In Search of a Common Spectrum Vocabulary: Spectrum Sharing and Interference Taxonomies

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Abstract

New technologies and the resulting changes to regulatory approaches have led to an explosion in the complexity and crowding of radio spectrum. This rapidly evolving landscape has led to the increased importance of two fields: interference management and dynamic spectrum sharing. However, the progress of both areas is hampered by the lack of shared vocabularies, which, if developed, could help to streamline communication between relevant parties in government, industry, and academia. This paper first presents a taxonomy to aid in the description of key spectrum sharing concepts and architectures to achieve a similar goal. Next, it defines a hierarchical taxonomy of physical-layer interference as an educational and practical tool for detection, identification, location, reporting, mitigation, and remediation of interference. Finally, the use of these two taxonomies is demonstrated through the application of the classification systems to spectrum sharing regimes and prominent case studies.

Introduction and Motivation

Radio spectrum ("spectrum"), once an abundant resource, has become exponentially more crowded as more and more sectors of the government and industry become increasingly reliant on it. For the better part of the twentieth century, governments across the world were able to allocate wide swaths of spectrum for a relatively small group of government and commercial uses with little concern for maximizing efficiency. Today, by contrast, spectrum has become so crowded that U.S. commercial stakeholders were incentivized to spend a whopping $81 billion for a (mere) 280 MHz of this valuable resource.[1]

The aggressive growth in spectrum demand has caused many regulators—at both the national and international levels—to begin rethinking their approaches to spectrum management.[2] Some, such as the United States' Federal Communications Commission (the "FCC"),[3] now utilize

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[1] Monica Alleven, *C-band's first phase tops charts with $80.9B*, FIERCE WIRELESS (Jan. 15, 2021, 12:51 PM), https://www.fiercewireless.com/regulatory/c-band-clock-phase-auction-tops-charts-80-9b.

[2] Int'l Telecomm. Union [ITU], Background Paper: Radio Spectrum Management for a Converging World, ITU Doc. RSM/07, at 5–8 (2004).

[3] The FCC is an independent agency and chief regulator of all private and commercial spectrum uses in the U.S. It serves as one half of the United States' bifurcated spectrum management regime; the National Telecommunications and Information Agency (NTIA), a subpart of the executive branch's Department of Commerce, regulates federal uses of spectrum. *See About the FCC*, FCC, https://www.fcc.gov/about/overview (last visited Apr. 3, 2022); *see also About NTIA*, NTIA, https://www.ntia.doc.gov/about (last visited Apr. 3, 2022).

specialized spectrum auctions to introduce an element of market influence into the spectrum management process.[4] As technological innovations have progressed, the FCC has also begun to experiment with different types of spectrum "sharing," including "dynamic spectrum sharing[5]," as evidenced by recent efforts such as the Citizens Broadband Radio Service ("CBRS," discussed in detail later in this paper[6]).

However, the path forward for these new developments has not been smooth. Many roadblocks have consistently vexed regulators and regulated entities alike as they try to forward their own interests, the interests of related parties, and the interests of society at large. One key issue that frequently arises in a wide variety of spectrum management discussions is the lack of a shared vocabulary.[7] The issue of dissonant vocabularies between various stakeholders frequently gets in the way of fruitful discussions that would produce solutions to some of the biggest topics in spectrum management.

This paper recognizes the gravity of the vocabulary issue and responds by tackling two related topics in spectrum management that suffer from a lack of shared vocabulary (and, more generally, a lack of shared understanding): spectrum sharing and interference management. Along with the identification of common terminology, this paper proceeds to organize those vocabularies into a pair of taxonomies to showcase the hierarchical relationships between the identified terms. These two taxonomies are presented together because of their deep topical interconnectedness; this paper hopes that a deeper understanding of interference will aid in a dialogue on spectrum sharing and vice-versa. More broadly, the taxonomies are intended to synthesize understanding of their topics from a wide array of stakeholder conceptions and to serve as a tool for further discussion and general application to spectrum management.

However, this paper first presents a brief review of prior work on these and related topics. Many of the materials referenced in this section provided inspiration for this project, and the authors are grateful to those whose work is referenced. Following this review, the two taxonomies are introduced, complete with diagrams, definitions, and explanations. Two case studies are provided for each taxonomy to illustrate their applications to real-world spectrum sharing regimes and interference events, respectively. Finally, this paper concludes with proposals for further investigation of the two topics.

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[4] *About Auctions*, FCC, https://www.fcc.gov/auctions/about-auctions (last visited Apr. 3, 2022).

[5] This paper refers to any of a variety of methods of sharing spectrum resources between two users in a dynamic fashion as "dynamic spectrum sharing." Note, however, that this term has become associated with sharing specifically between 4G and 5G and "Dynamic Spectrum Management Systems" is now frequently used to refer to dynamic sharing with federal users.

[6] For the purposes of this paper, CBRS refers to the three-tiered 3.5 MHz band service, *not* the "Citizens Band Radio Service" defined for short-distance two-way radio communications in channels between 26.965 MHz and 27.405 MHz. *Compare 3.5 GHz Band Overview*, FCC, https://www.fcc.gov/35-ghz-band-overview (last visited Apr. 29, 2022) *with Citizens Band Radio Service (CBRS)*, FCC, https://www.fcc.gov/wireless/bureau-divisions/mobility-division/citizens-band-radio-service-cbrs (last visited Apr. 29, 2022).

[7] *See, e.g.*, SILICON FLATIRONS CENTER, OUTCOMES REPORT: A SPECTRUM POLICY INITIATIVE CONFERENCE: FRONTIERS IN SPECTRUM SHARING 15 (2021), https://siliconflatirons.org/wp-content/uploads/2022/01/FY-22-Spectrum-Policy-Conference-Report_Final-1.pdf.

Review of Prior and Related Work

This paper is by no means the first effort to synthesize and organize a common vocabulary for some aspect(s) of spectrum management. One of the most prominent early examples can be found in the IEEE 1900.2 Standards, which set out recommended practices for conducting in-band and adjacent band interference analysis.[8] Similarly, the IEEE 1900.1 Standard for Definitions and Concepts for Dynamic Spectrum Access works toward creating a shared vocabulary for interference and sharing by providing standardized definitions for terms related to dynamic spectrum access.[9]

First, there have been several recent attempts to create taxonomies for both technical and regulatory aspects of spectrum sharing. Looking at the technical aspects of sharing frameworks, John Leibovitz and Ruth Milkman's 2021 white paper, *Taking Stock of Spectrum Sharing*, provides a comprehensive categorization system for sharing technologies.[10] This system includes categorizations for regimes as "sensing," "coordinating," or "informing." and informs much of the basis for the sharing taxonomy presented here.

On the regulatory side of things, there have been several attempts to create a taxonomy to categorize the different ways in which spectrum is licensed for sharing. A 2013 paper by Annalisa Durantini and Mauro Martino created a taxonomy of spectrum authorization and access models, separating spectrum authorization into three overarching categories: Dynamic Exclusive Use, Collective Use, and Eased Property Rights.[11] Alternatively, Sudeep Bhattarai *et al* organized authorization models broadly into Individual Authorization (licensed) and General Authorization (unlicensed) before dividing further into categories such as exclusive access and co-primary shared in their 2016 paper, *An Overview of Dynamic Spectrum Sharing: Ongoing Initiatives, Challenges, and a Roadmap for Future Research*.[12]

Turning to interference, several efforts have been made to synthesize and organize a common vocabulary with varying degrees of specificity. Of course, one prominent example can be found in the IEEE 1900.2 standards; in fact, the top two levels of the interference taxonomy presented in this paper are partially derived from the diagram shown in that work. More recently, the FCC's Technological Advisory Council (TAC) suggested the creation of a standardized interference taxonomy in its 2014 White Paper, *Introduction to Interference Resolution,*

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[8] *See* IEEE, IEEE RECOMMENDED PRACTICE FOR THE ANALYSIS OF IN-BAND AND ADJACENT-BAND INTERFERENCE AND COEXISTENCE BETWEEN RADIO SYSTEMS (2008), https://standards.ieee.org/ieee/1900.2/3738/ [hereinafter IEEE 1900.2-2008];

[9] *See* IEEE, IEEE STANDARD FOR DEFINITIONS AND CONCEPTS FOR DYNAMIC SPECTRUM ACCESS: TERMINOLOGY RELATING TO EMERGING WIRELESS NETWORKS, SYSTEM FUNCTIONALITY, AND SPECTRUM MANAGEMENT (2019), https://standards.ieee.org/ieee/1900.1/5629/ [hereinafter IEEE 1900.1-2019].

