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AUTOMATED FREQUENCY COORDINATION

AN ESTABLISHED TOOL FOR MODERN SPECTRUM MANAGEMENT

MARCH 2019

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Executive Summary

In recent years, 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 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.

Ofcom, the UK 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 TV White Space channels. In the United States, Congress in 2018 mandated development of a national spectrum plan that includes examining "existing and planned databases or spectrum access systems designed to promote spectrum sharing."

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 is (1) surging consumer demand for wireless connectivity and hence the need to intensively share underutilized frequency bands; (2) significant improvements in the computation power to efficiently and rapidly run advanced propagation analysis and coordinate devices and users in near real-time; and (3) more agile wireless equipment that can interact directly with a dynamic frequency coordination database. 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.

As this report details, while 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. This evolution has generally 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, most recently, 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 (the Citizens Broadband Radio Service).

Spectrum coordination databases have demonstrated the ability to facilitate a variety of regulatory frameworks, including licensed, unlicensed and lightly-licensed sharing regimes. 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. Regulators now have the models and technologies needed to authorize automated frequency coordination systems that best fit the NRA's policy goal, 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. In all cases the grant provided by the AFC is the equivalent to a time-bounded authorization (or license) to transmit.

Automated frequency coordination (AFC) systems 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). 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 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 translate 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.*

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,*
- *facilitates 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.*

AFC systems 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);*
- *dynamic adjustments to the admission control parameters (to mitigate, for example, aggregate interference).*
- *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, exploding consumer demand for data-intense applications on mobile devices, coupled with the potential benefits of 5G and IoT networks, are motivating regulators to consider how dynamic spectrum sharing can unlock unused capacity in occupied-but-underutilized bands. This report highlights three bands under active consideration, in the U.S. and/or Europe, for sharing managed by AFC systems, as well as the potential for database-assisted sharing in satellite bands and particularly by NGSO satellite constellations.

At the time this was written, in a trio of Proposed Rulemakings (NPRMs), the U.S. Federal Communications Commission is considering the authorization of an AFC to facilitate shared access by unlicensed, licensed, and lightly-licensed entrants in underutilized bands, including:

- **6 GHz:** A proposal to authorize an AFC system to manage unlicensed sharing across 850 megahertz in the 6 GHz band between 5925 and 7125 MHz. An AFC would coordinate at least outdoor deployments to insure no interference with tens of thousands of point-to-point microwave links and other incumbents.

- ***3.7-4.2 GHz**: A proposal to authorize coordinated shared access by fixed wireless broadband operators (point-to-multipoint) in a substantial portion of the downlink C-band that will continue in use for Fixed Satellite Service (FSS) incumbents.*

- ***37-37.6 GHz**: A proposal to authorize coordinated shared use of the lower 37 GHz band by a variety of commercial and federal government users. The Shared Access Licenses and frequency coordination system are yet to be defined.*

Similarly, the European Union and the UK have ongoing consultations that propose a degree of unlicensed or opportunistic licensed sharing in the 6 GHz and C-band (3.8-4.2 GHz), respectively:

- ***5925-6425 MHz**: Similar to the FCC's pending rulemaking, the European Commission has tasked a working group to study the regulatory and technical feasibility of authorizing unlicensed RLANs to operate on secondary basis in the 6 GHz band (5925-6425 MHz). A final draft report, including an assessment of coexistence scenarios with band incumbents, is expected by May 2019, followed by a public consultation and a final report by March of 2020.*

- ***3.8-4.2 GHz**: In the UK, Ofcom's proposal would enable 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. Both very small-area licenses (50-meter radius) and medium-power base station licenses (in rural areas only) initially would be coordinated by Ofcom and possibly later by an automated frequency coordination database system.*

Finally, the report reviews a number of emerging technological advances that can further amplify the benefits of AFC systems. These include the incorporation of more detailed, real-world GIS data (e.g., terrain, clutter, building heights and materials); real-time spectrum sensing data; the growing sophistication of propagation and interference modeling; value-added, cloud-based database services; and the potential to combine blockchain technology with dynamic database coordination.

Automated Frequency Coordination:

An Established Tool for Modern Spectrum Management

1. Introduction and Database Basics

As this report details, although spectrum database coordination is nothing new, it has very 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 band sharing – including for licensed fixed wireless links, unlicensed Wi-Fi and mobile/LTE – are 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 have emerged as candidates for shared use via automated frequency coordination, as described in Section 4 below.

In recent years, 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, Congress in 2018 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]

In Europe Ofcom, the UK regulator, stated in the agency's 2016 Statement concerning A *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.[2] In December 2018 Ofcom released a Consultation stating its intention "to work towards a Dynamic Spectrum Access (DSA) approach in bands where this is appropriate and practical to implement."[3] Ofcom proposed opportunistic sharing of the 3.8-4.2 GHz band (described further in Section 4 below), including a longer-term goal "to define the appropriate specification for both DSA equipment and database capability that would enable future transition to DSA."[4]

In addition to coordinating frequency assignments and interference avoidance, more dynamic databases offer the potential for additional functionality and efficiency far beyond what manual or database-assisted coordination can offer. Far greater efficiencies will also be possible going forward as more granular and real-world data (terrain, clutter, three-dimensional mapping, etc.) are incorporated into the algorithms that an automated frequency coordination system 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 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 in advanced economies. Despite these benefits, database coordination 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."[5]

While incumbent users of underutilized bands typically characterize the delegation of real-time spectrum access decisions to database algorithms 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, what's new are cloud-based solutions that vastly improve the speed at which coordination can be conducted, the rapid evolution of highly detailed geographic databases combined with clutter-aware propagation models, and transmitters and receivers capable of dynamically receiving information from databases. Once automated, coordination databases can also become platforms for new 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 informationexchange 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.[6] As the International Engineering Consortium explained:

> When a subscriber dials an 800 number, it is a signal to the switch to suspend the call and seek further instructions from a database. The database will provide either a real phone number to which the call should be directed, or it will identify another network (e.g., a long-distance carrier) to which the call should be routed for further processing. . . . [T]he response from the database . . . can be made to vary based on the calling number, the time of day, the day of the week, or a number of other factors.[7]

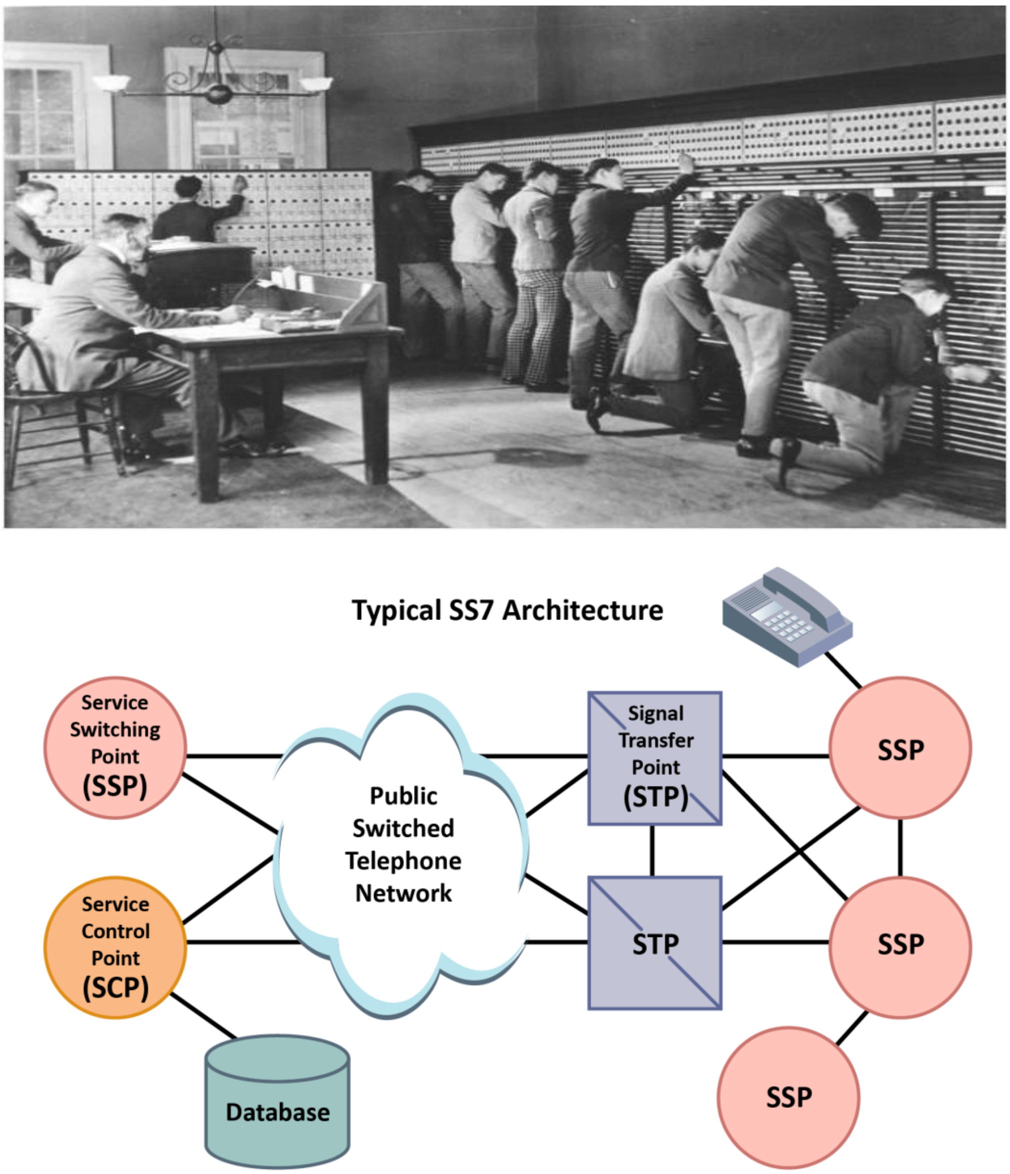

Figure 1: Manual switchboard operators (circa 1877) gave way over time to the automated call routing databases that characterized the SS7 signaling networks the ITU adopted as the international standard in 1988.

SS7 represented just one of a number of automated database networks that evolved to support efficient, low-cost, interconnected telephone connectivity worldwide.[8] Among the most advanced today is the Local Number Portability (LNP) database which, in the U.S., has been operated by a third-party contractor approved by the FCC since 1997 and overseen by a committee of major telecommunications providers. The UK's number porting system, also initiated in 1997, is similar.[9] The automated and interoperable nature of the LNP database system is critical:

> "When a call is made to the ported telephone number, the initiating service provider switch launches a query to its LNP call routing database to determine whether the telephone number has been ported. . . . If the number is not ported, the database response indicates that the call should be routed based on the telephone number."[10]

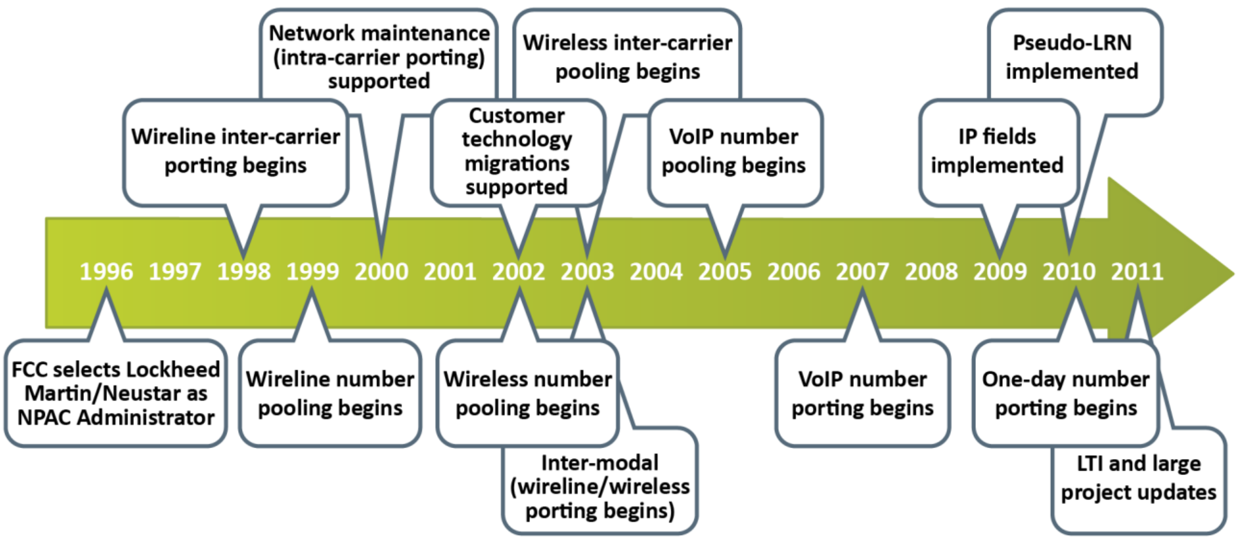

Figure 2: Phone number portability and forward call routing rely on automated database systems introduced in US and UK in 1997.[11]

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. GSM enabled full duplex voice telephony and expanded over time to include data communications. 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.

