/or users to report corrections or updates to licensing data, operating parameters, or to report incidents of interference;
- Develop additional value-added services that can be offered to stakeholders in the band, including to incumbents.

2. FREQUENCY COORDINATION SYSTEMS: MANUAL TO AUTOMATED TO DYNAMIC

The use of databases as a tool to coordinate frequency assignments – and avoid harmful interference – has a long and successful history. In the United States, thousands of MHz of spectrum are shared among unrelated entities through a coordination process either controlled by, or assisted by, databases operated by one or more commercial entities authorized by the FCC. As demand for spectrum has surged and technology has advanced, spectrum database coordination has evolved from manual, to database-assisted, to automated, to dynamic. DSMS technology has the ability to factor in real-world inputs beyond static licensing data, using propagation and/or interference modeling informed by how each device admitted to the band alters the interference environment, or by spectrum sensing or other dynamic awareness data.

Of course, the original and most basic spectrum coordination is done manually, informed by the many licensing databases maintained by NRAs, such as the Universal Licensing System (ULS) maintained by the FCC.[31] These licensing databases, though often rich in operational detail, are almost entirely static. ULS and others today enable electronic filing of licensing applications – which can speed the process – but manual staff review is generally still necessary and assignments are not granted instantaneously. Licensing databases play a key role in assisting coordination in shared bands, but do so primarily as an informational input for the agency staff or, increasingly, the external third parties that run the calculations and prepare coordination reports. It takes more to enable dynamic band sharing, particularly at scale and among users with divergent technologies.

A. Manual, Database-Informed Coordination

For decades most coordination and approval of licenses for fixed, site-based licenses (such as broad-cast transmitters and point-to-point links) has relied on an essentially manual process that relies on the NRA's licensing database.

A leading example is the coordination model used since 1974 in the U.S. to coordinate point-to-point microwave links in Fixed Satellite Service bands. The 6 GHz C-band alone has approximately 100,000 licensed links operating on one or more channels across 850 MHz of spectrum.[32] Generally, Part 101 of the Commission's rules requires an operator to complete coordination prior to filing an application for authorization.[33] "The applicant must, through appropriate analysis, select operating characteristics to avoid interference in excess of permissible levels to other spectrum users."[34]

For each link, an operator typically contracts with a qualified private firm to prepare the coordination analysis, which must be sent to other registered users in the area (who have up to 30 days to raise objections). Only then can the user file an application for authorization with the Commission, specifying the precise location and full technical parameters of the transmitter(s) to be used. The FCC then typically takes up to another 30 days to review and approve the license, which may be provisional if conditioned on buildout requirements. Although larger firms such as Comsearch – which coordinates over 10,000 links each year – now use their own proprietary database to largely automate the process, the cost and coordination time required to license a point-to-point link can be substantial.[35]

European NRAs maintain a similarly "conventional link-by-link assignment and centralized coordination" process for virtually all point-to-point links.[36] The primary difference from the U.S. process is that the analysis is typically done within the agency, using the regulator's own databases and analysis software, rather than by third-party coordinators. This additional cost is reflected in the licensing fee. NRAs have full access to licensing information (important since licensing databases are generally not as publicly available as in the U.S.) and responsibility to anticipate and resolve cross-border coordination (important in the EU where borders are numerous).

At the same time, the volume and complexity of fixed wireless coordination promises to grow considerably, even in bands not shared with an incumbent service. ECC Report 173 concluded that "current trends in the FS marketplace are for an ever increasing provision of . . . very high capacity links," for mobile infrastructure in particular, as "a viable alternative to deploying fiber optic, especially in rural areas, but equally in high density urban areas" where digging up roads can be disruptive or too costly.[37] In addition, the report recognizes a parallel growth in point-to-multipoint coordination as operators similarly seek to avoid the obstacles to trenching fiber by deploying high-capacity fixed wireless service to homes and businesses, as well as for mobile backhauling.

POINT TO POINT MICROWAVE LINK

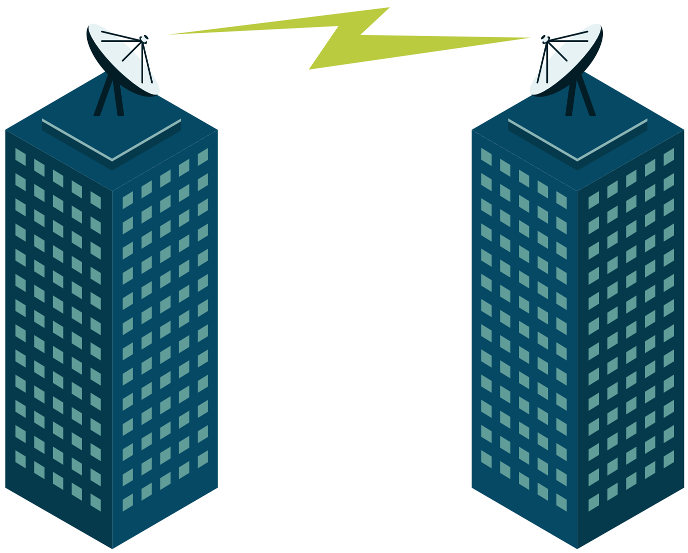


Figure 6: Point-to-point links have typically been subject to manual coordination.

A more recent variation of a regulator leveraging database-informed coordination is the coordination process for the Wireless Medical Telemetry Service (WMTS) in the United States. Hundreds of hospitals share two bands designated for medical devices that use very low-band spectrum. Since this licensed-by-rule spectrum is dedicated almost entirely for hospitals, the FCC designated the American Hospital Association (AHA) to maintain a registry that seeks to ensure nearby hospitals do not cause mutual interference and also to avoid certain exclusion zones (for radio astronomy in the band corresponding to TV Channel 37).[38] The database coordinator does not actually make frequency assignments. Its role is to register and notify WMTS users and equipment manufacturers of potential frequency conflicts. Any interference disputes not resolved by the parties are referred to FCC staff for final resolution.[39]

B. Semi-Automated, Database-Assisted Coordination: 70/80/90 GHz

For nearly three decades, spectrum databases have been harnessed to streamline the process of coordinating point-to-point (PtP) links in shared bands through a semi-automated process. Since 2004, in the U.S. the FCC has certified multiple commercial database operators, under delegated authority, to register, manage and coordinate PtP link registrations in the 71-76 GHz, 81-86 GHz and 92-95 GHz bands shared with federal government incumbents.[40]

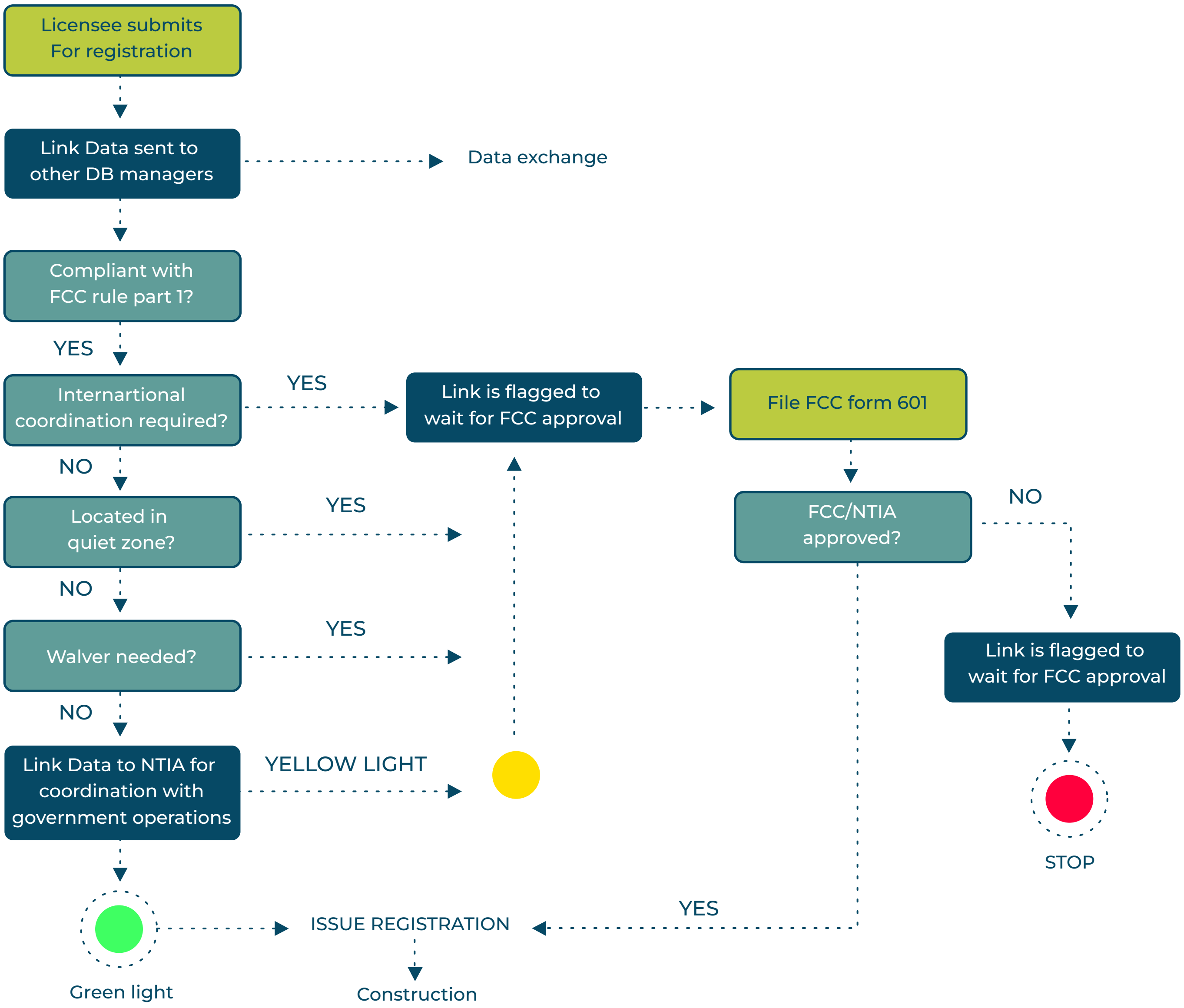


Figure 7: The 70/80/90 GHz link registration and database coordination process interconnects with a U.S. government database to ensure no conflicts with military or other agency use of the band.[43]

As the FCC noted at the time, in millimeter wave bands the highly-directional "pencil- beam" signal characteristics of PtP links "permit systems in those bands to be engineered in close proximity without causing harmful interference."[41] The FCC concluded this obviated the need for the traditional PtP frequency coordination process described just above. Instead, the FCC adopted a light-licensing framework coordinated by competing private database managers. Users apply for a non-exclusive, nationwide license to locate links, on a first-in basis, using any of the 12.9 GHz allocated for commercial use.[42] FCC rules allow multiple database coordinators to compete and to provide additional services such as link design, prior coordination and interference analyses.

To register a link, a licensee uses an online portal to enter the latitude/longitude and other required parameters. The frequency coordinator verifies that the proposed link path will not interfere with other registered users. Although the process is streamlined, because of the need to protect Federal Government operations – including classified systems – the FCC requires database operators to prior-coordinate with Federal users through a separate, non-public database.[44] The National Telecommunications and Information Administration (NTIA), the government's Federal spectrum manager, maintains an automated coordination database of Federal assignments in the band. When there is a request for a new commercial link, the database coordinator first checks the requested path for non-interference with non-Federal links. The database coordinator then relays the request to NTIA's database and receives approval, denial, or a hold for further consideration via an automated "green light, yellow light, red light" process (see illustration just above).[45]

In contrast, the UK ultimately adopted a very different "mixed management approach" for E-band frequencies 71-76 GHz and 81-86 GHz. The lower half of each band is coordinated in a traditional, link-by-link process by the agency itself, while the top half of each band is self-coordinated (light licensing) by operators that are obligated to do their own interference analysis and negotiate over any resulting interference issues.[46] Both approaches are essentially the manual-but-database-assisted process used for PtP links in 6 GHz and other fixed service bands. Australia, Russia and Czechia have adopted the "light licensing" approach to the E-band, although these are generally based on self-coordination and first-in-time registration, similar to the UK's framework for the upper half of each band. In 2022, India's TRAI similarly adopted an online registration process for E-band backhaul links.[47] "Responsibility for interference analysis rest[ing] with the licensee, who needs to check the WPC link database prior to link registration (links should be protected on a "first come, first served" basis)."[48]

C. Licensed Shared Access

The now decade-old European experiment with Licensed Shared Access (LSA) is another database-assisted model that intended to facilitate two-tier sharing between primary and secondary licensees. LSA would give an incumbent spectrum holder (e.g., large mobile carriers, government users) an opportunity to lease out all or part of their spectrum on a temporary basis to other operators while guaranteeing that no interference is caused to the incumbent. In this model, targeted initially at the 2300-2400 MHz band, the NRA plays a direct role in managing the database of information by which primary and secondary licensees share the band.[49] Unlike any of the band-sharing models adopted in the United States, the European framework for LSA is contingent on the agreement of both the incumbent and of the Mobile/Fixed Communications Network (MFCN) operator to the conditions of use of the spectrum.[50]

The European Communications Committee (ECC) encouraged CEPT member governments to deploy mobile networks in 2300–2400 MHz under the LSA regime.[51] ETSI supported this by releasing a standardized protocol for LSA in 2017. However, according to an indepth analysis by former Ofcom official William Webb and colleagues, "by the end of 2021, the only case of official European deployment of a LSA-like spectrum access regime was reported in The Netherlands, and only for the narrow case of spectrum access registrations for Program Making and Special Events (PMSE) wireless equipment, such as mobile wireless cameras."[52] Although the deployment of LSA remains stalled, Webb et al. report that the model "continues to be seen as a promising vision of database-enabled spectrum sharing," particularly with respect to facilitating and potentially automating secondary market leasing by incumbents to mobile operators seeking to enhance capacity with quality of service assurances in targeted areas.[53]

The LSA framework presumes that the NRA creates and operates a Licensed Shared Access Repository (LR), with a common database of information on the terms of sharing and the incumbent locations, operating parameters and other data needed by each LSA licensee. Each LSA licensee operates a proprietary LSA Controller within its own network, interfacing with the Repository. The LSA Controller, which is internal to the carrier's network, must check in periodically and report the status of its use, allowing the NRA's Repository to verify non-interference and ongoing compliance with the sharing agreement.[54]

LSA's two-tier and excluvely-licensed framework is very different from the automated frequency coordination databases adopted in the United States to enable open shared access to unused capacity in the TV broadcast, U.S. Navy and 6 GHz bands (described below). The centralized repository facilitates secondary access to unused spectrum only to the extent the incumbent agrees to share. "In LSA, the incumbent controls the availability and sharing terms of the sharable spectrum," whereas in the U.S. models for automated frequency coordination "the government regulator mandates the availability and terms of sharable spectrum" and thus "shares all spectrum by default."

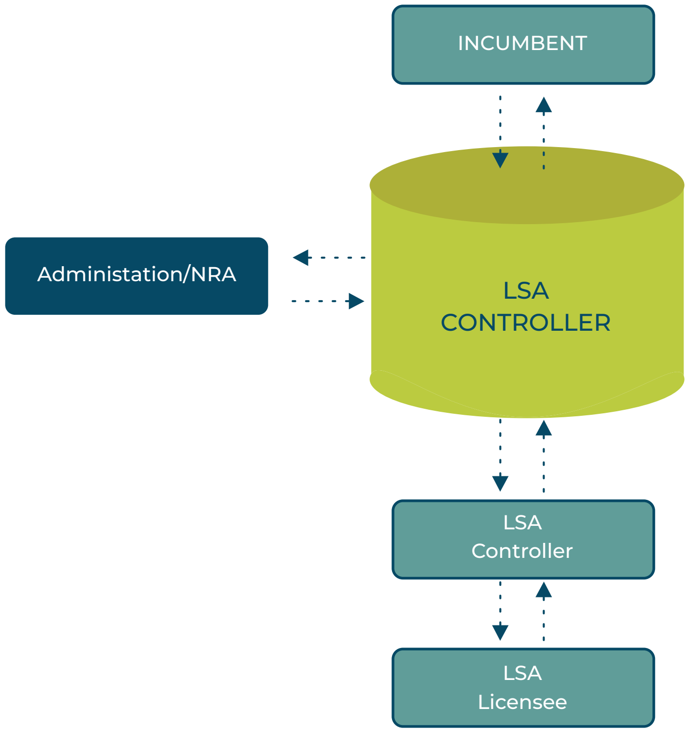


Figure 8: LSA functional blocks and interactions (Source: ECC Report 205)

D. Fully Automated Database Frequency Coordination: TV White Space

The first fully automated coordination systems were authorized to manage unlicensed access to vacant TV band channels, unused spectrum known as TV White Space (TVWS). Rules governing database-coordinated access to TVWS were finalized first in 2010 by the FCC, but have been adopted by a growing list of countries. The UK, South Korea, Japan, Singapore, the Philippines and Kenya have working systems managed, as in the U.S., by one or more automated geolocation database operators.[56] South Africa adopted TVWS rules in March 2018.[57] More than a dozen other countries have hosted successful TVWS pilots, most enhancing broadband connectivity to schools and in rural areas, including in Colombia, Taiwan, Jamaica, Namibia, Ghana, Tanzania, Trinidad and Tobago and Malawi.[58] Many of these initiatives have been assisted by the Model Rules and Regulations for the Use of Television White Spaces made available by the Dynamic Spectrum Alliance and its members.[59]

TV Bands Databases (TVDBs) are a direct illustration of the point emphasized at the top of this report: TVDBs do nothing more than automate the process of manual spectrum coordination. This automation speeds access, lowers costs, better protects incumbent licensees (broadcast stations and wireless microphones, most commonly), and accounts quickly for changes in their use of the band. It is particularly straightforward in the TV bands, where incumbent transmitters are fixed and their operating parameters are well known. Because the incumbent ecosystem is mostly static (fixed), the outcome of a secondary user's request to transmit is pre-computable, which means outputs from the calculation engine can be verified for any location in advance by the regulator. What's added is a user interface and automation, allowing for near-real-time and very granular assignments at low cost and with consistent accuracy.

As the schematic just below illustrates, TVDBs ingest incumbent licensing data, including geolocation and operating parameters, and calculate vacant channel availability, as well as allowed power levels. TV White Space devices (WSDs) are required to access a database server at least once per day (under U.S. rules, but in the U.K. every 15 minutes) or if the device changes location. The device receives a list of available channels and the maximum allowed transmit power (which is in part a function of frequency separation from local broadcast stations).

This fairly static coordination process is somewhat complicated on TV channels that are shared as well by licensed wireless microphones (e.g., in the U.S. and U.K.), which are intermittent and can be mobile. In the U.S. this incumbent protection data includes "reservations" of channels by licensed wireless microphones, which typically operate intermittently (for example, at major public events).[60] In this sense, the TVDB manages a three-tier system of sharing, at least in the U.S. and U.K. where licensed PMSE users (microphones) have priority access in relation to unlicensed device.

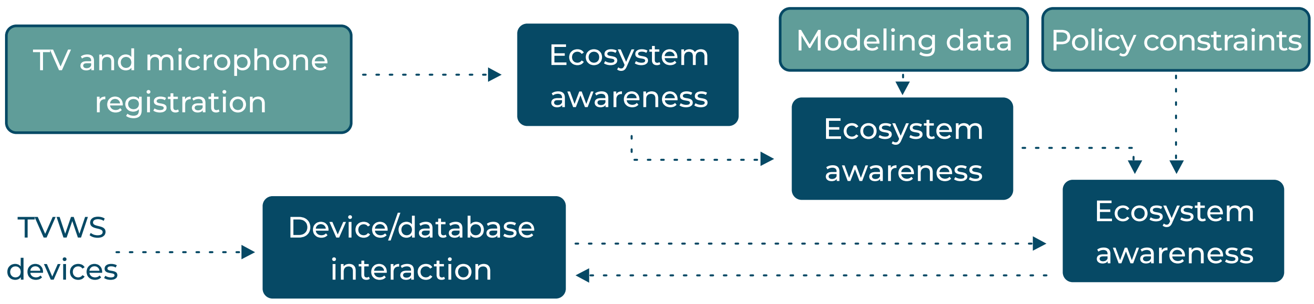


Figure 9: Simplified admission control system architecture for Television Whitespace Database (TVDB).

In the U.S. case, TV viewers are protected within standardized and static contours calculated using the relatively simple and very conservative (both unrealistic and often overly protective) FCC Curve propagation model that considers only the average height of terrain in a given direction, while taking no specific account of basic geographic features (e.g., mountains, lakes), nor of trees, buildings or other “clutter” that more sophisticated GIS models use. Ofcom’s TVWS rules, promulgated later and with the benefit of more granular pixel-based simulations of TV signal strength, permits more accurate database calculations and hence both more bandwidth for WSDs and more protection for viewers. However, neither Ofcom nor the FCC databases take account of terrain in protecting PMSE, instead assuming a worst-case, line-of-sight scenario.

Although TVDBs fully automate coordination, a few significant features simplify their implementation and distinguish them from the sort of dynamic and/or three-tier database coordination system described just below (CBRS in the United States). First, and most obviously, channel coordination in the TV bands is two-tiered; all shared-access users have the same license-exempt status, meaning they have no rights to interference protection vis-à-vis other shared-access users. And where only TV signals need protection (and no secondary users, such as wireless microphones, have “priority access”) incumbent stations are entirely fixed and so the calculation engine’s output of available channels for unlicensed use is entirely predictable.

Second, and relatedly, the TVDBs provide no coexistence management services. Like any other conventional unlicensed band, coexistence is left to voluntary, self-coordination among users or, if the regulator consents, to be offered as a value-added service by one (or more) of the TVDB operators. Interestingly, the earliest value-added service offered by one of the competing TVDBs in the United States (Spectrum Bridge), leveraged the database to allow wireless microphone operators to readily determine which channels were most free from potential interference (not only from unlicensed WSDs, but from nearby TV stations as well).

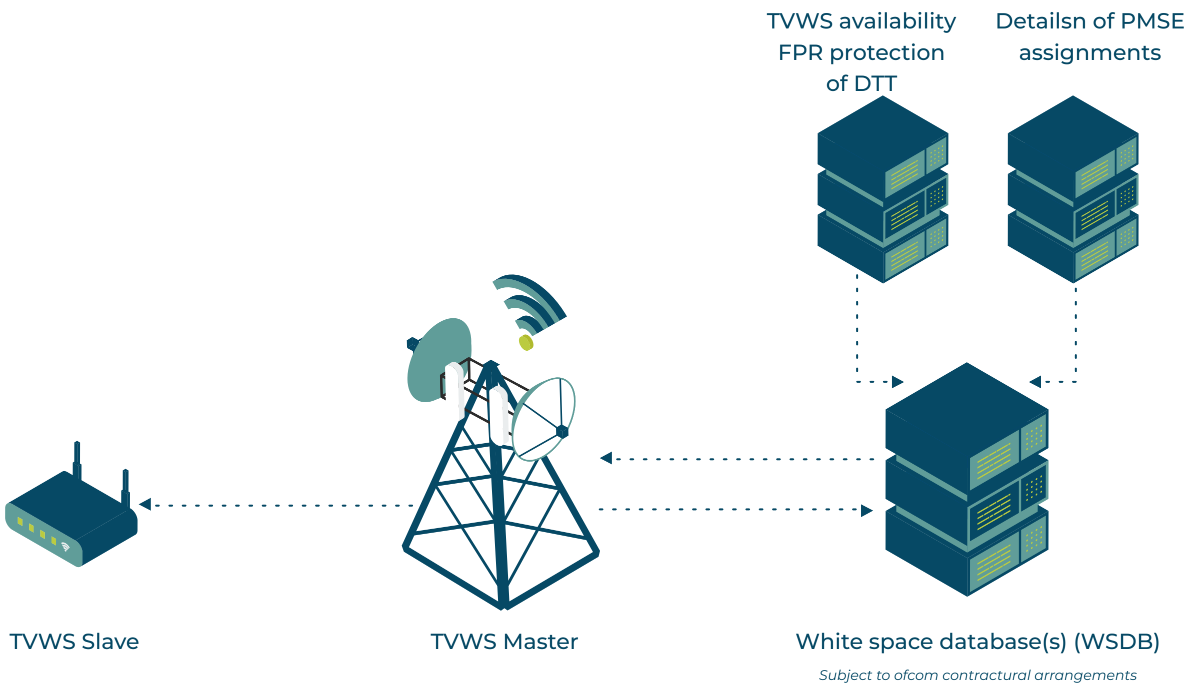


Figure 10: OFCOM’s architecture for Television Whitespace Database (TVDB).

