Automating Spectrum Sharing from the Ground Up

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Abstract

Future G networks will require more dynamic, agile support for the management of radio frequency spectrum on a fine-grained basis. The radio access network (RAN) technologies necessary to enable Dynamic Spectrum Access (DSA) have progressed significantly over the past 20 years, but the challenges of realizing the potential for DSA requires the co-evolution of the technologies, business models/market structures, and regulatory policy for wireless networks. This paper discusses a bottom-up, multi-disciplinary approach to DSA. In particular, we focus on the use of standards-based Spectrum Consumption Models (SCMs), and review on-going research to incorporate SCMs in an automated management framework based on incentive-compatible, technically-sound spectrum access contracts, or Spectrum Access Agreements (SAAs). This work is being undertaken as part of the NSF National Radio Dynamic Zone (NRDZ) research initiative and this paper provides an introduction to the core concepts of the SCM/SAA framework, project goals, and preliminary insights into how the SCM/SAA can help improve spectrum management and advance R&D efforts to enable the transition to a shared spectrum future. The SCM/SAA research represents a bottom-up effort to develop the techno-economic tools to facilitate market-based experimentation and development of spectrum sharing markets, business models, and applications to complement and render more economically viable and relevant emerging DSA technologies and top-down regulatory reforms aimed at lowering spectrum sharing barriers.

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1. Introduction

Future G networks will require more dynamic, agile support for the management of radio frequency spectrum on a fine-grained basis. The radio access network (RAN) technologies necessary to enable Dynamic Spectrum Access (DSA) have progressed significantly over the past 20 years, but the challenges of realizing the potential for DSA requires the co-evolution of the technologies, business models/market structures, and regulatory policy for wireless networks. Unfortunately, regulatory policies and business models have been slower to adapt. From an economic perspective, what DSA enables is the ability for wireless systems to treat spectrum resources more like commodities, reducing their co-specialization with other system components, and thereby enabling system unbundling and unleashing the *mix-and-match* opportunities for market forces to intrude.[2] To-date, top-down policy reforms aimed at enabling this have not been sufficient.

This paper discusses a bottom-up, multi-disciplinary approach to DSA. In particular, we focus on the use of standards-based Spectrum Consumption Models (SCMs)[3] that provide a mechanism for radio devices to declare their RF operational requirements and characterize their spectrum use

[2] Having mix-and-match options allows innovation in components to proceed semi-independently of overall system innovation. At this stage in the evolution of DSA, we do not yet have clear consensus on what is the best system architecture, precisely where technical/business interfaces ought to be, how those interfaces ought to be managed, etcetera. The Open Radio Access Network (O-RAN) effort seeks to enable expanded technical and business options for sharing resources from the masts to the RF, but precisely how those may best be organized and managed by industry and regulatory policymakers is an active and far from settled research challenge. In particular, O-RAN can help to enable new less vertically integrated market structures to emerge. The SCM/SAA capabilities discussed here are consistent with those goals. For further discussion of O-RAN, see Polese et al. (2023), Lin et al. (2023), and https://www.o-ran.org/.

[3] See IEEE P1900.5.2-2017 - IEEE Standard for Method for Modeling Spectrum Consumption.

boundaries. We summarize the key features of SCMs and discuss how they can enable incentive compatible and technically-sound spectrum access contracts, which we refer to as Spectrum Access Agreements (SAAs). These SAAs will provide the technical mechanisms for automating the transfer of spectrum usage rights dynamically among heterogeneous users. In economic terms, the SCMs provide the basic accounting primitives that the SAAs will reference and utilize to negotiate and craft enforceable contracts for dynamic spectrum sharing and/or secondary market agreements. Managing RF agile systems in frequency, time, and space opens up complex considerations for measurement, computation, and dynamic system control that require significant automation, but which therefore also engage complex economic contracting considerations when such management is shared among heterogeneous networks and users.[4] We present economic modeling results of SAAs being used for market-based sharing under a variety of governance regimes. We extend earlier modelling results of congestible resources using the SAA framework.[5]

This work is being undertaken as part of the NSF National Radio Dynamic Zone (NRDZ) initiative.[6] This initiative is facilitating at-scale pilot testing of DSA technologies, including SCMs, in radio innovation zones. In addition to explaining the progress to date, we present results from simulation modeling and economic market modelling for wireless services using SCMs with attention to the implications for regulatory enforcement and more flexible interference management. We also discuss the contracting economics and telemetry/computational challenges for enabling incentive-compatible automated DSA management using SCMs and how they are closely linked.[7] The SCM/SAA work helps build a bridge from DSA to top-down policy reform efforts that have sought to promote spectrum sharing via more flexible, liberalizing licensing regimes.

Section 2 will motivate the research project. It will set the stage for why our issue is "automating spectrum sharing from bottom-up" and how this effort fits within the NRDZ.

Section 3 will provide a review of the SCM and SAA concepts. SCM is already an IEEE standard, but work is continuing. SAAs are a concept in process and this paper is a work-in-progress to develop them.

Section 4 presents a snapshot of our current progress in developing the SCM/SAA framework via theoretical and empirical simulations motivated by current areas of special focus for advancing spectrum sharing capabilities.

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[4] To be clear, those economic contracting considerations extend broadly and are not limited to the exchange of value (usually represented in monetary terms), but also to other policy concerns such as the protection of privacy.

[5] Earlier work adopting models of competition with congestible reousources for spectrum settings includes Nguyen et al. (2016), Berry et al. (2020), and Adams and Yoo (2023).

[6] See https://new.nsf.gov/funding/opportunities/spectrum-innovation-initiative-national-radio.

[7] For example, computing and deconflicting spectrum use with SCMs from a large number of devices (tens to hundreds or more) is computationally demanding and progress has been made by the COSMOS NRDZ team to reduce the computational load and speed up this process. Further work is underway as part of this project, but a detailed discussion is beyond the scope of this paper.

Section 5 concludes with a summary and some thoughts on future directions.

2. Towards a Spectrum Sharing Future: Status Check

Radio frequency is fundamentally a shared resource[8] and enabling it to be shared more intensively is necessary for efficient spectrum management. Although spectrum use is already shared in certain bands,[9] the goal is to unlock opportunities to access under-utilized spectrum by lowering the costs of making such spectrum resources usable and facilitating the better matching of spectrum needs and technical capabilities via automated and market-based spectrum-management. The challenge is to facilitate sharing in all dimensions (temporal, spatial, frequency, etc.) among heterogeneous networks and users to reduce technical and economic barriers to wireless system design and spectrum utilization models.

2.1. From C&C to Shared Spectrum: top-down reforms

Historically, shared access to spectrum resources was managed by allocating dedicated spectrum frequency bands to specific users and uses, linked to specific technologies. The original model was one based on administrative assignment, of Command & Control (C&C), that relied on so-called "beauty contests".[10] Those dedicated legacy assignments failed to adapt as wireless technologies and the markets for the services they supported evolved. The government processes for making those assignments are too slow and cumbersome and government policymakers lack access to the market intelligence and technical expertise needed to keep up with the fast pace of digital technologies and wireless market needs. It has long been recognized that market mechanisms may prove more efficient at managing scarce spectrum resources than administrative control by government regulators.[11] This has helped fuel decades-long policy reform efforts to expand market-based access to spectrum resources.[12] That transition embraced the use of auction-based

[8] It is fundamentally a shared and renewable resource in that spectrum resources used at a particular time and place are not consumed, but are available for other uses at different times and locations.

[9] Even when spectrum resources are exclusively dedicated to use by a single user or use (e.g., an MNO, the government, for WLANs, etc.), different devices (radios) use the spectrum at different times and locations, or "share the spectrum" in economic terms.

[10] Under C&C, government administrators determined how many licenses would be awarded and therefore the resulting market structure and scarcity of spectrum resources. Would-be contenders for those licenses would participate in a government review process where they would tout their technical and business merits and the public policy benefits if they were awarded a license. Critics of the approach questioned the ability any such administrative process to out-perform market competition in identifying the best awardees, as well as the risks of insider-dealing and deadweight losses associated with excessive investments in bargaining positions.

[11] Coase (1959) early on argued that broadcast spectrum access might be better if left to a market. See Hazlett (2001), Lehr (2009, 2020), Ofcom (2004), and SPTF (2002) for discussions of need to move from administrative "command & control" spectrum management to more market-based approaches that facilitate more dynamic spectrum sharing.