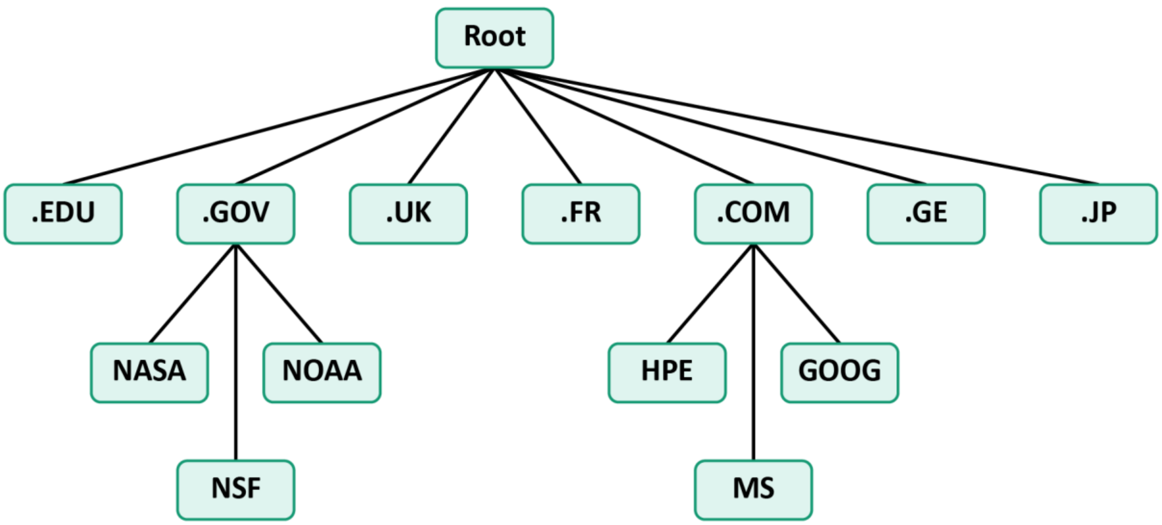

Figure 3: The Internet's Domain Name Service (DNS) is a distributed database process that connects domain names to IP addresses to facilitate the routing of Internet traffic. [13]

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 licenses over a defined (and typically 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. While early policy discussions around spectrum sharing mechanisms focused on decentralized cognitive radios capable of sensing other band occupants, regulatory solutions shifted fairly quickly to more centralized coordination mechanisms automated through agency-approved database operators, an advance typified by the adoption of TV White Space databases in a growing number of nations globally.

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 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 U.S. to coordinate point-to-point microwave links in Fixed Satellite Service bands. Today this coordination is database-assisted, as described further in the next section, but 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 automated frequency coordination (AFC) systems. AFCs simply automate the process of manual spectrum coordination.[14] As explained in the next section, in an AFC 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. Automated Frequency Coordination Databases: 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 and technologies needed to authorize automated frequency coordination systems that best fit the NRA's policy goal, 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. In all cases the grant provided by the AFC is the 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 C-band (3.7-4.2 GHz).*

- ***Opportunistic, unlicensed use of unused spectrum by frequency and location:*** *Examples include TV White Space and the FCC's proposal to authorize unlicensed sharing in the uplink C-band and other bands between 5925 and 7125 MHz.*

- ***Two-tier Licensed Shared Access based on geographic areas and database assist:*** *Various European NRAs are implementing this initially in the 2.3 – 2.4 GHz band (3GPP LTE band 40) based on multi-year sharing contracts with tier-one incumbents.*

- ***Three-tier shared access, combining licensed and opportunistic use:*** *For example, the U.S. Citizen Broadband Radio Service (CBRS) is managed by a dynamic database, sharing U.S. Navy radar spectrum at 3550-3700 MHz for a mix of licensed and lightly-licensed use (Spectrum Access System). In the UK, 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 automated frequency coordination 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.

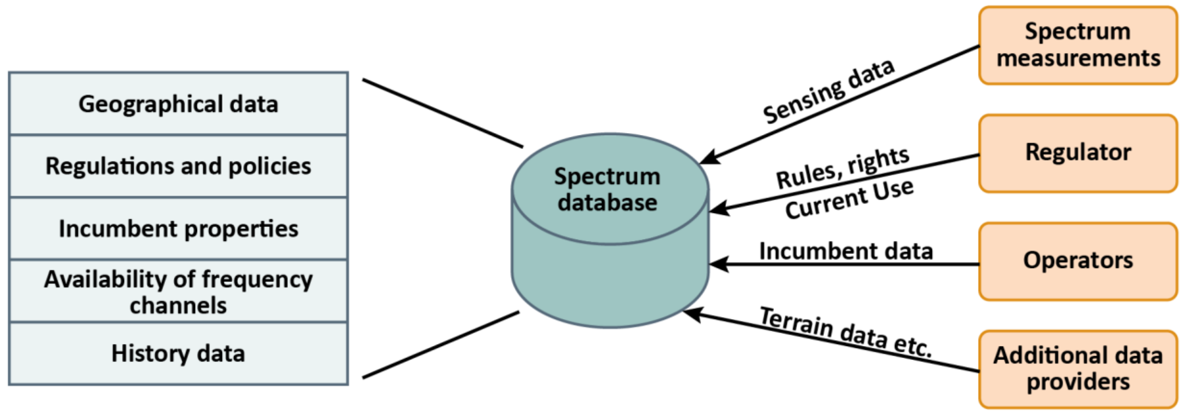

Figure 4- A general spectrum database model. *(Source: M. Höyhtyä, et al.)*[15]

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 typically 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 industry experts and representatives.[16]

With rules in place, one or more AFC 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 AFC to qualifying and certifying multiple, competing AFCs.[17] In either case the AFC 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.

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. In this respect, a shared environment positively changes the incentives of incumbents to ensure that their information in the database is accurate so that interference into these networks is prevented. 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 AFC operator may be required to collect a similar set of information from shared-access users that must be protected as part of granting any request for permission to transit. 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 operator requires to apply its algorithms. Registration is also an opportunity for the database operator to impose (or at least 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] If there are multiple database operators each operating an online self-registration portal, online synchronization of self-registration data between database operators must be frequent enough that requests for permission to transmit will not receive conflicting or incompatible results.

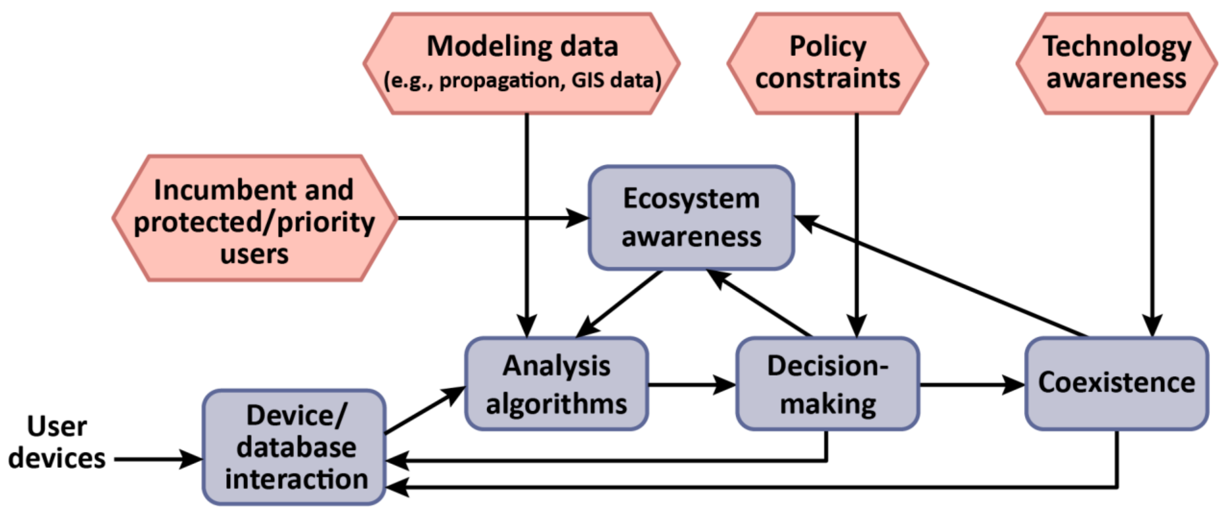

Figure 5: Conceptual architecture for an automated frequency coordination (AFC) system.

Importantly, AFC 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 database.[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. For example, 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]

Propagation loss has been studied extensively and is well understood, but typically the inputs to the analysis algorithms do not reflect real-world path loss.[24] 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. For example, at low power, Wi-Fi or other broadband devices may be able to operate far more extensively if the AFC 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.[25] This is discussed further in Section 5 below.

At this point, the AFC 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. If the AFC algorithms are faithful to the rules, there is no need for – and considerable downside in requiring – the cost and delay of agency review. 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., 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 AFC 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, AFC 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 AFC 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 Databases: 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 U.S., thousands of megahertz 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. While fully automated and dynamic coordination remains in development, we'll see in this section that AFC 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 databases employed in spectrum coordination are the many licensing databases maintained by NRAs, such as the International Bureau Application Filing and Reporting System (IBFS) maintained by the FCC.[31] These licensing databases, though often rich in operational detail, are almost entirely static. IBFS 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 broadcast 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.[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 per 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.

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 concludes 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.

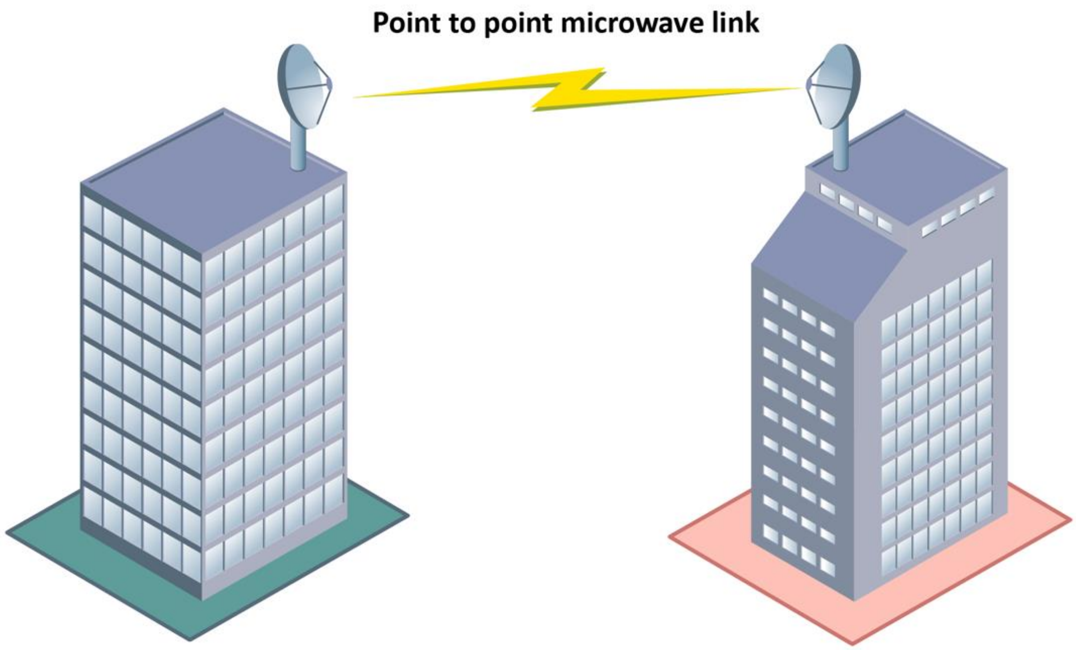

Figure 6: Point-to-point Fixed Service Links Require Coordination under Part 101.