[10] *See* JOHN LEIBOVITZ AND RUTH MILKMAN, TAKING STOCK OF SPECTRUM SHARING (2021), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3916386.

[11] *See* Annalisa Durantini and Mauro Martino, *The spectrum policy reform paving the way to cognitive radio enabled spectrum sharing*, 37 TELECOMMS. POL'Y 87 (2013).

[12] *See* Sudeep Bhattarai et al., *An Overview of Dynamic Spectrum Sharing: Ongoing Initiatives, Challenges, and a Roadmap for Future Research*, 2 IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKING 110 (2016).

Enforcement and Radio Noise.[13] Inspired by the 1900.2 standards, the TAC White Paper proposes certain expansions to the 1900.2 taxonomy to break down and categorize more elements of interference for enforcement and teaching purposes.

Where both the IEEE and TAC taxonomies take a broad approach to creating a general taxonomy of physical-layer interference, others have tackled specific interference-related components. One seminal example is *A Communications Jamming Taxonomy*. This 2016 IEEE paper categorizes and defines elements of a particular type of interference: intentional RF-layer interference, often called "jamming."[14] Additionally, that paper provided the authors with a different perspective on the appearance and structure of taxonomies in general.

Spectrum Sharing Taxonomy

While the term "spectrum sharing" is often used to denote new techniques in spectrum management, it is important to note that—at a high level—all spectrum is "shared." There is only one radio spectrum and all management techniques are attempts to share these resources between different users, whether dividing bands and auctioning rights to an entire band, or by enabling sharing between users within a band. This issue of perspective often arises when categorizing spectrum sharing and can lead to confusion based on a misunderstanding of the level at which the analysis is taking place. Even within a band itself, many different types of sharing may operate concurrently, with users with different access rights sharing in different ways.

The taxonomy presented here is designed to improve our ability to communicate the different manners of spectrum sharing by providing different categories of sharing systems, but precision is still key in defining the scope of conversations on spectrum sharing to ensure mutual understanding taxonomy can be applied to current spectrum sharing systems and how classification can differ depending on perspective.

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[13] *See* FCC TECH. ADVISORY COUNCIL, INTRODUCTION TO INTERFERENCE RESOLUTION, ENFORCEMENT AND RADIO NOISE 4–8 (2014), https://transition.fcc.gov/bureaus/oet/tac/tacdocs/meeting61014/InterferenceResolution-Enforcement-Radio-Noise-White-Paper.pdf.

[14] *See* Mark Lichtman, *A Communications Jamming Taxonomy*, 14 IEEE SECURITY AND PRIVACY 47 (2016). This taxonomy also presents an interesting example of a taxonomy that diverges from the traditional notion of a taxonomy as a tree-like structure (consider the paradigmatic Linnaean taxonomy (animal kingdom)). *See* Annie Marie Helmenstine, *Linnaean Classification System (Scientific Names)*, THOUGHTCO (July 30, 2019), thoughtco.com/linnaean-classification-system-4126641. However, as the communications jamming taxonomy shows, this structure is not the only legitimate form, since taxonomies are concerned with ordered and hierarchical classification. Hierarchies that allow cross-listing are known as "polyhierarchical." Polyhierarchical structures are more prominent in technology and design compared to the single-parent structures like the Linnaean taxonomy. For more on polyhierarchy, *see* Bob Kasenchak, *On Polyhierarchy*, SYNAPTICA (Sept. 30, 2021), https://www.synaptica.com/on-polyhierarchy/.

Diagram

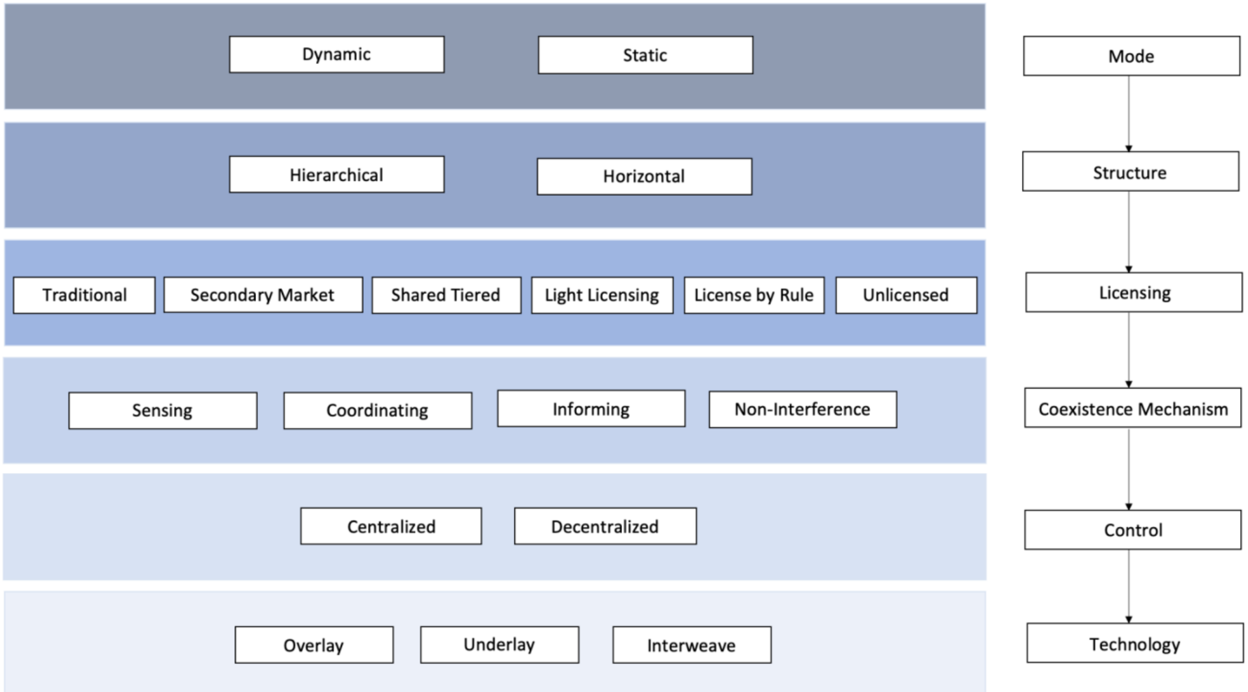

Diagram 1: Spectrum Sharing Taxonomy

Definitions and Explanations

As shown in Diagram 1 above, the taxonomy consists of six tiers designed to categorize not only the technical aspects of a spectrum sharing model, but also the regulatory aspects. In this section, the relevance of each tier of the taxonomy is explained and examples are given to describe the categories within each tier.

Mode

The highest tier of the spectrum sharing taxonomy differentiates between "dynamic" and "static" sharing. Dynamic spectrum access is defined in IEEE 1900.1 as the real-time adjustment of spectrum utilization in response to changing circumstances and objectives.[15] Static spectrum sharing occurs when users can coexist without the need for any dynamic spectrum use decisions. This may be when the interfering power level of a secondary user is always below a certain interference threshold, or when two users are separated by enough physical distance or time so as to not cause harm to one another. The distinction between dynamic and static sharing is vital to understanding issues that may arise between users of a shared spectrum resource. Issues with interference, while a distinct possibility with either type of sharing, are more complicated in dynamic sharing architectures where users must change behavior based on the behavior of others.

[15] *See* IEEE 1900.1-2019, *supra* note 9.

Structure

The next category in the taxonomy defines the structure in which spectrum is shared. Spectrum sharing systems are defined as either "hierarchical" or "horizontal" models depending on the rights of users to access spectrum resources in relation to other users. This distinction is critical, since understanding the rights of users within a sharing paradigm is a prerequisite for conflict remediation in the occurrence of an interference event.

- *Horizontal:* in horizontal sharing models, each user has equal rights to spectrum access. In other words, the allocation of spectrum resources is not prescribed, but must be decided between users. One example of horizontal sharing is Wi-Fi devices operating in unlicensed bands that use listen-before-talk techniques to efficiently utilize shared spectrum resources in a dynamic manner. Broadcast radio (at least during the daytime) is an example of static, horizontal sharing, where all users have the same rights as all other users but have no need to dynamically change usage since they operate on separate channels.
- *Hierarchical:* in hierarchical sharing models, users have different rights to spectrum access, with higher-tier users having priority. This model is prevalent across bands that share spectrum with federal services. One particular example is CBRS-style sharing, where the incumbent has the first right to spectrum access, Priority Access License (PAL) holders have secondary priority, and General Authorized Access (GAA) users are allowed to access spectrum resources as long as the other two tiers are not actively transmitting in a CBRS-protected geolocation.[16]

Licensing

After determining the presence of a hierarchy within a spectrum sharing system, the next level of the taxonomy breaks down the manner of licensing. This level is designed to give a basis for understanding the different ways spectrum is licensed and how licensing affects resource access.