Finally, TVDBs do not consider aggregate interference when computing the channels and power levels available to each device seeking unlicensed access. The interference calculation is entirely static and one-to-one; either the WSD – adjusted for power, bandwidth and height above ground level – is outside the protection contour of a local TV station (or registered wireless microphone system) or it is not. In other words, permission for a new WSD to operate does not depend on the proximity or channel selection of other WSDs previously admitted to the band. While this simplifies coordination, the inability of the TVDB to manage interference dynamically results in a maximum power per WSD "based on an estimate of worst-case density."[61]

E. Dynamic Coordination Databases: The CBRS Spectrum Access System

In 2015, the FCC voted unanimously to create the new Citizens Broadband Radio Service to coordinate new licensed and opportunistic access to unused spectrum in the 3550-3700 MHz band. The CBRS rules authorize the certification of competing frequency coordination systems – called Spectrum Access Systems (SAS) – to govern a dynamic framework for spectrum sharing among a three-tier hierarchy of users: incumbent licensees (U.S. Navy radar, FSS), Priority Access Licenses (PALs), and opportunistic (licensed-by-rule) General Authorized Access (GAA) users. SAS administrators are responsible for ensuring incumbent services are fully protected from interference and that PAL operators are similarly protected from GAA users. Based on the type of device (fixed or personal/portable), information about the transmitter's location and operating parameters, and the technical rules adopted to protect incumbent users from harmful interference, the SAS calculation engine determines the list of available channels at the PAL and/or GAA device location and its maximum permissible radiated power.

Seven PALs in each U.S. county were auctioned in 2020, raising $4.58 billion. Each PAL provides priority access to 10 MHz between 3550 and 3650 MHz. PAL channels are assigned dynamically, in order to protect tier one incumbents (U.S. Navy, FSS), while GAA users operate band-wide on an opportunistic basis. The GAA tier is technically licensed by rule; operators must register with a SAS. But GAA is also effectively unlicensed in the sense that it is open to anyone and conveys no protection against interference, although a SAS has the ability to optimize coexistence among users. GAA users can operate throughout the entire 150 MHz of the 3.5 GHz band on any frequencies not in use by PALs, FSS, or by the Navy. The FCC certified multiple SAS operators for commercial operation in early 2020, allowing opportunistic (GAA) use of the band initially, followed by licensed deployments after the completion of the auction for PALs later that same year.

Unlike all previous auctions for exclusive-use IMT spectrum, PALs offer interference-protected spectrum in relatively small areas (counties) and for "a wide variety of users, deployment models, and business cases, including some solutions to market needs not adequately served by our conventional licensed or unlicensed rules," the FCC stated, including small rural ISPs, enterprise and industrial users.[62] As the CBRS Order stated, the regulator's intention was to make a combination of licensed and opportunistic access available on a localized basis, and under uniform technical rules, to thousands of potential network operators, including rural ISPs, private LTE networks, office complexes, factories customizing machine-to-machine networks, utilities, airports, shopping malls, sporting arenas, school districts, and college and other campus networks.

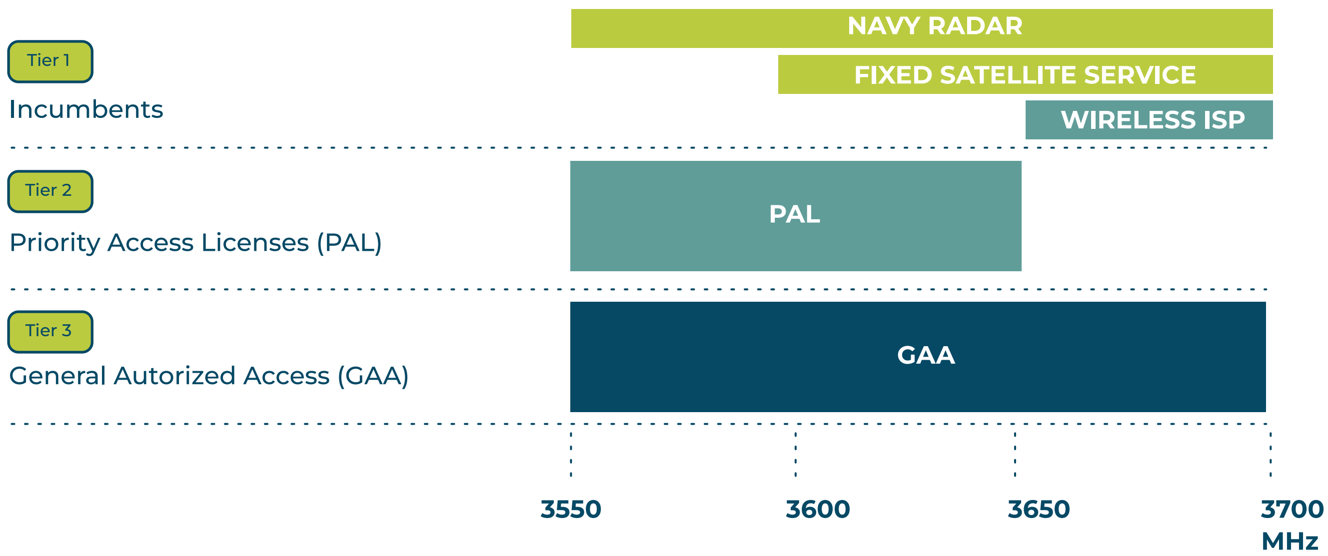


Figure 11: Three-tier coordination in the 3550-3700 MHz Citizens Broadband Radio Service.

With direct and affordable access to spectrum, enterprises and venues can deploy localized networks, including connectivity solutions customized and deployed by end users themselves. The auction for seven PALs in each U.S. county reflected this diversity, raising $4.6 billion from 228 diverse winning bidders–almost 10 times the number of winning bidders as in the subsequent auction for exclusive-use, very large-area licenses in the adjacent 3.45-3.55 GHz band. By automating open access to shared and localized spectrum capacity, a host of new services have emerged. In addition to adding capacity in targeted areas by the public mobile networks, and use of these frequencies by rural wireless Internet service providers (WISPs) in less densely-populated areas, a wide variety of private networks are also using the CBRS band. From business to leisure, hundreds of smart office, airport and stadium private networks have been deployed using CBRS as the result of having access to spectrum without the need for an individual license.

In less than three years (as of February 2023) more than 310,000 CBRS base stations had been deployed across the United States with the vast majority relying on the free-to-use GAA tier. The FCC had certified 187 different CBRS base station models and 496 different end user devices, ranging from traditional smartphones and IoT modules and gateways to security cameras, barcode scanners, and building management sensors.[63] Examples of such private wireless network deployments using the CBRS GAA tier include:

- **Factory Automation:** John Deere, a leading agribusiness manufacturer, uses CBRS to analyze data on welding patterns to train an algorithm on the best welds for future fabrications, and to track equipment and improve operational efficiency;
- **Utilities and Ports:** The Port of Long Beach, California, uses private networks to support automated-guided vehicles moving cargo and to improve real-time logistics;
- **Education:** School districts and libraries use GAA spectrum to close the 'homework gap' by connecting low-income student households directly to school networks;[64]
- **Sports & Hospitality:** The National Football League uses CBRS to provide secure communications between coaches and players and to supplement in-stadium Wi-Fi;

- **Smart Cities:** The City of Las Vegas and NTT announced a partnership to build a city-wide CBRS-based private 5G network as an open platform for local business;

- **Airports:** Boingo is leveraging CBRS at Chicago's O'Hare for a private cellular solution to securely connect enterprise IoT devices and power essential airport services.

CBRS: A Dynamic, Three-Tier Sharing Framework

The primary band incumbent is U.S. Navy radar operating primarily on ships that periodically come in and out of ports and naval bases, or pass close enough to the U.S. coastline that the noise floor in the band (aggregate interference) is an operational concern for the military. As shown in Figure 12 above, other incumbents include a small number of FSS earth stations and temporarily grandfathered fixed-wireless networks. CBRS devices (CBSDs) are required to continuously request permission from a SAS (a "heartbeat") to continue operating under their current channel assignment. These short-interval grants allow the coordination system to be sufficiently dynamic to protect Navy radars, which are mobile. To account for the fact that most Navy radar is operating on ships in motion, an environmental sensing capability (ESC) – a network of spectrum sensors along the U.S. coastline – detects incumbent naval radar use of the band and alerts the SAS to move new terrestrial commercial operations to non-interfering channels.

In a December 2022 report on "lessons learned" from CBRS, the FCC's Technological Advisory Council (TAC) stated that: "Despite nearly three years of commercial operation, there has been no reported interference from CBRS into protected incumbents in the band."[65] The U.S. Department of Defense likewise agreed that the SASs have fully protected U.S. Navy radar operations. In a November 2022 article, DoD official Vernita Harris called CBRS a "win-win situation" since "the U.S. military can continue to use critical radars systems while commercial users have leveraged CBRS in a variety of sectors, ranging from real estate to health care to utilities."[66] Harris went on to state that "[w]ith its use of the SAS, CBRS has eliminated many labor-intensive tasks, reduced opportunities for human error, and enabled over 228,000 CBRS devices (as of May 2022) to operate in the band and not interfere with DoD operations." As noted above, more than 320,000 access points were deployed by early 2023.

The one downside, the TAC concluded, is that "a large number of conservative assumptions are built into the CBRS protection framework (propagation parameters, interference protection criteria, etc.) to the extent that optimal shared spectrum efficiency may not have yet been achieved." As an example, the TAC cited reliance on the Irregular Terrain Model (ITM) to estimate propagation loss does "not take into account attenuation due to clutter, such as [from] buildings and foliage, hence the propagation loss is often underestimated, and predicted interference levels are overestimated."[67]

The dynamic nature of the SAS coordination framework is unprecedented in a number of critical respects:

- Three-tier sharing hierarchy
  The FCC decided, for the first time, to offer both interference-protected access (PALs, which are auctioned) and opportunistic access (GAA) in the same band. As noted above, there is a hierarchy of protection: The SAS protects incumbents against all shared-access users and it protects actual PAL deployments from GAA users. Devices (whether for PAL or GAA use) must be capable of operating across the entire 150 MHz, a requirement critical to this and other dynamic features higlighted here. The SAS can accommodate the enormous potential scale of access points – and efficient spectrum re-use – inherent in a low-power, small cell band that is in demand by both mobile carriers (for network densification) and a wide range of other industries, rural ISPs, indoor/outdoor venues (hotels, sporting arenas, office buildings) and industrial users (for IoT applications).

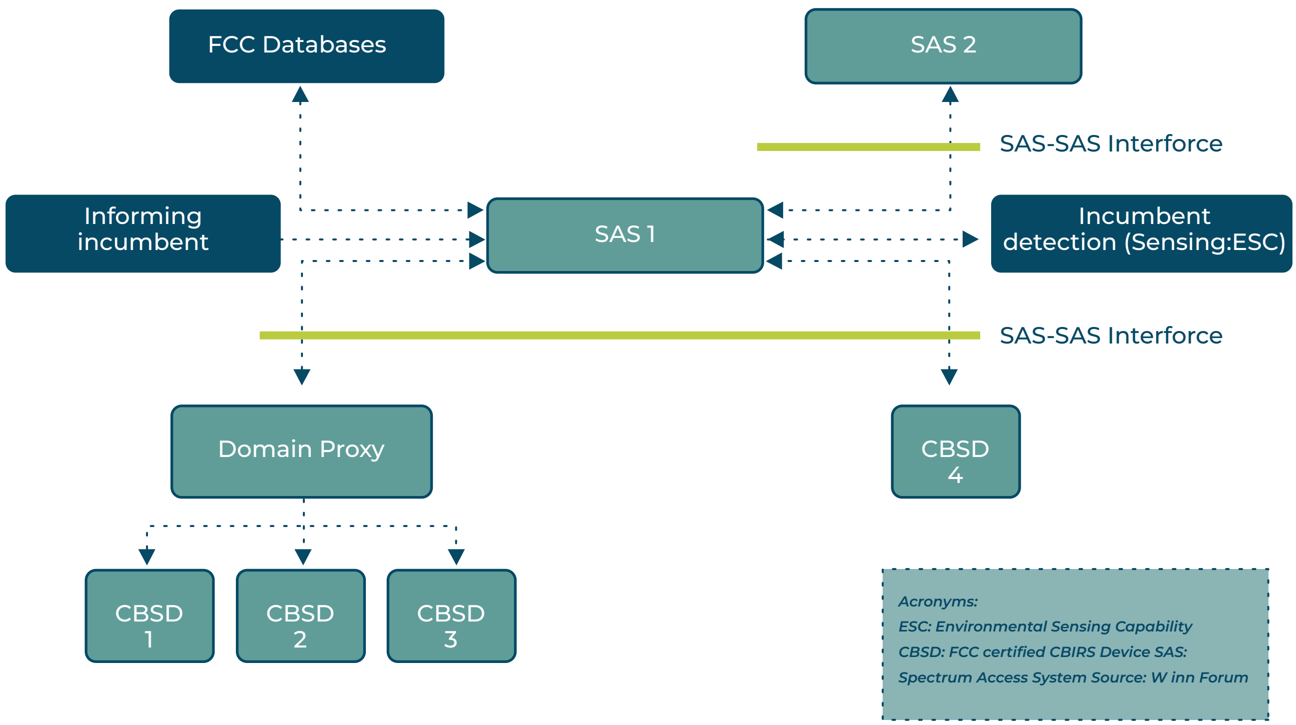


Figure 12: CBRS conceptual framework.

- Sensing network inputs

Notably, the military agreed to share the band, subject to SAS control and a capability to sense their radars, despite concerns related to interference from a higher noise floor and revealing ship locations. The ESC, a coastal network of spectrum sensors, provides each SAS with real-time awareness of naval radar on a channel. Each sensor is associated with a large and fixed geographic protection zone and relays sensing data to the SAS. Device authorizations expire after 300 seconds, which is the required interval from Navy radar detection by the ESC to channel shut down by the SAS (and all devices on the channel within 60 seconds). To address security concerns, the CBRS framework "obscures the actual location of naval radar, at the price of ... excluding more area than necessary to ensure protection."[68] In its recommendations, the FCC's TAC concluded that although ESCs have proven adept at detecting incumbent activity (i.e., Navy radar), "they have the substantial downside of negatively impacting CBRS use in areas within up to 80 km from the sensors."[69] The TAC recommended that primary reliance on sensing networks similar to ESC be avoided, and that a type of Incumbent Informing Capability (IIC) – through which incumbents report their activity or need for protection directly to the DSMS – would be more accurate and less preclusive.

- Dynamic interference protection

As noted above, TVWS database coordination is a static, one-to-one calculation. If the device is outside the protection contour of a TV station or (in the 6 GHz band), outside the protection contour of a fixed microwave link, it is authorized. In contrast, a dynamic frequency coordination system like the SAS takes account of the fact that the "[a]dmission of nodes into the ecosystem changes the entry conditions for future entrants."[70] Each SAS, as they synchronize, is updated to take account of each new grant or termination of permission to transmit. Using this information, the SAS is able to calculate aggregate interference from new commercial users to incumbents and enforce protection of these systems. Significantly, this gives a SAS the capability to manage aggregate interference in specific geographic areas.

The downside of requiring multiple spectrum coordination systems to take account of aggregate interference is that sharing the data and performing calculations on a daily basis can take substantial computing resources and time to complete. Accordingly, the FCC's TAC recommended "simplifying the manner in which aggregate interference is taken into account."[71]

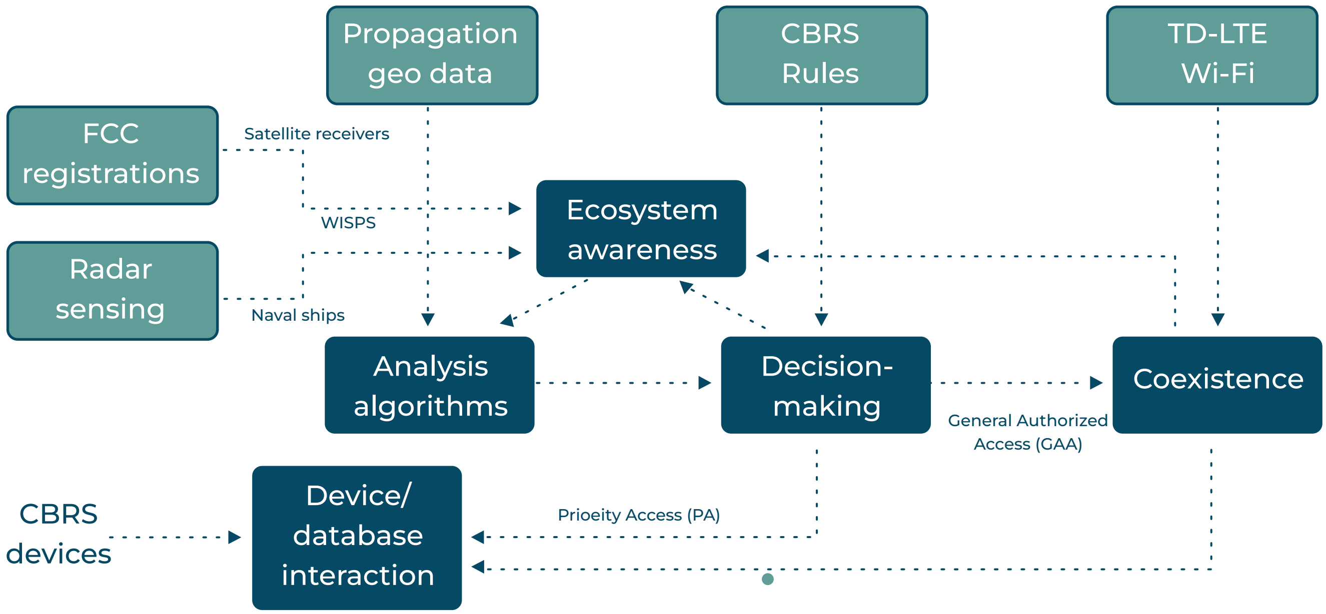


Figure 13: Admission control system architecture for three-tier, FCC-certified Spectrum Access System..

- Opportunistic access to all unused capacity
  Because each SAS has a "map" of all deployments on the seven PAL channels, it can facilitate opportunistic GAA use of vacant PAL spectrum in discrete geographic areas on a "use-it-or-share-it" basis. In the CBRS band, licenses (PALs) ensure interference protection for deployed nodes, but confer no right to exclude opportunistic users (GAA) when and where the spectrum is not in use. This discourages spectrum warehousing and ensures the band is used as intensively as possible, which is particularly important for rural and other less densely-populated areas where PALs may not be fully built out. Each PAL access point declares (or assigned by default) a PAL Protection Area (PPA). The SAS ensures that the aggregate interference at the PPA boundary from other PAL and GAA use does not exceed a set harm threshold.[72] While PALs are limited to seven 10-MHz channels, GAA is authorized across the entire band (150 MHz). When a PAL holder activates a new deployment, any current GAA authorization within the node's PPA is terminated.

- Coexistence optimization to enhance QoS
  Because the SAS has awareness of the transmit power, bandwidth and other characteristics of each CBSD authorized to operate in a local area, it has the ability to make assignments to GAA users that optimize performance and minimize mutual

interference. As Google's Preston Marshall has observed, this "can provide more confidence that a reasonable level of service can be assured . . . and minimize any 'gamesmanship' in the use of the spectrum."[73]

This is very different from self-coordination in a traditional Wi-Fi band, where a crude (but unplanned) coexistence is built into the listen-before-talk capability of devices; and different from TVWS and 6 GHz AFC database coordination, where users are given a list of available channels, but must self-coordinate in relation to other unlicensed users. For example, if there is 80 MHz available for GAA locally, and two users request 40 MHz each, the SAS can optimize by assigning one 3620-3660 MHz and the other 3660-3700 MHz. Further, if one of those users has two PAL channels, the SAS can (barring other considerations) assign a contiguous 60 MHz to that user (from 3600 to 3660 MHz). At its discretion, a NRA could make this either a mandatory or voluntary (value-added) feature of DSMS in a band.

3. THE BENEFITS OF AUTOMATED FREQUENCY COORDINATION

AFC systems yield substantial benefits to industry, regulators and consumers alike. Compared to manual or even database-assisted coordination, automated frequency coordination speeds access to spectrum, promotes more intensive use, better protects incumbent licensees, lowers costs for both operators and NRAs, ensures consistent outcomes, accounts quickly for changes in use of the band or changes in the NRA's rules, monitors spectrum use, and can assist the NRA in both ex ante and ex post enforcement actions.

A. Benefits to Industry, Consumers and the Economy

i. Expands spectrum capacity and efficiency to meet surging demand

Wireless connectivity is, like electricity, a critical input to most other economic activity and rapidly becoming even more pervasive. Demand for both mobile and fixed wireless data is surging while in most nations there are few if any desirable spectrum bands not already assigned and in use for a wide variety of private and public purposes. Total Internet traffic is both increasing substantially each year and shifting disproportionately to wireless devices. As the chart below indicates, Cisco's global survey of internet traffic has long forecasted continued year-over-year growth of 30 percent, with nearly 80 percent of all internet data traffic flowing over mobile (22 percent) or Wi-Fi networks (57 percent) by 2022.[74] Cisco projected that more widespread deployment of 5G will only increase the share of mobile device traffic offloaded onto fixed networks via RLANs and Wi-Fi. Globally, Cisco projects there would be nearly 550 million public Wi-Fi hotspots by 2022, up from 124 million hotspots in 2017, a fourfold increase.[75]

As a result, industry studies continue to project daunting deficits in the availability of both licensed and unlicensed spectrum. A study commissioned by the Wi-Fi Alliance projected a shortfall of between 500 MHz and 1 GHz of unlicensed spectrum by 2025,[76] while a report by CTIA, the U.S. wireless industry association, noted that "wireless traffic per site 'is projected to grow by an adjusted 343 percent' – all of which additional spectrum must be ready to absorb."[77] While wide swaths of spectrum have been reallocated in the millimeter wave bands above 24 GHz, particularly in the U.S., the more valuable mid- and low-band spectrum bands are all assigned and occupied by a wide variety of vital operations in most countries. Even in bands where incumbents can be relocated, in the U.S. clearing a band for reallocation and assignment by auction has taken an average 8.4 years – and 13 years for re-allocated spectrum to actually be deployed for exclusive mobile use.[78]

Although most demand has focused on mobile carrier networks and Wi-Fi use indoors, the growth of fixed-wireless networks is another driver of demand that is also critical to extending high-speed Internet access in rural and other less densely-populated areas where trenching fiber to the home or business is uneconomic. Outdoor PtP and PtMP deployments in unlicensed and shared bands are becoming increasingly critical to extend high-capacity internet into these areas and to provide an alternative to more expensive cable and telco wireline offerings in other areas. Ericsson projects there were at least 100 million fixed wireless access (FWA) connections by the end of 2022, a number that will triple by 2028, reaching over 300 million and 17 percent of total fixed broadband subscriptions.[79]

However, despite the need for high-capacity PtMP in areas where wireline connections are inadequate or uneconomic, there is little if any low- or mid-band spectrum available except in bands where usage potentially can be coordinated with incumbents (such as FSS licensees) that can be protected from interference. While a growing share of these FWA subscribers will be served by a 5G mobile networks on the carrier's own exclusively-licensed bands, thousands of WISPs, fiber and other wireline ISPs (such as cable internet companies operating as Wi-Fi-first MVNOs) need their own spectrum access to complete and improve quality of service.