A more recent variation of a regulator leveraging database-informed coordination is the coordination process for the Wireless Medical Telemetry Service (WMTS) in the U.S. 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 and LSA

More recently, 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]

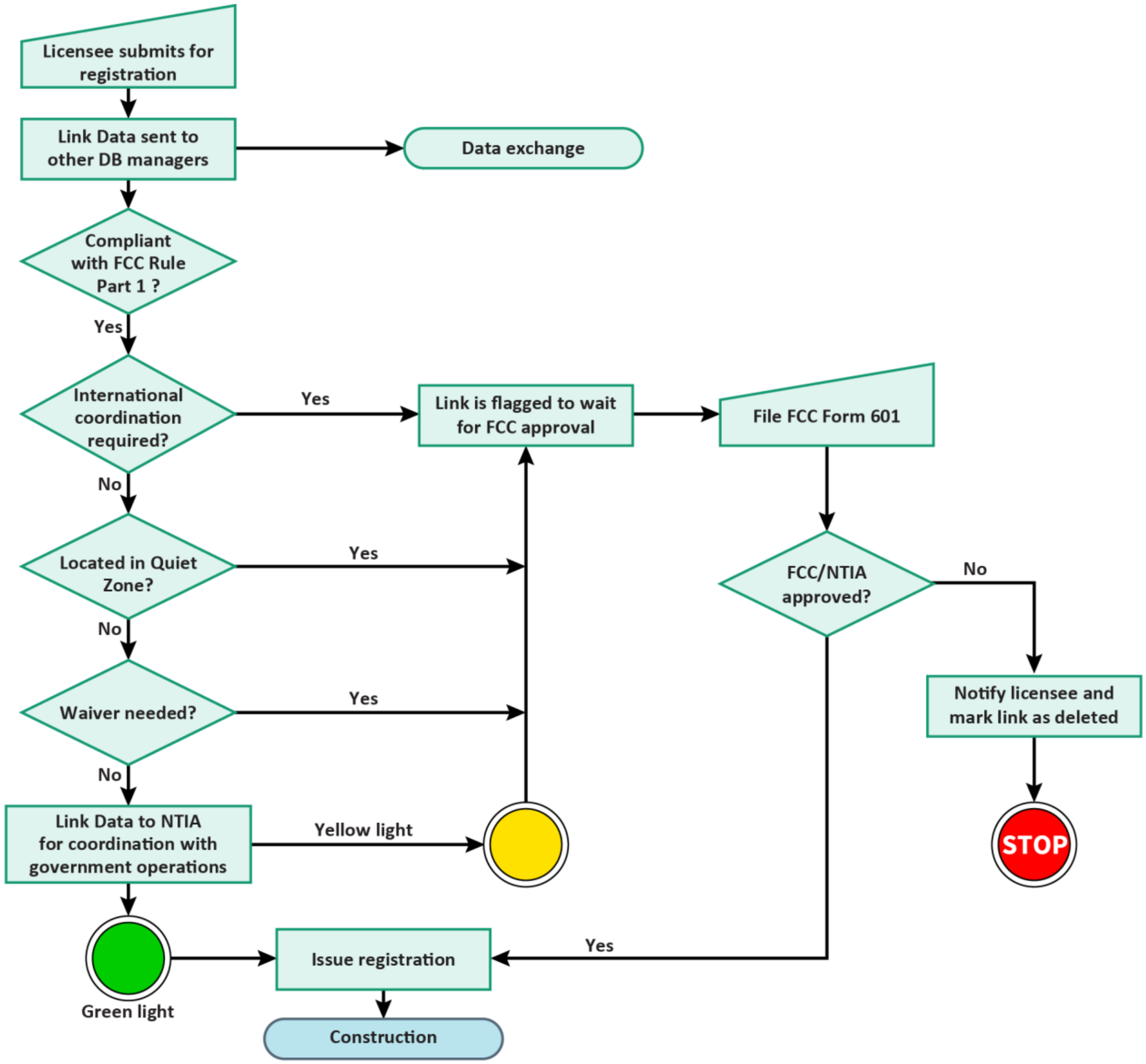

Figure 7: The 70/80/90 GHz link registration and database coordination process interconnects with a U.S. government database to ensure no conflicts with military or other agency use of the band.[41]

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."[42] 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.[43] The three coordinators compete and can also provide additional services such as link design, prior coordination and interference analyses.[44]

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 that the authorized database operators prior-coordinate with Federal users through a separate, non-public database.[45] The National Telecommunications and Information Administration (NTIA), the government's Federal spectrum manager, maintains an automated coordination database of Federal assignments on 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).[46]

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.[47] Both approaches are essentially the manual-but-database-assisted process used for PtP links in C-band and other frequencies. 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 registration, similar to the UK's framework for the upper half of each band.[48] India's TRAI has recommended an online registration process with "[r]esponsibility 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)."[49]

Licensed Shared Access

The European experiment with Licensed Shared Access (LSA) is another database-assisted model that facilitates two-tier sharing between primary and secondary licensees. In this model, targeted initially at the 2.3-2.4 GHz band, the NRA plays a direct role in managing the database of information by which primary and secondary licensees share the band.[50] Unlike any of the band-sharing models implemented to date in the U.S., 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.[51] Since LSA is explicitly aimed at facilitating carrier-deployed LTE, both the primary and secondary licensee retain exclusive rights over fairly wide geographic areas. LSA can be considered to be a database-assisted secondary markets mechanism.

The European framework presumes that the NRA creates and operates a Licensed Shared Access Repository (LR) database that provides 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.[52]

LSA's two-tier and exclusively-licensed framework is very different from the automated frequency coordination databases adopted in the U.S. to enable open shared access to unused capacity in the TV broadcast and U.S. Navy bands (described below). The centralized repository facilitates secondary and exclusive-use 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."[53]

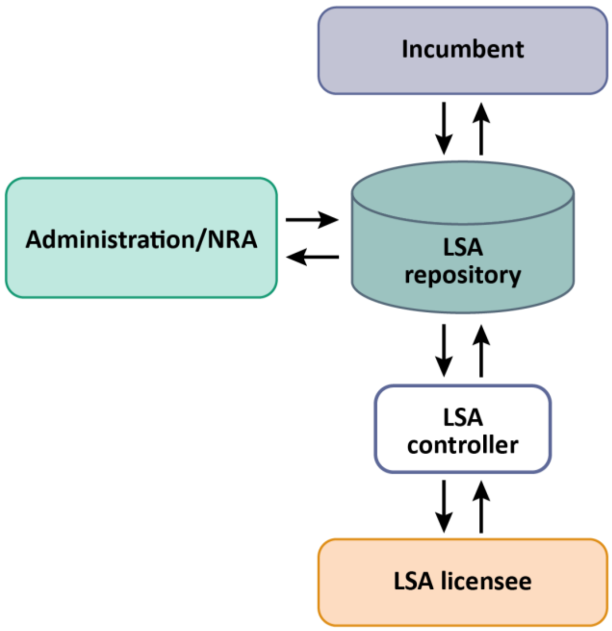

Figure 8: LSA functional blocks and interactions (Source: ECC Report 205

C. Automated Database Frequency Coordination: TV White Space

The first fully automated frequency coordination (AFC) systems facilitate 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 and Singapore have working systems managed, as in the U.S., by one or more automated geolocation database operators. South Africa adopted rules in March 2018 and is in the implementation process. Malawi, Ghana and Mozambique had draft TVWS regulations under review as of mid-2018.[54] And 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, Kenya, Tanzania, Trinidad and Tobago, and the Philippines.[55] 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.[56]

As AFC systems, 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, facilitates intensive use, 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 stations 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 automation, allowing for near-real-time and very granular assignments at low cost and with consistent accuracy. This 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. The U.S. rules permit licensed microphone operators to use a TVDB online portal to reserve channels, for specific times and places.

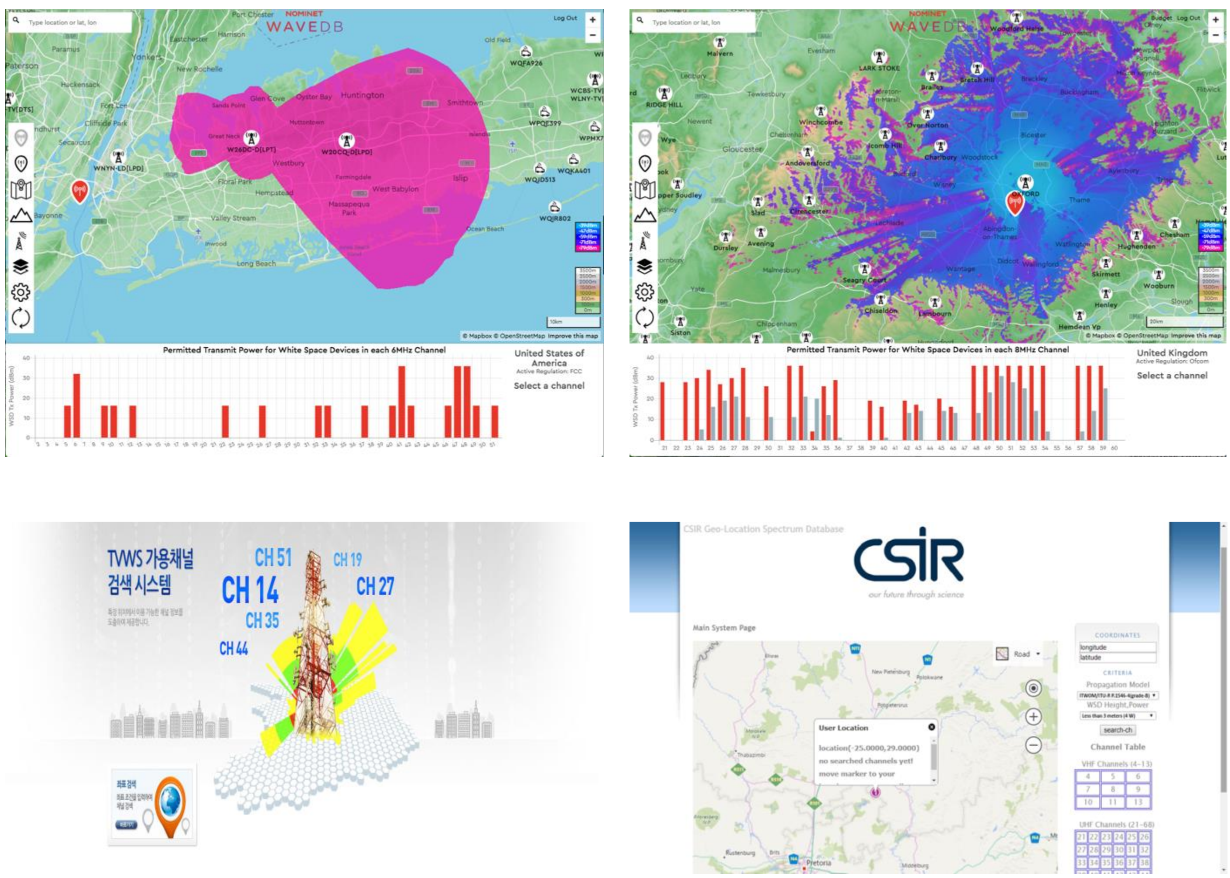

Figure 9: USA (top-left), UK (top-right), and South Korea's TVDBs (bottom-left) are operational; South Africa (bottom-right) finalized TVWS rules in 2018.

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. In the U.S. this incumbent protection data includes "reservations" of scheduled activity provided via an online portal by licensed wireless microphones, which typically operate intermittently (for example, at major public events).[57] 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.

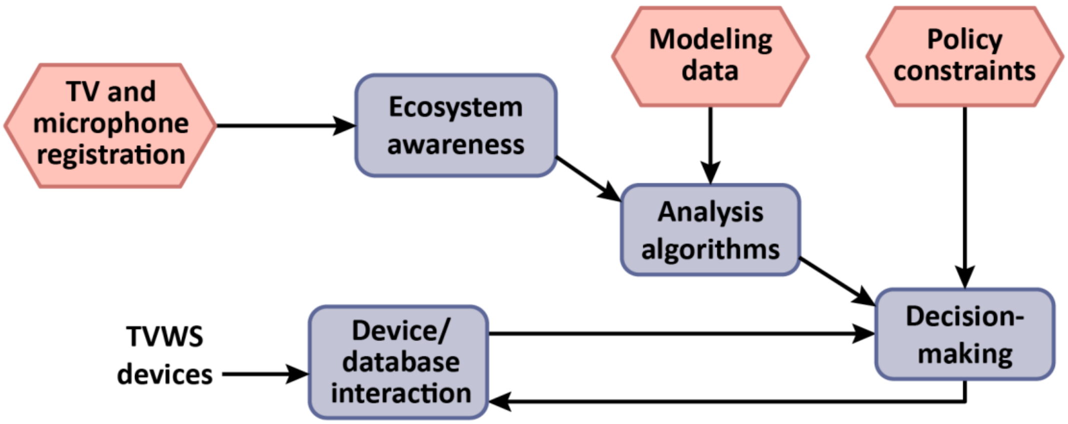

Fig 10: Simplified admission control system architecture for Television Whitespace Database (TVDB).

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). 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. Neither Ofcom nor the FCC databases take account of terrain in protecting PMSE.

Although TVDBs fully automate coordination, a few significant features both simplify their implementation and distinguish them from the sort of dynamic and/or three-tier database coordination system described just below (the U.S. Citizens Broadband Radio Service). First, and most obviously, automated frequency 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, at least none that are automatic or a mandatory feature of the assignment process. 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 services offered by one of the competing TVDBs in the U.S. (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).