[12] Primary exclusive-use spectrum licenses have been liberalized with licensees granted greater scope to choose the technology and how spectrum is managed across an expanding array of bands. Significant swaths of high-band, mid-band, and lower-frequency band spectrum has been reallocated, and in many cases, reassigned via spectrum auctions to new uses and users. At the same time, access to unlicensed

assignment methods starting with the allocation of PCS spectrum in the 1980s, replacing the lotteries that had been utilized previously to assign cellular licenses.[13] Auctions offered many benefits – they facilitated the migration of spectrum management from legacy C&C toward greater reliance on market forces, thereby taking advantage of the ability of market-forces to help direct the spectrum resources to the awardee with the highest expected value for the spectrum (at least at the time of the auction). Auctions also provided a mechanism for capturing a portion of the future value of the spectrum resources for the public treasury, rather than allowing it to be realized as a windfall gain to earlier C&C recipients (like the TV broadcasters) or the investor-pools under lottery assignments. However, auction assignments with long-lived licenses but without efficient secondary markets are not significantly better at ensuring dynamic assignment of spectrum resources than were the lotteries they replaced.[14]

Overtime, spectrum regulators have sought to address those issues by giving awardees of exclusive spectrum licenses more flexibility in how they manage their spectrum resource including greater freedom to select the technologies used, the services offered, and freedom to sub-lease or otherwise share spectrum with other users.[15] At the same time, spectrum regulators explored innovative auction designs, including the two-sided "incentive" auction to effect the transfer of critically important but under-utilized over-the-air TV broadcast spectrum for use by mobile broadband service providers.[16] And, to address the needs of private and local wireless network users and to

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spectrum and easements for secondary-use access to spectrum (e.g., UWB) have also been expanded. All of these different governance models co-exist across different RF bands simultaneously and collectively support different types of spectrum management models. In all cases, spectrum is shared, but the control of the sharing is managed differently such that opportunities, costs, and incentives to share the spectrum more intensively vary significantly.

[13] The introduction of cellular services sought to design in competition from the start. In each territory, two cellular licenses were awarded: one went to the incumbent wired local monopoly provider and the other was allocated via a lottery. The two licensed providers were required to enable roaming to facilitate the buildout of duopoly coverage. A number of the second licenses were awarded to investor pools that had no intention of building out networks, but planned to sell their licenses to the second provider, which turned out in most cases to be the incumbent wireline provider from outside the region. In the end, the lottery approach ended up assigning the spectrum to the same entities that would have been most likely to have acquired those licenses via an auction process, or even, via the beauty-contests that characterized earlier C&C spectrum assignments.

[14] As we explain further below, efficient secondary markets have negligible transaction costs, which turns out to be a quite significant challenge in the context of spectrum for lots of technical, economic, and regulatory (legal) reasons. See Cramton (2017) or Gomez et al. (2018).

[15] The relaxation of administrative restrictions on exclusive spectrum licenses went hand-in-hand with the secular trend from legacy public-utility regulation of telecommunications service providers toward greater reliance on market-based competition.

[16] For decades, it had been clear that TV viewing was moving from over-the-air to wired network distribution networks. At the same time, cellular network providers were seeking to expand their services, including to address the growing market for mobile broadband. It was clear to spectrum policy makers that reallocating the below 1GHz spectrum from over-the-air TV to mobile broadband would unleash significant social welfare benefits. Ultimately, a complex two-sided auction design was adopted to provide an incentive compatible way to get TV licensees and mobile broadband network operators to cooperate with the

accommodate the business model needs of wireless network and device operators that were not well addressed by exclusive-licensed spectrum, regulators allocated spectrum for unlicensed bands, which enabled the growth of WiFi networks that have now proved to be such an essential component in the provision of mobile broadband services.[17]

Although significant progress has been made, it is still clear that much more needs to be accomplished if spectrum is to be managed efficiently. Technical capabilities and the wireless markets' need for expanded access to spectrum resources and enhanced spectral agility far exceed what is actually in use. The range of wireless users and uses across all bands and for all purposes continues to expand as the thirst for expanded access to digital technologies pervades all economic and social activities. Government users tasked with national security and public safety missions and commercial wireless providers are competing for scarce RF resources to meet their expanding needs for always-available, everywhere, accessibility to digital computing and communication capabilities. At the same time, sensing applications such as radioastronomy, radio telemetry, and radar services are competing for spectrum. Indeed, the recent National Spectrum Strategy released by the White House is motivated by these concerns.[18]

Moreover, as those uses change over time as technology and real-world needs change, resources need to be reallocated on a much faster and fine grained (i.e., locally customized) basis than ever before. To deliver the sorts of seamlessly connected, ubiquitous service availability that users increasingly expect for their digital appliances, network operators need expanded dynamic, agile resource management capabilities.[19] Even if spectrum were not a scarce resource, radio agility would be needed to flexibly provide high-quality services over heterogeneous underlying network infrastructures.[20]

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refarming of the below 1GHz spectrum via the 2016 Incentive Auction (see https://www.fcc.gov/about-fcc/fcc-initiatives/incentive-auctions/how-it-works, Rosston (2012), or Connolly et al. (2018)).

[17] See Milgrom et al. (2011), Lehr (2009, 2020).

[18] https://www.ntia.gov/sites/default/files/publications/national_spectrum_strategy_final.pdf

[19] It is important to note that modern network operators already make use of a wide array of digital technologies in the RAN and elsewhere to facilitate dynamic resource management among users of their networks.

[20] Consider, for example, that end-users want a service like voice telephony to work wherever they are and using whatever device they choose. Supporting that sort of seamless, everywhere available service requires being able to share many resources flexibly – spectrum certainly, but also power, backhaul, and all of the other non-spectrum components needed to enable end-users to make any-to-any voice calls. When a service (like telephony decades ago, and broadband Internet access increasingly today) rises to the status of being perceived as basic infrastructure (like roads, water, electricity), end-users take it for granted and only pay attention when it is not available since its availability/use is regarded as so important that its absence is not a small problem but a major disruption. Not all wireless services rise to this level of importance, but sorting out which do or do not in any particular economic context is something that requires RF agility. Moreover, wireless agility can reduce overall system/service costs by acting as a substitute for more costly and reduced agility with respect to other resources. For example, cell phones allowing voice calls to be routed via WiFi instead of cellular spectrum significantly reduces the costs for handling those calls. The wireless technologies needed to enable that to happen existed long before the business models adapted to make that

In recognition of the need to expand commercial access to spectrum resources, additional important "top-down" regulatory initiatives have been undertaken. Those include the creation of a new sharing model in the 3.5GHz CBRS band; allowing unlicensed spectrum use in the 6 GHz band that coexist with existing users such as point-to-point microwave links; and exploring options for expanded terrestrial sharing of higher-frequency millimeter band spectrum at 28GHz and above. In each of these bands, the technical, regulatory, and market-challenges of enabling shared co-existence among heterogeneous networks and users confront different challenges, but some of those challenges are common. [21]

We will explore some of those differences further later (e.g., regarding how differences in the regulatory frameworks impact sharing options), but first let us focus on some of the common challenges.

2.2. Bottom-up to Shared Spectrum

While top-down regulatory reforms and industry leadership are needed to enable the expanded sharing capabilities, bottom-up techno-economic capabilities are needed for spectrum sharing to be technically and economically viable. From a technical perspective, radio networks need to be able to assess their local RF environment (i.e., what spectrum resources are available for use with the appropriate quality to support the radio's operation?), select the RF spectrum to use, and then manage the behavior of the radios so that it corresponds with the intended RF operational parameters and spectrum use boundaries.[22] That is true if the radio network consists of a single radio – whether a transmitter (Tx), receiver (Rx), or dual-capability device – or multiple radios. Mobile Network Operators (MNOs) do this over their potentially wide-area coverage areas for their millions of subscribers using many different types of devices and services that are continuously changing across space and time, and utilizing a mix of spectrum resources for which they hold exclusive-licenses for as well as other resources, including unlicensed and licensed spectrum sub-leased from other providers. WLAN operators may do this for devices operating in

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a common practice, and regulatory rules also needed to adapt (e.g., to address 911 calling challenges when calls are made via different wireless technologies instead of fixed-line handsets).