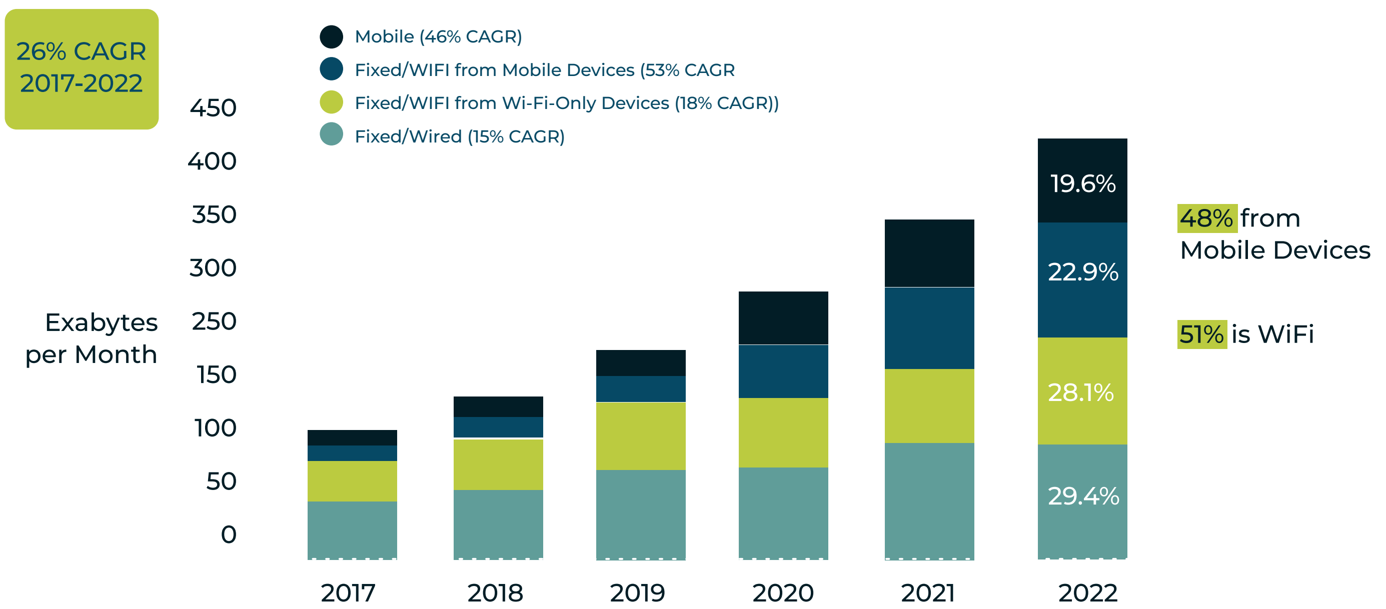


Figure 14: While Internet traffic continues to grow rapidly, compound annual growth rates (CAGR) are highest for Wi-Fi connectivity on mobile devices.[80]

Given the continued rapid increase in demand for spectrum capacity among a widening array of operators for mobile, fixed, unlicensed and enterprise networks, it becomes clear that DSMS can be a critical tool that yields important benefits to industry, consumers and the broader economy for several key reasons:

First, automated frequency coordination promotes more intensive and efficient use of the public resource. It is useful to keep in mind that, in general, it is spectrum access and not spectrum capacity that is scarce. Although many well-established uses of prime spectrum serve critical public needs – such as broadcasting, satellite video distribution, and military radar – only a fraction of the overall data-carrying capacity of many bands is being used on a frequency, geographic, directional or temporal basis.

Second, relative to the surging demand for wireless data, leveraging DSMS to unlock dormant capacity, while avoiding interference to incumbents, is the closest thing there is to a spectrum 'free lunch' for businesses and consumers seeking connectivity at low cost. Opening access to vacant spectrum and facilitating spectrum re-use keeps the cost of wireless connectivity more affordable, which increases consumer welfare both directly (more data for a given price) and indirectly by enhancing the productivity of businesses that rely on wireless data. Current examples include cloud-based services, which for mobile applications require both near-ubiquitous connections and relatively inexpensive data allowances.

Third, advances in dynamic frequency coordination offer far greater potential to make bandwidth abundant. Most spectrum coordination and sharing to date have focused on coordinating the local use of vacant spectrum. However, as frequency coordination databases become dynamic, advances in complementary technologies and techniques give regulators the option to greatly enhance these efficiencies. As discussed in more detail below (Section 5), coordination databases that incorporate real-world details on terrain, clutter (trees, buildings), and other GIS data sets that obviate the need for worst-case assumptions about interference will enable far more intensive spectrum use. An AFC system can also, for many bands, be enhanced with real-time inputs from spectrum sensing networks and/or devices that crowdsource awareness of the local spectrum environment. AI and machine-to-machine learning are likely to further improve performance.

ii. Protects incumbent operations from interference

A basic principle of dynamic spectrum sharing is that the coordination process should have little if any impact on incumbent systems. Accordingly, a foundational benefit of dynamic spectrum management is the consistent ex ante protection of incumbent operations, as well as the ability to remediate any interference that does result. As Google's Preston Marshall describes it, the focus of dynamic frequency coordination is the "prediction, and avoidance, of possible interference, rather than detecting and mitigating the condition."[81] Of course, database coordination is dependent on an accurate reporting of receiver locations and characteristics except in situations (such as Navy radars in CBRS) where spectrum sensing provides the SAS with a real-time proxy for that licensing information.[82] Alternatively, in bands where incumbent activity is periodic or mobile, an incumbent informing capability (IIC) could be preferable (this is described in Section 5 below).

So long as the rules require – and the automated spectrum management system enforces – non-interference, there is little if any cost to incumbents. Incumbents are not necessarily restricted from expanding or changing their location or frequency use, as they would be with a grandfathering approach. In the case of TVWS, for example, the use of an automated database (TVDB) not only protects viewers of over-the-air TV, but it also almost instantly accommodates any future licensing of new TV stations, or the movement of a station from one channel or tower siting to another. More generally, radio propagation modeling is well-established and rapidly becoming more granular as very detailed GIS data on terrain, clutter and other factors enhance the algorithms used by spectrum databases to enforce compliance with interference protection rules.

Primacy in a shared band is particularly valuable for incumbents in a low-value, declining, or less-intensively used band, where continued underutilization of the spectrum may be politically or economically unsustainable. For example, when the U.S. Congress required an auction of the 700 MHz band, TV stations were cleared from the band and relocated below 698 MHz. While the relocation of incumbents remains a viable option in some bands, in other bands sharing – and particularly the sort of intensive sharing enabled by DSMS – obviates the argument that the band is underutilized. [83] In the case of CBRS, the U.S. Navy and military more broadly shifted from opposition to general support for band sharing using DSMS as they felt increasing pressure to relocate or to compress operations into less spectrum, which they viewed as more expensive and disruptive alternatives by comparison.

Of course, there is always some risk of failure in the coordination system, or in individual devices, that could create instances of harmful interference. While there never has been nor will be zero risk of interference, technical and regulatory trends are moving in parallel to both minimize and rapidly remediate such scenarios. One regulatory approach, adopted for TVWS and to facilitate AFC management of unlicensed sharing in the 6 GHz band, are requirements that users register the location and technical characteristics of every access point, that end user devices not registered must be under the control of those APs, and that the permission to transmit must be renewed by the database at defined intervals (generally each 24 hours), allowing any user or device to be shut down quickly. Another approach, incorporated in the CBRS rules, allows satellite operators in the adjacent 3700-4200 MHz band to report any out-of-band interference directly to SAS (database) administrators as a 'backstop' to the automated, ex ante process.[84]

In short, unlike traditional unlicensed sharing (e.g., among Wi-Fi users at 2.4 GHz), dynamic database enforcement permits regulators to revisit and revise the rules that apply to operation of the installed base of devices. The DSMS provides the flexibility to amend protection criteria and algorithms, allowing regulators to respond to real-world experience and data over time without running the risk that devices are beyond recall.

iii. Lowers the cost of connectivity for providers

At the most general level, more spectrum re-use and bandwidth abundance lowers the cost of mobile and fixed wireless connectivity – for consumers and as an input to production for other industries. In addition to increasing the overall supply of spectrum – and reducing thereby the cost of bandwidth – DSMS can lower the transaction costs and delays associated with more traditional mechanisms, including auctions, manual coordination and secondary market transactions.

As the wireless ecosystem transitions from a focus on wide-area coverage to a focus on localized capacity, the number of access points will increase by orders of magnitude. In higher frequency bands, where wide channels enable greater capacity, the most intensive and efficient deployments will rely on small cells. In some bands this may result from a regulatory choice (as the FCC did with CBRS and in 6 GHz to protect fixed link incumbents) or from operator choices based on propagation characteristics and the need to densify existing networks. In shared bands, this scaling can only be achieved cost-effectively by an automated process that does not involve manual calculations, regulatory decision-making or politicking.

Lowering transaction costs for spectrum access lowers barriers of entry, thereby promoting competition, innovation and consumer choice. This benefit is magnified where automated frequency coordination facilitates low-cost access to valuable spectrum on a very localized and/or small-area basis, as described further below.

Another benefit of automated coordination is a substantial reduction in deployment times, including the time-to-market for new innovation, coupled with an increase in operational flexibility. Traditionally, access to licensed spectrum has required either the large upfront capital investments that typify auctions,[84] or a relatively expensive combination of manual coordination and regulatory fees on a site-by-site basis (e.g., for coordinating FS and FSS deployments). In contrast, an automated, flexible (dynamic) and very low-cost coordination process can facilitate a nimbler and more robust wireless ecosystem while lowering the costs of connectivity overall.

iv. Promotes direct spectrum access for innovation and productivity

DSMS is particularly useful for coordinating very localized access to unused spectrum capacity. The need to protect incumbent operations in shared bands typically means that spectrum will not be available over large geographies. Mobile carriers have resisted band sharing for this reason: their business models are based on very wide-area coverage and the efficiencies that flow from exclusive control of a band. As a result, any other enterprise seeking to deploy a network on a more localized or targeted basis has generally needed to either purchase a carrier-offered service or, more frequently, make do with unlicensed spectrum. However, where a band is allocated primarily for capacity (not wide-area coverage) – and particularly where incumbent licensees will retain primary status and require protection – coordinated sharing can best serve the public interest.

Dynamic frequency coordination, both by necessity (to protect incumbents) and by design (to promote more widespread access), has a greater ability to provide direct access to shared spectrum for a diverse range of business firms, small ISPs, critical infrastructure facilities, venues, public institutions and other entities. The advantage is that rural broadband, industrial IoT, private LTE networks, smart city applications, and other innovations can be piloted, customized and deployed on a local basis by the widest range of business firms and community anchor institutions.

The ability to rapidly and inexpensively coordinate spectrum access on a local and even temporary (or temporal) basis will be increasingly beneficial in a 5G/IoT economy where wireless data connectivity will be associated with virtually every system, venue and device – and where many thousands of firms and service providers will have needs and demands for customized networks. For example, while outdoor small cells may be the best use of coordinated access in the urban or suburban core, further out it may be backhaul, while the band could simultaneously support indoor, very low-power local area networks and use cases.[85] The three-tier Citizens Broadband Radio Service, described above, is an example.

B. Benefits to Regulators: Automated Coordination and Enforcement

Automated frequency coordination systems are likely, over time, to allow NRAs to put far more spectrum capacity to use with little or no increase in agency resources. Dynamic database management can give regulators more control over band sharing, better enforcement tools, a greater ability to monitor usage, and the option to outsource technical development and operations to stakeholders – and all while retaining ultimate authority, regulatory flexibility and even the ability to collect fees.

i. An Automated and Scalable Admission and Enforcement Tool

Regulators can choose to create or authorize an automated frequency coordination system to do any or all of the following functions at scale and at low or no cost to the agency itself:

- Collect, ingest and regularly update incumbent information from agency licensing records or as provided by NRA rules;
- Calculate protection contours and other algorithms by applying NRA rules;
- Verify that all registered device are certified in compliance with NRA rules;
- Register verified devices and networks, recording any required data on user identity, location, device type, operating parameters;
- Calculation engine: apply objective algorithms to grant or deny requests for permission to operate for whatever period of time is provided in NRA rules;[87]
- Optimize coexistence among secondary users, if relevant, based on NRA rules;
- Collect any usage or regulatory fees authorized or required by the NRA;
- Capture data and report on actual use of the band, as well as any anomalies that may inform future regulatory action;[88]
- Maintain the ability to identify and shut down a device or provider in cases of harmful interference of emergency;
- Dynamically adjust the device admission or operating parameters (in response, for example, to exceeding aggregate interference threshold in a geographic area);
- Provide a portal for incumbents and/or users to report corrections or updates to licensing data, operating parameters, or to report incidents of interference;
- Address cases where frequency access or operating rules differ among neighboring countries (e.g., differing 5.8 GHz RLAN rules across EU states).[89]

The growing need to accommodate burgeoning demand, smaller cell sizes, and more widespread deployments of local networks by a diverse range of users will push NRAs toward more sharing of underutilized bands. As this occurs, it becomes impractical for regulators to rely on manual coordination or to employ the staff necessary to shoulder all of the functions listed above. Even if possible, it's far faster and more cost-effective to rely on an automated system and focus agency resources on higher value-added activities.

Dynamic spectrum management systems also create capabilities for monitoring and enforcement assistance that NRAs typically do not have, particularly with respect to shared bands. As the ECC advised in relation to TV band databases, NRAs can benefit from "requir[ing] specific interference management functions from the database."[90] ECC Report 236 notes that in the UK, Ofcom requires WSDB providers to incorporate an information system that allows Ofcom to "see the locations and channels used by WS devices at any point in time." Ofcom also requires that WSDBs maintain a 'kill switch' function that enables the agency to "turn down any WS device within a short period of time" at the agency's command.[91] In the U.S. the coordination systems managing CBRS and standard power operations in 6 GHz effectively have this same capability since APs are registered at a specific location. In a band where a priority use requires a high degree of protection, these two features provide regulators with a level of visibility and control they currently do not have in relation to traditionally unlicensed bands.

Finally, DSMS can be used to optimize coexistence among users granted shared access to a band. Because the frequency coordination system has awareness of the spectral environment in each location, in addition to simply deciding the legality of operation, it can minimize interference among all users (both licensed and unlicensed, depending on NRA rules). For example, under U.S. rules for CBRS, users granted opportunistic access (GAA) are effectively unlicensed and not entitled to any interference protection. However, unlike unmanaged unlicensed bands, the SAS can make assignments using algorithms that attempt to optimize the coexistence of multiple GAA users, thereby accommodating the greatest amount of use of both the GAA segment of the band (80 MHz), as well as any locally-vacant channels in the licensed (PAL) portion on a use-it-or-share-it basis. [92]

ii. Coordination can be delegated while the NRA retains authority

One of the great benefits of database-driven frequency coordination, from a regulator's perspective, is that the coordination process can be outsourced while the NRA retains authority over the rules that are applied, including the option to amend them in the future. This approach maintains the NRA's complete authority, conserves agency resources, promotes scalability and private sector innovation, and reduces the risk of regulatory failure. Taken further, as the FCC did after adopting the CBRS, the design and operational details of the coordination system itself can be delegated to a multi-stakeholder group comprised of companies and individuals with the expertise and motivation to operationalize the high-level rules and goals adopted by the NRA. [93] Even if a NRA develops and operates an automated database process internally, this will still promote scalability, consistency and lower costs relative to a manual or case-by-case approach to coordinating assignments in shared bands.

In a report offering guidance for NRA implementation of a regulatory framework for TVWS geolocation database sharing, the EU's ECC described the pros and cons of three options for the implementation of database coordination functions that are applicable to other bands as well:

- The NRA develops and manages the database "much like an online licensing system."
- The NRA outsources the operation to an agency contractor, specifying in detail the tasks the administrator will carry out.
- The NRA qualifies and authorizes commercial database providers that may compete and collect fees from users to offset their costs.[94]

The Report emphasizes that regulators can choose the framework that best fits their situation. It concludes that, where feasible, "[c]ompetition between database providers will be beneficial to end users, as it is likely to drive innovation and give users greater choice."[95] The Report also concludes that although a monopoly database model "may have some efficiency benefits," including a greater likelihood of recovering its costs, a "multiple providers model will have lower risk of regulatory failure in that the NRA would not be attempting to choose the only supplier for a nascent market."[96]

In the United States, it's notable that the FCC has shifted almost entirely to a framework of certifying competing commercial database operators. For example, whereas the agency in the past authorized an industry association (e.g., the American Hospital Association) to coordinate shared use of medical telemetry spectrum among hospitals, more recently the FCC has authorized competing commercial database providers to coordinate shared access in the TVWS, CBRS, in the 70/80/90 microwave fixed link bands, and in the 6 GHz band for unlicensed use outdoors or at standard power. Of course, the large U.S. market is in a far better position to support competing DSMS providers. Particularly at the outset, a NRA may quite reasonably decide to select one DSMS for an initial period and then reassess.

In addition to achieving scalability and consistency without depleting a NRA's limited regulatory budget, the regulator can also minimize the time and cost of adopting rules and overseeing implementation by harnessing outside resources. At the front end, model rules may be available for a band that has already been pioneered by another country. For example, for TV White Space, the Dynamic Spectrum Alliance has published model rules that can easily be customized for local circumstances. [97] In relation to the 6 GHz band, the Open AFC initiative led by Broadcom, Meta and Cisco (described further below) will allow NRAs and new AFC operators in other countries to adapt the open source framework to their own nation's rules and incumbent protection needs.[98]

Another strategy is to adopt high-level rules and encourage industry – including both incumbent and new entrant companies – to engage in a consensus process to develop and recommend more detailed implementation guidance for the new sharing framework. Like the NRA's rules, the output from a multi-stakeholder process should be subject to the agency's ultimate approval and as technology neutral as possible. The FCC leveraged this approach (organized through two diverse industry associations) to harness both expertise and consensus in the development of technical standards for the implementation of both the SAS management of CBRS and, recently, the AFCs that will govern outdoor and standard power RLAN operations in 6 GHz.

iii. Gives regulators more visibility into and control over band sharing

A database-enabled coordination process can give regulators unique visibility into the usage of the band, allowing the NRA to choose to monitor or collect data on patterns of deployment, use cases, occupancy by geography, incidents of interference mitigation, or any number of other variables. Since experience with dynamic sharing remains limited, this visibility into the actual outcomes – combined with their authority to amend the rules and algorithms applied by database operators – should give regulators confidence that they can move ahead with robust sharing parameters and have both the insight and ability to adjust sharing criteria as needed. Dynamic database coordination also allows regulators to adopt incumbent protection criteria that are more service-and-technology neutral, allowing network operators or manufacturers (OEMs) greater flexibility to meet interference protection criteria (e.g., a 'kill-switch' capability or aggregate interference level) through varying and innovative techniques.

More generally, a database-driven DSMS that requires every device to periodically renew its authorization gives regulators the control and flexibility needed to change rules, band prioritizations and even band allocations without the deterrent of rendering devices or infrastructure obsolete. Rule and input changes (e.g., enhanced GIS data) can be implemented through software. So long as devices are required to be capable of automatically altering their power level and other operating parameters in response to the latest database authorization, regulators can adjust a band's spectral environment over time. Protection zones can be reduced or enlarged, aggregate interference limits can be capped, power limits or even time-of-day restrictions can be altered.

This ongoing control over band admission criteria and operating parameters can also be used to move over time from more conservative, over-protective limits on new uses to incorporating new data or technologies that enable more intensive use of a band. An example is a regulator's ability to incorporate more accurate GIS and location data over time. When the FCC initially certified TVDBs to manage access to vacant television channels, it defined static and uniform protection contours around TV transmitters using an over-simplified propagation model (FCC Curve) that only took average terrain height into account. The FCC also limited the maximum power of every device based on a worst-case assumption of device density (rather than allowing the TVDB to take into account actual density). In contrast, a half-decade later Ofcom's rules enabled more intensive sharing by providing TVDBs with pixel-based data that provides far more accurate protection contours based on detailed propagation modeling that takes into account clutter (buildings, trees and other real-world path loss).

iv. Cost recovery

As noted just above, one key benefit of outsourcing frequency coordination to one or more commercial database operators is the NRA's ability to externalize the cost of managing shared access to the band.

Database operators can be authorized to collect "fee for service" revenue to offset costs and potentially make a profit. For example, the NRA could approve a schedule of usage fees that database operators would collect as a routine aspect of the registration and verification process. Although the nature of the fees could vary widely, and can be adjusted over time, it's perhaps most important for the NRA to minimize transaction costs.

Delegating frequency coordination to third-party administrators does not preclude government revenue, if desired. Whether or not the agency faces increased direct costs under the regulatory framework, the fee collected by the database service provider could also include a regulatory or spectrum usage fee. Although the downside of any fee is to deter productive use of the resource – which typically stimulates economic activity more broadly – a regulatory or user fee may be particularly appropriate where the band (or a portion of the band) would otherwise be auctioned. Since band coordinators can collect any needed fee year after year, DSMS can facilitate recurring revenue that could exceed auction revenue over time.

While it is generally efficient for end users to bear the cost, the ECC has observed that "in a license exempt regime, it would be difficult to charge individual end users,"[100] particularly if there is not an end-user device registration requirement. If there is, it may be most efficient to incorporate the fee into the cost of the AP and/or end user device. Even in that case, however, there are alternatives, such as limiting fees to network operators (e.g., based on the number of registered access points), or tying fees to device certification (e.g., require devices to be pre-registered in the database by OEMs or retailers). ECC Report 236 contains a useful discussion of options for a "charging framework" and six principles for cost recovery in the context of spectrum database management.[101]

4. LOOKING AHEAD: DATABASE COORDINATED ACCESS TO 5G SPECTRUM BANDS

As Section 2 above detailed, the use of databases to coordinate frequency assignments in bands allocated for shared use is well established and emerging as a crucial component of the wireless ecosystem. Exploding consumer demand for data-intense applications on mobile devices, coupled with the potential benefits of 5G and IoT, are motivating regulators to look at how dynamic spectrum sharing can unlock unused capacity in occupied-but-underutilized bands.