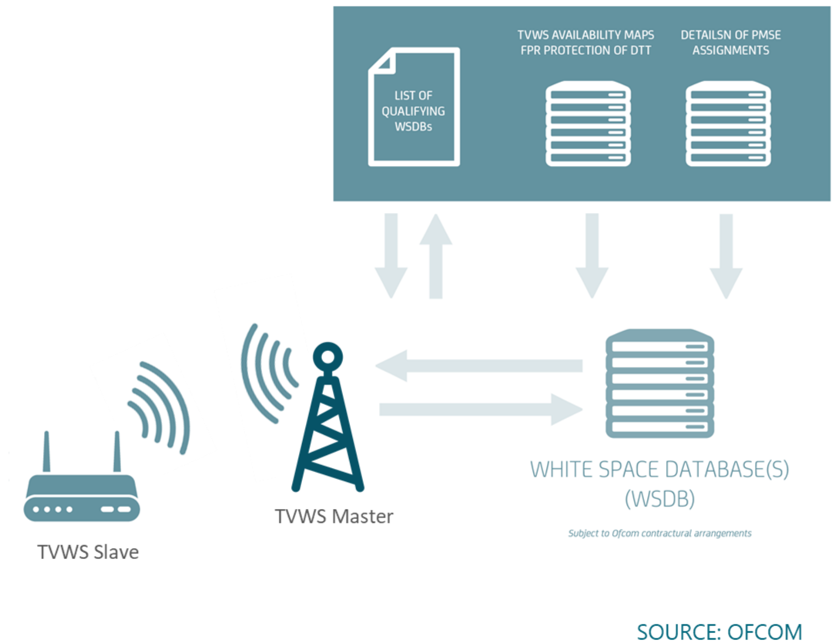

Figure 11: OFCOM's architecture for Television Whitespace Database (TVDB).

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 simplification might be a positive feature in some bands, in the TV bands it's in fact grossly over-protective and leaves useable spectrum fallow. As Preston Marshall explains in his book on three-tier sharing, in a band where the risk to incumbents derives primarily from aggregate interference, such a one-on-one interference calculation "means that the limits on power must reflect the possibility that a large number of nodes might be located in the vicinity of any one receiver, regardless of where they actually were located."[58] The inability of the TVDB to manage interference dynamically results in a maximum power per WSD "based on an estimate of worst-case density."[59]

D. Dynamic Coordination Databases: The CBRS Spectrum Access System

In 2015, a unanimous FCC adopted a new Citizens Broadband Radio Service (CBRS) to coordinate new licensed and opportunistic (unlicensed) 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), Priority Access Licenses (PALs), and opportunistic (effectively unlicensed) General Authorized Access (GAA) users. The SAS is responsible for ensuring incumbent services are fully protected from interference and that PAL operators are similarly protected from GAA users.

The GAA tier is effectively unlicensed, although the SAS strives to optimize coexistence among users. The lower 70 MHz of the band are assigned dynamically based on seven PALs (each license is for 10 MHz), while GAA users can operate band-wide. GAA users can operate throughout the entire 150 megahertz of the 3.5 GHz band on any frequencies not in use by PALs or by the Navy. Multiple SAS operators are currently in the final stages of certification, which will allow CBRS to be at least partly operational by mid-2019.

For the first time, CBRS offered *interference-protected spectrum* to "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.[60] As the *CBRS Order* stated, the regulator's intention was to make a combination of licensed and unlicensed spectrum available on a targeted basis to thousands of potential network operators, including rural ISPs, private "neutral host" LTE networks, office complexes, factories customizing machine-to-machine networks, utilities, airports, shopping malls, sporting arenas, and college and other campuses. With direct and affordable access to spectrum, enterprises and venues can deploy localized networks, including connectivity solutions customized and deployed by end users themselves, much as Wi-Fi is today.

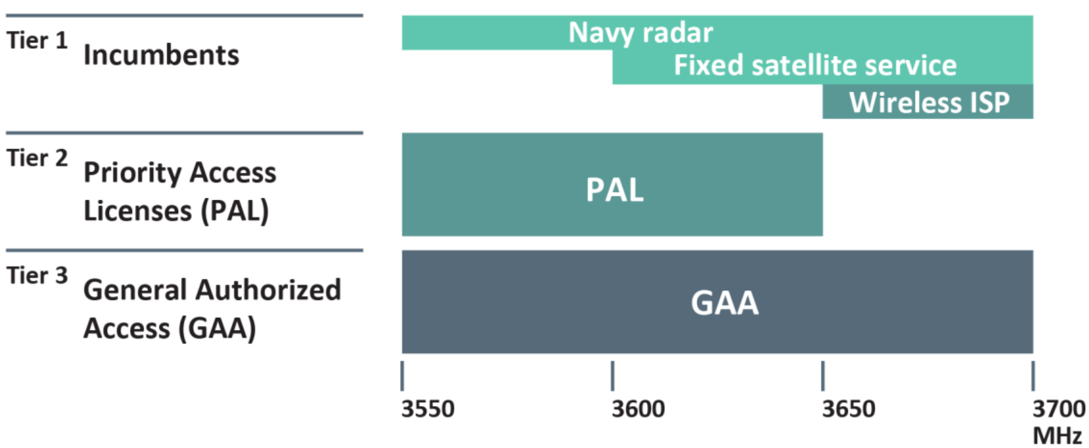

Figure 12: Three-tier coordination in the 3550-3700 MHz Citizens Broadband Radio Service.

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 the illustration just above indicates, 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 (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 radar, which are mobile. The SAS awareness of Navy radar, in turn, is assisted by an Environmental Sensing Capability (ESC), which will rely on a network of spectrum sensors along the U.S. coastline.

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, 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 megahertz, a requirement critical to this and other dynamic features highlighted 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).

- ***Sensing network inputs***

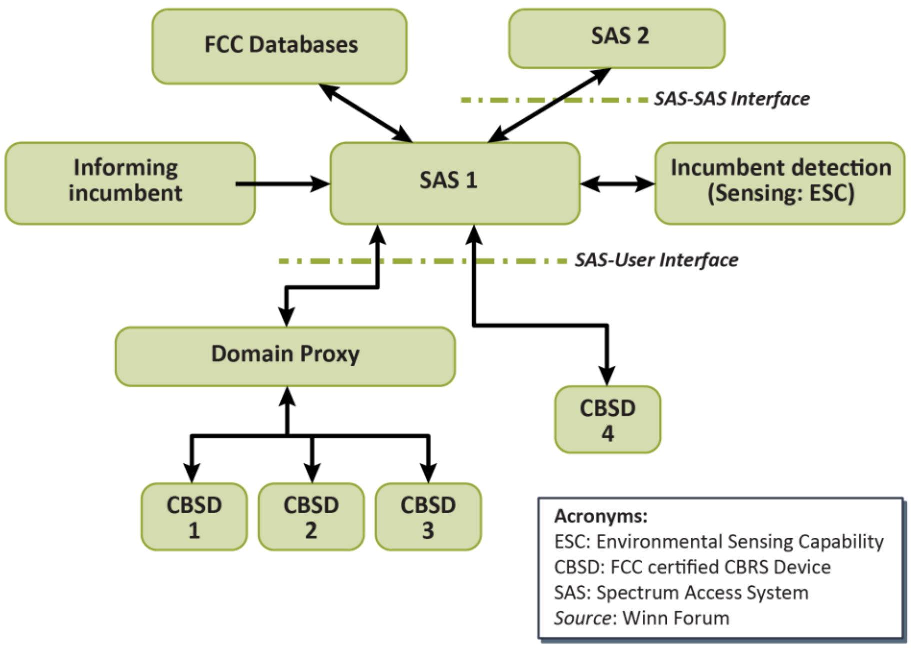

Figure 13: CBRS conceptual framework.

The ESC, a coastal network of spectrum sensors, provides real-time awareness of naval radar. Each sensor is associated with a large and fixed geographic protection zone and relays sensing data to the SAS. Notably, the military has been open to sharing the band, subject to SAS control and sensing, despite concerns about a higher noise floor and revealing ship locations. 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."[61] 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). Security is maintained by requiring that the SAS must verify the certification status of reporting ESC sensors.[62]

- ***Dynamic interference protection***

As noted in the section above, TVWS database coordination is a static, one-to-one calculation. If the device is not interfering with a TV station or licensed microphone, 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."[63] Each SAS, as they synchronize, is updated to take account of each new grant or termination of permission to transmit. Of course, the coordination database for 70/80/90 GHz described above has this same feature, since each newly approved PtP link path changes the calculation for future requests in that area. The SAS takes this concept to scale and applies it to monitor and address changes in the spectral environment over time. Significantly, this gives a SAS the capability to manage aggregate interference by geography and to optimize coexistence among GAA users.

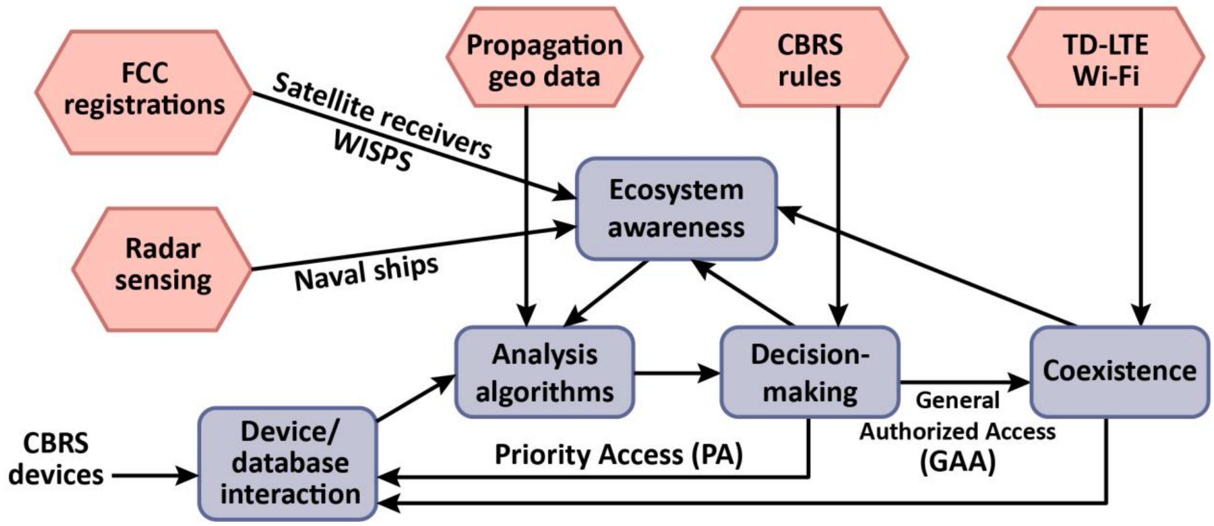

Figure 14: Admission control system architecture for three-tier, FCC-certified Spectrum Access System.

- ***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.[64] 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 device authorized to operate in a local area, it can make assignments to GAA users that optimize performance and minimize mutual interference. As 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."[65] This is very different from self-coordination in a traditional Wi-Fi band, where coexistence is built into the listen-before-talk capability of devices; and different from TVWS database coordination, where users are given a list of available channels, but must self-coordinate in relation to other unlicensed users (none of which are assigned to a specific channel based on optimization criteria). 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 megahertz to that user (from 3600 to 3660 MHz).

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 ongoing global survey forecasts 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.[66] Globally, Cisco projects there will be nearly 549 million public Wi-Fi hotspots by 2022, up from 124 million hotspots in 2017, a fourfold increase.[67]

As a result, industry studies project daunting deficits in the availability of both licensed and unlicensed spectrum. A study commissioned by the Wi-Fi Alliance projects a shortfall of between 500 MHz and 1 GHz of unlicensed spectrum by 2025,[68] while a report by CTIA, the U.S. wireless industry association, notes that "wireless traffic per site 'is projected to grow by an adjusted 343 percent' – all of which additional spectrum must be ready to absorb."[69] While wide swaths of spectrum are being reallocated in the millimeter wave bands above 24 GHz, the more valuable midand 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.[70]

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 support 5G applications at reasonable costs. In the U.S., the number of fixed-wireless subscribers is projected to double to 8 million by 2021, compared to 2016, with core industry revenues nearly doubling from $2.3 billion to more than $5.2 billion.[71] This does not even include hundreds of thousands of 5G fixed-wireless access points deployed by mobile carriers on their own licensed spectrum.[72] 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.

Spectrum band sharing – and an automated frequency coordination process to avoid interference to incumbent licensees – is therefore 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. Automated frequency coordination benefits the ecosystem and economy overall by enabling greater spectrum re-use while avoiding interference.

Second, relative to the surging demand for wireless data, leveraging AFC systems 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. Freeing up bandwidth 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.