[21] For example, the fact that the physics of RF propagation vary significantly in each of those frequency bands has important implications for measurement and computation, for spectrum sharing options, for the supply and demand for equipment and services operating in different bands, etcetera. Moreover, looking ahead, one strategic objective identified in the National Spectrum Strategy is the need to "pursue spectrum policies that maximize flexible use of spectrum, accommodate new and innovative technologies, and identify opportunities to expand spectrum access." The implementation of this plan will bring new regulatory initiatives to other bands.

[22] We use "Spectrum Use Boundaries" here broadly construed to include any characteristics that describe transmitter (Tx) or receiver (Rx) behaviors, and so include the frequency, power, direction of signal propagation, geolocation, protocol, modulation scheme, bandwidth, and other characteristics. As we explain later, there is no unique best way to characterize Tx/Rx behaviors, and in practice, many different model-based approaches have been developed, most of which are proprietary and bespoke to a particular spectrum management context. Creating a language and machine-readable syntax and semantics for characterizing Tx/Rx behavior represents a key first step toward enabling the bottom-up functionality that is needed for finer-grained dynamic sharing.

a single geo-contiguous area that may be served by a single access point and provide coverage over only a few hundred square feet. But even in those cases, the operations of the MNOs and WLAN operators may overlap and need to co-exist in the same spectrum space.[23] The range of devices that may co-exist and potentially cause RF interference for each other is expanding across virtually all bands.

Managing harmonious co-existence among heterogeneous wireless devices is a complex technical problem that needs to rely significantly on automated processes (implemented by software) even when all of the devices and spectrum resources in the relevant spectrum space are under the control of a single wireless network operator.[24] When the owners of the RF resources, devices, and radio networks operating in a spectrum space are under the control of heterogeneous agents, the management problem is inherently much more complicated. Enabling finer grained Dynamic Spectrum Access (DSA) (in all spectrum use boundary dimensions) and among heterogeneous networks and users is fundamentally a joint techno-economic design challenge.[25] In each case,

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[23] By "spectrum space" we mean a flexible concept to characterize the RF spectrum resources to be managed and the dimensions along which management may be effected.

Matheson and Morris (2012) defined a 7-dimensional electrospace (consisting of frequency, time, 3 spatial coordinates, and direction of propagation) for characterizing the energy received at a receiver, which is where the effects of spectrum interference are realized. A perfect receiver that can disambiguate a signal along any dimension can avoid harmful interference from other transmitters, but of course the limits of transmitter and receiver technologies and existing regulations and industry/market economics limits those capabilities which results in need for spectrum management to facilitate co-existence without harmful interference. Our conception can add to those technical dimensions, economic dimensions which may include other aspects of property rights and context. Although "spectrum space" is a flexible concept, for most of our work we will be referring to a geo-contiguous region of radio operations – a "radio zone" – which comprises multiple (potentially non-adjacent) spectrum bands. In that region, the radio environment is characterized by the physical topology, mix of radios and associated infrastructures, and wireless industry participants and users that are engaged in using the RF in the spectrum space. By focusing on a geo-contiguous location and at multiple time scales, including as close to real time as may be achievable, our goal is to explore the limits of real-time sharing opportunities on ever-finer grained dimensions of the electrospace. However, to enable these to fit with macro/real-world economic/spectrum management concepts, the spectrum space can be viewed as a recursive and flexible concept. Thus, the real-time management of spectrum resources at a single base station is part of the management of multiple base-stations in a spectrum zone, which is part of the coverage footprint for an operator involved in providing services over a larger area, which is part of national or indeed international spectrum management. And, the management of real-time behavior is a component of management of behavior at longer time-scales appropriate to usage behaviors (e.g., duration of a telephone call or user session which may be measured in seconds or minutes) to operations and investment behaviors which may be measured in days to years.

[24] Increasingly over time, radio functionality has been moved from hardware to software, and in so doing, that has enabled greater flexibility and adaptive capabilities for fine-grained control of radio spectrum use boundaries and digital signal processing. This is part of the evolution of software and cognitive radio technologies, but also the softwarization and virtualization of end-to-end digital networks (i.e., lots of other things like SDNs, NFV, etc. and the transition to smaller cell radio network architectures have enabled this agility).

[25] Managing co-existence among heterogeneous agents with divergent incentives is fundamentally an economic challenge, but how that may be addressed depends on the technical capabilities and contextual

techno-economic capabilities are needed (a) to collect and share the spectrum needs and behaviors of the multiple radio systems of transmitters (Tx) and receivers (Rx) that seek to utilize the spectrum to address the assessment function; (b) identify usage scenarios which can maximize valuable co-existence while minimizing harmful interference to determine which radios should use which spectrum; and then (c) implementing (or managing) those scenarios until it is time for a change to a new shared usage scenario. The economic challenge is to accomplish those tasks in a way that is incentive compatible for the diverse stakeholders and is economically socially efficient in terms of allocative, productive and dynamic efficiency.[26]

The top-down regulatory reforms noted earlier removed many of the regulatory impediments that precluded heterogeneous networks from exploiting DSA technologies across multiple bands governed by diverse regulatory (licensing) frameworks, but the automated capabilities to take advantage of this flexibility in a way that simultaneously solves the technical and economic challenges have been lacking. One key element missing from the landscape was a suitable framework for sharing information about the RF conditions and RF spectrum use boundaries among the heterogeneous wireless users in a spectrum space and then supporting the necessary economic capabilities (contracting, market-based transactions, enforcement mechanisms, etc.) to support decentralized, distributed DSA capabilities. That is a bottom-up challenge that helped motivate the evolution of the Model Based Spectrum Management (MBSM), Spectrum Consumption Models (SCM) and Spectrum Access Agreement (SAA) research efforts we explain further in Section 3.

2.3. Background for this project

The work described herein in subsequent sections is part of the NSF's research effort to promote the development of dynamic spectrum sharing technology. Specifically, the work is funded as part of the NSF's NRDZ-SBE program.[27]

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features of the local spectrum environment (i.e., what frequency band, demographics of spectrum users, regulatory frameworks, etc.).

[26] By socially efficient, we mean that total welfare or value for all of the users of the resource are maximized. Allocative efficiency means that resources are directed to their highest value uses. If the joint use of the resource is not viable such that the resource cannot be shared, then it should be assigned to the highest value users, which means that some users will be denied access. Productive efficiency means that the resource costs are minimized. Dynamic efficiency means that the resource usage (investment) is efficient over time. Because users may change their behavior and technologies can facilitate greater co-existence of competing uses in available spectrum resources, identifying the allocatively, productive, and dynamic efficiency solution is a joint optimization problem. The focus of spectrum management is increasingly toward enabling greater co-existence through cooperative management models, instead of assuming that user/usage models are fixed and opportunities for welfare improving joint co-existence are infeasible. The challenge is less one of determining which radios get to operate to protect against harmful interference, then determining how radios can jointly cooperatively modify their behavior to enable non-interfering co-existence.

[27] See https://new.nsf.gov/funding/opportunities/sii-nrdz-sbe-radio-spectrum-sharing-human. The NRDZ-SBE provides supplemental research support to address the "economic, social and incentive issues" associated with the development of NRDZ technologies.

Motivated by the need for dynamic spectrum sharing solutions, the NSF created the Spectrum Innovation Initiative: National Radio Dynamic Zones (SII-NRDZ) program.[28] In the short-term, this program seeks to fund research on the development and implementation of practical, end-to-end, dynamic spectrum sharing solutions and to conduct field trials in selected Radio Dynamic Zones (RDZs). In the long-term, this program seeks to establish a National Radio Dynamic Zone (NRDZ) to support at-scale research and experimentation on spectrum use/management technologies. Each RDZ is a geographic region in which dynamic spectrum sharing solutions are used to orchestrate electromagnetic energy within and beyond the zone. These RDZs are expected to be used as large-scale experimentation platforms to support research on coexistence of active and passive spectrum users including consumer broadband services and radio astronomy.[29]

In response to the SII-NRDZ solicitation, our collaborators[30] from the COSMOS-NRDZ project are designing and prototyping a spectrum Zone Management System (ZMS) to enable interference-aware spectrum sharing between active and passive RF devices. The ZMS prototype will be established around two facilities in West Harlem, New York City: (i) the COSMOS testbed sponsored by the NSF Platforms for Advanced Wireless Research (PAWR) program and (ii) the Cooperative Science Center for Earth System Science and Remote Sensing Technologies sponsored by NOAA (NOAA-CESSRST). The two facilities are in an Innovation Zone created by the FCC to facilitate research and testing. The project uses systems available at the facilities for spectrum sharing experiments such as passive receivers for weather monitoring (e.g., radiometers at 28 GHz), an environmental sensing satellite earth station receiver dish at 1.7 GHz or 7.7-8.2 GHz and a weather monitoring radar at 9.5 GHz. Spectrum sharing between unlicensed 5G cellular and Wi-Fi networks at 6 GHz is also being explored.