- *Traditional:* traditional licensing encompasses any type of licensing or authorization where an access license is given for a user to access spectrum resources on a primary basis. This includes exclusive use licenses, of course, but also other paradigms, such as co-primary sharing licenses in which access rights are granted to licensees on the condition that they coordinate with other co-primary license holders.
- *Temporary/Secondary Market:* while not strictly a license, it is necessary to also understand the secondary market aspect of spectrum access. The FCC's secondary market initiatives are designed to increase spectrum access by allowing for the temporary lease of spectrum resources from the incumbent to a secondary party.[17] This type of licensing

[16] For more information about CBRS, *see What is the Citizens Broadband Radio Service?*, CBRS WINNFORUM STANDARDS, https://cbrs.wirelessinnovation.org/what-is-cbrs (last visited Mar. 20, 2022).
[17] *See Secondary Markets Initiative and Spectrum Leasing*, FCC, https://www.fcc.gov/secondary-markets-initiative-and-spectrum-leasing (May 3, 2019).

is essentially a free-market approach to maximizing spectrum utilization through sharing by agreement.

- *Shared Tiered:* shared tiered licenses provide different access rights based on the tier of the user in question. A prime example of this is the CBRS Priority Access Licenses (PAL) regime, which grants holders the right to access a dynamically allocated 10 MHz channel within the band.
- *Light Licensing:* a band will often not be strictly unlicensed with unlimited numbers of users given access to it, but will instead have a minimal form of licensing. A good example of this is the concept of a Limited Collective Use of Spectrum (CUS) model, where a limited number of users are given access to spectrum resources under well-defined conditions.[18] This is distinct from strictly unlicensed usage since a degree of control is maintained over spectrum access. For instance, users may be required to register in a database before use; following registration, access is permitted on a first-come-first-served basis.
- *License-by-Rule:* the FCC can—by rule—authorize the use of spectrum without individual licenses in CBRS, radio control service, aviation radio service, and maritime radio service pursuant to 47 U.S.C. Section 307(e). Just as with individual licenses, the regulator may impose various types of use restrictions or revoke the license. This scheme is designed to reduce the administrative burden on the FCC of creating individual licenses and sets up a general permit system that allows spectrum use provided minimum requirements are met. While similar to light licensing, this is defined by the authority under which users are allowed to operate without an individual license within bands dedicated to these radio services.
- *Unlicensed:* under Part 15 of the FCC's rules, regulations are put in place under which transmitters may be operated without an individual license. The devices must meet defined technical/administrative provisions, including emission limits, but an unlimited number of users/devices meeting these requirements are allowed access.[19]

Coexistence Mechanism

The coexistence mechanism category divides spectrum sharing architectures based on the way in which sharing is achieved. This category should include whether an architecture is a "sensing," "informing," or "coordinating" scheme. It also includes a category for sharing that does not do any of the above, but is allowed on a "non-interference basis." Understanding how information is communicated about how and when spectrum users are utilizing spectrum resources is important for troubleshooting issues in the sharing process, as well as understanding the vulnerabilities of a particular spectrum sharing system.

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[18] Maria Massaro, *Next generation of radio spectrum management: Licensed shared access for 5G*, 41 TELECOMMS. POL'Y 422, 427–28 (2017).
[19] 47 C.F.R. § 15 (2022).

- *Sensing:* sensing systems utilize RF sensing capabilities to detect whether or not a spectrum resource is being used and make access decisions based on this information.
- *Coordinating:* coordinating systems use radio systems' known parameters to make access decisions and ensure that harmful interference does not occur.
- *Informing:* informing systems require users to inform others when they are utilizing spectrum resources so that interference can be avoided. Strict understanding of spectrum access rights is crucial, as a secondary user would need to take evasive action to avoid interference when the primary is using the band, whereas the primary would not need to do the same.[20]
- *Non-Interference Basis:* certain spectrum sharing methods require none of the above methods of sharing, and can instead be permitted to operate on a "non-interference basis." This is the case with static sharing and also with many dynamic, unlicensed sharing arrangements.

Control

The control category defines whether the sharing mechanism is "centralized" or "decentralized." Though it can vary depending on the type of coexistence mechanism, a centralized system implies that there is a central decision-making authority for spectrum access. For example, the CBRS Spectrum Access System (SAS) is a centralized authority for spectrum access decisions in a coordinating system. On the other hand, in decentralized systems decision making is moved to the edge (as in listen-before-talk systems). It is necessary to understand where spectrum access decisions are taking place within a sharing framework in order to locate problems that may arise with the sharing algorithm or system.

Sharing Technology

Finally, the way in which spectrum is concretely shared between users must be considered. For instance, do users switch to other channels to avoid interference, reduce power to a level below the interference threshold, or use some combination of techniques? Spectrum "overlay," "underlay," and "interweave" techniques are included in this category and provide specific details as to how users are behaving within a spectrum sharing framework, helping to understand interference issues that may arise.

- *Spectrum Underlay:* defined by IEEE 1900.1 as a method for "dynamic spectrum access by secondary spectrum users that exploit spectral opportunities transmitting below an interference threshold, not causing harmful or even disruptive interference to incumbent services." The standards also note that, in practice, interference that might degrade the incumbent service but does not disrupt its capability to communicate is considered spectrum underlay. This is in contrast to the definition given in the original document from 2008 that stated that underlay power limits and modulation requirements "protect primary users from interference." The distinction between protecting from all

[20] LEIBOVITZ AND MILKMAN, *supra* note 10, at 8.

interference and not causing harmful interference should be noted, as it raises the question of what level of interference is "harmful."

- *Spectrum Overlay:* defined by IEEE 1900.1 as "Dynamic spectrum access by secondary spectrum users that exploits spatial and temporal spectral opportunities in a non-interfering manner." A key difference between overlay and interweave access is that in overlay models, secondary users have prior knowledge of the primary user's transmission sequence.[21]
- *Spectrum Interweave:* secondary spectrum users sense absence of the primary and opportunistically make use of the space/time/frequency when the primary user is not transmitting/receiving.[22] This generally implies that the transmitter has the ability to sense the environment to take advantage of gaps in spectrum usage.

Case Studies

CBRS

In 2015, the FCC adopted rules for three-tier commercial spectrum sharing in the 3.5 GHz band (3.55-3.7 GHz).[23] The primary license holders in the band, Navy radars, fixed satellite service users, and Part 90Z licensees, retain first right of access while also granting Priority Access License (PAL) holders and General Authorized Access (GAA) users the ability to use the band. The primary licensees are guaranteed protection from harmful interference from either of the other two tiers, while PAL holders are granted rights of secondary access in advance of GAA users, who may utilize the band opportunistically. Access is coordinated through the SAS, which requires PAL and GAA users to register device parameters and contact the SAS daily before device transmission. The SAS works in coordination with the Environmental Sensing Capability (ESC), a collection of sensors designed to detect when Navy radar is using the band, to make access decisions for the other tiers of users. ESC sensors are set up only at coastal sites where radar is used and are not used in other areas throughout the country. Since 2020, the FCC has certified five entities to be Spectrum Access System (SAS) administrators and authorized full commercial deployment in the 3.5 GHz band.[24] [25] The diagram below illustrates how CBRS is described by the taxonomy:

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[21] *See* IEEE 1900.1-2019, *supra* note 9.
[22] *See* BIGLIERI ET AL., PRINCIPLES OF COGNITIVE RADIO 41–101 (2013).
[23] *See Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*, Report and Order and Second Further Notice of Proposed Rulemaking, 30 FCC Rcd. 3959 (2015).
[24] *See Wireless Telecommunications Bureau and Office of Engineering and Technology Approve Four Spectrum Access System Administrators for Full Scale Commercial Deployment in the 3.5 GHz Hand and Emphasize License Compliance Obligations in the 3650-3700 MHz Band Under Part 96*, Public Notice, 35 FCC Rcd. 117 (2020).
[25] *See Promoting Investment in the 3550-3700 MHz Band*, Report and Order, 33 FCC Rcd. 10598 (2018).