A. Unlicensed Sharing Across the 6 GHz Bands (5925-7125 MHz)

In 2020 the FCC became the first NRA to authorize unlicensed RLANs to coordinate shared use of four sub-bands (U-NII-5 to U-NII-8 in the channel plan below) that span the entirety of the 1,200 MHz from 5925 to 7125 MHz. In addition to authorizing low-power, indoor-only (LPI) use across the entire band, license-exempt access points can operate both outdoors and indoors at standard power (up to 4 Watts EIRP) in the 5925-6425 MHz and 6525-6875 MHz sub-bands – 850 MHz in total – under the control of an automated frequency coordination (AFC) system.[102] The FCC's 6 GHz rules permit outdoor RLAN access points to operate at "standard power" (same as under current U-NII-1 and U-NII-3 rules for the 5 GHz band) only if they are location aware and able to obtain an updated list of permissible channels and maximum power levels daily from an agency-approved AFC system.

Canada followed suit the following year. In May 2021 Canada's regulator – the Innovation, Science and Economic Development (ISED) department – authorized a contiguous 950 MHz (from 5925 to 6875 MHz) for standard-power use by RLANs, both outdoors and indoors, subject to AFC coordination[103] Like the United States, license-exempt devices can also operate on a LPI basis across the entire 1,200 MHz without database coordination. In its decision, ISED explained that standard-power RLANs "will support improved broadband Internet access for a large number of users in both residential and commercial contexts, including in rural and remote areas. . . . [and] serve existing and emerging high-bandwidth applications in outdoor and indoor high-density venues, such as industrial areas, sporting arenas, and campuses."

6 GHz: UNLICENSED/RLAN ALLOCATION ACROSS BAND SEGMENTS (U.S.)

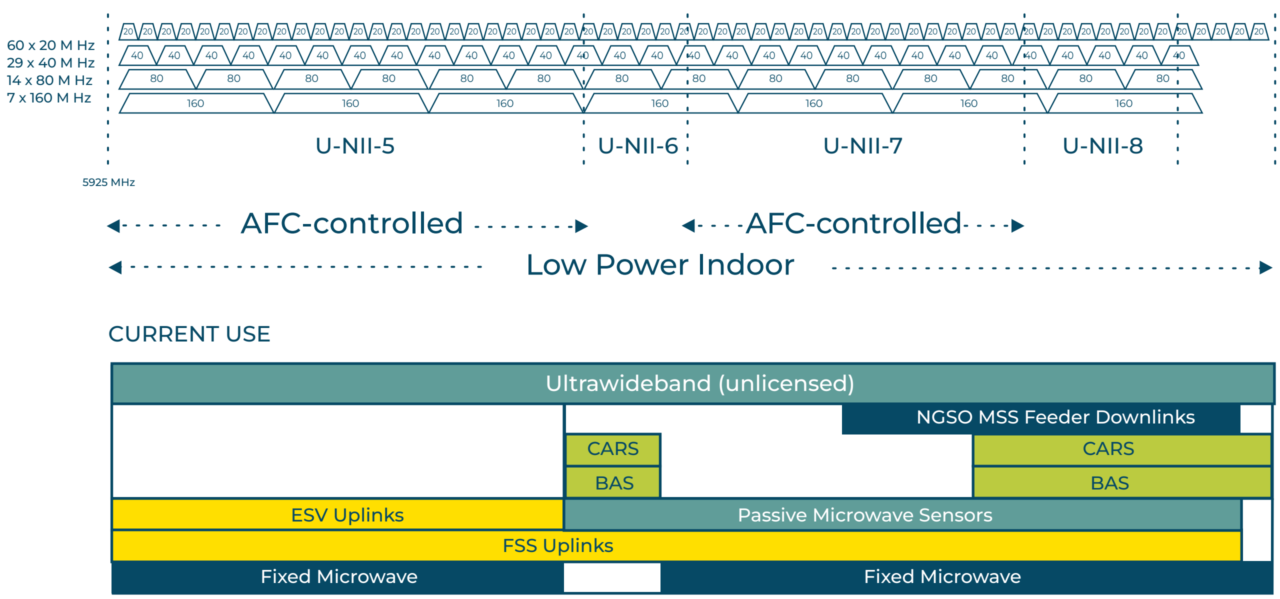
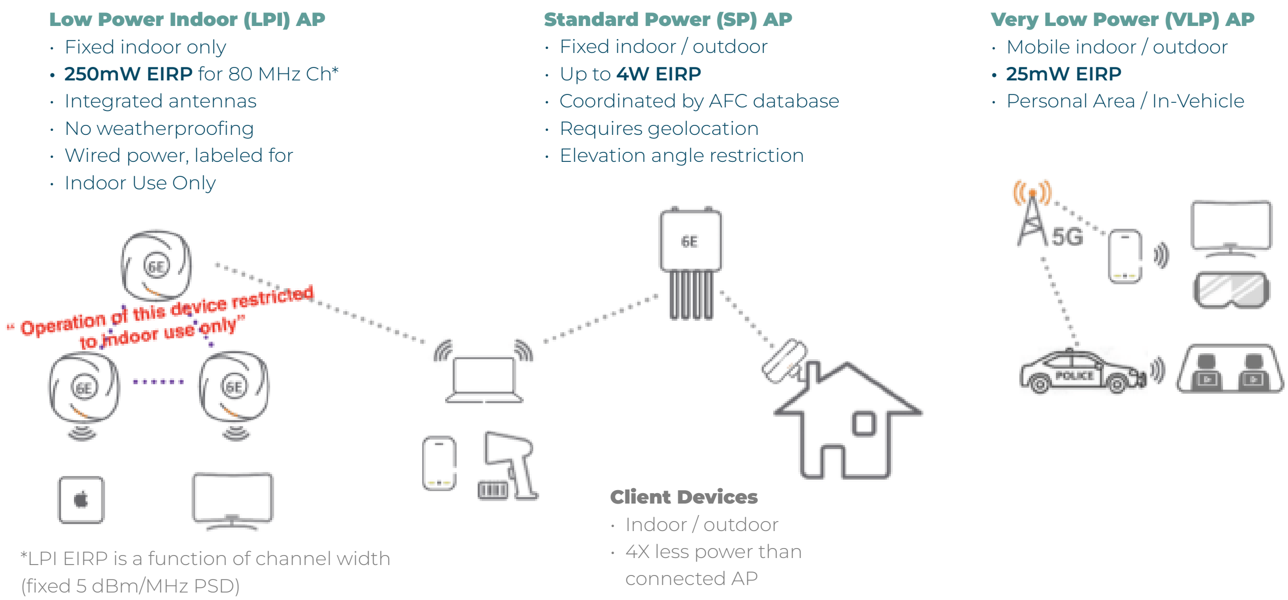


Figure 15. Source: Andrew Clegg, Google

The FCC and ISED are expected to certify multiple AFC system operators and permit standard power (SP) license-exempt devices to begin using the 6 GHz band by the fourth quarter of 2023. In November 2022 the FCC conditionally approved 13 AFC systems, subject to lab and field testing "to verify that they operate in accordance with the Commission's rules."[104] Many of these same AFC system developers are seeking to operate in Canada and other countries, which could speed deployment and reduce costs. Canada issued its decision on technical requirements for AFCs in December 2022 and invited interested parties to apply to become AFC System Administrators (AFCSAs).[105]

Other countries, including Brazil, the Kingdom of Saudi Arabia and South Korea have similarly adopted the entire 1200 MHz for licensed exempt devices and have proposed to permit standard power SP operations under AFC management across the entire band. In late February, 2023, Brazil's ANATEL closed a consultation requesting comment on its proposal to authorize license-exempt operations at SP for outdoor use under AFC control across the entire 6 GHz band.[106] In the Asia-Pacific region, Australian regulator ACMA and Malaysian regulator MCMC both asked specific questions about SP use and AFC coordination as part of their consultations on unlicensed operations in the 6 GHz band.

The Three Device Operating Modes in 6 GHz



Source: HPE Aruba Networks

In Europe, in November 2020 the EU's Electronic Communications Committee (ECC) approved the operation of WAS/RLANs in the lower portion of the 6 GHz band, from 5925-6425 MHz.[107] This initial authorization is limited to access points operating indoors at low power (a maximum EIRP of 23 dBm) and to very low-power (VLP) devices authorized for portable use both indoors and outdoors at a maximum EIRP of 14 dBm. The original EC mandate, which led to the initial authorization of 500 MHz for low-power, indoor (LPI) use, observed that "[b]etween 500 MHz and 1 GHz of additional [license-exempt] spectrum in various world regions may be needed to support expected growth in WAS/RLAN usage by 2020 . . . [and] support wide channels which are required for a growing number of applications which need a large bandwidth to achieve Gigabit speeds." [108]

In June 2022, the ECC went further and approved a work item to study the feasibility of higher power RLAN operations (up to 4W EIRP) in the 6 GHz band utilizing a "dynamic spectrum access coordination function," that is expected to provide similar capabilities to the AFC systems being certified in the U.S. and Canada. The Working Group (SE45) is tasked with studying and reporting to the ECC "technical conditions to enable the possible implementation of a dynamic spectrum access coordination function for WAS/RLANs in the 5945-6425 MHz frequency band . . . in a range of power levels up to 4 W e.i.r.p."[109] The target date for the report is May 31, 2024. In parallel, the ECC also tasked ETSI, the European standards body, to study "the feasibility of introducing a dynamic spectrum access coordination function" and "[p]ropose a regulatory framework to enable European and/or national implementation."[110]

EU Channel Allocation for lower half of the 6 GHz band (5925-6425 MHz)

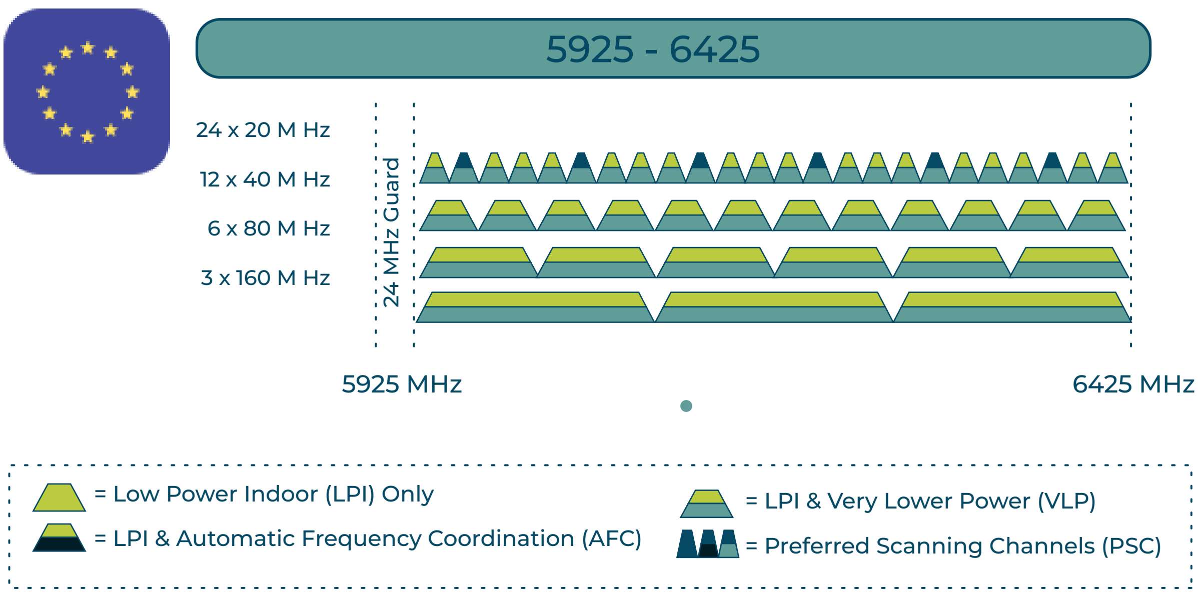


Figure 16. Source: HPE Aruba Networks

Of course, even if the EU ultimately authorizes SP operations limited to 5925-6425 MHz, European consumers and businesses will not have the contiguous wide channels needed to take full advantage of the capabilities of next generation Wi-Fi 6E and Wi-Fi 7. In particular, Wi-Fi 7 is designed to utilize 320 MHz channels that allow users to benefit from emerging applications – such as Augmented Reality and Virtual Reality (AR/VR) – with capacity needs that extend well beyond traditional internet connectivity. An Intel simulation study of the spectrum needs for Wi-Fi 7 "demonstrated that in moderate to high traffic load environments (e.g., enterprises, industrial plants, homes, hotspots) the availability of a single 320 MHz channel is insufficient . . . [I]f regulators only authorize the lower 500 MHz of the band . . . a significant number of moderate to demanding future applications will not function as intended and therefore residential, enterprise, government and industrial IoT users will not benefit from these emerging applications." [111]

How AFCs Enable Standard Power Operations and Protect FS Incumbents

AFC systems are designed to provide channel availability and power limits to license-exempt devices, while ensuring that incumbent systems, including fixed point-to-point microwave links, are protected from interference. Because the incumbent PtP microwave links are fixed, highly directional, and seldom change location or operating parameters, license-exempt operations at standard power outdoors and indoors can be coordinated by an AFC system that is substantially simpler that the Spectrum Access Systems that govern access to the U.S. CBRS band. The FCC and ISED concluded that an AFC can readily protect the roughly 100,000 Fixed Service (FS) PtP microwave links by calculating and enforcing a three-dimensional protection contour around each link's receive points (see Figure 17 below).

AFC Incumbent Protection

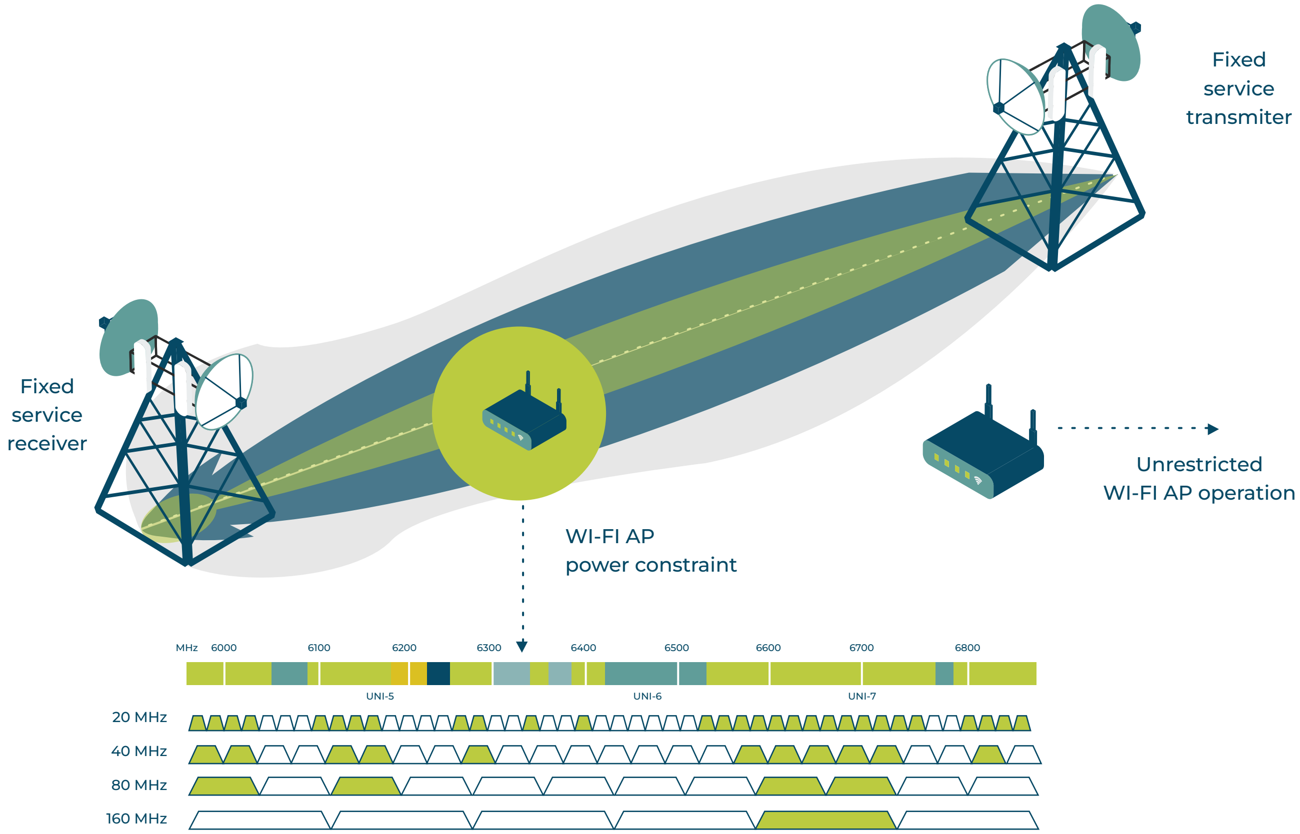


Figure 17: The AFC system enforces 3D protection contours to avoid RLAN interference to Fixed Service receiver operating on 6300-6330 MHz in this example. Contours vary based on low gain (UH6) vs. high gain (UH12) antennas.[112]

Like the TV Bands Database, the AFC is simply enforcing protection zones around static incumbent links based on incumbent-provided licensing data that will be continually updated. A grant to operate a Wi-Fi access point at a location is therefore a one-to-one calculation that is easily verified based on incumbent data.

Under the rules adopted by the U.S. and Canada, each SP access point is required to report its geolocation and location uncertainty, with a confidence level of at least 95%, to a certified AFC system. The AFC system authenticates the device and combines this geolocation information with propagation modeling and other data. The three-dimensional protection contours calculated by an AFC incorporates awareness of terrain and local ground clutter as well as the actual antenna in use by each incumbent receiver (e.g., high gain, low gain).[113] The AFC system calculates whether an AP at any location and height within the uncertainty region of an incumbent receiver could cause harmful interference. For each incumbent receiver, and for all positions and heights within the device uncertainty area, the AFC system uses a database lookup to determine the channels and permissible power limit at which the device can operate without causing undue risk of harmful interference.

The fact that multiple channels may not be available at a particular location makes it even more important that NRAs authorize very large blocks of contiguous spectrum for SP use. In this regard, Canada has so far the most productive rules, since ISED has authorized 950 contiguous MHz for SP use outdoors or indoors.

The diagram below (Figure 18) illustrates key elements of the AFC system architecture. Prior to transmitting, SP access points are required to check with an AFC system once every 24 hours for a list of available frequencies and associated maximum power levels at a specific geographic location. When an authorized and authenticated device queries an AFC for spectrum availability, the AFC assesses which incumbent receivers have the potential to receive excess energy from the license-exempt device based on its location and potential transmit power. The AFC calculates the availability of different size channels at a variety of power levels so that SP access points are able to select the optimal available channel and transmit power level combinations for its location. Under U.S. and Canadian[114] rules, AFC systems must be capable of determining the available frequencies in steps of no greater than 3 dB below the maximum permissible power of 36 dBm EIRP, and down to at least a minimum level of 21 dBm.

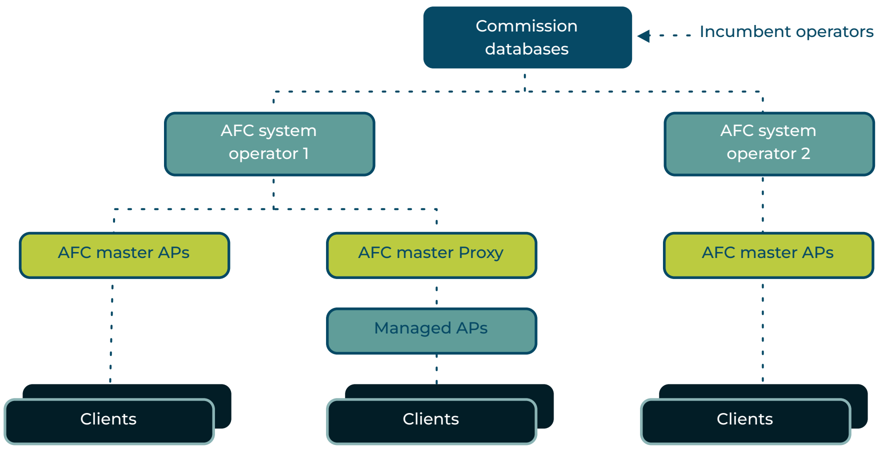


Figure 18: Simplified architecture for Automated Frequency Coordination in 6 GHz band.

The device must check in with the AFC daily to determine if any changes to incumbent use of the band have occurred that would alter the channel and transmit power options available to it. Likewise, the AFC system operators are required to update information on incumbent receivers stored in databases maintained by the FCC on a daily basis, ensuring the most accurate data is used to calculate and enforce protection contours sufficient to protect PtP links. Requests to operate are denied for any frequency where the RLAN's emission would exceed an interference threshold into any individual incumbent link. Automated frequency coordination allows incumbent services to add sites or modify their networks, since FCC databases will continue to be updated by incumbents as they do now and RLAN channel permissions expire automatically if not renewed within a period provided in the FCC's rules.

Because the incumbent radios licensed in the 6 GHz band are fixed and change very infrequently, the coordination process for the 6 GHz band will be simpler and more streamlined than the dynamic SAS used to coordinate sharing with Navy radar in the 3550-3700 MHz CBRS band. AFC system implementation can also be lightweight because the new shared-access users will be unlicensed with no first-in rights or expectations of interference protection. And although the accuracy of AFC-calculated protection areas will depend on information provided by band incumbents, the FCC addressed this by aligning incentives so that incumbents (who enjoy free use of the 6 GHz band) cooperate to the degree they are concerned about interference: "[W]e believe that licensees have significant incentives to maintain the continued accuracy of data in ULS to ensure that they are protected from harmful interference. We also note that licensees have an obligation to keep their information filed with the Commission current and complete." [115]

B. Opportunistic Coordination and Local Shared Licensing in the C-Band (3700-4200 MHz)

Beginning with the United Kingdom in 2019, more than a dozen NRAs have adopted a version of local shared access licensing to allow industry verticals and other smaller spectrum users to coordinate the use of vacant spectrum in the 3.7 – 4.2 GHz C-band to the extent it does not cause harmful interference to incumbent FSS or fixed PtP operations. Germany, Sweden and other NRAs have adopted variations of this framework (see chart below). In May 2023 the Canadien regulator adopted a shared local licensing framework for the 3900 MHz band (and for portions of the 26, 28 and 38 GHz bands) that the agency plans to coordinate using an automated database system.The goal has been to provide local access to spectrum for a more diverse range of users while also ensuring, through coordination and licensing, a more certain interference environment than is typical when enterprises rely on unlicensed spectrum bands.