The COSMOS ZMS is based on a new spectrum management approach that combines a standardized fundamental information model, measurement-assisted decision making, scalable spectrum sensing, and continuous risk analysis and management. The fundamental information model of the ZMS is based on SCMs, defined in Sec. 3. The COSMOS-NRDZ project is developing techniques for efficiently generating SCMs and using them in a large-scale ZMS. The project is developing spectrum sharing and interference management algorithms that use SCMs and measurement feedback to achieve high spectrum efficiency and scalability with low processing complexity and communication overhead. The ZMS is evaluated via simulations and via real-world experimentation at COSMOS and NOAA-CESSRST.

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[28] See NSF 22-579: Spectrum Innovation Initiative: National Radio Dynamic Zones (SII-NRDZ), https://new.nsf.gov/funding/opportunities/spectrum-innovation-initiative-national-radio/505990/nsf22-579/solicitation.

[29] See Mariya Zheleva, Christopher R. Anderson, Mustafa Aksoy, Joel T. Johnson, Habib Affinnih, and Christopher G. DePree, "Radio Dynamic Zones: Motivations, Challenges, and Opportunities to Catalyze Spectrum Coexistence", https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10038793.

[30] The COSMOS-NRDZ project includes faculty from Columbia, Rutgers, Syracuse, Duke, and CCNY Universities. For further information, see https://www.cosmos-lab.org/grant-from-the-nsf-sii-nrdz-program-to-support-research-in-the-cosmos-testbed-fcc-innovation-zone-and-noaa-cessrst/. See also, Netalkar et. al. (2023) and Stojadinovic et. al (2021).

3. SCMs and SAAs Explained

A **Spectrum Consumption Model (SCM)** is an information model that captures the boundaries of the use of spectrum by RF systems so that their compatibility (i.e. non-interference) can be arbitrated via standardized computational methods.[31] The relevant RF systems may be comprised of one or more Tx or Rx devices in the relevant spectrum space. The IEEE 1900.5.2 standard defines the structure of SCMs and the computational methods to compute compatibility. Work is underway to extend the information elements in an SCM and their use in an updated version of the standard. **Spectrum Access Agreements (SAAs)** leverage SCMs and add the economic governance components needed for automated spectrum management of heterogeneous radio networks in a spectrum space that considers economic inputs, business and regulatory rules.[32] Moreover, when SAAs are used we can think of the spectrum space as a spectrum secondary market (where the coordination and sharing of spectrum usage rights, expressed as SCMs/SAAs, may be exchanged, modified, and otherwise managed).

As we shall explain, SCMs represent an important step toward enabling machine-readable messages for sharing technical information among radios that are needed to effect distributed/decentralized spectrum management among heterogeneous radio devices. Of course, the SCM framework could be used by a centralized spectrum manager within the context of a single network, but that is not the focus or goal of this work.[33] Our goal is to contribute to the building of a scalable, evolvable, flexible framework for implementing spectrum sharing that can evolve as wireless markets, business models, regulatory policies and technologies evolve. As the first step, SCMs are akin to an "accounting" framework that provides a standardized language and data framework (an information model) that allows radio devices, network operators, and others with an interest in spectrum management to share information about the RF spectrum use boundaries of radio devices to facilitate spectrum management for harmonious co-existence without harmful interference. By themselves, the SCMs only provide a data model for sharing information in machine-readable form (i.e., that is capable of being used as inputs and outputs for software). To enable their use in spectrum management, economic governance functionality needs to be added. SAAs provide these capabilities, which are akin to economic "contracts" in so far as they instantiate an agreement among the parties as to what the expected radio behaviors, spectrum

[31] See IEEE (2017), Bastidas et al. (2018), and Stine & Bastidas (2015).

[32] The SAAs introduced here are an evolution of the concept originally referred to as Service Level Agreements (SLAs) in Stine & Caicedo (2014). The use of the SLA terminology was to borrow from the use of that term in standard ISP service agreements by which ISPs and other telecommunication service providers specified the technical performance and terms of their services. See, for example, TM Forum (2011).

[33] Although not a goal, it is certainly a benefit. The development of standardized practices that become industry best-practices can deliver learning, scale, and other cost-reducing benefits. Thus, we would not be surprised or disappointed if the SCM/SAA capabilities we are developing (including the software prototypes under development) found their earliest and most extensive application in the centralized management of single wireless network operations. Just as firms may be regarded as comprised of multiple internal markets with business units which are only imperfectly coordinated, so too may single network operators find value in managing internal network resource sharing using SCM/SAA market-enabling techniques.

use boundaries and interactions among the parties to the contract should entail. Our efforts to develop SAAs to leverage SCMs are still in early stages, and they are the key focus of this paper.

This brief introduction to SCMs/SAAs is intentionally abstract because the goal is to create bottom-up techno-economic capabilities that strive at this stage to be agnostic as to what the best spectrum sharing models may turn out to be. It is clear that regardless of the sharing model, minimizing the transaction costs associated with utilizing SCM/SAAs by spectrum users will be critical for their success. That certainly means ensuring that the computational/communications overhead associated with their use be as low and efficient as possible. Indeed, a challenge for the design of SCMs is how complex and feature-rich they need to be in general versus for specific applications. As with accounting, the architecture of SCMs is adaptable to enable prototyping and simulation research which may be tailored for different RF bands and RF environments.[34] Similarly, the nascent development of SAAs is intended to be quite flexible and business-model/spectrum management context agnostic. Although our goal is to be agnostic, we recognize that the evolution of SCMs/SAAs through theoretical modeling and empirical research, building toward prototyping and actual experiments will become tailored to specific contexts. Indeed, even at this early stage of development, we recognize that our design efforts are necessarily value laden. This is reflected in our focus on applying the SCM/SAA capabilities we are developing to addressing the spectrum sharing challenges in specific cases (CBRS, 6GHz, and 28GHz, as mentioned earlier) and on the framing of the theoretical modeling work we highlight later.[35] Our hope is that our efforts of building capabilities "bottom-up" will manage to meet with on-going "top-down" policy reforms to result in expanded, real-world spectrum sharing that delivers benefits that outweigh the costs of adopting such capabilities.

In the balance of this section, we explain in greater detail what SCMs are and our preliminary thinking about how they fit with SAAs.

3.1. SCMs on closer inspection

Figure #1 on its left side lists the constructs used to define the information that is included in an SCM, the rest of the figure illustrates the hierarchy of SCM models and their structure.[36] Transmitter and receiver models are the first level of the hierarchy. A transmitter model captures the extent of RF emissions of a transmitting device, including but not limited to: a spectral mask (i.e. frequencies used by the device) and power emissions, antenna radiation pattern (power map), possible locations of the device and times of operation. A receiver model conveys what is harmful interference to an RF device. They provide a limit to the aggregate interference that transmitter

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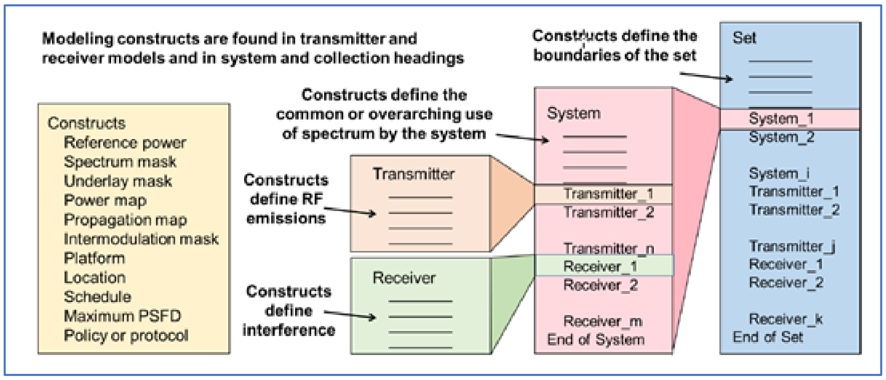
[34] Accounting practice includes lots of rules and guidelines that are generally applicable (e.g., the standard elements of a balance sheet, income statement, etc.), as well as lots of specialized rules for special situations which may differ by type of industry, asset, transaction, etc. Accounting rules may include mandatory as well as optional rules. Analogously, SCMs are adaptable to the needs of different radio environments (devices, capabilities, networking situations, etc.).