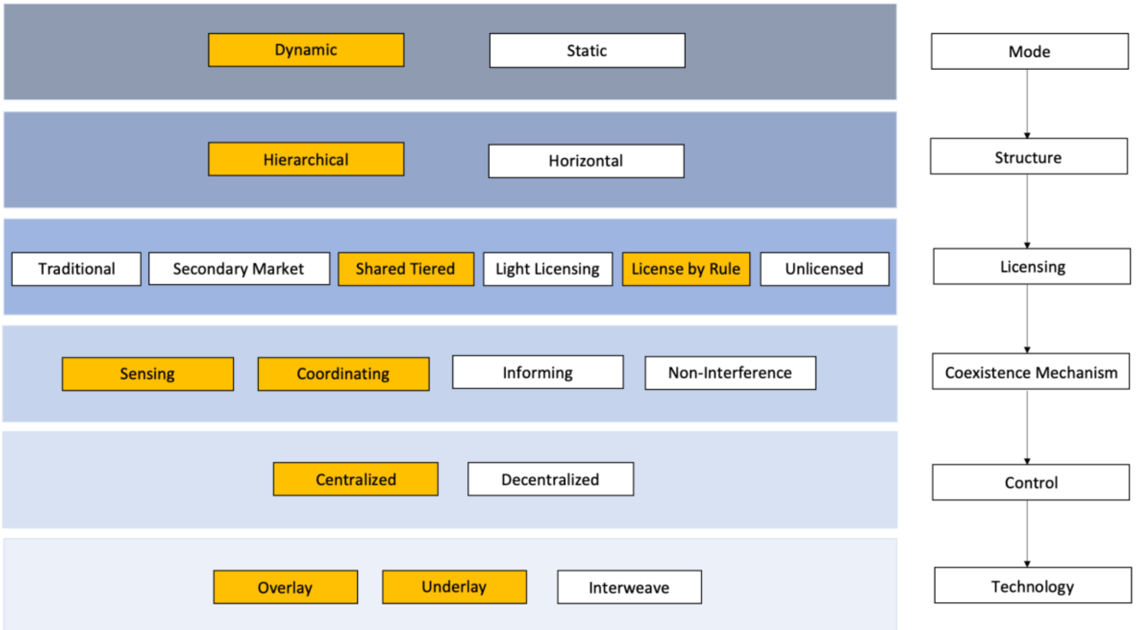

Diagram 2: Spectrum Sharing Taxonomy Applied to CBRS

As shown in the diagram, the taxonomy is designed so that multiple categories can be used to describe a sharing framework. To illustrate how CBRS fits into the taxonomy, each tier is explained below:

- *Mode:* CBRS is a form of dynamic sharing as spectrum access decisions are made dynamically based on information contained in the SAS and provided by the ESC.
- *Structure:* CBRS is a strictly hierarchical structure with three tiers of users with different rights to access the 3.5 GHz band. It is important to note, however, that within each individual tier, spectrum is shared horizontally. For example, GAA users have equal access rights with any other GAA users operating.
- *Licensing:* CBRS is a type of shared tiered licensing, where license-by-rule is also applied to the lowest tier of users. Both Incumbent Access and Priority Access Licenses are forms of shared tiered licensing, in which individual access licenses are granted with different rights to access and interference protection. However, General Authorized Access users are licensed by rule to operate in the band and are not granted any individual licenses. In this case, both categories are applied to the scenario since categorizing it as shared tiered alone would imply that users in each tier hold individual licenses.
- *Coexistence mechanism*: CBRS is both a sensing and a coordinating system. The Environmental Sensing Capability (ESC) has the ability to sense the RF environment for incumbent signals and communicate this information back to the SAS, providing the sensing element, whereas the SAS access decisions are coordinated based on users' provided transmitter parameters. However, where ESC is not feasible, a fully portal-based system with users uploading operating parameters is also sometimes allowed.

- *Control:* all spectrum availability decisions are made by the SAS, making CBRS a centralized sharing model. However, the actual spectrum utilization decisions are made by the CBRS devices (CBSDs) and reported back to the SAS. An important note is that this is not one overarching centralized authority as there are multiple SASs serving CBSDs in different locations nationwide.
- *Technology:* CBRS uses both underlay and overlay techniques. Devices may choose to underlay transmissions by reducing power, to overlay transmissions by switching the frequency channel they are using or, to determine time they are transmitting based on information provided by the SAS.

6 GHz Band

Classifying spectrum sharing architectures can prove complicated as often there are multiple types of sharing happening in any given band. The 6 GHz band is a perfect example of this. The FCC approved the use of Automated Frequency Coordination (AFC) in the 6 GHz band in a Notice of Proposed Rulemaking from April 2020. The 6 GHz band was originally designated for fixed microwave links used by a variety services (including public safety), as well as satellite uplink operators, and these services maintain primary access. The band was first opened for sharing some sub-channels with low-power, indoor Wi-Fi access points. Starting in 2020, the FCC opened up the entire band to indoor low-power access points and requested proposals from prospective AFC providers to allow the use of unlicensed standard power access points under the control of an AFC system in portions of the band, enabling outdoor operations. AFC is a database approach to frequency coordination that allots users available frequency channels with a permissible transmit power. Initial proposals to be an AFC operator in the 6 GHz band were submitted in late 2021.[26] [27] The diagram below shows how spectrum sharing operations in the 6 GHz band fit into the sharing taxonomy:

[26] *See Unlicensed Use of the 6 GHz Band; Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz*, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd. 3852 (2020).
[27] *See* FCC Requests 6 GHz Automated Frequency Coordination Proposals, 86 Fed. Reg. 58267 (Oct. 21, 2021).