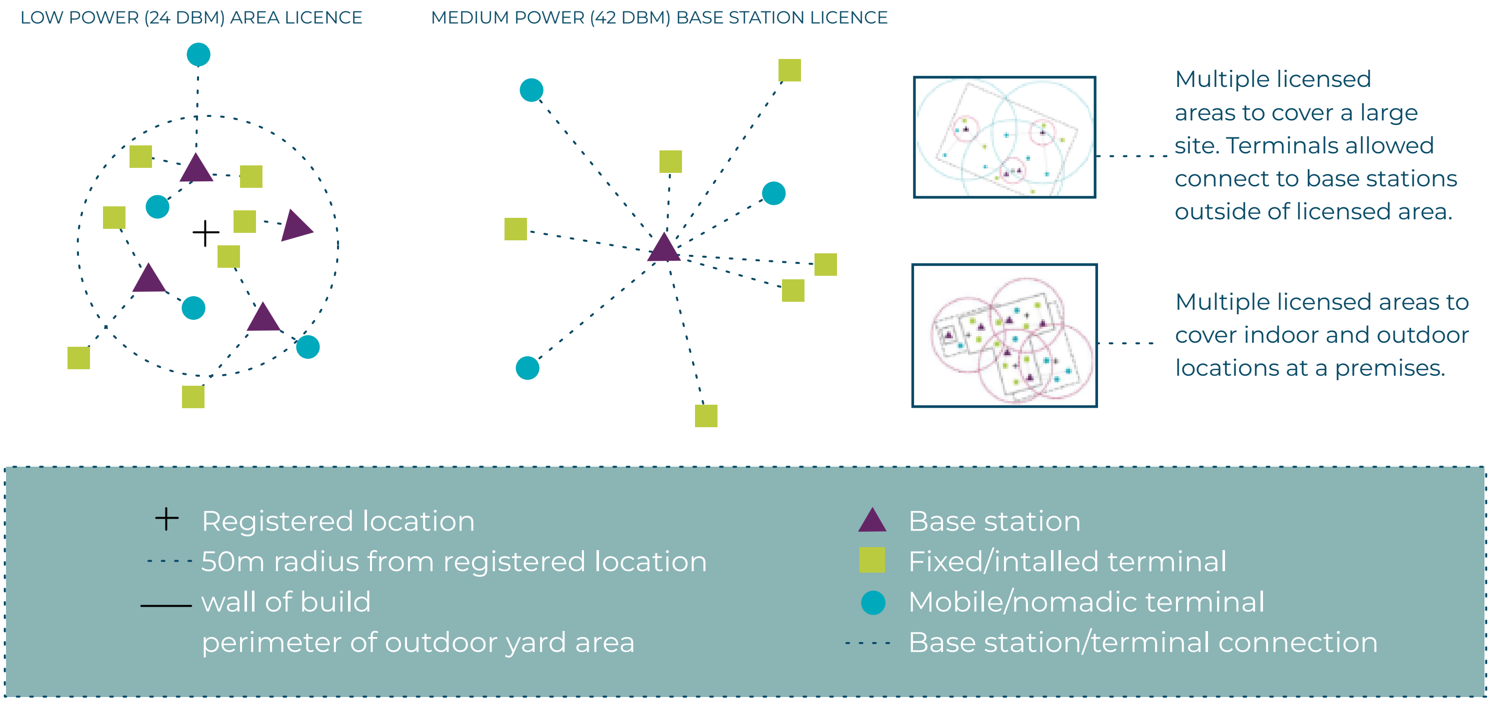
As the European Commission stated in its 2021 mandate to study a broad adoption of this approach under common technical rules: "The deployment of reliable and resilient wireless local-area connectivity is increasingly becoming a necessity for business-critical industry processes, such as related to automated manufacturing in smart factories."[116] In adopting its framework, Ofcom similarly noted that intended users include "manufacturers connecting machinery wirelessly, farmers connecting agricultural devices such as irrigation systems and smart tractors wirelessly, enterprise users setting up secure private voice and data networks within a site, as well as rural wireless broadband connectivity using fixed wireless access (FWA)."[117]

Countries Authorizing Portions of 3.7-4.2 GHz for Local Shared Access

Germany	3.7–3.8 GHz (verticals)
United Kingdom	3.8-4.2 GHz (Shared Access Licenses)
Netherlands	3.4-3.45 and 3.75-3.8 GHz
Sweden	3.72-3.76 GHz
France	3.8-4.0 GHz
Denmark	3.74-3.8 GHz
Brazil	3.7-3.8 GHz
Australia	3.7-3.8 GHz (remote areas), 3.8-4.0 GHz
Japan	4.6-4.8 GHz
South Korea	4.6-4.7 GHz
Canada	3.90-3.98 GHz
Bahrain	3.8-4.2 GHz
Saudi Arabia	4.0-4.2 GHz (under consideration)
UAE	4.0-4.2 GHz (under consideration)

In the United Kingdom, Ofcom in 2019 adopted a framework to authorize coordinated shared access to vacant C-band spectrum from 3.8 to 4.2 GHz for both mobile and fixed terrestrial broadband use on a localized basis, including for indoor use.[118] Ofcom had correctly anticipated that "users (particularly smaller spectrum users) are likely to want simple and cost-effective access to spectrum and a managed interference environment, beyond what can be achieved using license exempt spectrum."[119] According to Ofcom, as of year-end 2022, more than 1,600 Shared Access Licenses (SALs) have been issued.[120] The agency also designated smaller amounts of shared access spectrum for mobile use at 1800 MHz, 2390-2400 MHz and (for indoor-only use) at 24.25 – 26.5 GHz.

SHARED ACCESS LICENCE: LOW AND MEDIUM POWER



Source: Ofcom [121]

The Ofcom framework permits both mobile and fixed wireless networks to coordinate shared use of vacant channels on a co-primary basis with incumbent FSS earth stations and fixed P2P licensees. Two types of licenses are granted for three-year terms: First, a small-area, low-power license with a radius of 50 meters; and a medium-power license, initially limited to rural areas only, authorized on a per base station basis and defined with respect to maximum transmit power (42 dBm).[122] Users can aggregate contiguous low-power licenses over a larger area under a single authorization (see diagram below). Similar to the FCC's CBRS band, the use cases envisioned include private LTE and 5G New Radio networks, including for indoor enterprise (e.g., neutral host and IoT networks), as well as fixed wireless PtMP networks covering a larger outdoor area.[123]

Currently, access to spectrum by new users is "coordinated by Ofcom and authorised through individual licensing on a per location, first come first served basis."[124] The agency proposed that its licensing fee (£950 per license) will need to reflect "the cost of the specific coordination IT system specifically developed for this product."[125] Helen Hearn, Ofcom's Spectrum Director, stated recently that longer-term Ofcom's goal is "to automate much of the Shared Access licensing process to allow users to better serve themselves. Automation should significantly reduce the time taken for licensees to receive their licences from weeks to a matter of hours or even minutes."[126]

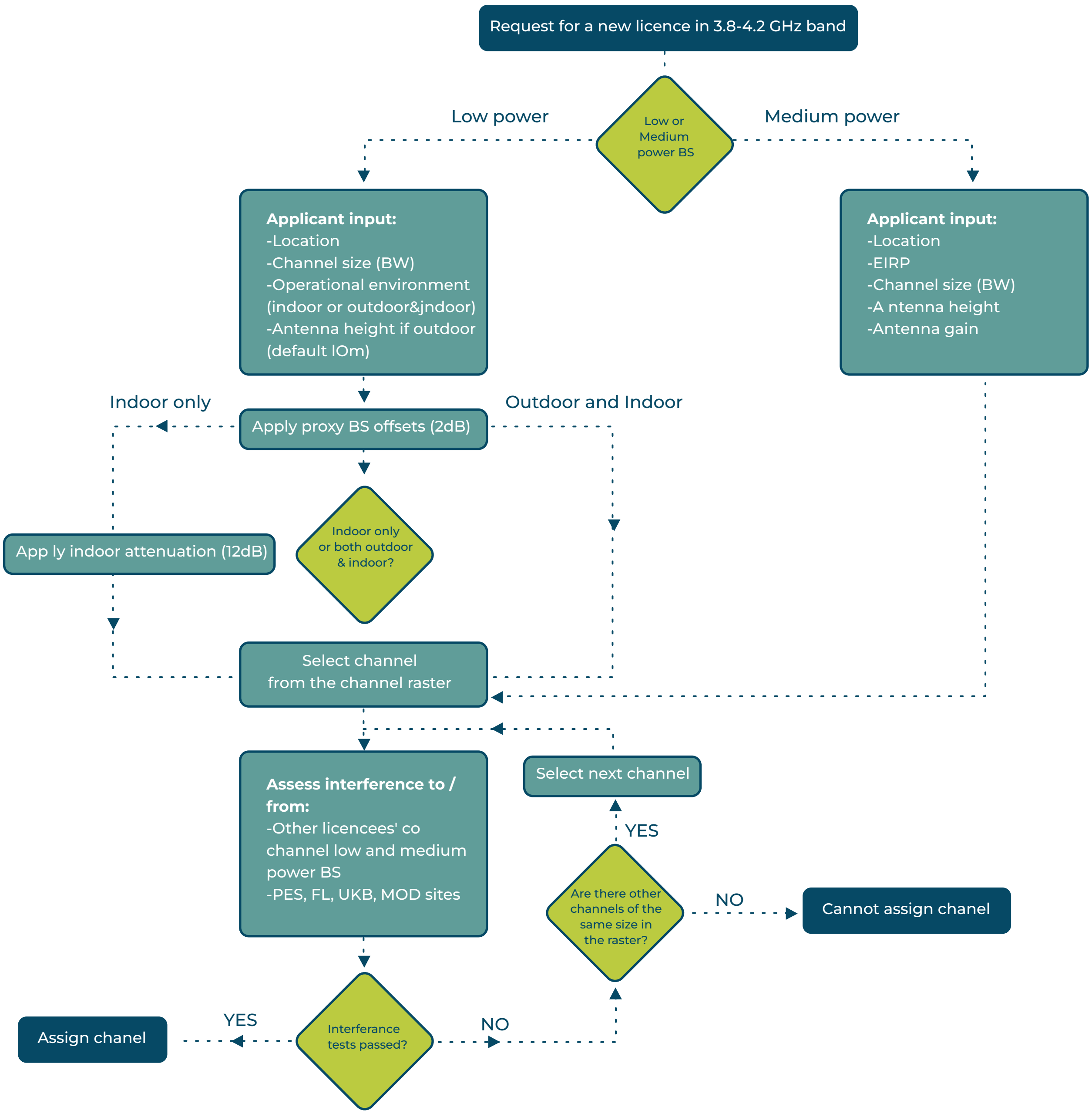


Figure 19: Ofcom's coordination approach for low- and medium-power shared access to 3.8-4.2 GHz band.[125]

In the EU, at least five NRAs have already adopted local shared access to at least some portion of the 3.7-4.2 GHz band, paving the way to broader adoption under what regulators hope are common rules. As noted above, the European Conference of Postal and Telecommunications Administrations (CEPT) is pursuing a 2021 mandate to study a common harmonized study to encourage implementation while protecting incumbent services.[128] The CEPT mandate notes that that EU's 5G for Europe: An Action Plan "identified a need for coordinated action at Union level, including the identification and harmonisation of spectrum for 5G to serve innovative business models and solutions for locally licensed access to spectrum."Accordingly the mandate asks CEPT to "assess the technical feasibility of the shared use of the

3.8-4.2 GHz frequency band" with a "focus on vertical users and other terrestrial wireless use cases" and "harmonised technical conditions for the shared use of the band."[129] A final report is expected in March 2024.

3.7 – 4.2 GHz in the U.S.

In the U.S., the consolidation of FSS in the C-band and the resulting auction of 280 MHz that brought $84 billion to the U.S. Treasury began with a proposal for coordinated sharing very similar to what Ofcom initially adopted. Prior to that 2021 auction the spectrum between 3700 and 4200 MHz was dedicated almost exclusively to video and data downlinks used by more than 20,000 registered FSS earth stations, most of them receive-only. A proposed rulemaking adopted unanimously by the FCC in July 2018 proposed to both consolidate FSS use of the band, freeing up a portion for auction, and to authorize coordinated shared access by fixed wireless broadband operators to at least a portion of the C-band that will continue in use for FSS incumbents.[130]

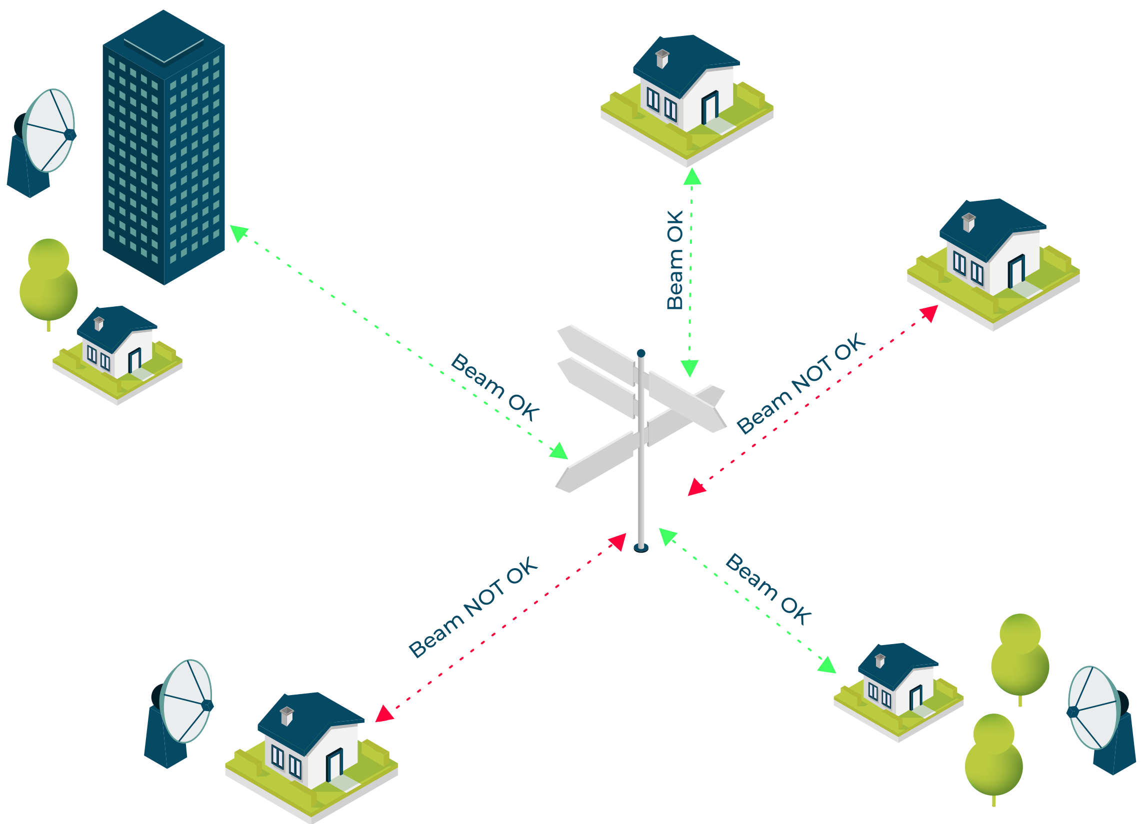


Figure 20: Automated frequency coordination of directional PtP fixed wireless with FSS earth stations. Unlike mobile use, fixed PtMP is inherently directional and can be sectorized to coexist with FSS.

The Fixed Service is co-primary in the band, but barely over 100 PtP links had been coordinated due to a presumption that earth stations are protected over very large geographic areas for use of all 500 MHz across all visible satellite transponder slots (a "full-band, full-arc" protection policy adopted a half-century ago when spectrum above 3 GHz was plentiful).[131] Coexistence between fixed wireless access (PtP and PtMP) and FSS is possible since, unlike mobile use, fixed PtMP is inherently directional and can be sectorized to share without interference to FSS earth stations. [132]

To make coordination possible, the FCC proposed to protect earth stations from interference for only those frequencies and antenna elevation angles they verify are in actual use, ending “full band, full arc” warehousing of vacant spectrum capacity.[133] After observing that the current, manual coordination process for new fixed PtP links in C-band is slow and expensive, the Commission sought comment on adopting “an automated coordination process for point-to-multipoint FS applications.”[134] The NPRM also proposed to protect only registered earth stations that provide the information necessary to coordinate shared access and to disclose actual use of specific transponders and corresponding frequency ranges by each individual antenna at earth station sites.

Ultimately, the leading FSS incumbents (Intelsat and SES) proposed as an alternative that they could voluntarily consolidate their operations in 200 MHz of the band above 4000 MHz in exchange for “incentive payments.” The FCC agreed that it could do this using the incentive auction authority granted by Congress in 2012 to clear TV broadcasters from the 600 MHz band. In March 2020 the Commission adopted an order that led to reallocating 3700-4200 MHz, auctioning 280 MHz, requiring winning bidders to reimburse incumbents for billions of dollars in transition costs and incentive payments, and deferring any consideration of the original proposal to coordinate local sharing of the remaining 200 MHz with ongoing FSS use.[135]

C. Coordinated Sharing in 42 GHz and with Government Users in 37-37.6 GHz (U.S.)

As part of its broader “Spectrum Frontiers” initiative to allocate millimeter wave spectrum above 24 GHz for 5G mobile and fixed operations – primarily by auction – the FCC also set aside 600 MHz of spectrum at the bottom end of the 37/39 GHz band (from 37 to 37.6 GHz) for non-exclusive and coordinated sharing between federal and commercial users on a co-primary basis.[136] Federal operations are currently limited to 14 military bases and several locations used by the NASA space agency.

After initially deferring a decision on the unallocated 42-42.5 GHz band, the FCC in June 2023 proposed to authorize coordinated shared access to the band for fixed wireless access (point to multi-point), possibly as part of a common and DSMS-coordinated sharing framework with the lower 37 GHz band.

In 2016 the FCC initially determined access to the 37 GHz band will be licensed by rule (registered, but non-exclusive) and managed “through a coordination mechanism, which it would develop more fully through government/industry collaboration.”[137] Although there is some commercial use of the band for fixed point-to-multipoint broadband (most of it for line-of-sight fixed wireless to multi-tenant households), 37-37.6 GHz is manually coordinated under temporary experimental licenses (STAs) while the FCC works out the details of a general coordination mechanism with incumbent federal users.

The FCC envisions “a first-come-first-served licensing or registration scheme, in which actual users have a right to interference protection, but no right to exclude other users.”[138] Intended uses of the band include point-to-point links (e.g., for backhaul and backbone links); PtMP fixed wireless broadband systems; single base station IoT-type systems (for example, in a factory); “and carrier-based deployments of mobile systems using the Lower 37 GHz Band as supplemental capacity.”[139] To facilitate sharing and lower device costs, the FCC (as it did for CBRS) required devices to be operable across the entire 37 GHz band.

The FCC proposed in June 2023 to authorize local shared use of the currently unused 500 MHz in the 42-42.5 GHz band for terrestrial broadband, possibly under the sharing rules that will govern the lower 37 GHz band. Before the FCC's unanimous vote on the proposal, Chairwoman Jessica Rosenworcel stated: “It could involve non-exclusive nationwide licenses that leverage a database to facilitate coexistence. It could also entail site-based licensing. To get even more out of this effort we ask if our approaches could be combined with shared-used models in other spectrum bands, like the lower 37 GHz band”.

Site-based registration could be coordinated at first through a simple, semi-automated coordination system and evolve into a fully-automated, database-coordinated system over time (based on multi-stakeholder input, including from Federal agency users). To register a site, licensees would file "specific information about each site sufficient for a third-party coordinator to conduct an interference analysis," including its location, height above ground level, EIRP, transmitter azimuth, and channel size. [140] The coordination system would conduct an interference analysis under which previously registered sites would be protected at a modeled receive signal strength specified in the FCC's rules. Using DSMS, an operator could receive a near-immediate response, making the system far faster and less costly than traditional fixed service link or site coordination processes. The coordination mechanism could also be used to enforce the construction (build-out) requirements and could evolve over time to add enhancements that increase the efficiency of the band.

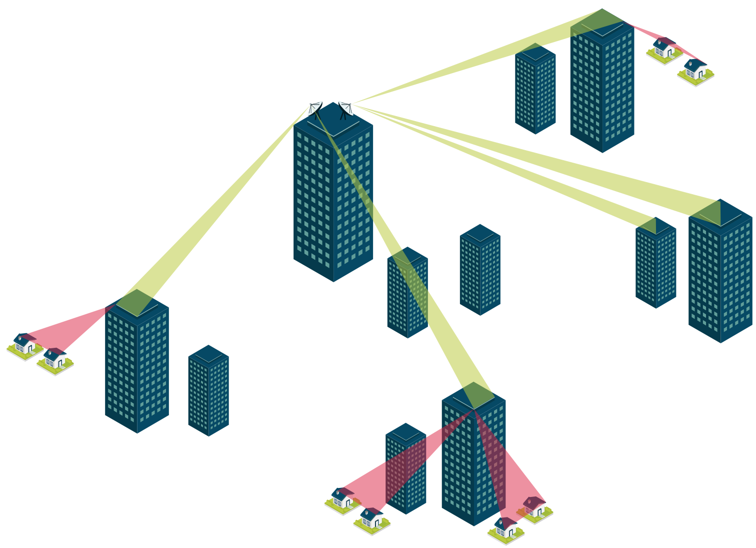


Figure 21: Fixed wireless access using database-enabled frequency reuse in millimeter bands

D. Coordinated Sharing for Fixed Wireless Access in the 10 and 12 GHz bands (U.S.)

While new bands for IMT garner the most attention, in the United States the FCC is also considering the use of DSMS to coordinate more intensive sharing of underutilized upper-mid-band spectrum for fixed point-to-point (PtP) and point-to-multipoint (PtMP). Active proceedings are pending on two adjacent bands that together comprise more than 1000 MHz. One is the 12.2 – 12.7 GHz band, which is currently used on a co-primary basis as a satellite downlink band for constellations of LEO satellites (part of the larger 10.7-12.7 GHz allocation) and for digital broadcast satellite (DBS) TV service. The adjacent 12.7-13.25 GHz band is far less occupied, although nomadic Broadcast Auxiliary Service incumbents and other uses are longstanding licensees. A third apparently underutilized band, at 10-10.5 GHz, is used for military radar.

The FCC initially requested comment and data on whether mobile 5G (IMT) could coexist with satellite incumbents in the 12.2 – 12.7 GHz band. [141] After a long comment period that included engineering studies from various parties, the FCC tentatively concluded (as of March 2023) that mobile devices cannot coexist with NGSO receivers. The agency is still considering whether a coordination mechanism could allow FWA to operate on a secondary, coordinated basis. In its Notice of Proposed Rulemaking, the FCC stated that the 12 GHz band could "support opportunistic use of unused spectrum on a localized basis, such as for high-capacity fixed wireless in rural and less densely populated areas."[142] Rural broadband and digital divide advocates argue that open, coordinated access to unused spectrum in the 12 GHz band would provide rural ISPs and other entities with the spectrum-for-infrastructure they need to expand broadband services and help to bridge the digital divide.[143]

In 2022 the FCC opened a Notice of Inquiry requesting comment on whether the adjacent 12.7 – 13.25 GHz band can be more intensively shared or even reallocated to promote terrestrial broadband use.[144] The band is lightly-used by broadcast auxiliary services, cable TV relay service, FSS and fixed microwave services. As in the CBRS band, a major advantage of opening the 12.7 GHz band for coordinated shared use on a secondary basis is avoiding the costly, disruptive and lengthy process associated with clearing and moving incumbents in the band. Moreover, a shared, open-access framework similar to CBRS could provide spectrum on a very localized basis to meet the growing need for more wide-channel spectrum for enterprises and for fixed wireless ISPs, particularly in rural, tribal and other underserved communities.

In August of 2022, a group of stakeholders focused on closing the rural digital divide filed a Petition for Rulemaking asking the FCC to authorize coordinated shared access to vacant spectrum in the 10 GHz band (10 – 10-5 GHz), a band believed to be used exclusively by the U.S. military for radar applications. The Wireless Internet Service Providers Association (WISPA) and other parties explained in the Petition that the rapidly increasing demand for high-capacity, fixed wireless broadband service in rural, tribal and other less densely-populated areas requires substantially more upper mid-band spectrum to support point-to-point (PtP) and point-to-multi-point (PtMP) deployments.[145] Although the military briefly considered and rejected sharing the 10 GHz band a decade ago, that was prior to CBRS and the Defense Department's public embrace of dynamic database coordination as proving to be effective in protecting radar operations.[146] The Petition remains pending.