[35] As part of our on-going NRDZ research efforts, we are currently investigating the possibility of implementing active sharing in the CBRS and 6 GHz spectrum bands, and anticipate discussing that work further in a future paper. The work at 28 GHz is focused on measurements and protecting passive devices and is at a much earlier stage of development.

[36] See IEEE (2017).

devices can cause to a receiver in the temporal, spatial and spectrum dimensions. System models are a collection of transmitter and receiver models that do not constrain each other and that collectively capture the spectrum use of an RF system. An SCM set is a collection of system, transmitter, and receiver SCMs. Sets can also be used to structure lists that describe spectrum that is available for use (SCM authorization sets), identify constraints to spectrum use (SCM constraint sets), and to make a request for spectrum (SCM request sets).[37]

Figure 1: SCM Information Model and Hierarchy



The SCMs emerged as part of the effort to advance automated methods to support Model Based Spectrum Management (MBSM).[38] The SCMs provide the syntax and semantics for describing RF usage behaviors in a standardized, machine-readable form that can be used by a MBSM to manage the behavior of wireless devices in a relevant spectrum space. As already noted, the SCMs provide the "accounting" syntax and semantics for sharing information or "messages" about spectrum use boundaries. When radio systems share SCMs, it is possible to compute – using a standardized set of procedures – whether the SCMs are compatible. IEEE standard 1900.5.2 for SCMs provides a "generalized method for modeling spectrum consumption of any type of use of radio frequency spectrum and the attendant computations for arbitrating the compatibility among models."[39]

This standardized SCM framework provides a loose coupler between radio devices with different Tx/Rx characteristics and different spectrum management methods that allows independent innovation and flexible mix-and-matching between technologies and spectrum management techniques.[40] This decoupling is important because the technologies (algorithms, measurement capabilities, related capabilities) for managing spectrum utilization and the applications the need to use spectrum continue to evolve with the business models, regulations, and wireless

[37] See Bastidas et al. (2018), Stine & Bastidas (2015).

[38] See Stine & Schmitz (2014) for discussion of MBSM.

[39] See Bastidas et al. (2017). Work on developing the standard began in 2012, and the IEEE Std. 1900.5.2 "Standard for Method for Modeling Spectrum Consumption" was adopted in December 2017 (see https://ieeexplore.ieee.org/document/8398607).

[40] In this way, SCMs in the spectrum management domain aim to be analogous to how the Internet Protocol (IP) provides the "narrow waist" of the Internet that allows independent, decoupled innovation in the applications that are supported over the Internet and the heterogeneous networking technologies that support the Internet (see Stine and Bastidas, 2015).

technologies. The sharing of SCMs and their use to identify and implement sharing opportunities is an asymmetric, imperfect information challenge, subject to strategic and regulatory constraints.[41]

In many common spectrum use compatibility determination scenarios such as those for spectrum sharing and/or dynamic spectrum access environments, the information conveyed in an SCM can be used to compute a link budget between transmitter(s) and receiver(s) and determine if the transmitter will cause interference to the receiver above its acceptable level. This computation is referred to as the *compatibility* computation.[42] The procedure for that computation is also part of the IEEE standard for SCMs. The SCM constructs are faithful to the physics of spectrum use but in a manner that simplifies arbitration and computation of compatibility. Modeling is artful in so far as different modelers may make different choices for assessing compatibility. For example, simpler models may facilitate faster and less resource intensive computations, whereas more complex models may be able to identify and unlock additional white-space sharing opportunities.[43] The choices can affect the efficiency of the system and the amount of information that is shared.[44]

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[41] Different radio devices, systems, and sensors in a spectrum space may collect different spectrum use information based on their vantage point (e.g., time and location in the spectrum space) and measurement capabilities. Sharing of detailed, granular data may threaten privacy, strategic interests, or expose systems to security risks. Also, computation and communication resource constraints and limitations in measurement capabilities may limit what measurements are feasible or may be used in a particular sharing context. The SCM/SAA framework is designed to allow flexibility in the level of detail collected via measurements, shared via SCMs, and incorporated in SAAs to address these challenges. Determining what is the right level of detail to balance cost, efficiency and incentive concerns is sharing-context specific and an active area of on-going research.

[42] See Bastidas et al. (2018), Stine & Bastidas (2015).

[43] An open research challenge is to identify the appropriate mix of SCM complexity to balance the benefits of better dynamic spectrum utilization and the information decision-making costs of computing and implementing a more efficient solution. The creation, exchange, analysis, and implementation of SCM message-based solutions contributes an overhead cost for managing market-based sharing. A disadvantage of legacy, fixed dedicated assignments of spectrum usage rights was that it left many sharing opportunities unexploited when the rights holder had surplus spectrum that could have been used (shared) by another entity with significant potential gains from trade (i.e., a market-clearing price that was well above the opportunity cost to the owner of the rights and well below the opportunity cost to the entity seeking usage rights). However, identifying those situations where gains-from-trade are feasible and implementing an economic mechanism for effecting the sharing opportunity incurs transaction costs that are an offset to any gains that might be realized. A key challenge for spectrum management using SCMs is to enable sufficiently low-cost automation of spectrum management functionality that can be matched to relevant market contexts. One concern is that incumbents with excess spectrum resources may prefer a world where their competitors confront higher spectrum access costs and may not be interested in such gains-from-trade if they threaten future profits by facilitating competitive threats from new ventures. The bottom-up capabilities for trading are necessary but not sufficient to ensure such trading will actually occur and deliver the competitive and innovation benefits hoped for by policymakers. Promoting those goals will also involve top-down efforts to design market mechanisms that are privately incentive compatible with social goals.

[44] Moreover, in general, there is no a priori expectation that SCM messages would be trustworthy. Radio devices or systems may convey misleading or incorrect SCM messages because of errors (in software, measurements, or otherwise) or strategic reasons (e.g., to secure more privately advantageous spectrum access, collect market intelligence, or even to disrupt MBSM efforts). The design of an MBSM system with

Thus, modelers can model in ways that obfuscate sensitive classified or proprietary aspects of spectrum use. This ability helps address one of the more significant barriers to spectrum sharing, which is the incentivize the sharing of RF relevant information needed to compute compatible configurations. Because RF usage is not "widgets" but rather a complex concept, this poses a difficult technical (and economic) matching problem that is not amenable to the simple neoclassical economics of marginal cost pricing in commodity markets. Although wireless innovation and our goal in enabling enhanced DSA sharing is to render RF resources more commodity-like, we recognize that spectrum as a morphable, intangible asset, will never be a "widget-like" commodity.[45]

The IEEE standard for SCMs is currently being enhanced to specify standardized XML and JSON schemas that will improve the automated exchange and interpretation of SCMs between spectrum management systems and/or devices and is also being considered for Spectrum Management operations within the DOD.

3.2. SAAs on closer inspection

As noted, SCMs are machine readable and capture the boundary of the uses of spectrum by RF systems so that their compatibility can be arbitrated. As such, they can be used to negotiate agreements among spectrum users to effect spectrum management. SCMs can enable incentive compatible and technically-sound spectrum access contracts,[46] which we refer to as Spectrum Access Agreements (SAAs). These SAAs provide the technical mechanisms for automating the transfer of spectrum usage rights dynamically among heterogeneous users. In economic terms, the SCMs provide the basic accounting primitives that the SAAs will reference and utilize to negotiate and craft enforceable contracts for dynamic secondary markets. The different entities participating in an SAA can assess compatibility to each other's modeled spectrum use and identify the changes needed in their own use to achieve compatibility.

Overall, and building on the work previously described in Stine and Bastidas (2014), a SAA between two or more spectrum users documents a common understanding of the aspects of

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SCMs needs to consider how to promote trusted SCM exchange. That may be examined as a mechanism design (truth-revelation challenge) or game theoretic challenge.