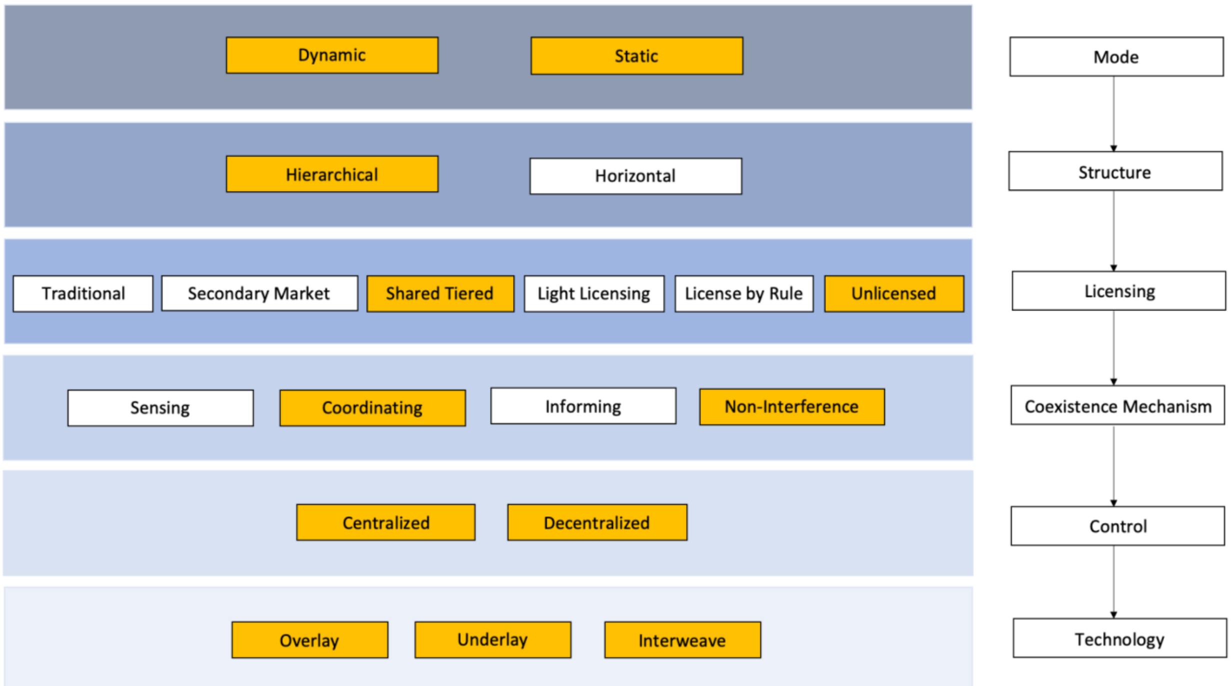

Diagram 3: Spectrum Sharing Taxonomy Applied to the 6 GHz Band

- *Mode:* spectrum sharing in the 6 GHz band contains both dynamic and static elements. Low power devices operating indoors share spectrum statically with the primary users (though dynamically amongst themselves), whereas the standard power access points share dynamically with the primary using AFC (and also share dynamically amongst themselves). As this clearly illustrates, the categorization of sharing mode can be entirely dependent on the perspective from which the sharing method is assessed. If looking at the sharing relationship between the primary and secondary users, the 6 GHz band is both static and dynamic, whereas sharing within a tier of users is solely dynamic.
- *Structure:* sharing in the 6 GHz band is hierarchical, with incumbents sharing resources with unlicensed, lower priority users. Additionally, this applies when looking at sharing in the band as a whole. Between users within each tier, sharing remains horizontal. As such, there is a possibility to highlight both categories depending on the goal of the assessment.
- *Licensing:* the 6 GHz band has both shared tiered licensees and unlicensed users. The primary users hold a shared-tiered license since the license does not guarantee exclusive use but does guarantee primary access and protection from other users. While this is similar to a traditional license, for the purpose of this taxonomy, traditional licensing incorporates only exclusive use licenses and co-primary types of licensing. Since the primary users in the 6 GHz share resources with unlicensed users, this is considered a shared tiered license. The secondary users are unlicensed and permitted to operate under Part 15 of the FCC rules.

- *Coexistence Mechanism:* sharing in the 6 GHz is done both on a non-interference basis and through coordination. Low-power indoor access points are allowed to operate throughout the band on a non-interference basis with the incumbent. However, standard power, outdoor access points must coordinate spectrum access through an AFC system. Among the unlicensed users, sensing capabilities may also be used for spectrum access within the same tier.
- *Control:* much like the coexistence mechanism, sharing controls in this band are both centralized and decentralized. Access decisions for standard power devices are coordinated centrally by the AFC system, whereas access for low power devices is decentralized since there is no central decision making authority. Access decisions are also decentralized among unlicensed users.
- *Technology:* 6 GHz sharing is a mixed approach between overlay and underlay models. Low power devices underlay the primary transmissions and standard power devices use knowledge of primary licensee operations provided by the AFC system to overlay transmissions.

Interference Taxonomy

As spectrum-enabled devices and networks have proliferated across all sectors of government and industry, the importance of efficient spectrum management has surged right alongside. Today, the spectrum landscape is incredibly complex and crowded, with an almost endless number and variety of users and their services competing for a functionally scarce spectrum resource. This scarcity (whether inherent or administratively-imposed is beyond the scope of this paper), combined with the diversity of needs for different services, means that efficient allocation and governance are essential to a functioning system.

However, even with efficient allocation and management, interference[28] is a constant and growing issue. After all, different services require different environments to operate efficiently: a mobile cell phone can function in a wildly different spectrum environment than can a sensitive radio astronomy antenna. Yet despite these disparate needs, constantly growing demand for spectrum inevitably leads to situations where interference abounds. Even in less crowded environments, interference is now widely acknowledged as a fact of life for all types of spectrum users.

Despite the pervasive and growing problem of interference, policy responses have lagged significantly. As earlier sections have suggested, much of this sluggishness can be traced to a lack of common understanding between regulators and regulated parties. When confusion permeates all of the five commonly understood interference response stages—detection, identification, location, reporting, mitigation, and remediation (including prosecution)—

[28] The International Telecommunication Union—the international regulatory body that oversees spectrum—and the FCC define interference as "[t]he effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radiocommunications system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy." ITU R.R. No. 1.166 (2020); 47 C.F.R. § 2.1(c) (2022).

proactive responses become nearly impossible. With these issues in mind, this paper now presents a comprehensive taxonomy of physical-layer interference, an explanation of the terminology contained within, and application of the taxonomy to several infamous interference stories.[29]

Diagram

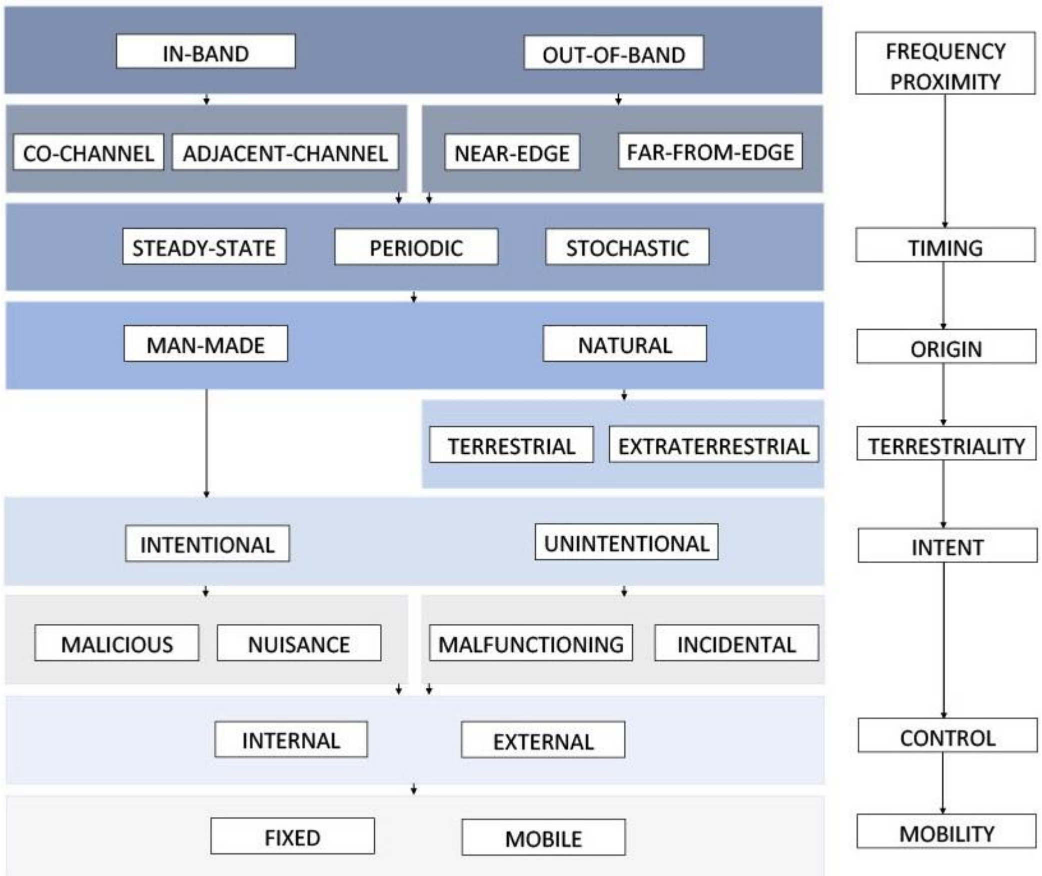

Diagram 4: Interference Taxonomy

[29] This taxonomy applies primarily to non-thermal-noise interference. Additionally, this taxonomy focuses on electromagnetic interference (EMI) rather than electromagnetic compatibility (EMC). For more on the differences between these categories, *see EMI vs EMC*, RF WIRELESS WORLD, https://www.rfwireless-world.com/Terminology/EMI-vs-EMC.html (last visited Apr. 29, 2022).

Definitions & Explanations

Frequency Proximity[30]

At the highest levels of the taxonomy is the classification of "frequency proximity." In other words, how close in the frequency domain is the interfering signal to the desired signal? Under this category are two commonly understood distinctions: "in-band" and "out-of-band."[31] These divisions are essential for an interference investigation since they provide insight into the potential sources and powers of interference. For example, in-band interference is likely to be geographic spillover, illegal operation without intent to interfere, or jamming. By contrast, out-of-band interference may be caused by a high power differential between two services in adjacent bands or intermodulation.

Within in-band, a further distinction can be made between co-channel and adjacent-channel interference. Co-channel interference is typically a result of geographic spillover, but could also be a result of jamming. Adjacent-channel interference, on the other hand, is somewhat more akin to out-of-band interference—it may be caused by inappropriate action of adjacent channel operators, poor receiver filters, or even propagation modeling errors or anomalies.