E. Database-Assisted Satellite Sharing

A future frontier in database-coordinated spectrum sharing will focus on satellite bands, including coordination among divergent satellite networks. A useful overview is found in a 2017 IEEE paper that summarizes a comprehensive study carried out as part of the European Space Agency's Advanced Research in Telecommunications Systems program. The paper notes that in response to surging demand for more broadband access and bandwidth, "[t]he satellite industry is currently undergoing a major transformation due to the rapid technological advances in small satellite systems and very high throughput satellite systems, as well as the trend of moving from broadcasting to broadband connectivity."[147] This transformation parallels developments in terrestrial wireless networks and will intensify the need to make more intense use of existing satellite bands. "The reason why database approaches have been proposed for satellite communications is basically the same as for terrestrial systems: databases provide better protection to incumbent users," or higher priority users, particularly in "highly dynamic spectrum sharing scenarios."[148]

The European Space Agency study identified four potential spectrum sharing scenarios:

(a) two satellite systems sharing the same spectrum (e.g., sharing between geostationary orbit (GSO) and non-geostationary orbit (NGSO) satellite systems);

(b) satellite system as a secondary user of spectrum (e.g., satellite terminals exploiting spatial separation to share with fixed terrestrial microwave links);

(c) extension of a terrestrial network through coordination with a satellite network (e.g., a collaborative LTE network that extends coverage in rural areas); and

(d) expanded secondary use of the satellite spectrum by terrestrial systems (e.g., terrestrial FS and IMT coordination into C-band).

With respect to sharing among satellite systems, the report focuses on database-coordinated sharing among incumbent GSO systems and NGSO, low-Earth orbit (LEO) satellite constellations currently being deployed by companies including OneWeb, SpaceX and Amazon. These constellations will comprise thousands of LEO satellites. The study found that database-assisted coordination should be reliable and useful in large part because of the predictability of the position of NGSO satellites over time (ephemeris), which can be used to anticipate and adjust to avoid interference situations.[149] Assuming that the database has accurate inputs from both the GSO and NGSO operators in the band – most critically the NGSO satellites' ephemeris and associated power level received on the ground – the coordination database can then:

(1) alert in advance each system of any in-line interference situation by predicting when and where it will happen,

(2) assist in adopting the appropriate interference mitigation strategy for these cases [which will likely be "changing the operating frequency in the feeder link"], and

(3) answer requests for more bandwidth from each system and allocate spectrum accordingly.[150]

The potential role and benefits of a third-party clearinghouse or database mechanism to facilitate "good faith coordination" among NGSO constellations sharing spectrum is also being considered in a pending FCC proceeding aimed at clarifying the rules around NGSO prioritization and spectrum sharing.[151] The FCC proposes to clarify that although a NGSO operator approved in an earlier processing round must be protected from harmful interference by a later-round system, all operators would still be subject to "good faith coordination" requirements intended to promote entry, competition and spectrum efficiency. While the agency does not propose any specific coordination mechanism at this time, the Commission notes that "information sharing among NGSO FSS operators is essential to their efficient use of spectrum" and invited comment on what information and coordination mechanisms should be required.[152]

Comments by stakeholders suggested that several categories of operational information (e.g., gateway site locations, satellite selection algorithms, ephemeris data, beam pointing angles) could ultimately be coordinated through a neutral third-party clearinghouse or DSMS certified by the FCC. Intelsat, for example, proposed that the FCC "could further facilitate more effective good-faith coordination by facilitating an industry-led, limited-access database in which the above system parameters would be available to NGSO applicants and grantees."[153]

The authors of the ESA study and IEEE survey noted just above acknowledge that much more research and testing is needed before database-coordinated sharing among such disparate satellite systems can be relied upon, including the impact of aggregate interference from the deployment of relatively dense mega-constellations of small NGSO satellites. Nonetheless, in theory coordination both between satellite and many terrestrial uses, as well as among satellite operators, development of an automated database coordination system could benefit operators and NRAs in the future as the number and size of small satellite constellations lead to more congestion and conflicts in the satellite bands.[154]

5. TECHNOLOGY IS RAPIDLY ENHANCING THE POTENTIAL FOR DYNAMIC SPECTRUM ACCESS

As the sections above demonstrate, the functionality and reliability of database-enabled frequency coordination have advanced rapidly over the past decade, from database-assisted coordination (in fixed bands), to automated frequency coordination (for unlicensed access to the 6 GHz band and vacant TV channels), to dynamic spectrum access (in the new CBRS band at 3550-3700 MHz in the U.S.). Spectrum database coordination has already proven it brings a myriad of current and potential benefits to all stakeholders, including incumbent services, new shared-access users, consumers and regulators.

Further advances are visible on the near-to-medium-term horizon. The most important of these technical advances is likely to be the increasing incorporation of extremely accurate, real-world GIS data and the growing sophistication of propagation and interference modeling. A related concept is the increasing move toward 'dynamic protection areas,' rather than the rigid and overly-protective 'exclusion zones.' The benefits of these advances are likely to be amplified further by the application of artificial intelligence (AI) and machine learning.

Another promising input to real-world awareness of the spectral environment is real-time sensing data. The SAS relied on to coordinate three-tier sharing in the CBRS band is the first to incorporate sensing, relying on a network of coastal sensors designed to protect U.S. Navy radar. But the future will reveal that this is a crude first step toward what is likely to be some combination of crowdsourced sensing (by devices) and more ubiquitous fixed or mobile sensing networks that may serve as a pooled resource for dynamic sharing in many different bands. In parallel, the recent interest by the U.S. government in developing an Incumbent Informing Capability could allow DSMS operators to collect far more precise inputs from incumbent or priority operations. This would be particularly valuable in bands where primary users are mobile or episodic, as U.S. Navy radar is in the CBRS band.

Database operators are also likely to offer a host of innovative value-added services. Among these is the potential to combine blockchain technology with dynamic database coordination. This section only explores these emerging technologies at a surface level, but together they provide further evidence that NRAs that fail to take advantage of these new, more dynamic approaches are likely to lag behind in the global race to a wireless future of bandwidth abundance.

A. Real-World GIS Data and Propagation Modeling

As noted earlier, propagation loss has been studied extensively and is well understood.[155] Spectrum databases that incorporate real-world details on terrain, clutter (trees, buildings), and other GIS data sets can enable far more intensive spectrum use.[156] An AFC database informed by real-world GIS datasets does not need to make generic, worst-case assumptions about interference. With more accurate awareness of the physical environment, DSM systems have the computation power to calculate actual path loss based on the characteristics of the shared-access device, the protected receiver, and the actual physical path between the two.

As Preston Marshall explains in his book on three-tiered sharing, the propagation models in use today "were based on few data points and limited computation resources."[157] This leads to unrealistic, worst-case outcomes that undermine the policy purpose of secondary sharing. Marshall notes that the lack of real-world granularity inherent in relying solely on terrain-based modeling, such as the FCC Curve model (based on Longley-Rice terrain modeling) that defines static exclusion zones around TV station transmit sites in the FCC's TVWS rules, is exemplified by comparing a more sophisticated GIS mapping of Manhattan. The Longley-Rice terrain-based model depicts the island as it was in 1600 – without buildings or even trees. In reality, particularly for terrestrial use at higher frequencies, an actual RF propagation view of Manhattan is dominated by scatter loss from physical obstacles that could accommodate dense deployments of low-power devices without interference to incumbents in a number of bands.

The advances in propagation and interference modeling that could inform the computational awareness of automated frequency coordination systems include:

Scatter Loss Modeling: As noted just above, very detailed GIS databases are becoming available that geolocate, and regularly update, all the physical obstacles along the path between shared-access transmitter and incumbent receiver, including buildings, trees, and other structures.

Three Dimensional Modeling: Including data on clutter yields awareness in only two dimensions unless the height of buildings, trees and terrain are factored in. "In deployments that are enterprise, residential and indoor focused, many of their interference paths will be vertical, rather than horizontal," Marshall observes."[158] In reality, access points that may appear co-located to a less sophisticated path loss model could actually be dozens of meters apart vertically and separated by multiple concrete floors as well. The path loss rules for indoor-only uses – and particularly in commercial buildings typified by more dense and mineral-based materials – could be calculated to be very different than outdoor use, for example.[159]

Antenna Patterns: Existing TVWS protection frameworks (with the exception of the DSA Model Rules) assume the TVWS device has an omnidirectional antenna. CBRS, by contrast, allows the device to submit parameters describing the direction and beamwidth of its antenna, allowing more realistic coexistence modeling to take place.

Modeling Aggregate Interference: A dynamic database – such as the SAS in CBRS – "estimates the impact of each individual emitter in the ecosystem and aggregates the total emissions of each of the emitters."[160] The SAS is therefore able to assure incumbent users – specifically, the U.S. Navy – that aggregate interference in the band in coastal zones will not rise above a certain harm threshold.

A related concept is the increasing interest in 'dynamic protection areas,' rather than the rigid and overly-protective 'exclusion zones' that characterized shared access to vacant TV channels in the U.S. Whether an automated frequency coordination system authorizes a new user within a given distance of an incumbent's transmit or receive location should vary depending on the power, height and other characteristics of the device making the request. A DSM system can calculate this based on all the available awareness data. The AFC rules adopted by the FCC for RLAN operations in 6 GHz embrace this concept by allowing AFCs to authorize the use of channels at a lower power in the outer protection contour near a fixed (FS) link, rather than prohibiting use entirely.

B. Spectrum Sensing and AI

While GIS data adds a more real-world but generally static set of inputs to frequency coordination, spectrum sensing can add a more real-time and dynamic set of inputs. Much like spectrum coordination databases, the technology of spectrum sensing and modulation recognition have been around for decades. Spectrum sensors are routinely employed to measure changes in the noise floor and actual usage of frequency bands, including by "spectrum observatories" that measure spectrum occupancy changes, trends and anomalies both in real time and over long periods of time.[160] What is new are efforts to incorporate sensing "to allow non-primary access to unused spectrum by a licensed or unlicensed device."[162]

When designed as inputs for DSMS, spectrum monitoring systems can add unique data on the actual spectral environment in an area, and in real time.[163] More generally, a working group of the U.S. Department of Commerce Spectrum Management Advisory Committee (CSMAC) identified four key application areas for spectrum sensing:

(1) Quantify opportunities and support regulatory action prior to sharing;

(2) Operationally support the sharing process once the spectrum has been designated for sharing;

(3) Assess usage and interference trends and to assess further rule modifications after shared spectrum operations are in place; and

(4) Support NRA enforcement requirements.[164]

As the section on CBRS described, to protect Navy radar systems on ships that move unpredictably (and on a classified basis), SAS operators are required to deploy a network of sensors (an ESC) along the nation's coastlines. The sensors are located at intervals that correspond to the size of a Protection Zone designed to both detect radar above a pre-defined threshold and to obscure the specific location of Navy vessels. The ESC reports sensing data in real-time to the SAS, which has 300 seconds to notify devices in the Protection Zone to vacate to a different channel. The device must relocate to a new temporary channel assignment within 60 seconds. [165]

While the ESC implementation in the CBRS band has proven to be overly preclusive, it is also quite likely a precursor to a variety of future sensing and monitoring implementations. Sensing networks can be fixed and targeted geographically based on a purpose (such as achieving a higher degree of sharing in core urban areas, or a specific incumbent protection mission, as the ESC does vis-à-vis naval radar). In the future it's also likely that spectrum sensing will be greatly enhanced by applying machine learning (ML) and deep learning (DL) techniques. For example, one study applied deep learning to enhance the detection of radar waveforms in the CBRS band.[166]

Sensing networks can also be mobile – for example, collecting and offloading spectrum occupancy measurements continuously from roof-mounted sensors on ubiquitous fleets of police, taxi, and/or delivery service vehicles. While these sensing inputs would not be continuous, aggregated it could potentially cover wider areas with measurements from a very diverse and dynamic set of locations over time. Sensing inputs can perhaps most effectively be crowdsourced by user devices that are location aware and in regular contact with a frequency coordination system.[167]

For its part, recent rapid advances in AI are likely to augment the capabilities and efficiencies of dynamic spectrum management systems, particularly when local spectrum occupancy data is available in near real-time to the DSMS. The EU's Radio Spectrum Policy Group made this point in its 2021 survey on advances in spectrum sharing: "AI and supporting technologies . . . [can] improve and speed up the coordination processes, offering dynamic access to specific spectrum, in a responsive manner according to the needs of specific services (periods of use, range, capacity, etc.)."[168] The RSPG report suggested that applying AI techniques to information collected through "collaborative spectrum sensing" could "support the near-instantaneous granting of spectrum for ad hoc mobile access requirements such as those that might be needed for Internet of Things applications."

C. Incumbent Informing Capability

Dynamic frequency coordination is most challenging where incumbent priority users are not "fixed" with respect to geolocation and/or time of operation. As previously discussed in the section describing the spectrum sensing as an input to the SASs that protect U.S. Navy radar operations in the 3.5 GHz CBRS band, passive sensing is least burdensome for incumbent operators, but has also proven to be costly to deploy, often inaccurate (due to false positives), and overly preclusive, resulting in suboptimal utilization of prime spectrum. In a December 2022 report on "lessons learned" from CBRS, the FCC's Technological Advisory Council recommended that "[d]etecting incumbent activity solely by the use of dedicated sensors should be avoided." The TAC recommended that "other options should be explored, including Informing Incumbent Capability (IIC), a limited version of which has been deployed by DoD in the CBRS band." [169]

In response to the experience with CBRS and the growing commercial demand to share unused spectrum in other government bands, the U.S. Department of Commerce has proposed to create an Incumbent Informing Capability (IIC) that would pro-actively inform coordination both among government users (since many agencies share spectrum) and with the private sector. In a 2021 whitepaper, the director and staff of the Department's Office of Spectrum Management described the IIC as "a mechanism for more reliably informing 'new entrants' in a shared spectrum band when incumbent federal systems are operating in close proximity and thus need to be protected." They stated that by reporting the locations and times that federal operations need protection, the IIC "could replace extra layers of sharing techniques such as the environmental sensing capability (ESC)" with "an enhanced, near-real-time Spectrum Coordination System (SCS)." [170]

IIC Incumbing Informing Capability

Figure 22: Proposed Incumbent Informing Capability (Source: NTIA, U.S. Department of Commerce)

As the agency's diagram suggests, government users would affirmatively report operational information (time, location, frequency, power) to the IIC, which would in turn interface securely with an authorized Spectrum Coordination System, or DSMS, that like today's SAS in CBRS would grant or rescind time-limited permission to transmit to commercial and presumably secondary users. The IIC would also incorporate a "process to resolve interference in real time (i.e., while the incumbent operations are underway) to prevent impacts to vital federal operations." By effectively creating a government-side DSMS, the agency states that it "expects the capability to evolve over time toward a dynamic spectrum sharing paradigm in selected bands where 'everyone informs'," and aligns with the agency's Vision Statement of "anytime anywhere access to spectrum for all users." [171]

The IIC could greatly accelerate the sharing of wide swaths of underutilized federal spectrum – particularly in bands currently dedicated in whole or large part to military radar use (e.g., 3.1-3.65 GHz, 10 GHz, portions of 5 GHz). There is strong bipartisan support in the U.S. Congress. In 2022 legislation funding the creation of the IIC, along with a requirement that federal spectrum users supply it with operational information, passed the U.S. House of Representatives and nearly passed the Senate as part of a larger bill to renew FCC auction authority.[172] That legislation is likely to be taken up again and passed during 2023.

D. Value-Added Services by DSMS Operators

DSMS operators have the capability to add value-added services for both incumbents and entrants, which can also help to offset the costs of coordination. These value-added services, although not required by the NRA, can help users optimize quality of service, facilitate and streamline private secondary market transactions, recycle crowd-sourced spectrum sensing data, incorporate more detailed GIS data to enable even more intensive sharing, and other innovations that will derive from a more dynamic, data-rich awareness of users and the environment. Ofcom recognized this in its 2016 Statement on *A Framework for Spectrum Sharing:* "In the future, the concept could potentially be extended to manage access between opportunistic sharers, improving quality of service."[173]

Examples of value-added services have already emerged in shared bands. For example, Spectrum Bridge, one of the original TV Band Database operators certified by the FCC, fairly quickly found there was a market for providing band occupancy data to incumbent users, specifically licensed wireless microphone operators that could benefit by finding the cleanest available channels at a given location and time. Comsearch, certified by the FCC to coordinate and register fixed point-to-point links in the 70/80/90 GHz bands (and described further above), also provides pre-coordination analysis and other services to licensees. Under the CBRS framework, SAS operators have the ability to help optimize coexistence among the unlicensed (GAA) users that have no right to interference protection. Ofcom has similarly observed, in relation to coordinating unlicensed sharing of TVWS channels, that a NRA could decide that this coexistence assistance – aimed at optimizing quality of service – should be an optional, value-added service.[174]

E. Blockchain Technology

Blockchain technology, famous for its initial application to record Bitcoin transactions, implements a shared, distributed ledger that provides a low-cost and secure way to record transactions and track assets among verified parties. A blockchain's primary purpose is to make a single, sequential record of transactions among verified parties. Each transaction record is a 'block' and they are 'chained' together in a manner that is sequential, verified, secure from cyberattacks, and saved in a permanent, distributed database that minimizes transaction costs. Blockchain can be applied to a wide variety of assets and transactions, whether tangible (real estate, auto leases) or intangible (patents, copyrights), including – potentially – spectrum sharing and secondary market transactions.[175]

Blockchain may have the potential to enhance frequency coordination and secondary market transactions, particularly in shared bands that will need (or benefit from) database coordination. A blockchain not only speeds transactions and minimizes their cost, it also ensures transparency and trust, including among regulators in contexts where it is fashioned to facilitate a public policy purpose. In that context, a blockchain can be a permissioned network limited to parties, or types of transactions, that are pre-approved by a NRA or other certificating authority. In some scenarios (e.g., secondary market transactions on exclusively-licensed bands) it may be the right database solution; whereas in other scenarios it might enhance the functionality of spectrum coordination databases or, in other situations, not add sufficient value to justify the additional overhead costs for users.[176]

At least three possible applications have been outlined by regulators, academics and others: First, a blockchain can potentially improve coordination and reduce interference among users of a shared band, particularly an unlicensed or licensed-by-rule band, such as wireless microphone (PMSE) and Wi-Fi hotspot operators. These applications were the initial focus of a blockchain trial by France's Agence Nationale Des Frèquences[177] The trials focused on the unlicensed bands at 2.4 and 5 GHz, as well as TV band spectrum between 470 MHz and 789 MHz used by wireless microphones for program-making and special events (PMSE).[178] ANFR believes PMSE is a prime candidate for blockchain since microphones can be densely packed at major events and it can be difficult for regulators to effectively coordinate them to avoid interference.[178] ANFR expects to leverage this blockchain to coordinate PMSE on a large scale during the 2024 Paris Olympics. [180]

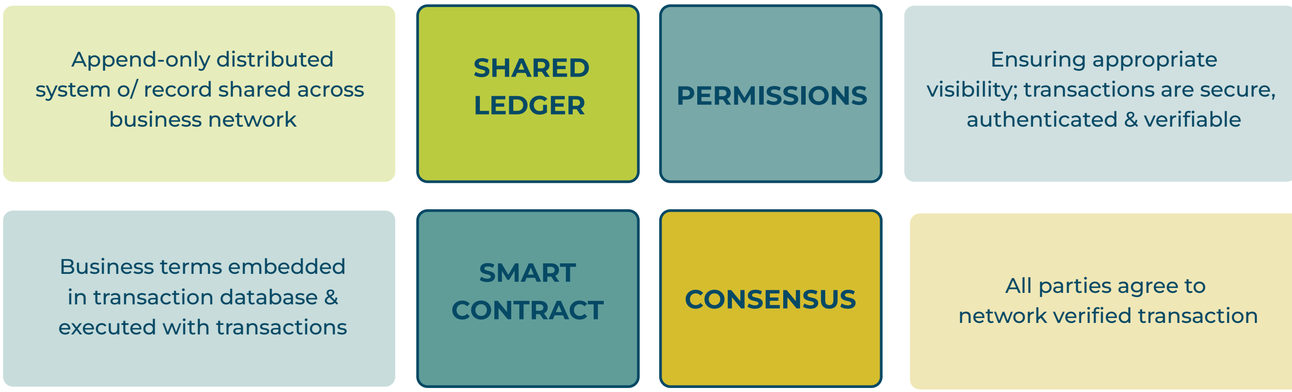


Figure 23: Key concepts of a blockchain application for business transactions.[181]

A second potential application for blockchain is to verify and execute spectrum sharing agreements between primary and secondary users in licensed spectrum. An anticipated advantage of a spectrum blockchain is that secondary market transactions can be automated, subject to pre-determined conditions, and transparent to permitted users as well as to the regulator.[182] Under one scenario, the primary licensee can continually update the spectrum available for short-term auction to other interested parties.

The blockchain validates and records all transactions, with license terms (such as duration) enforced automatically according to the terms of standardized "smart contracts" associated with each block (transaction record).[183] For example, a 2017 paper proposed a blockchain and smart contracts as an efficient means to manage service level agreements for mobile network operators seeking "small cells as a service" in a localized, on-demand basis.[184]

A third potential application for a blockchain is the automation of ex post enforcement. As automated frequency coordination scales up the intensity and quantity of shared use among a multiplicity of users, databases such as the SAS for CBRS can potentially be leveraged to lower the costs of enforcement by creating a permanent record of transactions and by automating certain ex post enforcement steps. [185] Academics have suggested that a blockchain could be incorporated in DSMS databases to facilitate the enforcement of "collective action rights" of secondary users in addition to the interference protection rights of incumbents.[186] It could also be used by a regulator to collect 'pay-as-you-go' fees on spectrum use, including variable fees based on priority or congestion.

It's important to realize that although relying on a blockchain to coordinate among "permissioned" users verified by the regulator, such as licensed PMSE operators, may justify the transaction costs, in most scenarios involving an unlicensed or shared band open for general use (such as license-exempt Wi-Fi bands, or General Authorized Access in the FCC's CBRS frame-work), a blockchain may not be scalable or cost-effec-tive.[187] For example, requiring each device in a high-traffic band to register its location and monitor activity on a decentralized blockchain could generate overhead costs that exceed any benefits.[188] In this regard, the RSPG in its 2021 spectrum sharing survey noted that "in order to allow the operation of the blockchain and to validate transactions, a suitable set of radio resources would typically need to be available at all times for the communications among nodes, increasing the overhead and reducing the available net capacity."[189] It also appears unlikely that a blockchain can serve as the "calculation engine" in a dynamic frequency coordination environment that incorporates environmental data (e.g., GIS or dynamic sensing or occupancy data) or takes account of other heteroge-nous or changing technical parameters among users in the band.

6. CONCLUSIONS & POLICY RECOMMENDATIONS

As the demand for wireless connectivity continues to surge, the use of databases to coordinate more intensive and efficient spectrum sharing has emerged as a critical regulatory tool. Regulators in a number of countries have authorized automated and even dynamic frequency coordination databases to manage assignments in shared bands. These dynamic spectrum management systems have proven they can protect incumbent operations, including military and public safety systems, from harmful interference. Although spectrum database coordination is nothing new, it has in recent years evolved from manual, to automated, to dynamic – adding automation and propagation modeling to static licensing data. Database solutions are active today from low- and medium- to high-frequency bands, and with various degrees of complexity.

DSMS technology is now sufficiently mature, scalable, secure and available as a service from a number of top-tier commercial providers. There is no question that today NRAs have the technical ability to automate frequency coordination and thereby lower transaction costs, use spectrum more efficiently, speed time to market, protect incumbents from interference with certainty, and generally expand the supply of wireless connectivity that is fast becoming, like electricity, a critical input for most other industries and economic activity. DSMS solutions are good for consumers, competitive entrants, and innovation by making wireless connectivity more accessible, fast and affordable.