[45] Spectrum usage rights are a social/regulatory construct that can change with our institutional governance structures (e.g., ITU, FCC, etc.), technologies (which are limited by laws of physics, but what is possible is also a matter of technology and economics), and market needs (what capabilities people want and what they are willing to invest to get those capabilities). The management of spectrum demarcated by frequency bands and at different time-scales is a regulatory construct that is deeply embedded in the legacy of how wireless technology and use has evolved, but other techniques for defining or managing RF use are feasible. For example, spread spectrum offers one such example.

[46] We are careful here to use "contracts" loosely since economists and lawyers do not precisely agree on what constitutes a contract. For an economist, a contract is a construct with broader application than what lawyers regard as a legal contract, but economists borrow significantly from the lawyers' conceptualization and the legal interpretation is of practical import and relevance to the real-world enforcement of SAAs whether by regulatory action, court adjudication, or private negotiation. In light of the desire to automate spectrum management, these details may be of special relevance, beyond the scope of this paper. For a further discussion of automatable contracts see Lehr (2021).

spectrum use and the roles and responsibilities of all parties in maintaining compatible spectrum use. It provides a verifiable and flexible mechanism for addressing an enduring challenge in spectrum management: how to define "harmful interference"? With exclusively licensed spectrum, one interpretation might be that any unauthorized and undesired radiation from radios unaffiliated with the licensee might be deemed to constitute harmful interference. In light of the technical difficulties inherent in identifying and eliminating all unaffiliated RF energy from a licensee's band[47] and the ambiguity as to whether the unaffiliated RF energy results in any economic harm to the licensee or anyone else, such a definition is problematic.[48] It tends to result in worst-case interference protection policies that result in under-utilized spectrum and harms innovation and competition in wireless services. However, achieving consensus on a better definition of what constitutes "harmful interference" and embedding that in statute and regulatory rulings has also proved problematic.[49] The SCM/SAA approach side-steps this challenge by introducing a flexible framework that can allow stakeholders to reach a contract documenting their agreement on what constitutes appropriate radio behaviors including what are acceptable levels of interference and what should happen if those agreements are not met. The SCMs provide the technical boundaries of the expected behavior of the contracting parties radios.

In keeping with the contracting metaphor, an SAA should also document the process and details for assessing compliance of each entity's SCM which includes defining what needs to be measured and how, where and when it should be measured and the procedures to handle SAA violations (or other deviations from expected behavior that require exception handling). It is worth noting that SCMs support the inclusion of probability-based values which allow for a softening of the spectrum use boundaries defined in the SCM, which in turn can facilitate spectrum sharing interactions and risk management capabilities.

Finally, and again consistent with the contracting metaphor, SAAs may include mechanisms for incorporating considerations (often in the form of monetary payments) delivered to the "seller" as

[47] The unaffiliated RF energy in a licensee's exclusive band may come from background sources in the environment and unintentional radiators, as well as out-of-band (OOB) or in-band transmissions from unaffiliated transmitters. Whether this energy has any negative impact on the licensees use of the spectrum by causing noise or interference for the licensees radios depends on the technical characteristics of the unaffiliated sources. With unaffiliated intentional transmitters, those can include the power, duration, direction, distance, and other characteristics of those transmissions. Given the complex propagation characteristics of RF in different bands due to interactions with the environment and to antenna and other radio operating characteristics, monitoring, identifying, and controlling in-band, and especially OOB, radio interference is difficult and varies with time and distance from the intentional transmitter.

[48] See Marcus (2014).

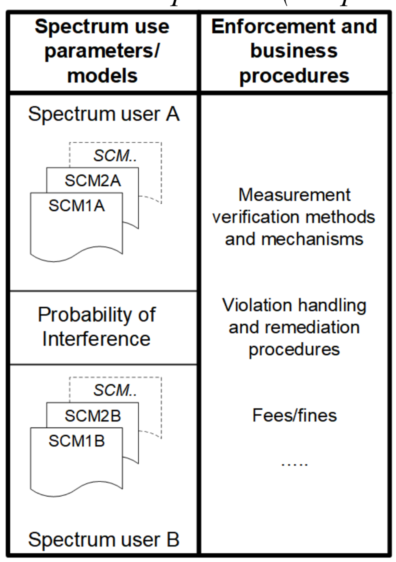
[49] See IEEE (2012). From the Executive Summary: "In recent years, many of the spectrum policy controversies in the United States have dealt with the basic issue of whether a proposed technology or service will cause 'harmful interference' to existing spectrum users. Resolving these issues has typically taken several years in an era where technology is moving at 'Internet speed' …… Changing the definition is probably impractical, due to the long list of precedents over decades that have been built on the current definition, even though it is not established by statute."

compensation for the usage rights translated to the "buyer" in any spectrum sharing transaction effected by the SAA.[50]

The precise framing of what an SAA may look like in a particular context and what components are needed remains a work-in-process, but in keeping with the goal to be flexible enough to accommodate a diverse range of business, technical, and market sharing contexts. Moreover, as work progresses to develop prototype systems and RF empirical measurements to assist in the refinement of MBSM algorithms and techniques, the design of the SAAs will evolve.

Stine & Bastidas (2014) identified some of the key functionality needed to augment the technical SCMs to enable the SAAs. Those key functions are summarized in Figure #2 (adapted from their earlier paper, reproduced below:[51]

Figure 2: SAA high-level structure and components (Adapted from Stine & Bastidas, 2014)



The hypothetical SAA sets forth the expected technical radio behaviors of the spectrum users (in this case, two radio networks, A and B, although this could easily be generalized to include many radio networks, some consisting of individual radios and others consisting of networks of radios). Having identified a collection of SCMs that are compatible, after perhaps some negotiation process, those are then an essential component of the SAA, setting forth the expected radio

[50] We are careful here to reserve significant flexibility for the valuation transfer role of contract consideration. Although the SCM/SAA framework is compatible with monetary-based spectrum trading in real-time markets, in many cases, the value-based incentive mechanisms may be much more complicated and encompass behavior over longer-time-periods and multiple transactions. For example, the value-transfer mechanisms may be part of some periodic settlement process as in Internet peering interconnection agreements or cellular mobile roaming agreements, or even reputation-based incentive management schemes.

[51] In Stine & Bastidas (2014), they referred to SAAs as SLAs (Service Level Agreements), as explained in Note 32 *supra*.

operational boundaries in time, space and spectrum. Those SCMs typically do not specify hard performance boundaries, but rather probabilistic bounds. Moreover, those probabilistic bounds may be governed by business processes that may include payments or other forms of consideration for rights holders that are willing to voluntarily accept interference from other radios in the spectrum space. Therefore, even radios operating within their SCMs may cause interference for other radios that is expected and is not viewed as a violation of the SAAs. However, during the duration of the SAA, radios may intentionally or unintentionally violate their SCMs by operating or appearing to operate outside of their SCMs.

To render adherence to the SCMs incentive compatible, there needs to be an enforcement mechanism as part of the SAAs. The enforcement mechanism needs to have a verifiable way to monitor compliance with the SAA. That could be supported in multiple ways, including spectrum sensors (measuring radio behaviors), self-assessment (e.g., radio black boxes[52]), and/or mutual verification, with or without the participation of trusted third-parties. The measurement methods employed by the monitoring ought to be specified as part of the SAA. The business processes may include incentive payments of fines or other forms of incentive/penalty consideration to induce incentive-compatible compliance with the SAA.

Those business processes will also need to specify remediation procedures to adjust radio behaviors and SCM/SAA terms in the event of expected or unexpected changes in the radio environment. For example, the SAA may specify SCMs for commercial operations, but be subject to potential pre-emption by first-responders (an expected but rare change in the radio environment) or to relaxation of SCM requirements in the event of equipment failures (an unexpected change in the radio equipment). The SCM/SAA remediation may define default behaviors in the event that previously unanticipated events occur.

Finally, the SAA will need appeal and dispute resolution rules and processes, which may include providing recourse to trusted third-party adjudication in the event that participants wish to challenge the authority of the SAA to govern radio behaviors. The third-party adjudication could be provided in the form of binding arbitration, via an administrative "spectrum court," or regulatory authority (e.g., the FCC).