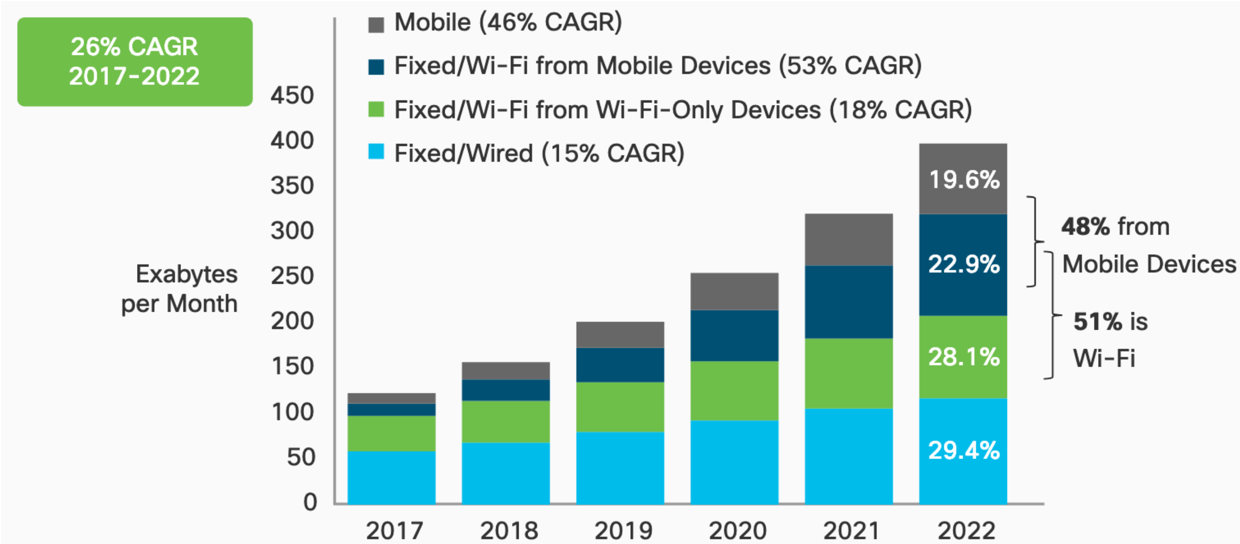

Figure 15: While Internet traffic continues to grow rapidly, compound annual growth rates (CAGR) are highest for Wi-Fi connectivity on mobile devices.[73]

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 automated frequency coordination 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."[74] The starting assumption is that incumbent users "are not required to develop new functionality to report status to an admission control system, but either statically declare their positions and characteristics, or are dynamically detected."[75] 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 supplies a proxy for that licensing information to the database.[76]

So long as the rules require – and the automated database system enforces – non-interference to incumbent operations, 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 others sharing – and particularly the sort of intensive sharing enabled by automated frequency coordination – obviates the argument that the band is underutilized.[77] In the case of CBRS, the U.S. Navy and military more broadly shifted from opposition to general support for band sharing using dynamic databases (coupled with sensing to protect U.S. Navy ships) 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 strengthened for CBRS, are requirements that users register the location and technical characteristics of every access point, that mobile 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, 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.[78]

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 database 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 – automated coordination 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 – and particularly in shared access bands – the most intensive and efficient deployments will rely on small cells. In some bands this may result from a regulatory choice (as the U.S. FCC did with CBRS) or from operator choices based on propagation characteristics and the need to densify existing networks. For example, one Wall Street study of Verizon's announcement in early 2018 that its initial '5G' push would be to offer an additional 30 million homes gigabit-fast service using *fixed wireless* operating primarily on millimeter wave bands above 28 GHz would require more than 350,000 access points. [79] 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 should be expected to lower 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 closely associated with low transaction costs 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,[80] or legions of lawyers and a long process to achieve a new frequency allocation, 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.

Finally, in addition to a core function of coordinating frequency access without disturbing incumbents, dynamic databases are likely to add additional, value-added services that can help users optimize quality of service, facilitate private secondary market transactions, recycle crowd-sourced spectrum sensing data, incorporate more detailed GIS data to enable even more intensive sharing, and facilitate other innovations that can result from a more dynamic, data-rich awareness of users and the environment. This is discussed further in Section 5 below.

iv. Promotes direct spectrum access for innovation and productivity

Dynamic databases are 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.

Automated 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.[81] The three-tier Citizens Band 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;*[82]
- *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;*[83]
- *Maintain the ability to identify and shut down a device or provider in cases of harmful interference or emergency;*
- *Dynamically adjust the device admission or operating parameters (in response, for example, to exceeding an 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.*

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.

Moreover, an automated frequency coordination system creates 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."[84] *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.[85] 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, it's useful to distinguish the even more nuanced capability of dynamic AFC systems to optimize coexistence among users granted shared access to a band. For example, under U.S. rules for CBRS, users granted GAA are effectively unlicensed and not entitled to any interference protection. However, unlike unmanaged unlicensed bands, the SAS will 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.[86] Indeed, 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).

ii. Coordination can be delegated while 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 Citizens Band Radio Service, 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.[87] 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 elaborates the pros and cons of three options for the provision 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.*[88]

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."[89] 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."[90]

In the U.S., it's notable that the FCC has shifted almost entirely to a framework of certifying competing commercial database operators to manage frequency coordination in shared bands. Although the agency has 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 Commission has authorized competing commercial database providers to coordinate shared access in the TVWS, CBRS and 70/80/90 microwave fixed link bands, as described above. In all cases, as ECC Report 236 emphasized, it is important to regulators that "devices get their operating parameters from a database that has calculated them according to the rules laid out by the NRA."[91]

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.[92] This also promotes harmonization, allowing the country to benefit from economies of scale for devices, software and database systems. At time of writing they are in use in several countries for field trials and are expected to form the basis of the future regulations and coexistence frameworks of those countries.

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 WInnForum, a diverse industry group focused on spectrum sharing) to harness both expertise and consensus in the development of technical standards for the implementation of the SAS management of three-tiered sharing in CBRS.

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 a 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 AFC system 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 the 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).[93] 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. Presumably database operators would 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, AFCs 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,"[94] particularly if there is not an end-user device registration requirement. 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.[95]

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 critical 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.

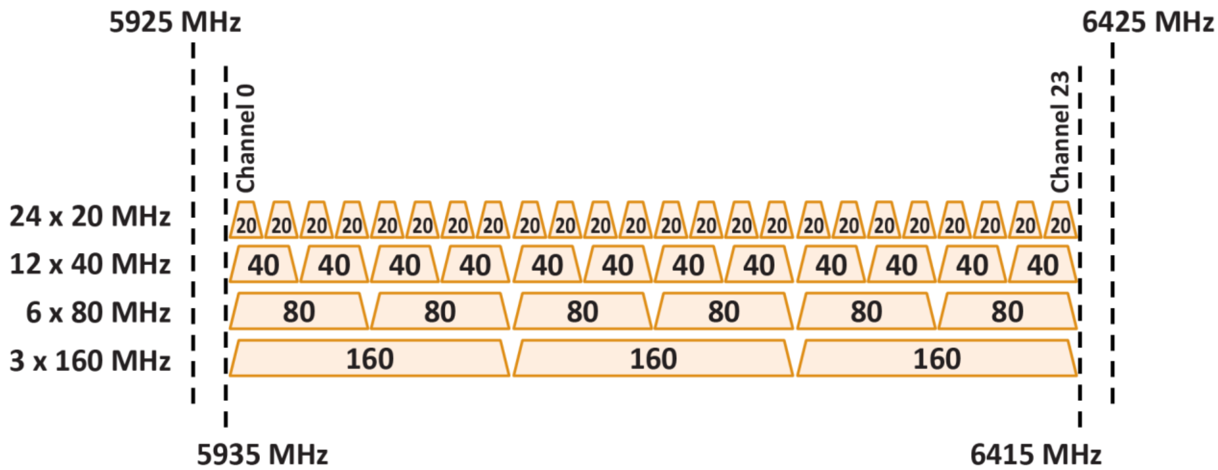

Figure 16: Proposed ECC band plan for license-exempt sharing of 5925-6425 MHz by RLANs.

This section highlights three bands under active consideration, in the U.S. and/or Europe, for sharing managed by automated frequency coordination systems, as well as the exploration of database-assisted sharing in satellite bands and particularly by NGSO satellite constellations.

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

The U.S. Federal Communications Commission adopted a Notice of Proposed Rulemaking (NPRM) in October 2018 that proposes to authorize unlicensed RLANs to coordinate shared use of four sub-bands (U-NII-5 to U-NII-8) that span the entirety of the 1,200 megahertz from 5925 to 7125 MHz. This sharing framework would specifically include the uplink portion of the conventional C-band (5925-6425 MHz) currently occupied both by FSS earth station uplinks and by more than 50,000 registered Fixed Service (FS) PtP microwave links. Although PtP links are high-power and directionally focused, the FCC's premise is that FS receivers can be protected from interference within a calculated three-dimensional protection contour. Unlicensed use of the 5925-6425 MHz and 6525-6875 MHz sub-bands will be subject to control by an automated frequency coordination (AFC) system, described further below, while unlicensed use of the other two sub-segments tentatively is proposed to be limited to lower-power and indoor-only use without the need for database coordination.[96]

In Europe, an ECC Working Group (SE 45) has similarly received a mandate from the European Commission to "study [the] regulatory and technical feasibility of the introduction of WAS/RLANs in the band 5925-6425 MHz, including an assessment of coexistence scenarios with band incumbents."[97] The group's work is ongoing and expected to produce a final draft report on sharing by May of 2019, followed by a public consultation and a final report scheduled by March of 2020.[98] The project enjoys extensive technology industry support. An in-depth whitepaper by DIGITALEUROPE, which represents leading technology companies, concludes that to meet the global need for additional license-exempt spectrum, "the 5925-6425 MHz frequency range [is] the most promising in terms of coverage, incumbent compatibility and sufficient contiguous wide channels" and should be pursued "outside of the WRC-19 process."[99] The EC mandate 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] to support wide channels which are required for a growing number of applications which need a large bandwidth to achieve Gigabit speeds."[100]

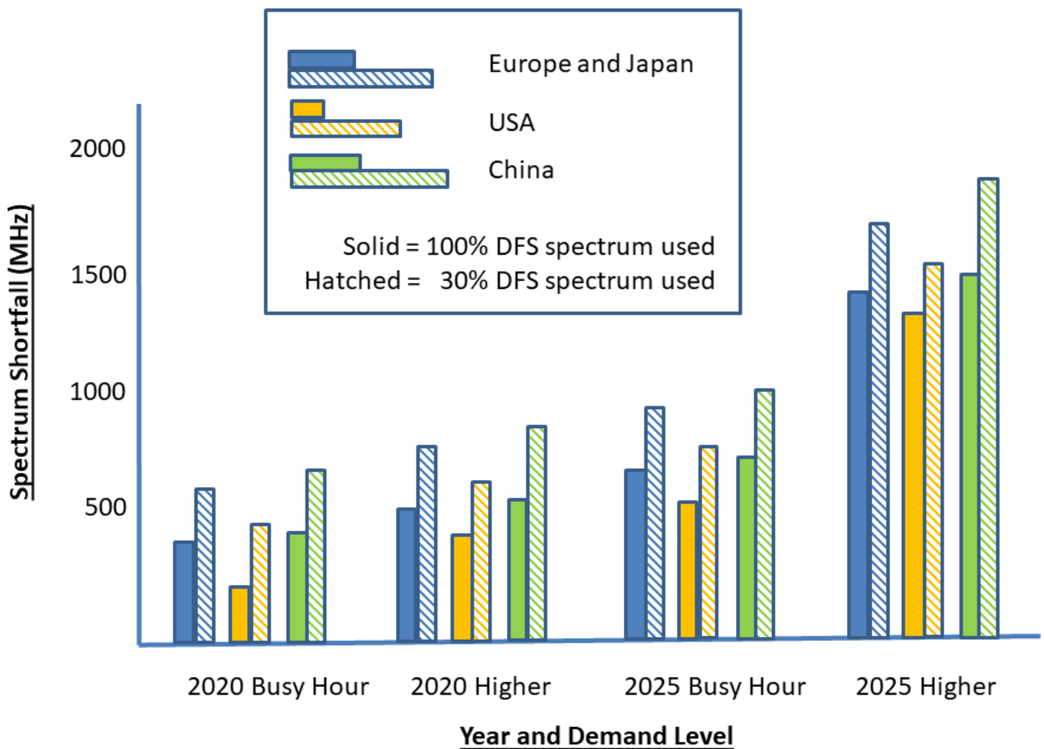

Figure 17: Illustration of the projected license-exempt spectrum shortfall per region, by year and demand level.[101]

In the U.S., the FCC has proposed to adopt a high-tech industry coalition framework that would authorize unlicensed sharing of the larger 5925 – 7125 MHz band subject to "comprehensive *ex ante* interference protection through an automated frequency coordination process that proactively prevents RLAN operation in situations where it could cause harmful interference" to incumbent FS or FSS operations.[102] The FCC rulemaking proposes to permit outdoor RLAN master devices to operate in the band 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 a list of permissible channels of operation from an agency-designated AFC system. The FCC also proposes a class of lower-power and indoor-only devices that would not require database coordination. Indeed, a simulation study submitted by the coalition suggests that even for outdoor RLANs, database coordination may only be needed to safeguard against interference to incumbent links in at most 1 in 500 cases.[103]

Band (MHz)	Primary Allocations	Reference used in the NPRM[63]	Devices
5925-6425	Fixed Service FSS	U-NII-5	Standard-Power Access Point (subject to AFC)
6425-6525	Mobile Service FSS	U-NII-6	Low-Power Access Point (indoor only)
6525-6875	Fixed Service FSS	U-NII-7	Standard-Power Access Point (subject to AFC)
6875-7125	Fixed Service Mobile Service FSS[64]	U-NII-8	Low-Power Access Point (indoor only)

Figure 18: FCC Proposed Framework for Two Classes of Unlicensed Sharing Across 5925-7125 MHz.