DSMS can serve as a force multiplier for regulators: By automating assignments and monitoring usage, databases both enhance efficient allocation of national spectrum resources while strengthening enforcement and ensuring the protection of incumbent users with a higher licensing priority. The availability, flexibility and reliability of DSM systems help NRAs to meet the growing and very diverse spectrum needs of both industries and individuals.

DSA Policy Recommendations:

- NRAs should work towards a dynamic shared access approach in any underutilized band (e.g., 6 GHz, 3.8-4.2 GHz) where coordinated sharing is appropriate and practical to implement.
- NRAs should authorize the simplest possible database solution that will achieve the regulatory goal – and only require frequency coordination directly through the DSMS (rather than through a slower or more costly process).
- NRAs should adopt clear rules, but not prescribe particular technologies or standards for DSMS.
- Consulting industry and convening a representative, multi-stakeholder process to develop and assist in implementing the DSMS can help to conserve agency resources and leverage industry expertise.
- Study and consider the adoption of best practices developed by industry or other NRAs, particularly when that can speed time to market and promote harmonization regionally or globally (e.g., the DSA model rules for TVWS, or Open AFC for 6 GHz).
- NRAs should consider the benefits of certifying a private sector entity to manage the DSMS – or, if demand justifies it, multiple and competing DSMS providers – but always in strict adherence to agency rules.
- Smaller nations with many borders, or that lack a large domestic market, should consider the efficiencies of a regional approach to frequency coordination, such as a shared or interconnected DSMS.
- When feasible, it is cost-effective to leverage a DSMS and operator to manage multiple bands, rather than require a series of separate systems.
- Require – or at least allow – DSMS coordinators to use the most granular and real-world GIS data available for propagation and interference modeling.
- Permit DSMS operators to experiment with and generate revenue from value-added services in addition to the basic coordination service that complies with NRA rules.

Acknowledgements: The Dynamic Spectrum Alliance would like to thank its members who made this report possible, particularly the report's principal author, Michael Calabrese (New America). Special thanks as well to Martha Suarez (DSA President), Chuck Lukaszewski and David Wright (HPE Aruba Networks), Jennifer McCarthy (Federated Wireless), Bill Davenport (Cisco), Michael Daum (Microsoft), Alan Norman (Meta), Pasquale Cataldi (Policy Impact Partners), Andrew Clegg and Preston Marshall (Google), and Mark Gibson (Comsearch), all of whom served as reviewers, editors and advisors to this report and/or the original 2019 edition.

END NOTES:

[1] Ray Baum's Act of 2018, Pub. L. 115–141, § 614, 132 Stat. 1080, 1109 (2018). The FCC and U.S. Department of Commerce released a request for comment (RFC) on a National Spectrum Strategy on March 15, 2023. The RFC specifically requests input on the Commerce Department's Office of Spectrum Management proposal to develop a government DSMS – an Incumbent Informing Capability – with a goal of promoting more efficient sharing of federal government bands both among federal users and by the private sector.

[2] European Communications Office, ECC Work Programme Database, "Higher power WAS/RLAN in 5945-6425 MHz," Working Group SE45, Reference FM 58 (Oct 6, 2022 start date), https://eccwp.cept.org/WI_Detail.aspx?wiid=811.

[3] Id.

[4] European Commission, Radio Spectrum Policy Group, "RSPG Opinion on Spectrum Sharing—Pioneer Initiatives and Bands," RSPG21-022, Final (June 21, 2021), https://radio-spectrum-policy-group.ec.europa.eu/system/files/2023-01/RSPG21-022final_RSPG_Opinion_Spectrum_Sharing.pdf.

[5] Office of Communications (Ofcom), "A Framework for Spectrum Sharing," Statement, at 27 (April 14, 2016) ("Ofcom 2016 Statement"), available at https://www.ofcom.org.uk/__data/assets/pdf_file/0028/68239/statement.pdf. See also Ofcom, Spectrum Management Strategy (April 30, 2014), available at https://www.ofcom.org.uk/__data/assets/pdf_file/0021/71436/statement.pdf.

[6] Ofcom, "Ofcom's Plan of Work 2022/2023" (March 25, 2022), https://www.ofcom.org.uk/__data/assets/pdf_file/0019/234334/Statement-Plan-of-Work-2022_23.pdf. See also Ofcom, "Enabling Opportunities for Innovation: Shared Access to Spectrum Supporting Mobile Technology," Consultation, at 6 (Dec. 18, 2018) ("Ofcom 2018 Consultation"), available at https://www.ofcom.org.uk/__data/assets/pdf_file/0022/130747/Enabling-opportunities-for-innovation.pdf.

[7] Ofcom 2016 Statement.

[8] See International Telecommunication Union, "Introduction to CCITT Signalling System 7," available at https://www.itu.int/rec/T-REC-Q.700-199303-I/en. SS7 networks were deployed by AT&T and MCI WorldCom in 1989. See AT&T to deploy SS7 by year-end, Data Communications, Aug 1, 1989; R.N. Lane, Arthur D. Little Decision Resources, Ind. Rpt. No. 1023667, Carrier Provisions of SS7 Services - Industry Report, at 2 (Sept. 1, 1989).

[9] In its rules, the U.S. Federal Communications Commission (FCC) defined call-related databases as those used "for billing and collection or the transmission, routing, or other provision of a telecommunications service." 47 C.F.R. § 51.319(e)(2). Such databases include the Line Information Database (LIDB), the Toll Free Calling database, number portability databases, and AIN databases.

[10] "To facilitate this type of porting solution [onward forwarding], communications providers typically maintain a common database which holds up-to-date details of ported numbers and their current providers which they can use as a source of routing information." Office of Communications (Ofcom), "Routing Calls to Ported Telephone Numbers," Statement (April 1, 2010), available at https://www.ofcom.org.uk/__data/assets/pdf_file/0023/45653/statement.pdf.

[11] In 1997 Neustar implemented and deployed "the world's first number portability database," according to the National Portability Administration Center (NPAC). See NPAC, https://www.npac.com/number-portability/the-npac-neustar-lnp.

[12] For a general, non-technical overview, see Wikipedia, Network Switching Subsystems, available at https://en.wikipedia.org/wiki/Network_switching_subsystem#Description.

[13] Taken from Rus Shuler, How Does the Internet Work? (Pomeroy IT Solutions, 2002), available at https://web.stanford.edu/class/msande91si/www-spr04/readings/week1/InternetWhitepaper.htm.

[14] AFC systems are known by different names in various frequency bands, such as "Spectrum Access System" (SAS) in 3.5 GHz in the U.S., "TV Bands Databases" (TVDBs) in many countries, and "Licensed Shared Access Controller" (LSA) in Europe.

[15] An example is the Wireless Innovation Forum (WInnForum), an industry standards body designated by the FCC to develop the standards and protocols for implementation of three-tier dynamic sharing in the new Citizens Broadband Radio Service (CBRS) at 3550-3700 MHz, pursuant to Part 96 of the Commission's rules. See CBRS WInnForum Standards, available at https://cbrs.wirelessinnovation.org/.

[16] M. Höyhtyä, J. Ylitalo, X. Chen, and A. Mämmelä, ``Use of databases for dynamic spectrum management in cognitive satellite systems,'' in Cooperative and Cognitive Satellite Systems, S. Chatzinotas, B. Ottersten, and R. De Gaudenzi, Eds. (San Francisco, CA, 2015), at 337-371.

[17] See ECC Report 236 at 30-32. The NRA typically runs an approval process to ensure the operator is well-qualified. In the U.S., the FCC has certified multiple commercial database operators in several shared bands, including the 70/80/90 GHz, TV White Space and CBRS bands. The agency seeks public comment on the selections, in addition to requiring certain qualifications and a pre-certification testing period.

[18] Electronic Communications Committee, European Conference of Postal and Telecommunications (CEPT), "Guidance for national implementation of a regulatory framework for TV WSD using geo-location databases," ECC Report 236 (May 2015). As an example, the Report notes that "in some CEPT countries PMSE [wireless microphone] access is license exempt and registered . . . the lack of such information is a key challenge in protecting PMSE against WSD [White Space Devices]." Id. at 28.

[19] In the U.S. context, an example is the 2018 FCC proposal to authorize fixed wireless broadband operators to coordinate localized point-to-multipoint deployments into available frequencies in a portion of the satellite C-band at 3700-4200 MHz. Earth stations that receive downlinks on the band are not currently required to report what frequencies they are actually using, information the FCC indicated it would need to require if the rulemaking had adopted a coordinated sharing framework. See Notice of Proposed Rulemaking, Expanding Flexible Use of the 3.7 to 4.2 GHz Band, Order and Notice of Proposed Rulemaking, GN Docket No. 18-122, FCC 18-91 (July 13, 2018).

[20] See ECC Report 236 at 28-29.

[21] Id. at 36-40 (discussing various cost recovery and fee options).

[22] See ECC Report 236 at 25.

[23] An example is Ofcom's studies and resulting protection rules, which were also used as the foundation for the DSA Model Rules for TV White Space sharing. See Ofcom, Implementing TV White Spaces, Statement, Annex 9 (Feb. 12, 2015), available at https://www.ofcom.org.uk/__data/assets/pdf_file/0025/58921/annexes.pdf.

[24] See Preston Marshall, *Three-Tier Shared Spectrum, Shared Infrastructure, and a Path to 5G* (Cambridge Univ. Press, 2017), at 80-81 and 104-110 for an overview various propagation and interference modeling options.

[25] At the same time, there are trade-offs to consider concerning the cost of including more granular data, the need for more frequent updates, and even the propagation of band. For example, in TV and other low-frequency bands, clutter would have far less impact on spectrum re-use than in mid- and high-frequency bands. Regulators can choose less accurate propagation models initially to provide a higher level of protection to incumbent users, which occurred with both the U.S. and U.K. TV White Space rules, although presumably greater experience and comfort with automated frequency coordination will permit NRAs to take full advantage of their potential to open access to new bandwidth.

[26] See, e.g., ECC Report 236 at 29-30.

[27] This is discussed further in Section 5E concerning the potential to integrate blockchain functionality.

[28] See Marshall at 85-86.

[29] See ECC Report 236 at 42.

[30] See ECC Report 236 at 42, which notes that database operators can collect a "wealth of data about the types of devices and the characteristics of their use." In addition, "the NRA may require specific interference management functions from the database."

[31] See, e.g., Federal Communications Commission, Universal Licensing System: Databases (ULS database downloads for specific wireless radio services are available as zip files, updated weekly and supplemented by daily transaction reports), available at http://wireless.fcc.gov/uls/index.htm?job=transaction&page=weekly; FCC, International Bureau Application Filing and Reporting System (IBFS enables electronic filing and search tools that provide access to up-to-date application information and various reports), available at http://licensing.fcc.gov/prod/ib/forms/index.html.

[32] FCC, Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz, Notice of Inquiry, FCC 17-104, GN Docket No. 17-183, at ¶¶25, 35 (Aug. 3, 2017). An analysis by SNL Kagan projects that "[d]riven by the spike in mobile data use, by 2025 tower sites will grow at a CAGR of 3.9%," and that "there could be more than 200,000 towers and over 400,000 sites in use in the next 10 years." See "Report Predicts Tower, Small Cell Outlook Through 2025," RCR Wireless News (July 15, 2015); available at: https://www.rcrwireless.com/20150715/cell-tower-news/report-predicts-towertrends-through-2025-tag20.

[33] 47 C.F.R. § 101.103. For the U.S., the administrative aspects of the coordination process are set forth in Section 101.103(d), in the case of coordination of terrestrial stations with earth stations, and in Section 25.203, in the case of coordination of earth stations with terrestrial stations.

[34] See U.S. Federal Register, Fixed Satellite Service and Terrestrial System in the Ku-Band, Summary, FCC First Report & Order, ET Docket No. 98-206 (rel. Dec. 8, 2000), available at https://www.federalregister.gov/documents/2001/02/16/01-3710/fixed-satellite-service-and-terrestrial-system-in-the-ku-band.

[35] See, e.g., "Comsearch Microwave: Expert Coordination Prevents Harmful Interference," available at https://www.comsearch.com/services/frequency-coordination-fcc-licensing/microwave/.

[36] ECC, CEPT, "Fixed Service in Europe: Current use and future trends post 2016," ECC Report 173 (updated April 27, 2018). Similarly, in the UK, Ofcom authorizes point-to-point fixed links on a first-come basis, subject to the agency's coordination and technical frequency assignment criteria. See Ofcom, Technical Frequency Assignment Criteria for Fixed Point-to-Point Radio Services with Digital Modulation (OfW 446), July 2018, available at https://www.ofcom.org.uk/__data/assets/pdf_file/0017/92204/ofw446.pdf.

[37] Id. at 2. See also European Communications Office, "ECO Report 04, Fixed Service in Europe, Implementation Status (July 3, 2018).

[38] Subject to FCC Part 95 rules, the AHA's American Society for Healthcare Engineering is designated as the exclusive WMTS frequency coordinator. See FCC, Wireless Medical Telemetry Service (WMTS), at https://www.fcc.gov/wireless/bureau-divisions/broadband-division/wireless-medical-telemetry-service-wmts.

[39] FCC, American Society for Healthcare Engineering of the American Hospital Association (ASHE/AHA), at https://www.fcc.gov/wireless/bureau-divisions/broadband-division/wireless-medical-telemetry-service-wmts/american

[40] In 2016 the agency approved a third competing database manager, Key Bridge Global LLC, for the 70/80/90 GHz bands. FCC, "Order and Notice to Database Managers for the 70/80/90 GHz Link Registration System Under Subpart Q of Part 101," Wireless Telecommunications Bureau, WT Docket No. 13-291 (rel. Aug. 26, 2016).

[41] FCC, "Wireless Bureau Opens Filing Window for Proposals to Develop and Manage Independent Database of Site Registrations by Licensees in the 71-76 GHz, 81-86 GHz and 92-95 GHz Bands," Public Notice (rel. March 12, 2004).

[42] See generally FCC, Report and Order, Allocation and Service Rules for the 71-76 GHz, 81-86 GHz and 92-95 GHz Bands, WT Docket 02-146 (2003). The bands are allocated to Federal Government use on a co-primary basis.

[43] The diagram is adapted from those filed jointly by the three companies that initially proposed to develop and manage an independent database of site/link registrations for licensees in the 71-76 GHz, 81-86 GHz and 92-95 GHz bands. Ex Parte Letter from Comsearch to the FCC, Appendix A, WT Docket No. 02-146 (Sept. 9, 2004), at 5.

[44] The classified nature of some Federal Government operations precludes the use of a public database containing both government and non-government links. See Allocations and Service Rules for the 71-76 GHz, 81-86 GHz and 92-95 GHz Bands, WT Docket No. 02-146, Report and Order, at ¶ 48 (2003).

[45] See Wireless Telecommunications Bureau Announces Permanent Process for Registering Links in the 71-76 GHz, 81-86 GHz, and 92-95 GHz Bands, Public Notice, DA 05-311 (rel. February 3, 2005). A "green light" response indicates that the link is coordinated with the Federal Government; a "yellow light" response indicates a potential for interference to Federal Government or certain other operations. See generally 47 C.F.R. § 2.106 (US388, US389). In the case of a "yellow light," the licensee must file an application for the requested link with the Commission, which in turn will submit the application to NTIA for individual coordination.

[46] Ofcom, "Spectrum Management Approach in the 71-76 GHz and 81-86 GHz bands" (Dec. 16, 2013), available at https://www.ofcom.org.uk/__data/assets/pdf_file/0011/50240/statement.pdf.

[47] Ministry of Communications, Department of Telecommunications, "Guidelines for allotment of E-band (71-76/81-86 GHz) carriers to Telecom Service Providers (TSPs) with Access Service authorization/license and having Access Spectrum in IMT bands" (July 25, 2022).

[48] Suyash Ray, et al., "The Economics of Releasing the V-band and E-band Spectrum in India," National Institute of Public Finance and Policy (New Delhi), Working Paper No. 226 (April 2, 2018), at 15-16, available at http://www.nipfp.org.in/media/medialibrary/2018/04/WP_226.pdf.

[49] See European Conference on Postal and Telecommunications, Electronic Communications Committee, "Licensed Shared Access (LSA)," ECC Report 205 (approved Feb. 2014).

[50] "Subject to the national decision, the NRA (together with the key stakeholders) needs to negotiate the terms of the LSA licence in such way that a balance is found between providing the MFCN operator an adequate amount of predictability in their future access to the band on one hand, and allowing the future development of the incumbent service on the other hand." European Conference on Postal and Telecommunications, Electronic Communications Committee, "Operational guidelines for spectrum sharing to support the implementation of the current ECC framework in the 3600-3800 MHz range," ECC Report 254, at 29 (approved Nov. 18, 2016).

[51] ECC Decision (14)02, "Harmonised technical and regulatory conditions for the use of the band 2300-2400 MHz for Mobile/Fixed Communications Networks (MFCN)," June 27, 2014, https://docdb.cept.org/document/443.

[52] Arturas Medeisis, Vladislav Fomin and William Webb, "Untangling the Paradox of Licensed Shared Access: Need for Regulatory Refocus," Telecommunications Policy, Vol. 46 (May 2022).

[53] Id.; see Maria Massaro and Fernando Beltran, "Will 5G lead to more spectrum sharing? Discussing recent developments of the LSA and the CBRS spectrum sharing frameworks," Telecommunications Policy, Vol. 44, Issue 7 (August 2020), https://doi.org/10.1016/j.telpol.2020.101973.

[54] See generally ECC Report 205, supra; Marshall at 27-29.

[55] Marshall at 29. See also Massaro and Beltran, supra ("slow implementation of LSA is possibly due lack of enforcement powers of European bodies").

[56] See Marc Gelian Ante, et al., "A Survey and Comparison of TV White Space Implementations in Japan, the Philippines, Singapore, the United Kingdom, and the United States," International Journal of Advanced Technology and Engineering Exploration, Vol 8 (July 2021), https://www.accentsjournals.org/paperInfo.php?journalPaperId=1315.

[57] Independent Communications Authority of South Africa (ICASA), "Regulations on the Use of Television White Spaces," Notice 147 of 2018 (March 23, 2018), available at https://www.ellipsis.co.za/wp-content/uploads/2017/04/Regulations-on-Use-of-TVWS-23-March-2018.pdf.

[58] For more background on successful pilot deployments and background on Microsoft's initiative to leverage dynamic spectrum and TV White Spaces to promote connectivity, see https://www.microsoft.com/en-us/research/project/dynamic-spectrum-and-tv-white-spaces/.

[59] Dynamic Spectrum Alliance, Model Rules and Regulations for the Use of Television White Spaces, version 2.0 (Dec. 2017), available at http://dynamicspectrumalliance.org/wp-content/uploads/2018/01/Model-Rules-and-Regulations-for-the-use-of-TVWS.pdf. See also Alistair Braden, "Enabling TVWS and Protecting Incumbents," Nominet Blog (Jan. 15, 2018), available at https://www.nominet.blog/long-read-enabling-tvws-protecting-incumbents/.

[60] In addition, two vacant TV channels in every local market were set aside for exclusive use by unlicensed (non-broadcast) microphones. These unlicensed wireless mics continue to have access to any vacant channel, although to none exclusively.

[61] Preston Marshall, *Three-Tier Shared Spectrum, Shared Infrastructure, and a Path to 5G* (Cambridge University Press, 2017), at 23-24, 87.

[62] FCC, First Report and Order, Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band, 30 FCC Rcd 3959 (2015), at 3962 (emphasis added) ("CBRS Order"). In its final order in 2016, the FCC summarized the unique purpose of its three-tier sharing: "The Citizens Broadband Radio Service takes advantage of advances in technology and spectrum policy to dissolve age-old regulatory divisions between commercial and federal users, exclusive and non-exclusive authorizations, and private and carrier networks." FCC, Order on Reconsideration and Second Report and Order, Amendment of the Commission's Rules with Regard to Commerical Operation in the 3550-3650 MHz Band, GN Docket 12-354 (2016), available at https://apps.fcc.gov/edocs_attachmatch/FCC-16-55A1.pdf.

[63] Testimony of James Assey, NCTA-The Internet & Television Assn., U.S. House Committee on Energy and Commerce, Subcommittee on Communications and Technology, "Defending America's Wireless Leadership," at 6 (March 10, 2023).

[64] Matthew Marcus and Michael Calabrese, "Case Studies of School and Community Networks Able to Close the Homework Gap for Good," New America and Schools Health Libraries Broadband (SHLB) Coalition (August 2023), https://www.shlb.org/uploads/Policy/Policy%20Research/Anchor-Nets-Case-Studies-final.pdf.

[65] FCC Technological Advisory Council, "Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS," at 2 (Dec. 2022) ("TAC Report"), https://www.fcc.gov/sites/default/files/recommendations_to_the_federal_communications_commission_based_on_lessons_learned_from_cbrs.pdf.

[66] Vernita Harris, Office of the CIO, U.S. Department of Defense, "A Spectrum Sharing Success Story: Citizens Broadband Radio Service," LinkedIn Blog (Nov. 14, 2022), https://www.linkedin.com/pulse/spectrum-sharing-success-story-citizens-broadband-radio-harris/.

[67] TAC Report, supra, at 2; see also Clegg, Andrew, "Propagation in the 3.5 GHz CBRS Band," WInnComm 2019, available at https://winnf.memberclicks.net/assets/Proceedings/2019/TS1.3%20Clegg%20updated.pdf.

[68] Marshall at 227.

[69] TAC Report, supra, at 4.

[70] Marshall at 79.

[71] TAC Report, supra, at 4.

[72] See Marshall at 227. "The aggregate interference permitted at this boundary, or interior, of a PAL service area is -80 dBm/10MHz . . . computed at a height above the ground of 1.5 meters."

[73] Marshall at 86. He explains that because LTE is emerging as the de facto standard for CBRS, SAS coordination serves as an effective substitute for a LTE control function, enabling "a degree of coordination between sovereign network operators" that he terms "Federated LTE." Ibid.

[74] Cisco, Cisco Visual Networking Index: Forecast and Trends, 2017– 2022, White Paper, at 23 & fig. 22 (updated Nov. 26, 2018) ("Cisco VNI"), available at https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html. Mobile device traffic was expected to reach 6.9 GB per month per active smartphone in North America by the end of 2017. See Ericsson Mobility Report, at 14 (June 2017), available at https://www.ericsson.com/assets/local/mobility-report/documents/2017/ericsson-mobility-reportjune-2017.pdf.

[75] Cisco VNI, supra, at 21. Cisco reports that Western Europe had the highest number of hotspots, with 48 percent of the world's Wi-Fi hotspots in 2017, but that Asia is likely to have the highest number (47 percent) by 2022. "Critical enablers of Hotspot 2.0 adoption are higher speed Wi-Fi gateways and the adoption of the IEEE 802.11ac and the latest 802.11ax standards." Ibid.

[76] Steve Methley & William Webb, Quotient Assocs. Ltd., Wi-Fi Spectrum Needs Study, at 29 (Feb. 2017) ("between 500 MHz and 1 GHz of new spectrum will be needed in 2025 to satisfy the anticipated busy hour"), available at https://bit.ly/2NSC7YL.

[77] GSMA, Vision 2030: Insights for Mid-Band Spectrum Needs (July 2021); see also CTIA, Licensed Spectrum, at 10 (Feb. 2017), available at https://api.ctia.org/docs/default-source/default-document-library/ctia-white-paper-licensed-spectrum.pdf ("wireless traffic per site 'is projected to grow by an adjusted 343 percent' – all of which additional spectrum must be ready to absorb").