We can explore potential non-SCM based SAAs by considering how they exist in certain relevant contexts. First, as noted already, a single wireless network operator with full control over a spectrum space is analogous to a centralized spectrum manager, and implicitly, could be viewed as the ultimate example of C&C spectrum management. Setting aside any mechanism design issues (e.g., moral hazard and asymmetric information challenges that constrain the degree of control that even a central planner has), in principle at least, the centralized spectrum manager can

[52] Radios could be equipped with "black boxes" akin to airplanes (a suggested approach we owe to John Chapin) that would record radio operating parameters. Those black boxes might be queried by the spectrum manager in real-time or accessed forensically to assess SAA violations. The need to query the black-boxes and the authority to do so could be limited to situations and to designated trusted authorities where probable violations of the SAA have been detected. Limiting access to the black-boxes to such special circumstances reduces the computational and communication load of processing what might be quite detailed measurement data that is only needed if disputes arise and which general public disclosure of might pose a risk to privacy and security of the radio networks.

collect RF intelligence from all the radios in its domain, compute the optimal co-existence solution that minimizes costs and maximizes total usage value (aggregating the value associated with all users seeking to share the spectrum space), and then can enforce that solution by instructing all of the radios to act according to that solution. That would be the fully cooperative, coordinated solution. Indeed, when an MNO seeks to manage the sharing of its scarce spectrum resources across its many customers, it is approximating trying to solve such a problem – although the MNO has to contend with real-world mechanism design challenges and a host of other problems.

The management of devices in unlicensed WiFi bands offers a very different type of spectrum access framework. In the extreme version of that model (excepting managed WiFi networks comprised of multiple WiFi devices), each individual radio accesses the spectrum individually, con strained only by a listen-before talk mechanism to coordinate spectrum use with other WiFi radios along with the requirement that the radio complies with existing unlicensed band rules. In effect, in the unlicensed model, there is a very simple set of spectrum use rules/agreements beyond device approval and certification standards. This contrasts with the quite active spectrum access management by an MNO or other private wireless network operator within the spectrum space they control.

Under the exclusive licensed model (the "MNO model"), the central planner has strong incentives to take into account the interference effects of its customers' radios and to use the spectrum under its control efficiently to maximize the total net value realized. Under the unlicensed (the "WiFi model"), users have to contend with the risk that other users will impose an externality cost in the form of interference that the unlicensed users have no legal recourse but to accept. Since unlicensed spectrum was first introduced in the 1980s, advocates for either model have argued about which approach results in a more efficient mechanism for managing spectrum property rights, and policymakers have addressed those debates by providing spectrum resources for both models.[53]

Finally, MNOs and unlicensed users do indeed share spectrum. Roaming agreements which may come in many forms are a regular type of business arrangement among competing MNOs to enable coverage and capacity needs to be met when supporting customers on their own networks is technically or economically undesirable. Smartphone users typically switch between WiFi and cellular networks based on performance and cost considerations, and wireless network providers often integrate WiFi, cellular and other terrestrial and non-terrestrial (e.g., satellite) wireless networks into their services. Indeed, to better compete in today's mass market telecommunication services markets many legacy cable-TV competitors like Comcast and Charter as well as new competitors like Google now offer competitive mobile broadband services that are principally supported via their WiFi networks, but operate as MVNOs with service provided by legacy MNOs to expand coverage – in effect, reversing the off-loading proposition that has long allowed MNOs to benefit from off-loading cellular network traffic to WiFi to economize on scarce spectrum resources.

This complex array of contractual arrangements and enforcement mechanisms that apply across these different SAA contexts which exist today are the same sort of complexity that we hope to be

[53] For example, see Hazlett (2001) and Lehr (2004). Since 2000, the FCC has allocated significant additional bandwidth for exclusive, flexible licensed spectrum and unlicensed spectrum below 10GHz.

able to support, but in a lower-total-transaction-cost and automated way via the SCM/SAA capabilities under development. By "total transaction cost" we mean all of the costs incurred by all of the parties that would be impacted by and need to cooperate in order for the adoption of the new SCM/SAA capabilities is to be successful.

At a minimum, it means that automation of sharing needs to deliver net benefits relative to today's solution. Absent regulatory mandates, it has to be viewed as privately profitable (at least weakly) for it to be incentive compatible for the entities participating in SCM/SAA sharing to incur the adoption costs for the technologies needed. The benefits of participation may derive from lower costs (e.g., reducing the opportunity costs of retaining under-utilized spectrum resources) or expanded business opportunities (e.g., being able to tap into new sources of revenue).[54] Thus, developing software and automated SCM/SAA capabilities to facilitate the entry of new types of providers of POTS calling services is not a compelling usage case.[55] In today's marketplace, enabling voice telephony services may be necessary for a service provider to compete in retail telecommunication services, but there are so many ways to make free calls using such a wide array of spectrum resources already that that is not a compelling usage case for enabling DSA.

Indeed, a challenge is that by rendering RF resources more commodity-like, DSA reduces the artificial opportunity cost or scarcity rents that might otherwise give rise to value creation in using scarce spectrum resources more efficiently.[56] In effect, if user A can simply switch to a less

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[54] One obvious example is the ability to lease under-utilized spectrum, but that requires the secondary-market enabling capabilities that the SCM/SAA framework seeks to provide to exist and be adopted. In the absence of secondary-markets with sufficiently low transaction costs, the opportunity cost from retaining under-utilized spectrum resources is negligible. Moreover, if spectrum scarcity serves as an entry barrier to competition, relaxing that barrier may have adverse implications for incumbents. In short, enabling efficient secondary markets will confront numerous challenges, but a necessary requirement is that the basic technologies needed to share spectrum exist and can be adopted.

[55] POTS is short-hand for "Plain Old Telephone Service," an acronym that is increasingly being relegated to history. Some pundits started referring to "PANs" (Pretty Awesome New Stuff) to signal that telecommunication services were changing in the late 1990s (i.e., "POTs and PANs", see https://www.nae.edu/19579/19582/21020/7338/7506/POTSandPANSTelecommunicationsinTransition).

[56] Unlike other physical resources, the commodification of RF is subject to significant constraints induced by the physics of RF propagation and limitations of the underlying hardware; however, with smaller cells and more adaptive DSA hardware/software, spectrum agility has the economic effect of rendering different RF "bundles" more fungible, thereby enabling network operators to realize the significant benefits of resource commodification. A key feature of commodity resources is that they are more easily traded or transferred from low value to higher value uses. When RF management emerged, dedicated frequency/location spectrum rights were paired closely with dedicated RAN hardware. With the explosion of wireless for all sorts of digital uses, the services with significant economic value have been increasingly decoupled from the underlying RF. For example, earlier cell phones (and WiFi radios) operated in one or a very limited number of frequencies, whereas today, modern wireless devices are not tied to a single band of spectrum (e.g., a iPhone 15 supports both LTE and 5G in around 30 different spectrum bands as well as 3 bands of WiFi connectivity). This decoupling of RF and the services and the rise in RF and network agility is illustrated by the transformation and growth of an expanded array of mobile wireless services offered via an expanded and diverse array of wireless technology platforms. This is a transformation that has involved all levels of the end-to-end network architectures as demonstrated by and enabled by the transition to

congested and lower cost spectrum resource to accomplish the same task, then user A's willingness to pay for any particular spectrum resources is reduced. If all users can do that, it is like lowering the level of the sea, even if particular spectrum resources may become more valuable in specific contexts.[57] In effect, the success of market sharing may reduce the scarcity and need for DSA that SCM/SAA capabilities may enable. Countering this effect, however, is the waterbed effect of how less valuable (more abundant) spectrum resources may shift scarcity to other resources that may be more localized with other spectrum. For example, a spectrum agile base station may be better able at lower cost to accommodate the lack of spectrum agility or other non-spectrum-related deficiencies of other radio system components. What this means is that it remains uncertain how best spectrum resources might be shared or traded. At a minimum, they may include all of the RF-relevant information in today's SCMs, but the relevant SAAs may reference other resources that are only directly or indirectly tied to RF resources. In that event, it may be desirable to expand SCMs (the information model used by SAAs) to address those additional features.

For our purposes, we put those sorts of refinements into the SAAs, recognizing that SCMs are only concerned with technical items that help define the boundaries of spectrum use for any RF device, system or collection of systems. Thus, the SAAs and associated SCMs may comprise a complex collection of dynamically evolving elements that may evolve to suit the needs of specific spectrum usage contexts, and what those may look like may vary by band, what users and devices are being managed, and the technical-economic (market) environment that is being addressed. Those might be summarized in terms of usage models, and a range of usage models are being investigated.