Because the incumbent services in U-NII-5 and U-NII-7 bands are fixed, the FCC proposes to allow unlicensed use at standard power outdoors and indoors subject to an AFC system. The agency "envision[s] the AFC system to be a simple database that is easy to implement."[104] Incumbent PtP microwave links and FSS earth stations are fixed, highly directional, and seldom change location or operating parameters. Like the TV Bands Database, the AFC "System Operator" 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.

Prior to transmitting, "standard-power access points [would] be required to obtain a list of permissible frequencies from an AFC system . . . or a list of prohibited frequencies in which it cannot operate."[105] Further, the FCC states that "the AFC system must be designed to ensure that unlicensed operations protect new and modified licensed operations" and "periodically verify whether frequency availability has changed."[106] Client devices (e.g., smartphones and IoT devices) will be permitted to operate across the entire band subject to control by compliant *Master* devices (e.g., routers or access points).[107]

The image below illustrates the key elements of the AFC system architecture. The AFC system operator will regularly update information on incumbent receivers stored in databases maintained by the Commission, which it will use to automatically calculate and enforce protection contours sufficient to protect PtP links, denying requests to operate where the RLAN's emissions exceed an interference threshold into any individual incumbent link. Automated frequency coordination allows incumbent services to add sites or modify their networks, since Commission 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.

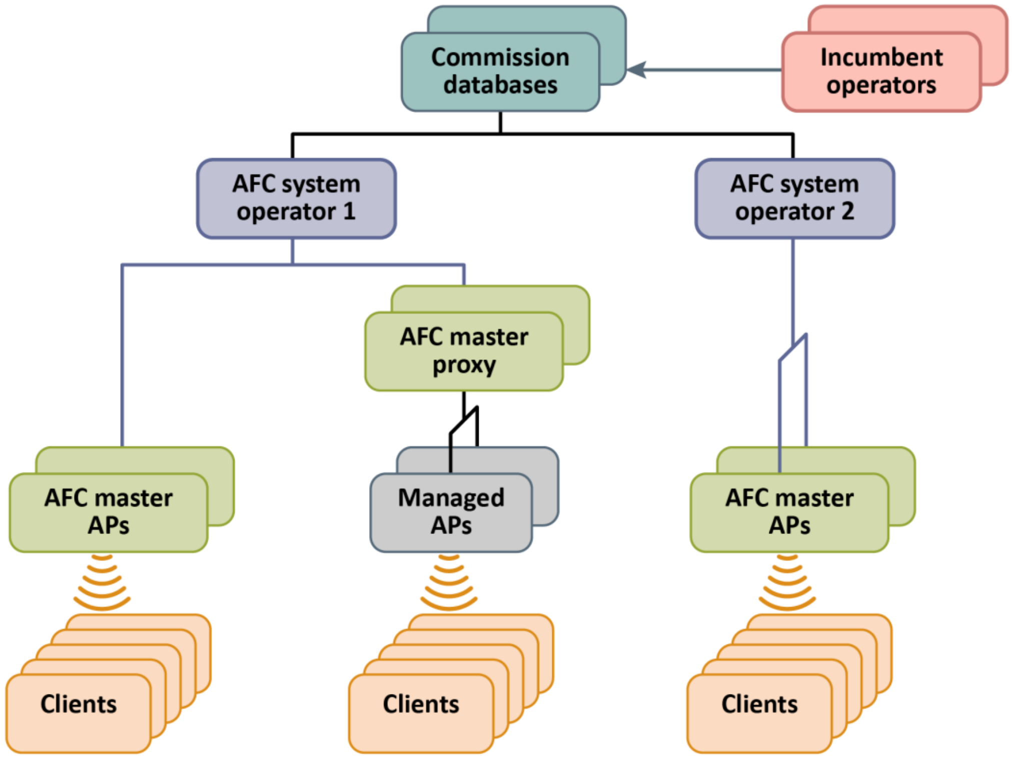

Figure 19: Simplified architecture for Automated Frequency Coordination in 6 GHz band.

The high-tech industry coalition proposal suggested that one or multiple *AFC System Operators* should be certified to calculate "protection contours for licensed systems based on applicable databases and identifies available frequencies for RLAN use."[108] This process is illustrated in the diagram below. Under this proposal, three-dimensional protection contours would incorporate awareness of terrain and local ground clutter as well as the actual antenna in use by each incumbent receiver. Each *AFC Master Access Point (AP)* would be required to be aware of its geographic location and elevation and to certify the accuracy of the position fix as part of the equipment authorization process. This information will be shared securely with the AFC System Operator, which protects not only the AP itself but also all of its client devices by enforcing an operating service area around each AP. If any portion of the service radius or the location accuracy radius comes into contact with a 3D protection contour for any incumbent receiver then the frequency range used by the incumbent(s) will be disallowed for that AFC Master device.

Because the incumbent radios licensed in the 6 GHz band are fixed and change very infrequently, the coordination process for the 6 GHz band is expected to be simpler and more streamlined than the dynamic SAS used to coordinate sharing with Navy radar in the 3550-3700 MHz CBRS band, as described above. The 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. The Commission's response to multiple commenters in the Notice of Inquiry phase of the proceeding who raised concerns over the accuracy of the FCC databases is also worth noting: "[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."[109]

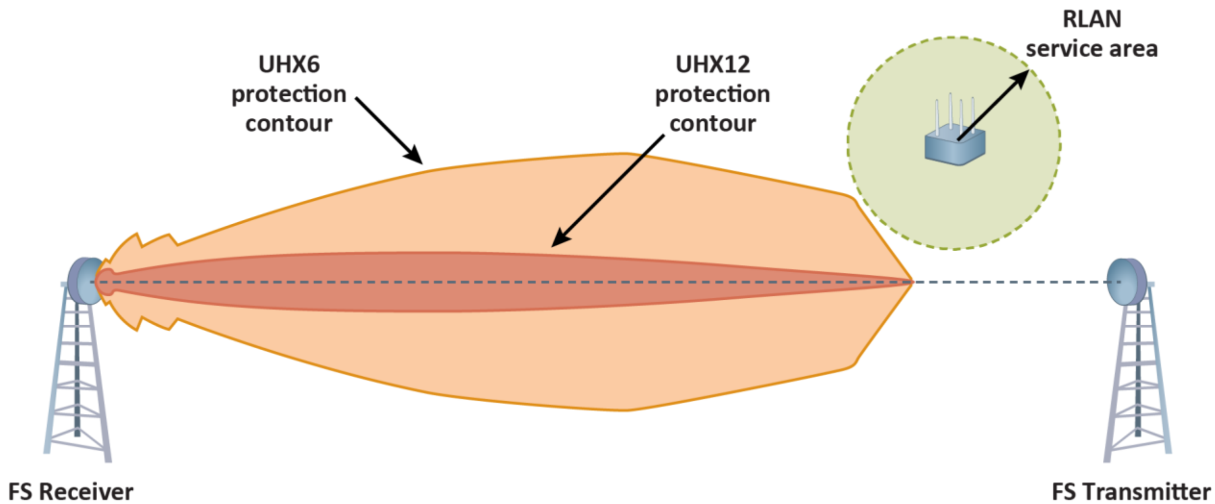

Figure 20: The AFC system enforces 3D Protection contours to avoid RLAN interference to Fixed Service receivers.[110]

B. Proposals for Opportunistic Coordination of PtMP and Mobile in the C-Band (3700-4200 MHz)

Both the FCC and Ofcom initiated proposed rulemakings during 2018 intended to authorize opportunistic, shared access to unused spectrum in the C-band. In the U.S., the 500 MHz between 3700 and 4200 MHz are at present dedicated almost exclusively to video and data downlinks used by more than 20,000 registered FSS earth stations, most of them receive-only. A Notice of Proposed Rulemaking (NPRM) adopted unanimously by the FCC in July 2018 proposes 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.[111] The Fixed Service is co-primary in the band, but barely over 100 PtP links have 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 considered plentiful).[112]

The FCC’s 3.7 GHz NPRM also proposes to clear at least the bottom portion of the band for exclusive mobile licensing, tentatively by authorizing private market negotiations between the three primary C-band satellite operators and interested mobile carriers. As the FCC’s band plan suggests (see just above), clearing would start with at least 100-200 MHz from the bottom up; whereas coordinated sharing by rural and other ISPs for local deployments of high-capacity, point-to-multipoint (PtMP) terrestrial broadband would be co-primary from the top of the band down. Tentatively PtMP could coordinate into 160 MHz up to as much as 320 MHz, depending in large part on the prospects for clearing FSS off the lower portion of the band, which is a FCC priority.[113] Coexistence between 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. [114]

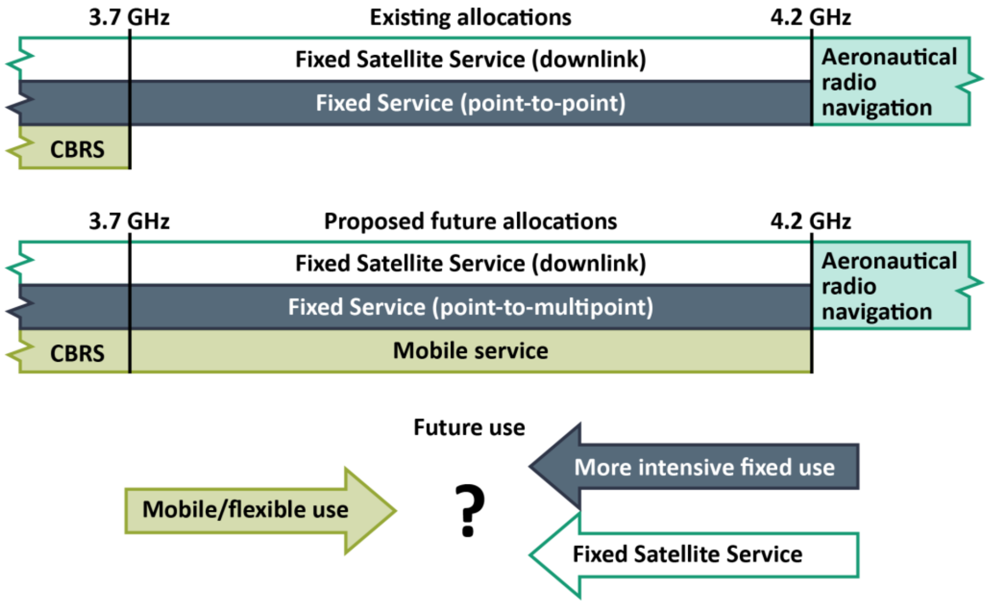

Figure 21: Existing and Proposed Future Allocations in the downlink C-band (3.7 - 4.2 GHz).

To make coordination possible, the FCC proposes 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.[115] To that end, the 3.7 GHz NPRM proposes 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. The NPRM proposes to require earth stations to report for each antenna:

- earth station call sign;
- geographic location;
- licensee and point of contact information;
- antenna gain, azimuth and elevation gain pattern, azimuth relative to true north;
- antenna elevation angle;
- satellite(s) at which the earth station is pointed;
- transponder number(s) and how often each transponder is used;
- antenna site elevation and height above ground.[116]

Although the FCC's proposal to authorize fixed PtMP sharing is not premised on AFC, the Commission also seeks comment on adopting "an automated coordination process for point-to-multipoint FS applications."[117] The agency observes that the current, manual coordination process for new fixed PtP links in C-band is slow and expensive. It would require a rural or small town ISP, for example, to prepare for each access point "a prior coordination notice that provides technical detail on the proposed facility's transmit and receive characteristics," send that report "to all FS and FSS licensees and prior applicants who might receive interference," give those parties 30 days to respond, resolve any concerns raised, and only then can the ISP file an application online at the FCC for final approval.[118] This manual coordination process may be even more problematic for a fixed PtMP deployment since the precise location and elevation of client sites (customer premises) are not known in advance.