- *In-Band:*
  - *Co-Channel:* interference which originates from the same designated channel, whether from geographical overlap or intentional disruption.[32]
  - *Adjacent-Channel:* interference which originates from a channel adjacent to the channel used by the recipient.[33] This type of interference frequently occurs near the edge of the geographic service area, since the channels are likely subject to the same service rules, but may appear differently for less geographically-bound services, such as those provided by satellite. Because of the service-rule symmetry, the interference often bears similar characteristics to the recipient.
- *Out-of-Band:*[34]
  - *Near edge:* interference which originates from a source directly adjacent to the frequency band and channel used by the recipient. It is important to recognize that near-band-edge interference is similar in nature to adjacent channel interference, but occurs where one emitter (either the source or recipient) is at the very top of its band (perhaps with a small or non-existent guard band, and the other is located

[30] IEEE 1900.2-2008, *supra* note 9, at 18; *see also* FCC TECH. ADVISORY COUNCIL, *supra* note 13.

[31] For this paper, "band" is defined according to its regulatory understanding; i.e., the frequency range defined and allocated to a certain use (or collection of uses) by a regulatory authority. For a more technical definition, *see* ITU R. R. No. 1.147 (2020).

[32] IEEE 1900.2-2008, *supra* note 8, at 5.

[33] *Id.* at 18.

[34] One topical example of the concerns of out-of-band interference is found in the clash between the FCC and the Federal Aviation Administration (FAA) over concerns of interference to radio altimeters (instruments on aircraft that determine a plane's altitude and distance from nearby objects) in the 4.2–4.4 GHz band from new 5G wireless systems in the 3.7 GHz band. Despite nearly 500 MHz of distance between the two, certain last-minute tests had revealed the possibility of out-of-band interference that resulted in a national crisis over the 5G rollout. *See* Stephen Gandel, *How 5G Clashed With an Aviation Device Invented in the 1920s*, NEW YORK TIMES (Jan. 19, 2022), https://www.nytimes.com/2022/01/19/business/5g-radio-altimeters-airlines.html.

at the bottom of its band. While subtle, this difference is essential because, in contrast to adjacent-channel interference, the characteristics of the source and recipient will not necessarily match (perhaps due to disparity in service rules).
    - *Far from edge:* interference which originates from sources outside of the nearest channels in an adjacent band (potentially due to intermodulation).

Timing[35]

The timing of interference may give many clues as to the source and purpose of the interfering signal. It may also help determine the steps needed to remediate the interference. This taxonomy identifies three primary categories of interference timing: steady-state, periodic, and stochastic.

Steady-state interference is that which is relatively constant in power after it first appears. This is often the simplest interference to identify since it is relatively easy to trace a constant emission or radiation. Periodic interference is that which begins and ends at highly regular intervals. It is the second-easiest interference to identity since it likely results from automated processes or tightly-controlled human activity. Finally, patterned interference is that which appears in response to a triggering event that is not neatly periodic. Stochastic interference is the most difficult to diagnose since it may initially appear random; the underlying pattern may not reveal itself for a long period of time or without careful investigation of (often) unexpected causes.

- *Steady-state:* interference that remains constant in degree once it appears.
- *Periodic:* interference that occurs at specific, evenly-spaced intervals and lasts for approximately the same amount of time.
- *Stochastic:* interference that occurs in association with one or more triggering events, which, while those events may be partially or fully random, eventually reveals a pattern over an extended time frame. This terminology stems from the definition of "stochastic": "[something] that follows some random probability distribution or pattern, so that its behavior may be analyzed statistically but not predicted precisely."[36] This category of interference is best understood in context; see the two case studies below for greater detail.

Origin[37]

Below the timing category is the "origin" category: whether the interference is "man-made" or "natural." It is essential to know whether unintentional interference comes from a man-made

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[35] U. S. DEP'T OF HOMELAND SEC., NATIONAL RISK ESTIMATE: RISKS TO U.S. CRITICAL INFRASTRUCTURE FROM GLOBAL POSITIONING SYSTEM DISRUPTIONS 4 (2013), https://rntfnd.org/wp-content/uploads/DHS-National-Risk-Estimate-GPS-Disruptions.pdf [hereinafter DHS RISKS OF GPS DISRUPTIONS].

[36] *Stochastic*, Oxford Eng. Dictionary Online, https://www-oed-com.colorado.idm.oclc.org/view/Entry/190593?redirectedFrom=stochastic& (last visited Apr. 4, 2022).

[37] U.S. DEP'T OF TRANSP., GPS DEPENDENCIES IN THE TRANSPORTATION SECTOR 5 (2016), https://rosap.ntl.bts.gov/view/dot/12386.

or natural source because such information can support inferences about the sophistication of the interfering signal, the potential predictability of the interfering signal, and the potential slate of remedial measures available to respond to the interference.[38]

- *Man-made:* any interference that comes from a source created or influenced by human activity.
- *Natural:* any interference not created by a man-made device or direct human activity.

"Terrestriality"

Within the category of "natural" interference, it is important to understand whether that interference comes from a source within the Earth's atmosphere (is "terrestrial"), such as weather-based interference, or whether that interference comes from a source outside of it (is "extraterrestrial"), such as solar radiation flares. Aside from the analytical utility of understanding the origin of natural interference, it is also useful to assist parties impacted by interference in determining what remedial measures are most appropriate.

- *Terrestrial:* natural interference originating from an earth-bound or atmosphere-bound source.
- *Extraterrestrial:* natural interference originating from outside the Earth's atmosphere.

Intent[39]

Within "man-made" interference is "intent," which is vital for investigative and remedial measures. Whether interference is "unintentional" as opposed to "intentional" provides valuable insights into the avenues of remediation that an impacted party may take. Interference that is "unintentional" may be incidental or the result of malfunctioning/improperly calibrated equipment, which can assist parties with identification. This, in turn, can impact the path that parties will take to remediate such interference.

"Intentional" interference may also be further subdivided into "malicious" and "nuisance" interference. For example, a construction manager may utilize a cell phone jammer (and thus engage in nuisance interference) for workplace safety purposes. By contrast, a foreign entity might employ a similar jammer to disrupt military communications; this would be "malicious" interference. While both actions are illegal and ultimately may lead to the same consequences, they are analytically distinct and worth distinguishing between, particularly for the purposes of an interference investigation.

- *Intentional:* interference that is caused by a source intending to disrupt the affected signal.

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[38] This paper does recognize that interference is often "cumulative" in the sense that the ultimate negative effects of interference felt by the recipient are actually a combination of various different sources, some of which may be natural, and some of which may be man-made. Nonetheless, this distinction remains important for parsing what components of the ultimate interference have what origin—at least to the extent possible.

[39] U.S. DEP'T OF HOMELAND SEC., GOT COMMS? RECOGNIZING AND MITIGATING INTENTIONAL AND UNINTENTIONAL INTERFERENCE 2 (2017), https://www.dhs.gov/sites/default/files/publications/OIC_NGFR_JamX_APCO-Got-Comms_170813-508.pdf.

    - *Malicious:* intentional interference created for the express purpose of shutting down communications systems *to facilitate further bad acts*.
    - *Nuisance:* intentional interference done for the purpose of safety, testing, or rendering a location distraction-free (such as a cell phone jammer in a classroom).
- *Unintentional:* interference caused by a source that does not intend to disrupt the affected signal
    - *Incidental:* interference caused by the operation of non-signal emitting electronic or mechanical components of a device (e.g., EMI) as a byproduct of the normal operation of the device.
    - *Malfunctioning:* interference caused by damage, poor calibration, or misuse of a signal-emitting device.

Control[40]

From a diagnostic perspective, it is useful to determine for investigative and remedial purposes whether the interference is caused by devices/actions within the control of the party that is being interfered with (and the converse). This is distinct from "self-interference," which is incidental or unintentional interference *within* a device or *particular* system.

- *Internal:* interference caused by devices under the control of those within the party that is experiencing interference. This is *not* interference "internal" to a device.
- *External:* interference caused by devices outside of the control of the party experiencing interference.

Mobility[41]

The mobility of the interference source (whether it is "fixed" or "mobile") is a key determinant in identification and response. For example, the knowledge that interference comes from a fixed geographic source can assist investigators in narrowing down the potential type of interfering device or the motivation of the actor behind the interference. This taxonomy does not use the third determination used in some literature of "portable" since it adds somewhat little to the more expansive definition of "mobile" in these circumstances.

- *Fixed:* the source of interference is geographically stationary over time.
- *Mobile:* the source of the interference varies in geographic origin over time.