[78] See Thomas K. Sawanobori & Dr. Robert Roche, "From Proposal to Deployment: The History of Spectrum Allocation Timelines" (July 20, 2015), http://www.ctia.org/docs/default-source/default-document-library/072015-spectrum-timelines-white-paper.pdf; Federal Communications Commission, Connecting America: The National Broadband Plan (2010), available at http://dowload.broadband.gov/plan/national-broadband-plan.pdf.

[79] Ericsson, "Fixed Wireless Access Outlook: More than 300 Million FWA Connections by 2028," https://www.ericsson.com/en/reports-and-papers/mobility-report/dataforecasts/fwa-outlook#:~:text=There%20will%20be%20more%20than,2028%2C%20reaching%20over%20300%20million.

[80] Cisco VNI at 23 & fig. 22.

[81] Marshall at 104. Ideally, coordination should be "invisible to the current users of the spectrum being shared." Id. at 82.

[82] In the case of CBRS, incumbent receiver locations and frequencies in use are determined from different sources depending on the service. While the detection of naval radar use will be reported by a network of coastal sensors, FSS sites are protected based on information earth stations report to the FCC's public licensing database, which the SAS ingests (the International Bureau Application Filing and Reporting System, or IBFS). See Marshall at 60-67.

[83] In the U.S., both of these forces are presently in play as the FCC decides what share of the downlink C-band (3.7-4.2 GHz), currently dedicated to Fixed Satellite Services, should be cleared for exclusive licensing or, instead, shared with FSS incumbents using an automated frequency coordination database system. This is discussed further in section 4 below.

[84] See Marshall at 64. As described in Section 4 below, this 'backstop' approach has been proposed for the AFC governing unlicensed sharing across the 6 GHz band, where database coordination is static and simpler than in the dynamic CBRS context.

[85] Federal Communications Commission, Connecting America: The National Broadband Plan (2010), available at http://dowload.broadband.gov/plan/national-broadband-plan.pdf. See also Marshall at 45 (a traditional auction "is the equivalent of asking a startup enterprise to first pay for a building, build the building, and wait for completion before a business could be started.").

[86] Ibid.

[87] See European Conference of Postal and Telecommunications Administration (CEPT), Electronic Communications Committee, ECC Report 236 (May 2015) (ECC Report 236).

[88] See ECC Report 236 at 42, which notes that database operators can collect a "wealth of data about the types of devices and the characteristics of their use." In addition, "the NRA may require specific interference management functions from the database."

[89] Eric Fournier, "Spectrum Sharing in Europe/France," Agence Nationale des Fréquences (ANFR), Presentation to WinnComm 2022, at 4 (Dec. 15, 2022).

[90] Ibid.

[91] Ibid.

[92] See Marshall at 85-86, concerning coexistence optimizations and the "use-it-or-share-it" concept; ECC Report 236 at 47 (noting that dynamic database technologies "could, without regulatory intervention, incorporate mechanisms to deal with contention such as polite protocols.").

[93] See WInnForum, CBRS Standards, available at https://cbrs.wirelessinnovation.org/.

[94] ECC Report 236 at 30-36. There are, of course, possible variations within each of these options, as well as hybrid approaches, which ECC Report 236 develops in greater detail than we will here.

[95] ECC Report 236 at 36. The Report also notes that a NRA can preempt the potential problem of "rogue" (unauthorized) database providers by requiring that all devices certified to operate in a shared band "can only transmit according to the parameters provided by a database that is in the [NRA's] list." Id. at 41.

[96] Ibid.

[97] Dynamic Spectrum Alliance, Model Rules and Regulations for the Use of Television White Spaces, version 2.0 (Dec. 2017), available at http://dynamicspectrumalliance.org/wp-content/uploads/2018/01/Model-Rules-and-Regulations-for-the-use-of-TVWS.pdf.

[98] See Open AFC Software Group, Telecom Infra Project, https://telecominfraproject.com/open-afc/.

[99] See Marshall at 22-27 for a more detailed explanation of the FCC's worst-case approach to limiting the viability of shared access to the vacant TVWS channels.

[100] ECC Report 236 at 38-39.

[101] Id. at 37-40.

[102] FCC, Report and Order and Further Notice of Proposed Rulemaking, Unlicensed Use of the 6 GHz Band; Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz, ET Docket No. 18-295 (rel. Apr. 24, 2020) ("Report and Order").

[103] Innovation, Science and Economic Development Canada (ISED), Decision on the Technical and Policy Framework for Licence-Exempt Use in the 6 GHz Band (May 2021); see also ISED, Radio Local Area Networks (RLANs) Operating in the 5925-7125 MHz Band (Dec. 20, 2022). The FCC decided to consider authorizing AFC-managed Standard Power devices at a future time in U-NII-6 (6.425-6.525) and U-NII-8 (6.875-7.125) where mobile Broadcast Auxiliary Services are authorized.

[104] FCC, Office of Engineering and Technology, "OET Announces Conditional Approval For 6 GHz Band Automated Frequency Coordination Systems," Public Notice, DA 22-1146, ET Docket No. 21-352 (Nov. 2, 2022), https://www.fcc.gov/document/oet-announces-conditional-approval-6-ghz-band-afc-systems.

[105] ISED, "Automated Frequency Coordination (AFC) System Specifications for the 6 GHz (5925-6875 MHz) Frequency Band," DBS-06 (Dec. 20, 2022), https://ised-isde.canada.ca/site/spectrum-managementtelecommunications/en/devices-and-equipment/radio-equipment-standards/database-specifications-dbs/dbs-06- automated-frequency-coordination-afc-system-specifications-6-ghz-5925-6875-mhz-frequency-band.

[106] ANATEL, Public Consultation No. 79, "Automated Frequency Coordination System (5.925-7.125 GHz band)," Request for Comments (Nov. 21, 2022), https://apps.anatel.gov.br/ParticipaAnatel/Home.aspx.

[107] Electronic Communications Committee (ECC), CEPT Report 75, "Report from CEPT to the European Commission in Response to the Mandate" (Nov. 20, 2020).

[108] European Commission, Directorate-General for Communications Networks, Content and Technology, "Mandate to CEPT to Study Feasibility and Identify Harmonised Technical Conditions for Wireless Access Systems Including Radio Local Area Networks in the 5925-6425 MHz Band for the Provision of Wireless Broadband Services," at 4 (Dec. 19, 2017), available at https://www.cept.org/Documents/ecc/41497/ecc-18-047-annex_mandate-rlan-6-ghz. Wi-Fi 6E (IEEE 802.11ax) can seamlessly support 6 GHz operations and achieve gigabit throughputs by aggregating channels as wide as 160 MHz. Industry studies project a shortfall of more than 1,000 MHz of license-exempt mid-band spectrum over the next five to ten years. See Steve Methley & William Webb, Wi-Fi Spectrum Needs Study, Quotient Associates Ltd (Feb. 2017), at 29 ("[B]etween 500 MHz and 1 GHz of new spectrum will be needed in 2025 to satisfy the anticipated busy hour."), available at https://tinyurl.com/ybh94pvx ("Wi-Fi Alliance Study").

[109] European Communications Office (ECC), "Higher power WAS/RLAN in 5945-6425 MHz," SE45_05 Work Item Details (start date July 10, 2022), https://eccwp.cept.org/WI_Detail.aspx?wiid=812.

[110] European Communications Office (ECC), "Higher power WAS/RLAN in 5945-6425 MHz," FM_58 (start date June 10, 2022), https://eccwp.cept.org/WI_Detail.aspx?wiid=811.

[111] Dmitry Akhmetov, Reza Arefi, et al., "Spectrum Needs of Wi-Fi 7," Intel White Paper (2022), https://www.intel.com/content/dam/www/central-libraries/us/en/documents/spectrum-needs-wi-fi-7-whitepaper.pdf.

[112] Chuck Lukaczewski, HPE Aruba Networks, presentation at 2021 DSA Global Summit (June 2021).

[113] U.S. and Canadien rules require the following propagation models: For distances up to 30 meters, the AFC system uses a free space path loss propagation model; for distances greater than 30 meters and up to 1 kilometer, the AFC system shall use the Wireless World Initiative New Radio phase II (WINNER II) model, taking in to account the appropriate propagation scenarios to represent urban, suburban and rural paths; for distances greater than 1 kilometer, the AFC system should use the Irregular Terrain Model (ITM) with the point-to-point configuration combined with the appropriate clutter models defined in Recommendation ITU-R P.2108 for urban and suburban environments and in Recommendation ITU-R P.452 for rural environments. See FCC rule 47 CFR 15.407(l)(1) (available at https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-15) and ISED rules DBS-06 Issue 1 (available at https://ised-isde.canada.ca/site/spectrum-management-telecommunications/en/devices-and-equipment/radio-equipment-standards/database-specificati

ons-dbs/dbs-06-automated-frequency-coordination-afc-system-specifications-6-ghz-5925-6875-mhz-frequency-band).

114 See FCC rule 47 CFR 15.407(k)(2) (available at https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-15) and ISED rules DBS-06 Issue 1 (available at https://ised-isde.canada.ca/site/spectrum-management-telecommunications/en/devices-and-equipment/radio-equipment-standards/database-specifications-dbs/dbs-06-automated-frequency-coordination-afc-system-specifications-6-ghz-5925-6875-mhz-frequency-band). Both the United States and Canada have adopted rules that allow Standard Power access points to operate at an EIRP of 36 dBm and with a maximum power spectral density (PSD) of 23 dBm/MHz.

115 6 GHz NPRM, supra, at ¶ 39.

116 European Commission, "Mandate to CEPT on Technical Conditions Regardig the Shared Use of the 3.8-4.2 GHz Frequency Band for Terrestrial Wireless Broadband Systems Providing Local-Area Network Connectivity in the Union" (Dec. 16, 2021) (CEPT 2021 Mandate), https://digital-strategy.ec.europa.eu/en/library/radio-spectrum-cept-mandates.

117 Ofcom, Statement, "Enabling Wireless Innovation through Local Licensing," at 1 (July 25, 2019), https://www.ofcom.org.uk/__data/assets/pdf_file/0033/157884/enabling-wireless-innovation-through-local-licensing.pdf.

118 Id. The proposal also applies to shared access in 1781.7-1785 MHz, paired with 1876.7-1880 MHz and 2390-2400 MHz. 9

119 Ofcom, Enabling Opportunities for Innovation: Shared Access to Spectrum Supporting Mobile Technology, Consultation (Dec. 18, 2018) ("Ofcom 2018 Consultation"), at 23, available at https://www.ofcom.org.uk/__data/assets/pdf_file/0022/130747/Enabling-opportunities-for-innovation.pdf.

120 Helen Hearn, Ofcom, Spectrum Director, Presentation at WinnCom (Dec. 15, 2022).

121 Presentation of Helen Hearn, Ofcom, supra.

122 Id. at 23-25.

123 Id. at 15. These "private wireless networks could be deployed by many different kinds of users for a wide range of purposes, including IoT devices. Larger bandwidths, available in this band, would support wideband IoT devices . . . 5G technology could support ultra-reliable, low-latency communications which may be needed for some industrial uses such as wireless automation, control and monitoring."

124 Id. at 21.

125 Id. at 61. Ofcom proposes a cost-based average licensing fee of £80 per 10 MHz based on its actual experience and cost to coordinate the roughly 27,000 Business Radio Tech Assigned licenses through a similar process. Some 40 percent of those costs are attributed to the IT system. The proposed fee would also vary from £80 to £800 depending on the channel size licensed (ranging from 10 to 100 MHz). Id. at 62-63, 65.

126 Presentation of Helen Hearn, Ofcom, supra, at 7. See also Ofcom 2019 Statement, at 94. ("We are commencing work . . . to assess whether it would be appropriate in the future to transition towards dynamic spectrum access supported by a fully automated authorisation database approach in the bands outlined under our spectrum sharing framework, where radio equipment would communicate directly with the spectrum assignment database.")

127 Id. at 50, Figure 15.

128 CEPT 2021 Mandate, supra.

129 Id. at 1.

[130] Notice of Proposed Rulemaking, Expanding Flexible Use of the 3.7 to 4.2 GHz Band, Order and Notice of Proposed Rulemaking, GN Docket No. 18-122, FCC 18-91 (July 13, 2018) (3.7 GHz NPRM).

[131] In reality, a large share of registered earth stations actually use a small portion the band corresponding to one or more transponders. For example, the National Public Radio system reports that all 475 of its earth stations rely on a single transponder that uses a standard 36 MHz C-band channel in the lower portion of the band.

[132] See Ex Parte Presentation of Google and Broadband Access Coalition to 26 FCC Staff, GN Docket No. 17-183 (March 29, 2018).

[133] See 3.7 GHz NPRM at ¶ 39.

[134] Id. at ¶ 124.

[135] FCC, Report & Order, "In the Matter of Expanding Flexible Use in the 3.7-4.2 GHz Band," GN Docket No. 18-122, 35 FCC Rcd 2343 (March 3, 2020), https://www.fcc.gov/document/fcc-expands-flexible-use-c-band-5g-0.

[136] FCC, Third Report & Order, Memorandum Report & Order, and Third Further Order of Proposed Rulemaking, Use of Spectrum Bands Above 24 GHz For Mobile Radio Services, GN Docket No. 14-177 (rel. June 8, 2018).

[137] Id., Spectrum Frontiers 3d FNPRM, at ¶ 59.

[138] Id. at ¶ 65.

[139] Id at ¶ 63.

[140] Id. at ¶ 61, citing Starry, Ex Parte Presentation to FCC, GN Docket No. 14-177, at 2 (July 14, 2017).

[141] Expanding Flexible Use of the 12.2-12.7 GHz Band, Notice of Proposed Rulemaking, WT Docket No. 20-443, GN Docket No. 17-183, 36 FCC Rcd. 606 (Jan. 15, 2021) ("12 GHz NPRM").

[142] Id. at ¶ 54.

[143] See, e.g., Linda Hardesty, "WISPA Wants 200 MHz Allocated to Close Digital Divide," Fierce Wireless (March 24, 2021), https://www.fiercewireless.com/wireless/wispa-wants-200-mhz-allocated-to-close-digital-divide.

[144] Expanding Use of the 12.7-1325 GHz Band for Mobile Broadband or Other Expanded Use, Notice of Inquiry and Order, GN Docket No. 22-352, FCC 22-80 (rel. Oct. 28, 2022).

[145] Coordinated Sharing Coalition, Petition for Rulemaking, Amendment of Part 101 of the Commission's Rules to Enable Greater Commercial Use of the 10.0-10.5 GHz Band (filed Oct. 4, 2022). See also Letter to the FCC from 250 WISPs Supporting the 10.0-10.5 GHz Band Sharing Petition for Rulemaking (Dec. 8, 2022), at 2.

[146] Vernita Harris, Office of the CIO, U.S. Department of Defense, "A Spectrum Sharing Success Story: Citizens Broadband Radio Service," LinkedIn Blog (Nov. 14, 2022), https://www.linkedin.com/pulse/spectrum-sharing-success-story-citizens-broadband-radio-harris/.

[147] Marco Höyhtyä, Aarne Mämmelä, et al., "Database-Assisted Spectrum Sharing in Satellite Spectrum: A Survey," IEEE Access, Vol. 5, at 25322 (Nov. 6, 2017).

[148] bid.

[149] Id. at 25335.

[150] Ibid.

[151] Federal Communications Commission, Order and Notice of Proposed Rulemaking, Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems, IB Docket No. 21-456, RM-11855 (Dec. 15, 2021).

[152] Id. at ¶ 23.

[153] Comments of Intelsat License LLC, Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems, IB Docket No. 21-456, RM-11855, at 10 (March 25, 2022).

[154] IEEE Access Survey, supra, at 25338.

[155] See Marshall at 80-81 and 104-110 for an overview various propagation and interference modeling options.

[156] See Monica Allevan, “Google and other databases likely to make spectrum sharing easier,” Fierce Wireless (Oct. 12, 2017), available at https://www.fiercewireless.com/wireless/google-and-other-databases-likely-to-make-spectrum-sharing-easier.

[157] Marshall at 106. Marshall observes as well that most of the propagation models in use today were developed to perform communications link analysis, which is a fundamentally different analysis than the modeling characteristics used for link closure and interference. Id. at 104-105.

[158] Id. at 108.

[159] See Presentation of Apple, Broadcom, et al. to FCC, Expanding Flexible Use in Mid-Band Spectrum between 3.7 and 24 GHz, GN Docket No. 17-183, at 9 (Aug. 2, 2018).

[160] Marshall at 109.

[161] The Illinois Institute of Technology’s Spectrum Observatory, which has collected spectrum occupancy data in Chicago continuously for over a decade, is a leading example. See, e.g., Dennis Roberson, “Illinois Institute of Technology Spectrum Observatory,” Presentation to WSRD Workshop #5 (31 March 2014), available at https://www.nitrd.gov/nitrdgroups/images/7/79/Illinois_Institute_of_Technology_-_Dennis_Roberson.pdf.

[162] Lee Pucker, “Review of Contemporary Spectrum Sensing Technologies,” survey prepared for IEEE-SA P1900.6 Standards Group, at 1 (2017). Indeed, sensing was originally considered by the FCC as the primary mechanism to avoid interference for unlicensed sharing of vacant TV channels (TVWS), but ultimately the agency decided that sensing could not adequately protect “hidden nodes” that could not be detected by the access point.

[163] Id at 4. See also M. Höyhtyä et al., ``Spectrum Occupancy Measurements: Survey and Use of Interference Maps,'' IEEE Commun. Surveys Tutorials., vol. 18, no. 4 (4th Quarter, 2016), at 2386-2414.

[164] Dr. Paul Kolodzy, Keynote Speech at “NSF Workshop on Spectrum Measurements Infrastructure,” Workshop Report, U.S. National Science Foundation (April 2016), at 16-17. Dr. Kolodzy co-chaired the CSMAC subcommittee on Spectrum Measurement and Enforcement.

[165] See Marshall at 62-63 for a detailed description.

[166] Raied Caromi, et al., “Deep Learning for Radar Signal Detection in the 3.5 GHz CBRS Band,” presented to 2021 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN) conference (2021).

[167] An example is the DARPA RadioMap program, which provides a "crowd sourcing" capability by adding software to many existing U.S. military RF devices that enable them to observe and report on their local spectral environment. Dr. Joe Evans, DARPA, Keynote Speech, "NSF Workshop on Spectrum Measurements Infrastructure," Workshop Report, U.S. National Science Foundation, at 18 (April 2016). "[N]ew software has been created to assist in the geolocation of emitters, the determination of the calculated field strength for the emitters and the interpolation or extrapolation of this data to estimate the spectrum intensity (and hence the availability of spectrum for shared usage) across an environment." Evans stated that the U.S. Marine Corps is field-testing this capability. Ibid.

[168] European Commission, Radio Spectrum Policy Group, "RSPG Report on Spectrum Sharing: A forward-looking survey," RSPG21-016 Final (Feb. 10, 2021) ("RSPG 2021 Spectrum Sharing Survey"), at 28-29.

[169] FCC Technological Advisory Council, "Recommendations to the Federal Communications Commission Based on Lessons Learned from CBRS" (Dec. 2022), at 2.

[170] Michael DiFrancisco, Edward Drocella, Charles Cooper and Paul Ransom, "Incumbent Informing Capability (IIC) for Time-Based Spectrum Sharing," National Telecommunications and Information Administration (NTIA) – Office of Spectrum Management (Feb. 22, 2021), https://www.ntia.doc.gov/report/2021/ntia-report-incumbent-informing-capability-iic-time-based-spectrum-sharing#:~:text=The%20IIC%20is%20a%20mechanism,Spectrum%20Coordination%20System%20(SCS).

[171] Id. at 2-3, 7.

[172] Spectrum Innovation Act of 2022, H.R. 7624, 117th Congress (2021-22), passed July 27, 2022.

[173] Office of Communications (Ofcom), A Framework for Spectrum Sharing, Statement, at 28 (April 14, 2016), available at https://www.ofcom.org.uk/__data/assets/pdf_file/0028/68239/statement.pdf.

[174] Id. at 28, n. 39. "Under the current TVWS framework, databases provide information to users about whether and on what frequencies and at what power levels they may transmit to avoid causing harmful interference to incumbent users in and adjacent to the band. Coordination to prevent interference between different white space users is not currently mandated in the UK."

[175] For a good general overview of blockchain technology and applications, see Manav Gupta, Blockchain for Dummies, IBM Limited Edition (John Wiley & Sons, 2017).

[176] See RSPG 2021 Spectrum Sharing Survey, supra, at 28-31 (discussing functionality and when blockchain may not be feasible or cost-effective).

[177] Agence Nationale Des Frèquences, "Blockchain: Launch of the First French State Blockchain," ANFR website, available at https://www.anfr.fr/en/anfr/news/all-news/detail-of-the-news/actualites/blockchain/.

[178] See Juliette Raynal, "State Prepares Blockchain for Free Frequencies," L'Usine Digitale (April 18, 2018), available at https://www.usine-digitale.fr/article/l-etat-prepare-une-blockchain-pour-les-frequences-libres.N681954.

[179] "France to trial blockchain for spectrum management," PolicyTracker (May 23, 2018).

[180] Eric Fournier, "Spectrum Sharing in Europe/France," Agence Nationale des Fréquences (ANFR), Presentation to WinnComm 2022, at 2 (Dec. 15, 2022).

[181] Id. at 15.

[182] See generally Martin Weiss, Kevin Werbach, et al., "On the Application of Blockchains to Spectrum Management," 46th Annual Telecommunications Policy Research Conference (Sept. 2018), at 10-12, available at https://ssrn.com/abstract=3141910.

[183] See Khashayar Kotobi and Sven G. Bilén, “Secure Blockchains for Dynamic Spectrum Access: A Decentralized Database in Moving Cognitive Radio Networks Enhances Security and User Access,” IEEE Vehicular Technology Magazine (March 2018).

[184] Emanuele Di Pascale, Jasmina McMenamy, et al., “Smart Contract SLAs for Dense Small-Cell-as-a-Service” (March 2017), available at https://arxiv.org/pdf/1703.04502.pdf.

[185] See “Final report: The Second Enhancing Access to the Radio Spectrum Workshop Technical Report,” National Science Foundation (October 20, 2015); U.S. Dept. of Commerce Spectrum Management Advisory Committee (CSMAC), Enforcement Subcommittee Technical Report, NTIA (May 12, 2015).

[186] Amer Malki and M.B.H. Weiss, “Automating Ex-Post Enforcement for Spectrum Sharing: A new application for Block-chain technology,” 44th Annual Telecommunications Policy Research Conference (Sept. 2016). See also M.B.H.Weiss, W. H. Lehr, et al., “Socio-technical considerations for spectrum access system (SAS) design,” 2015 IEEE Dynamic Spectrum Access Networks (DySPAN) International Symposium, at 35-46 (Sept 2015).

[187] See Martin B.H. Weiss, Kevin Werbach, et al., “On the Application of Blockchains to Spectrum Management,“ 46th Annual Telecommunications Policy Research Conference, at 8-9 (Sept. 2018), availabe at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3141910.

[188] Ibid. The authors state that this overhead could include the need to allocate channels for users to broadcast entries to all other users, since by definition there is no centralized repository or control. Accord RSPG 2021 Spectrum Sharing Survey, supra, at 30-31

[189] RSPG 2021 Spectrum Sharing Survey, supra, at 30.

For more information,
scan the QR code below:

Dynamic Spectrum Alliance
3855 SW 153rd Drive
Beaverton, OR 97003
USA