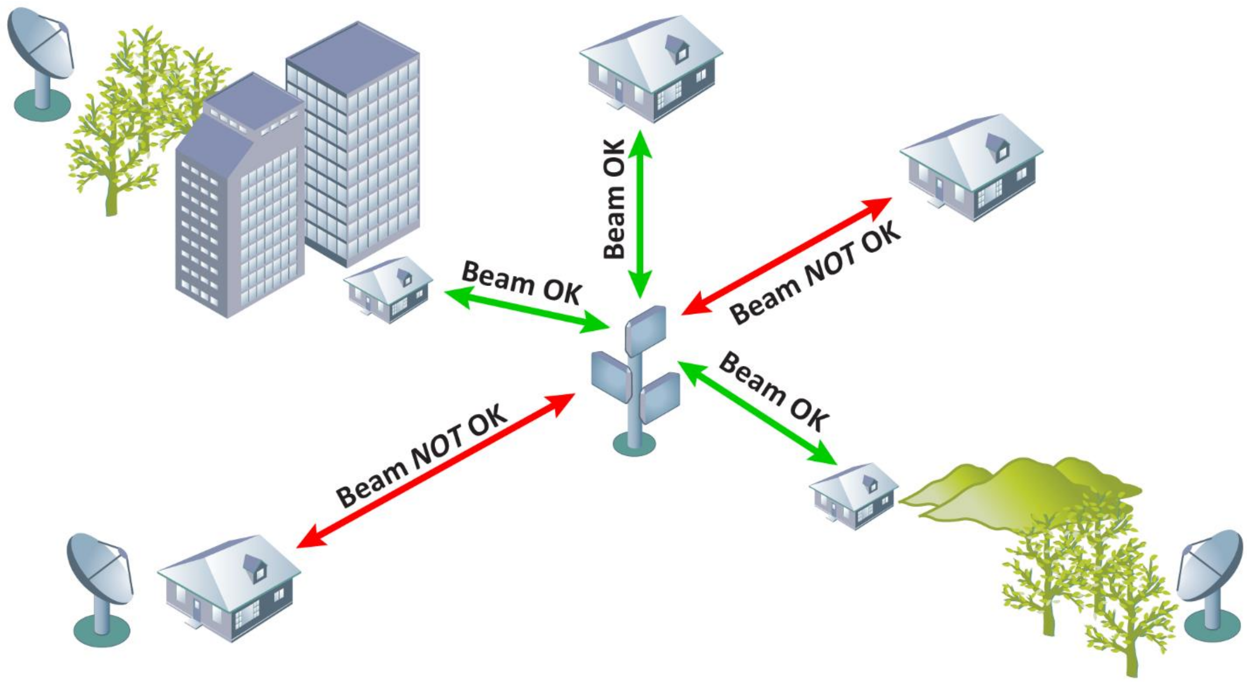

Figure 22: Automated frequency coordination of directional PtP fixed wireless with FSS earth stations. Unlike mobile use, fixed PtMP is inherently directional and can be sectorized to coexist with FSS.

Moreover, the NPRM notes that requiring (or at least allowing) coordination by sectors and variable power (rather than assuming a uniform, circular service area with a fixed radius and power levels) could enable more successful coordination and more intensive use of the band. Companies and consumer advocates supporting the AFC proposal have argued that the lack of a calculation engine using real-world propagation modeling would slow deployments, increase costs, leave more spectrum fallow, and quite possibly protect FSS incumbents less accurately.[119]

In the UK, Ofcom issued a consultation in December 2018 proposing a similar approach to coordinating 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.[120] The proposal evolved from an April 2016 call for input describing a potential opportunistic access framework that would allow localized access to vacant capacity in the band to the extent it does not cause harmful interference to incumbent FSS or fixed PtP operations.[121] Ofcom describes its intention "to work towards a Dynamic Spectrum Access (DSA) approach in bands where this is appropriate and practical to implement when suitable equipment is available."[122] The Consultation describes this new approach as an opportunistic and database-driven effort:

> Under a DSA approach, equipment communicates directly with a database to be granted access to spectrum at the location and time required on whichever frequencies are unused at the time by existing users. This is the approach which underpins TV white space devices in the UK, and the CBRS proposal in the USA.[123]

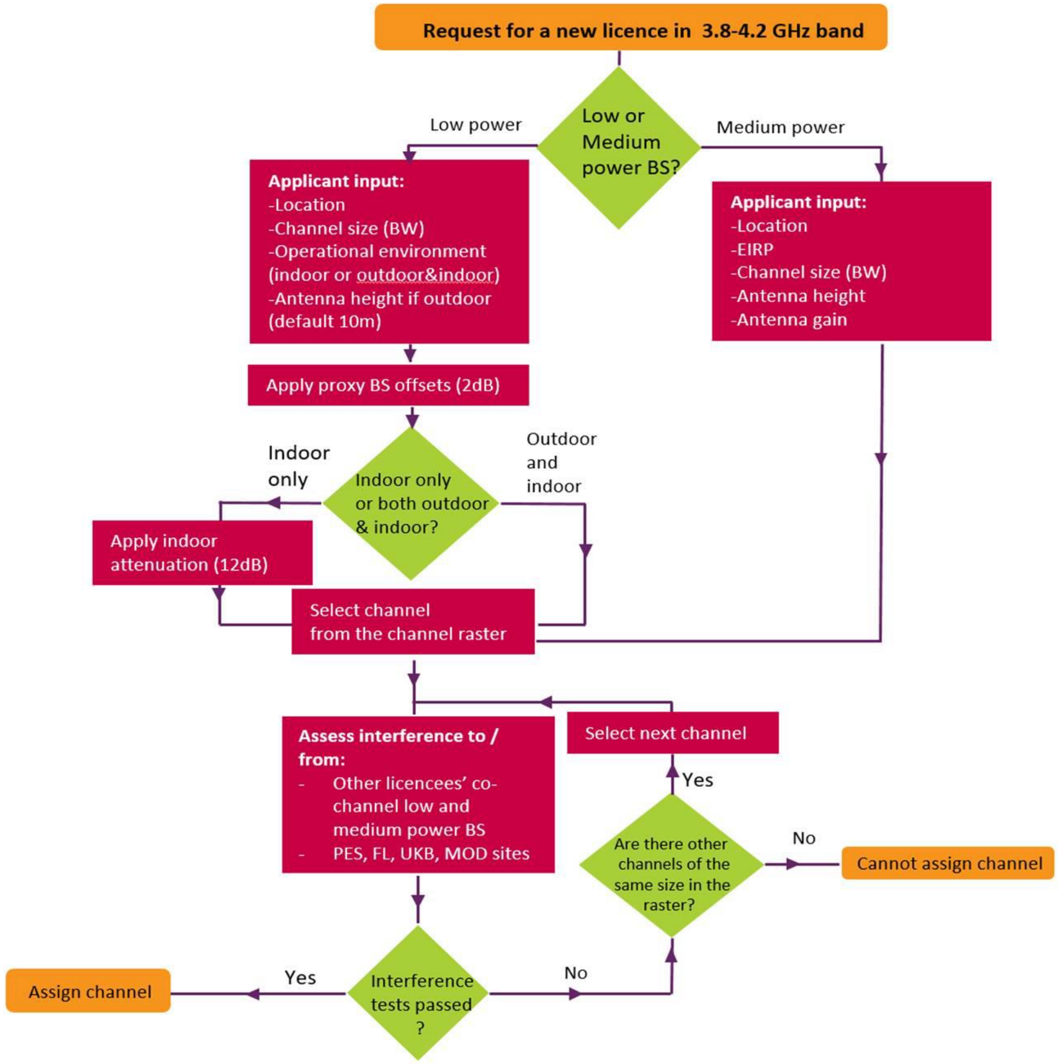

Figure 23: Ofcom's proposed coordination approach for low- and medium-power shared access to 3.8-4.2 GHz band.[124]

With respect to facilitating opportunistic, licensed local use of vacant channels in the 3.8-4.2 GHz band, Ofcom explains 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."[125] The Ofcom proposal would enable 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. 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.[126]

Two types of licenses would be granted: First, a small-area 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.[127] Users can also aggregate contiguous low-power licenses over a larger area under a single authorization. The agency proposes that its licensing fee will need to reflect "the cost of the specific coordination IT system specifically developed for this product."[128]

Initially, access to spectrum by new users will be "coordinated by Ofcom and authorised through individual licensing on a per location, first come first served basis."[129] Ofcom suggests that longer term the agency "would like to work with industry to define the appropriate specification for both DSA equipment and database capability that would enable future transition to DSA."[130]

C. Coordinated Sharing with Federal Users in 37-37.6 GHz (U.S.)

As part of its broader "Spectrum Frontiers" initiative to open wide bands of millimeter wave spectrum above 24 GHz for 5G mobile and fixed operations, the FCC is currently seeking comment on a coordination mechanism to facilitate non-exclusive sharing of 600 MHz of spectrum at the bottom end of the 37/39 GHz band (from 37 to 37.6 GHz).[131] The band is allocated on a co-primary basis between Federal government and commercial users for fixed and mobile operations. Until the Spectrum Frontiers proceeding, the FCC had not authorized any commercial operations in the band. Federal operations are currently limited to 14 military bases. In 2016 the FCC initially determined that Federal and non-Federal users would share the band on a co-primary basis. Access to the 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."[132] The FCC views this band as an opportunity to continue to develop its use of more dynamic techniques between both commercial users, and commercial and 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."[133] Intended uses of the band include point-to-point links (for example 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."[134] 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's pending *Third Further Notice of Proposed Rulemaking* seeks comment on the specific coordination mechanism for the band, including whether it should utilize a database-coordinated access model that could be similar to what has been proposed for fixed wireless coordination with FSS in the 3700-4200 MHz C-band and for unlicensed sharing outdoors in the uplink C-band above 5925 MHz (both described above).

Site-based registration could be coordinated through a third-party frequency coordinator that could be semi-automated at first 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.[135] The coordination mechanism 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 an AFC system, the operator could receive a near-immediate response, making the system far faster and potentially less costly than traditional fixed service link or site coordination processes. Licensees would also be able to negotiate alternative sharing arrangements with incumbents, where feasible. 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 24: Fixed wireless access using database-enabled frequency reuse in millimeter bands

D. 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 recent 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 concludes that “[f]uture satellite systems can largely benefit from the ability to access spectrum bands other than the dedicated licensed spectrum band.”[136] It 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.”[137] 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,” particularly in “highly dynamic spectrum sharing scenarios.”[138]

The 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 the emerging NGSO, low-Earth orbit (LEO) satellite networks in development by companies including OneWeb, SpaceX and LeoSat. These mega-constellation networks will comprise hundreds and perhaps even 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.[139] 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 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 to requests for more bandwidth from each system and allocate spectrum accordingly.[140]

The authors of the ESA survey acknowledge that 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, should benefit in the future from implementation through an automated database coordination system.[141] The alternatives to sharing may be even more problematic as they may result in only one NGSO operator being able to operate (a major issue from a competitive standpoint), or a band segmentation regime being applied that leads to both an inefficient use of spectrum and potentially destroys the viability of many if not all the NGSO networks’ business cases.

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 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 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.'

Another promising input to real-world awareness of the spectral environment is real-time sensing data. The CBRS Spectrum Access System 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 communicating to the AFC) and more ubiquitous fixed or mobile sensing networks that may serve as a pooled resource for dynamic sharing in many different bands.

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.[142] Spectrum coordination databases that incorporate real-world details on terrain, clutter (trees, buildings), and other GIS data sets can enable far more intensive spectrum use.[143] An AFC database informed by real-world GIS datasets does not need to make generic, worst-case assumptions about interference. As recognized in the FCC's *6 GHz NPRM*, with more accurate awareness of the physical environment, AFC 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."[144] 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 – while 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:

- ***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.*

- ***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.[145] 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.[146]*

- ***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."[147] 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. An AFC system can calculate this based on all the available awareness data, including whether the risk of harm is aggregate interference (which the AFC can estimate) or the operation of individual devices.[148]

B. Spectrum Sensing as an Input to Dynamic Frequency Coordination

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.[149] What is new are efforts to incorporate sensing "to allow non-primary access to unused spectrum by a licensed or unlicensed device."[150]

When designed as inputs for automated frequency coordination, spectrum monitoring systems can add unique data on the actual spectral environment in an area, and in real time.[151] 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.[152]

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 Environmental Sensing Capability) 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.[153]

While the ESC implementation is purely protective in nature, it is also quite likely the prototype for 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).

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.[154]

C. Value-Added Services by Database Operators

Automated frequency coordination operators are likely to add value-added services for both incumbents and entrants, while also helping database operators 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."[155]

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, the FCC requires SAS operators to optimize coexistence among the unlicensed (GAA) users that have no right to interference protection. However, as Ofcom has observed, under a different framework (the unlicensed sharing of TVWS channels, for example) a NRA could decide that this coexistence assistance – aimed at optimizing quality of service – should be an optional, value-added service.[156]

D. 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. [157]

Blockchain may have the potential to enhance frequency coordination and secondary market transactions, particularly in shared bands that will need (or benefit from) an AFC database. A blockchain not only speeds transactions and minimizes their cost, but 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.

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 appear to be the initial focus of a blockchain trial announced by France's Agence Nationale Des Frėquences, in what is likely to be the first involvement of a regulator in a blockchain open to users.[158] The trials, expected to be operational by the end of 2018, will reportedly be limited to 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).[159] 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.[160] A second trial will coordinate Wi-Fi use among start-ups at "French Tech Central," a technology incubator in France's Station F, where the ANFR is also located.[161]

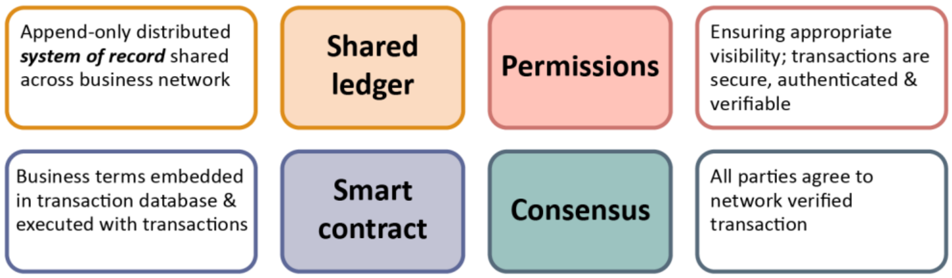

Figure 25: Key concepts of a blockchain application for business transactions.[162]

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.[163] 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).[164] 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.[165]

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.[166] Academics have suggested that a blockchain could be incorporated in the SAS or other frequency coordination databases to facilitate the enforcement of "collective action rights" of secondary users in addition to the interference protection rights of incumbents.[167] 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 note 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, a recent academic analysis observes that 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 framework), a blockchain may not be scalable or cost-effective.[168] 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.[169] 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 data) or takes account of other heterogenous 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 real-time assignments in shared bands. These frequency coordination 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

Database technologies are widely available, sufficiently mature, scalable and secure. 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. AFC solutions are good for consumers, competitive entrants, and innovation by making wireless connectivity more accessible, fast and affordable.