[40] U.S. DEP'T OF HOMELAND SEC., RADIO FREQUENCY INTERFERENCE BEST PRACTICES GUIDEBOOK 2 (2020), https://www.cisa.gov/sites/default/files/publications/safecom-ncswic_rf_interference_best_practices_guidebook_2.7.20_-_final_508c.pdf.

[41] *See generally* DHS RISKS OF GPS DISRUPTIONS, *supra* note 35.

Case Studies

The Parkes Radio Telescope[42]

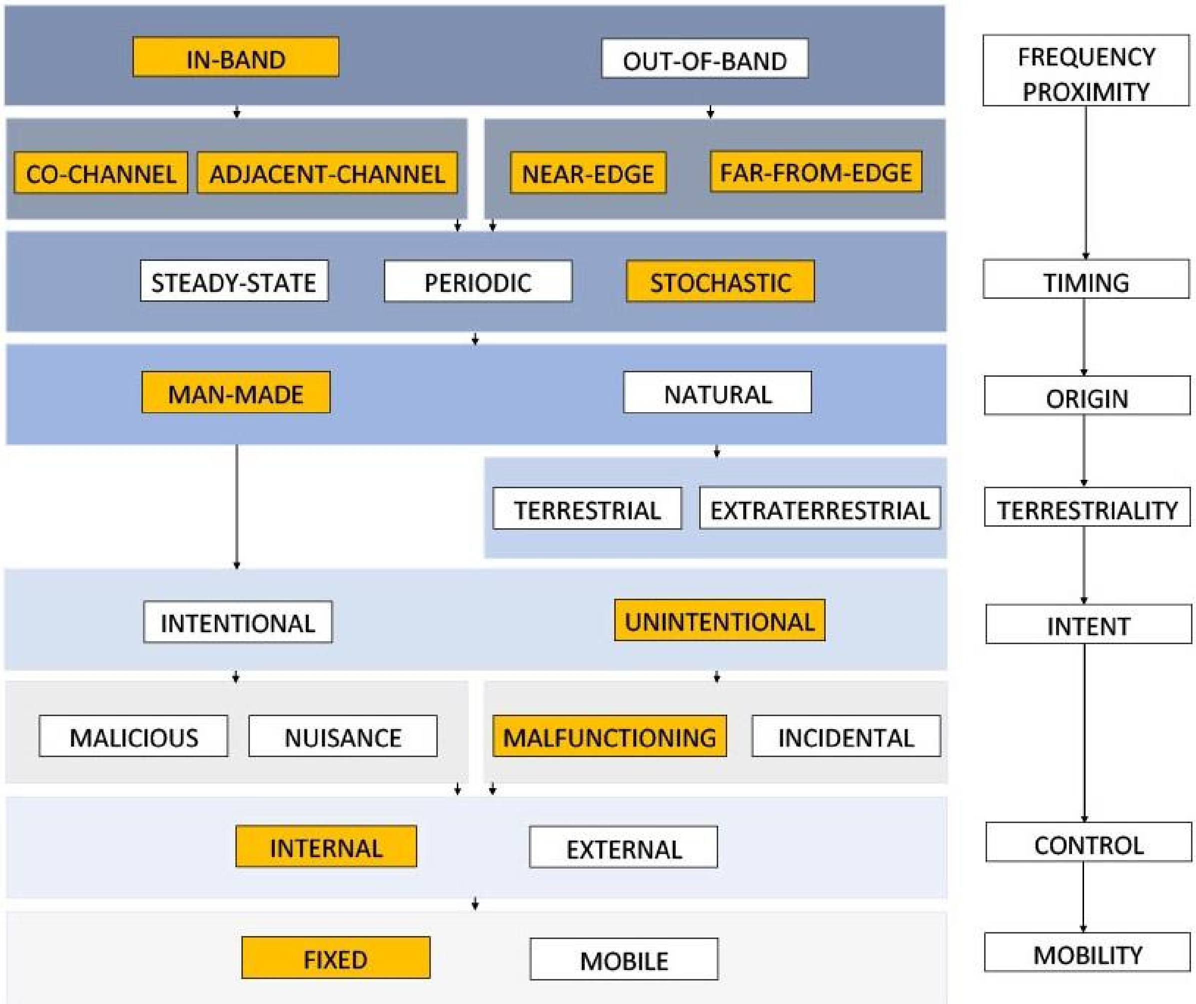

Diagram 5: Interference Taxonomy Applied to the Parkes Microwave

The Parkes radio telescope, located in New South Wales, Australia, is one of the southern hemisphere's largest and most powerful single-dish radio astronomy telescopes.[43] The massive telescope began operation in 1961 and, with several upgrades, remains in operation today.[44] However, starting in 1998, astronomers at the telescope began to detect strange radio signals.[45] Given that the signals were quite local (they emerged from within a radius of just a few miles), the scientists assumed that the occasional signals were atmospheric—in particular, that they were

[42] Monica Tan, *Microwave Oven to Blame for Mystery Signal That Left Astronomers Stumped*, THE GUARDIAN (May 5, 2015, 3:21 PM), https://www.theguardian.com/science/2015/may/05/microwave-oven-caused-mystery-signal-plaguing-radio-telescope-for-17-years.
[43] *Parkes radio telescope*, COMMONWEALTH SCI. AND INDUS. RSCH. ORG., https://www.csiro.au/en/about/facilities-collections/atnf/parkes-radio-telescope (last visited Apr. 28, 2022).
[44] *Id.*
[45] Tan, *supra* note 42.

caused by nearby lightning strikes.[46] Additionally, the signals were only ever detected during the daytime.[47]

However, in early 2015, the astronomers installed a new interference-monitoring receiver at the station and detected a strong signal at 2.4 GHz. Oddly enough, this was the exact frequency signature of a microwave oven.[48] Seeking answers, the researchers tested the facility's microwave and discovered that, while it did not emit radiation while closed, the microwave did generate interference if opened in the middle of a heating session.[49] Thus, the mystery was solved, but had been doubly difficult to pin down because of its sporadic nature: not only did the interference only appear when a staff member opened the microwave in the middle of a heating session, but it only appeared when the dish was pointed in the direction of the microwave.[50]

The uniqueness of this interference anecdote makes it a perfect candidate for the application of this paper's interference taxonomy. The classification for the microwave interference to the telescope would be as follows:

- *In-Band & Out-Of-Band:* thanks to the enormous range of signals that the Parkes telescope is designed to pick up, the interference from the microwave may have been within or without the telescope's designed band of reception.
- *Stochastic:* this case provides a seminal example of "stochastic" interference. While the use of the microwave itself was arguably periodic (highest use during lunchtime), the complicating factors of telescope direction and odd microwave use times ultimately mean that the interference can only be classified in relation to the triggering event (microwave opening) rather than a specific time interval.
- *Man-made:* since the microwave is a machine.
- *Unintentional, Malfunctioning:* since the interference was not caused by a person acting with intent to interfere, this is classified as "unintentional" interference. Since the interference was only caused when the microwave was operated in an unusual manner (opening the door before finishing), it is classified as "malfunctioning."
- *Internal:* the microwave was located in the same facility as the telescope and fell under the same authority.
- *Fixed:* the microwave was never moved, so it is classified as "fixed."

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[46] *Id.*
[47] *Id.*
[48] *Id.*
[49] *Id.*
[50] *Id.*

The Newark Pick-up Truck[51]

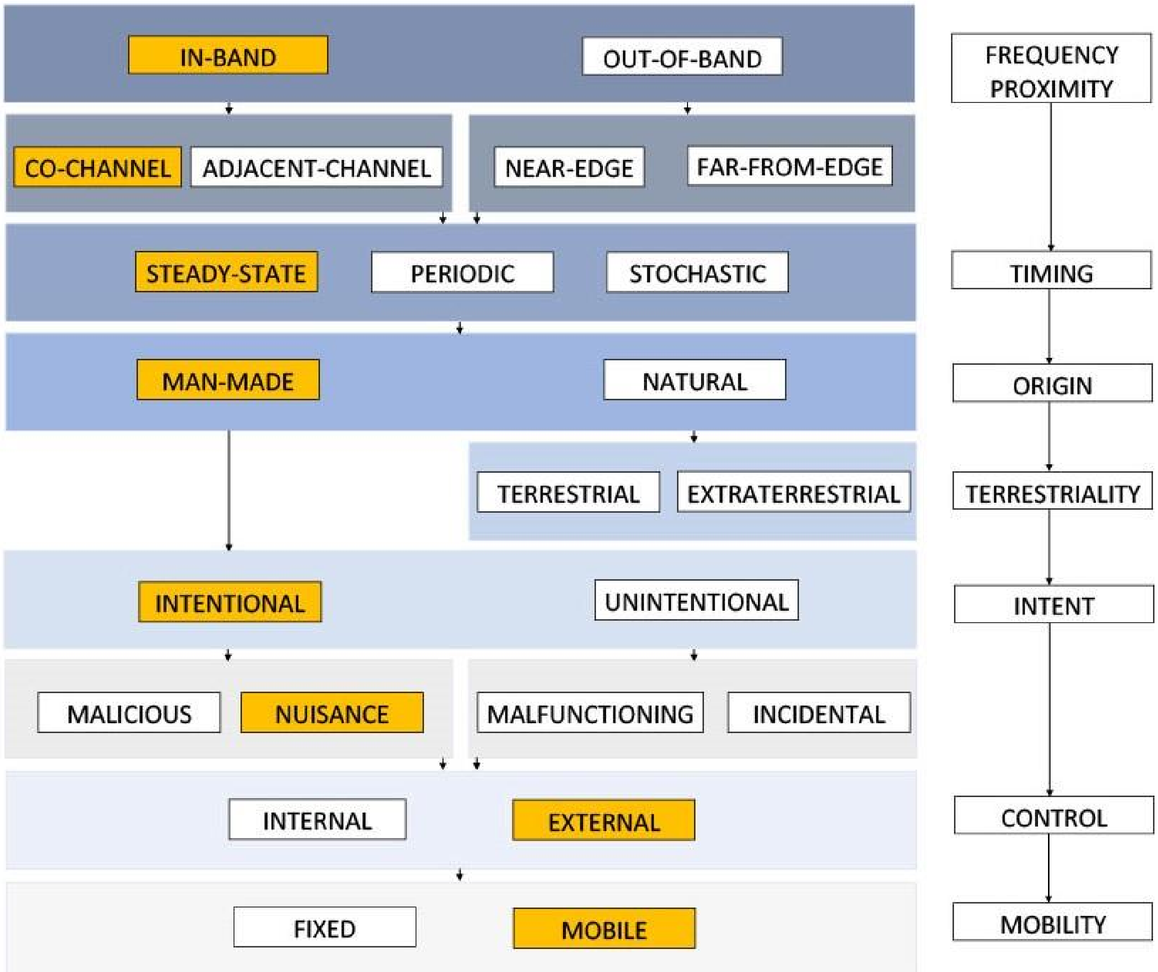

Diagram 6: Interference Taxonomy Applied to the Newark GPS Jammer

In August of 2012, the FCC's enforcement division received a complaint from the Federal Aviation Administration (FAA) about an unknown source of interference at Newark Liberty International Airport in Newark, New Jersey.[52] Apparently, the interference was affecting Newark's ground-based augmentation system (GBAS), which "provides enhanced navigation signals to aircraft in the vicinity of an airport for precision approach, departure procedures, and terminal area operations."[53] The reported interference was severe enough that it was impacting the ability of the airport to operate safely.

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[51] Steve Strunsky, *N.J. Man Fined $32K for Illegal GPS Device That Disrupted Newark Airport System*, NJ.COM (Mar. 30, 2019, 2:35 AM), https://www.nj.com/news/2013/08/man_fined_32000_for_blocking_newark_airport_tracking_system.html#:~:text=The%20FCC%20said%20an%20aircraft,FCC%20fined%20the%20driver%20%2431%2C875.

[52] *In the Matter of Gary P. Bojczak; Whitehouse Station, New Jersey*, Notice of Apparent Liability for Forfeiture, 28 FCC Rcd. 11589, 11590 (2013).

[53] *Id.*

In response to the report, the FCC's enforcement division sent an investigator to the airport.[54] The investigator was eventually able to trace the interference to a pickup truck parked on airport property that was emanating signals "within the restricted 1559 to 1610 MHz band…[that] were blocking the reception of GPS signals by the GPS receivers used in the GBAS."[55] When the driver was found, it was discovered that he had installed a GPS jamming device in his company truck to block his employer's GPS tracking system.[56] Fortunately, once the driver surrendered the jammer, the interference stopped. The man was initially fined nearly $32,000, but the FCC eventually settled for a lesser amount.[57]

Once again, the interference taxonomy can be quickly and easily applied to this scenario:

- *In-Band, Co-Channel:* since the GPS jamming device used by the driver was operating in the exact same frequency channels as Newark's GBAS system, it is classified as "in-band, co-channel."
- *Steady-State:* since the driver was presumably operating the jammer constantly to avoid detection by his employer (even while parked; hence the investigator's easy job finding the source), this is classified as "steady-state" interference.
- *Man-made:* the jamming device was man-made.
- *Intentional:* the driver operated the jamming device with intent to cause interference to GPS signals.
- *Intentional, Nuisance:* since the driver did not intend to cause harm to the airport's operations but merely to avoid detection by his employer, this interference is classified as "nuisance."
- *External:* the source of the interference was outside of Newark airport's control (hence why it required a report to the FCC's enforcement division), so the interference was "external."
- *Mobile:* finally, since the pickup was often moved around while still emitting its jamming signal, the interference is considered "mobile."

Opportunities for Further Development

These taxonomies are intended to lay the groundwork for easing discussions around spectrum sharing and interference management, but there is more work to be done to create a shared understanding of the many interrelated concepts surrounding these topics. This paper could be aided by an accompanying in-depth glossary of what is meant by concepts such as "radio dynamic zones" or "co-primary." While much of this work is laid out already in IEEE 1900.1, there is room to expand and update the included definitions.

One area of particular interest (and confusion) is the definition of "harmful interference." While beyond the scope of this particular paper, it is difficult to have a productive conversation on sharing or interference without a shared idea of what interference constitutes as "harmful."

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[54] *Id.*
[55] *Id.*
[56] Strunsky, *supra* note 51.
[57] *Id.*; *In the Matter of Gary P. Bojczak; Whitehouse Station, New Jersey*, Order, 31 FCC Rcd. 1706, 1706 (2016).

This is both an engineering question (i.e. how should we measure and determine harmful interference to a service) and a regulatory one (i.e. how can we establish interference protection criteria to both protect primary users and maximize spectrum usage). These are complicated problems unlikely to be resolved in the near future, but a strong and clear definition of harmful interference is essential to any discussion on increasing spectrum utilization.

Of course, one major opportunity for further investigation can be found *within* the categories defined in these taxonomies. Consider, for example, the sophisticated engineering explication of "jamming" found in Marc Lichtman *et al*.[58] Many of the other categories on these taxonomies can be further subdivided and analyzed from a variety of perspectives. Another example can be found in note 38 to this paper, which recognizes that interference—as received—is often "cumulative," appearing as the sum total of multiple natural and man-made sources. Our goal for this paper was to synthesize a common, high-level vocabulary for these two topics; there is plenty of room to dive deeper into the myriad subtleties that remain.

This paper also recognizes that the lack of a common vocabulary is only one of a myriad of topical issues facing spectrum management.[59] In fact, debate could be had regarding whether and to what extent other, more foundational problems must be addressed before turning to the vocabulary issue. Consider, for example, the FCC's newly-reopened proceeding on the issue of receiver performance.[60] If adopted in some form, new receiver performance guidelines or standards could hail a sea change in interference management that might alter the specifics of interference or sharing terminology. Furthermore, the adoption (in some form) certain proposals, like the "interference limits policy" and "harm claim thresholds" proposed by the TAC, might increase the importance of clear common interference terminology, but may also alter the importance of certain types of terminology in comparison to others.[61]

Finally, the authors stress that real progress on the common vocabulary issue can only be made through open discussion between all commercial, scientific, and regulatory stakeholders. The terminology in this paper has been drawn from a wide array of sources in each of these different areas and is intended to show the value of diversity of input on this issue.

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[58] *See generally* Lichtman, *supra* note 14.

[59] *See generally* SILICON FLATIRONS CENTER, *supra* note 7.

[60] *See Promoting Efficient Use of Spectrum through Improved Receiver Interference Immunity Performance*, Notice of Inquiry, FCC 22-29 (2022).

[61] *See* FCC TECH. ADVISORY COUNCIL, INTERFERENCE LIMITS POLICY AND HARM CLAIM THRESHOLDS: AN INTRODUCTION (2014), https://transition.fcc.gov/oet/tac/tacdocs/reports/TACInterferenceLimitsIntrov1.0.pdf.