AFC solutions are also 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 AFC 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 Spectrum 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 AFC (rather than through a slower or more costly process).

- NRAs should adopt clear rules, but not prescribe particular technologies or standards for AFC systems.

- Consulting industry and convening a representative, multi-stakeholder process to develop and assist in implementing the AFC system 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 promotes band or technical harmonization regionally or globally (e.g., the DSA model rules for TVWS).

- NRAs should consider the benefits of certifying a private sector entity to manage the AFC system – or, if demand justifies it, multiple and competing AFC providers – but always in strict adherence to agency rules.

- Require – or at least allow – AFC system coordinators to use the most granular and real-world GIS data available for interference modeling.
- 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 AFC.
- When feasible, it is cost-effective to leverage AFC systems and operators for multiple bands, rather than require a series of separate systems.
- Permit AFC operators to experiment with and generate revenue from value-added services in addition to the basic coordination service that complies with NRA rules.

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End Notes:

[1] Ray Baum's Act of 2018, Pub. L. 115–141, § 614, 132 Stat. 1080, 1109 (2018).

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[4] *Id*. at 6.

[5] Ofcom 2016 Statement.

[6] *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).

[7] International Engineering Consortium, "Signaling System 7 (SS7)," Web ProForum Tutorial (2004), available at https://www.cs.rutgers.edu/~rmartin/teaching/fall04/cs552/readings/ss7.pdf.

[8] 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.

[9] "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.

[10] NPAC, "How LNP Works," available at https://www.npac.com/number-portability/how-lnp-works.

[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] 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.

[16] 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/*.

[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, a current example is the FCC proposal to authorize fixed wireless broadband operators to coordinate localized point-to-multipoint deployments into available frequencies in at least 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 has indicated it will need to require if its proposed rulemaking adopts 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 5D 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] 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.

[42] 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).

[43] *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.
[44] *See* FCC, Keybridge Global Designated as a 70/80/90 GHz Database Manager (Aug. 26, 2016), https://www.fcc.gov/document/key-bridge-global-designated-708090-ghz-database-manager.

[45] 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).

[46] *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.

[47] 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.

[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), available at http://www.nipfp.org.in/media/medialibrary/2018/04/WP_226.pdf.

[49] *Id*. at 15-16.

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

[51] "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).

[52] *See generally* ECC Report 205; Marshall at 27-29.

[53] Marshall at 29.

[54] 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.

[55] For more background on successful pilot deployments and background on Microsoft's regional geolocation database, see Microsoft White Spaces Database, available at http://whitespaces.microsoftspectrum.com/. *See also* Microsoft, Airband Initiative (describing rural broadband initiatives in the U.S. and globally), available at https://www.microsoft.com/en-us/airband.

[56] 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/.

[57] 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.

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

[59] *Id*. at 24.

[60] 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.

[61] Marshall at 227.

[62] *Id*. at 225.

[63] Marshall at 79.

[64] *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."

[65] 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*.

[66] 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.

[67] *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*.

[68] 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.

[69] 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, *citing* Coleman Bazelon & Giulia McHenry, "Substantial

Licensed Spectrum Deficit (2015-2019): Updating the FCC's Mobile Data Demand Projections," The Brattle Group, at 19 (June 23, 2015), available at http://www.brattle.com/system/news/pdfs/000/000/891/original/Substantial_Licensed_Spectrum_Deficit_(2015-2019)_-_Updating_the_FCC's_Mobile_Data_Demand_Projections.pdf?1435613076.

70 *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.

71 Carmel Group, *Ready for Takeoff: Broadband Wireless Access Providers Prepare to Soar with Fixed Wireless* (2017), available at https://bit.ly/2LSF6zv.

72 Verizon announced it will rely on millimeter wave spectrum to deploy gigabit-fast 5G fixed-wireless service to an additional 30 million homes beginning in late 2018. Joan Engebretson, "CFO: Verizon 5G Plans Will Target 30M Homes Outside of FiOS Markets with Fixed Gigabit Wireless, *Telecompetitor* (Dec. 5, 2017), available at https://www.telecompetitor.com/cfo-verizon-5g-plans-will-target-30m-homes-outside-of-fios-territory-with-fixed-gigabit-wireless/

73 *Cisco VNI* at 23 & fig. 22.

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

75 Marshall at 81.

76 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.

77 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.

78 *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.

79 *5G: Known Unknowns*, New Street Research (Apr. 17, 2016), available at www.newstreetresearch.com/download/5G%20April%202016%20slides.pdf.

80 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.").

81 *Ibid*.

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

[83] *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."

[84] *Ibid*.

[85] *Ibid*.

[86] *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.").

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

[88] 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.

[89] ECC Report 236 at 36.

[90] *Ibid*.

[91] *ECC Report 236* at 41. 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." *Ibid*.

[92] 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.

[93] *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.

[94] *ECC Report 236* at 38-39.

[95] *Id*. at 37-40.

[96] FCC, Notice of Proposed Rulemaking, *Unlicensed Use of the 6 GHz Band*, ET Docket No. 18-295, GN Docket No. 17-183 (Oct. 23, 2018) (*6 GHz NPRM*).

[97] 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) ("EC Mandate to CEPT"), available at https://www.cept.org/Documents/ecc/41497/ecc-18-047-annex_mandate-rlan-6-ghz. The band 5925-6425 MHz is currently used across Europe by the Fixed Service and Fixed Satellite Service (Earth to space), but is also "allocated by ITU Radio Regulations (RR) to the Mobile service on a primary basis." *Id*. at 1.

[98] *Id*. at 6; *see* ECC/CEPT, SE 45 – WAS/RLANs in the frequency band 5925-6425 MHz, available at https://cept.org/ecc/groups/ecc/wg-se/se-45/client/introduction/.

[99] DIGITALEUROPE, *Whitepaper on 5925-6425 MHz (6 GHz) Wireless Access Systems/Radio Local Area Network (WAS/RLAN)*, at 18 (Feb. 2018), available at http://www.digitaleurope.org/DesktopModules/Bring2mind/DMX/Download.aspx?Command=Core_Download&EntryId=2611&language=en-US&PortalId=0&TabId=353.

[100] EC Mandate to CEPT at 4. The next generation of Wi-Fi, 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"); Qualcomm, *A Quantification of 5 GHz Unlicensed Band Spectrum Needs* (July 2016) (projecting a need for 1,280 megahertz of mid-band unlicensed spectrum), available at https://www.qualcomm.com/documents/quantification-5-ghz-unlicensed-band-spectrum-needs.

[101] Wi-Fi Alliance Study, *supra*. "DFS" refers to Dynamic Frequency Selection and the portion of the 5 GHz band that requires Wi-Fi to operate subject to a radar detection and avoidance capability. *See* https://www.wi-fi.org/knowledge-center/faq/what-is-dynamic-frequency-selection-dfs.

[102] Letter to the FCC from Apple, Broadcom, et al., *Expanding Flexible Use in Mid-Band Spectrum between 3.7 and 24 GHz*, GN Docket No. 17-183, at 3 (June 12, 2018).

[103] RKF Engineering Services, *Frequency Sharing for Radio Local Area Networks in the 6 GHz Band* (Jan. 2018), *attached to* Letter from Paul Margie, Counsel, Apple Inc., Broadcom Corp., Facebook, Inc., Hewlett Packard Enterprise, and Microsoft, to Federal Communication Commission, GN Docket No. 17-183 (Jan. 26, 2018). The study simulated the impact of one billion RLAN devices, operating under existing U.S. rules for the U-NII-1 band at 5150-5250 MHz, on incumbent operations. One key finding was that 99.80% of the FSS receivers within the continental U.S. would experience aggregate interference levels from RLAN operations below -6 dBm I/N and that no instance of interference above that threshold caused a link to fall below its availability design threshold (which were assumed to be 99.999% availability or better).

[104] *6 GHz NPRM*, *supra*, at ¶ 25.

[105] *Ibid*.

[106] *Id*. at ¶¶ 29-30.

[107] *Id*. at ¶ 53.

[108] Presentation to FCC by Apple, Broadcom,, et al., *Expanding Flexible Use in Mid-Band Spectrum between 3.7 and 24 GHz*, GN Docket No. 17-183, at 3 (filed Aug. 2, 2018).

[109] *6 GHz NPRM*, *supra*, at ¶ 39.

[110] Presentation to FCC by Apple, Broadcom, et al., *Expanding Flexible Use in Mid-Band Spectrum between 3.7 and 24 GHz*, GN Docket No. 17-183 (filed Aug. 2, 2018).

[111] 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*).

[112] 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 megahertz C-band channel in the lower portion of the band.

[113] *See 3.7 GHz NPRM*, *supra*, at ¶ 119. The FCC requested comment on the different options that would depend in part on how much of the band can be cleared of incumbent FSS operations and over what time frame.

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

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[115] *See 3.7 GHz NPRM* at ¶ 39.

[116] *Id*. at ¶ 41. The FCC coupled the NPRM with an Order requiring FSS space station operators to report "for each transponder operating in the 3.7-4.2 GHz range . . . the frequency range of transponder and transponder number" based on "the former center-frequency requirement for C-band space stations." Combined with the enhanced earth station reporting of actual frequencies in use, this allows a coordination system to factor in frequency separation.

[117] *Id*. at ¶ 124.

[118] *Id*. at ¶ 117. The coordination procedures for terrestrial FS operations with satellite operations are set forth in §§ 101.21(f) and 101.103 of the Commission's Rules. Generally, § 101.103 requires entities to complete coordination, including the 30-day notice to nearby incumbent users, prior to filing an application for authorization.

[119] *Id*. at ¶ 124, citing *Petition of Broadband Access Coalition for a Rulemaking to Amend and Modernize Parts 25 and 101 of the Commission's Rules to Authorize and Facilitate the Deployment of Licensed Point-to-Multipoint Fixed Wireless Broadband Service in the 3700-4200 MHz Band*, RM- 11791 (June 26, 2017).

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

[121] Office of Communications (Ofcom), *3.8 GHz to 4.2 GHz band: Opportunities for Innovation* (April14, 2016), available at http://stakeholders.ofcom.org.uk/consultations/opportunities-for-spectrum-sharing-innovation.

[122] *Ofcom 2018 Consultation*, *supra*, at 10.

[123] *Ibid*.

[124] *Id*. at 50, Figure 15.

[125] *Ofcom 2018 Consultation*, *supra*, at 23. The proposal also applies to shared access in 1781.7-1785 MHz, paired with 1876.7-1880 MHz ("1800 MHz shared spectrum"), and 2390-2400 MHz ("2300 MHz shared spectrum").

[126] *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."

[127] *Id*. at 23-25.

[128] *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.

[129] *Id*. at 21.

[130] *Id*. at 6 &10.

[131] 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).

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

[133] *Id*. at ¶ 65.

[134] *Id* at ¶ 63.

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

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

[137] *Ibid*.

[138] *Ibid*.

[139] *Id*. at 25335.

[140] *Ibid*.

[141] *Id*. at 25338.

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

[143] *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.

[144] 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.

[145] *Id*. at 108.

[146] *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).

[147] Marshall at 109.

[148] One example of how this could be modeled, proposed in a paper by a group of wireless engineers, uses an aggregate interference approach to limit the number of shared-access users able to operate closer to the incumbent, thereby "improv[ing] the overall spectrum utilization while ensuring a probabilistic guarantee of interference protection to the PUs." Sudeep Bhattarai, Jeffrey Reed, et al., "Defining Incumbent Protection Zones on the Fly: Dynamic Boundaries for Spectrum Sharing," 2015 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN).

[149] 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.

[150] 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.

[151] *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.

[152] 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.

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

[154] 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.*

[155] 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.

[156] *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."

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

[158] 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/.

[159] *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.

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

[161] "State Agency of France is associated with a startup to manage radio frequencies with blockchain," *Steemit* (April 2018), available at https://steemit.com/bitcoin/@yosel1n/state-agency-of-france-is-associated-with-a-startup-to-manage-radio-frequencies-with-blockchain.

[162] *Id*. at 15.

[163] *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.

[164] *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).

[165] 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.

[166] *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).

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[167] 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).

[168] *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.

[169] *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.