For example, a single wireless network operator (MNO) may regard the radios it supports as an internal market comprised of different clusters of users or services.[58] The MNO could use a pricing mechanism to allocate bandwidth among those multiple service categories, using SCMs characterizing the aggregate behavior of each service type to facilitate internal admission control rules and spectrum allocation decisions. The SAA could specify the shadow prices for moving resources among categories that would apply during a management cycle, with those prices reset

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NFV/SDN and the succession of IEEE/3GPP generations of standards-based technologies. See Lehr, Queder et al. (2021), Oughton et. al (2021).

[57] This is a bit like what happened with over-the-air radio advertising rates. Overall, radio advertising has lost revenues as other media (e.g., the Internet) have attracted advertising dollars; however, in certain locations and times (e.g., drive-time radio advertising in metro areas) has become more valuable for its niche ability to address a particular advertising context.

[58] To make the example concrete, but to keep it simple, imagine the MNO has three clusters of homogeneous groups of subscribers to manage comprised of mobile smartphones (engaged in two-way mobile broadband communications), fixed video receivers (for streaming media), and fixed IoT sensors. The usage of each service shifts over time as the MNO adds subscribers and subscribers dynamically adjust their usage behavior. For each service and each session, the MNO needs to ensure adequate spectrum resources are available to meet the MNO's service quality commitments to its subscribers. To manage self-congestion, the MNO needs to know how to allocate the spectrum it controls to each category of service, and then make lots of other network operational and business decisions for how each customer's service and session is managed. Those business decisions may include dynamic pricing for using specific applications. The shadow price for spectrum resources provides a signal of the opportunity cost for additional spectrum resources that can be used to guide decentralized operational decisions for how to provision the different services.

at regular intervals, resulting in new SCMs for each category. The entire SCM/SAA model could be run in a digital twin, and because all of the associated usage would be internal to the MNO, no actual inter-service-category financial (budgetary) settlements need to take place – the entire model could serve solely as a planning tool for business managers. Of course, if that were all the SCM/SAA capabilities would be used for, it would hardly be worth the effort invested thus far. A more ambitious application would be actually to implement the resource allocation model in automated systems, potentially to coordinate how an MNO manages traffic across its multiple cell sites, using prices to decentralize the real-time resource allocation management that might otherwise be characterized as a much more complex-to-solve linear programming optimization problem.[59]

A still more ambitious application and the one we are ultimately focused on is the potential to use the SAA/SCM framework and its automation capabilities to facilitate the management of spectrum among multiple firms and users via a spectrum secondary market. In that context, the spectrum users economic incentives to cooperate in maximizing the total realized value from utilizing the spectrum more efficiently cannot be presumed to be aligned, but the opportunity to transfer usage rights among users creates an opportunity for gains from trade and Pareto improvements for all participants, assuming that the transaction costs of the secondary market transfers enabled by the SCM/SAA framework are sufficiently low.

Key functionality that the SAA's need to enable are measurement and enforcement capabilities. The measurement capabilities will impact the information sets available to the participants in the spectrum space. Ensuring the right measurement information is collected and shared to facilitate efficient interference risk management while attending to the incentive challenges (e.g., desire to avoid sharing strategically sensitive information or to free-ride on the measurement efforts of others) will pose a challenge for the RF sensing infrastructure supporting the SAAs. This might be a mix of third-party passive and active sensing infrastructure, as well as device-specific and management entity sensing infrastructure. Those measurement capabilities will constrain the enforcement options, but those are also necessary to ensure that SAAs constrain radio behaviors appropriately even when that may not be in the interests of particular radios. If the possibility of SAAs constraining behavior does not ever arise, then there is no need for SAA contracts, although even in a fully-cooperative environment, the SCM/SAA functionality could be useful for computing and announcing the optimal compatible radio behaviors. However, failures of cooperation due to changing circumstances, measurement errors or system failures, or incentives to defect from (renegotiate) prior agreements make the need for credible enforcement mechanisms essential, even if those are rarely invoked under normal operations. For example, rewards and penalties (e.g., speeding ticket fines that escalate with speed and insurance discounts for ticket-free reputations) can induce incentive compatible, non-deviating behavior even when few tickets are ever issued.

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[59] One advantage of using markets instead of central planning to solve resource allocation problems is that it can greatly simplify the computational challenges. Instead of solving for the activity levels of a large number of variables that share a common resource that is constrained (the linear program formulation), it is often easier to solve the dual problem for the shadow prices of the much smaller number of resource constraints. The prices serve as summary statistics that facilitate decentralized decision-making.

The SCM/SAA framework may be applied in a range of market settings. For example, it could be used to facilitate secondary markets where spectrum usage rights are transferred among parties dynamically to maximize the total usage value realized. Entities with exclusive use licenses to spectrum (e.g., MNOs, or perhaps, spectrum brokers) could use SCM/SAAs to manage a real-time market for spectrum, authorizing SCMs for radios in the spectrum space and charging usage or leasing fees for those rights.[60] The framework could also be applied in a decentralized market that might be organized as a series of bilateral or multilateral contracts among MNOs (or other network operators) in a way analogous to Internet interconnection agreements. The computation of compatible SCMs could be managed by an automated program and run as a distributed auction. Indeed, one might even imagine such a model operating in unlicensed spectrum.[61]

4. Preliminary Insights and Analysis of SAAs

In the following we discuss some potential usage cases motivated by recent spectrum policy that could benefit from the SCM/SAA framework.

4.1. CBRS and Temporal-based spectrum sharing

One paradigm for sharing spectrum among heterogeneous users is to *temporally share* the spectrum in a given location, meaning that at any one time only one type of user is approved for having access to the spectrum.

The recent Citizen Band Radio System (CBRS) is an example of a regulatory framework to enable such temporal sharing, where temporal sharing of the 3.55-3.7 GHz band is controlled via a Spectrum Access System (SAS). In the CBRS, temporal sharing is implemented on a priority basis among three different tiers of users, where the highest tier represents incumbent federal users of the band, the second tier are commercial users with priority access licenses (PALs) and the lowest

[60] Those with spectrum rights might delegate a spectrum broker to manage those rights on their behalf in return for a market-management fee, and the spectrum broker might augment the resources with usage rights to spectrum controlled by the spectrum broker and related infrastructure (power, DAS facilities, backhaul connections, etc.). Such a spectrum broker could use the SCM/SAA capabilities to act as a neutral host, managing co-existence among multiple service providers within a spectrum space. That might be a stadium, shopping mall, private-campus, MDU. In effect, the spectrum broker would serve as a traffic cop operating like private security forces do in gated communities. Within the confines of the gated communities the enforcement rights of the broker would be different than outside the gated community, but that would not render enforcement of SAA contracts infeasible.

[61] In unlicensed spectrum, no users have exclusive usage rights and so users cannot prevent unaffiliated users from transmitting and potentially causing interference for other users. However, users in a spectrum space can decide to cooperate if they want to. The SCM/SAA framework provides a mechanism for creating incentives for voluntary cooperation. For example, the unlicensed radios could agree to cooperate according to negotiated SCMs and contribute funds to an escrow account that would be used for penalties or rewards for radios that adhered to their SCMs. If no SCM violations occurred, then all radios would reclaim their escrow commitments, while radios that violated their SCMs under the SAA, would be penalized and the penalties redistributed to the other radios. Of course, the cooperating radios could not preclude non-cooperating radios from transmitting in the unlicensed spectrum, but addressing that challenge is just another incentive challenge.

tier is the Generalized Authorized Access (GAA) tier, which allows commercial users to access the band without needing a PAL.

Each PAL provides the licensee exclusive access to 10MHz of the CBRS spectrum within a county, provided that incumbent users do not need the spectrum. GAA users can access the spectrum that is not used by either a PAL or incumbent users. Multiple GAA users can access the same portion of the spectrum, and no GAA users have a priority right with respect to other GAA users that may cause interference. To prevent GAA users from interfering with incumbent users, CBRS users are required to provide information about the location and power levels of their access points, referred to as Citizens Broadband Radio Service devices (CBSDs). The SAS then uses this information to perform aggregate interference calculations to determine which CBSDs must vacate a channel to protect incumbents and PAL licensees, both of which have prioritized usage rights to interference protection against each other and against GAA users. One may regard the location and power information provided by the GAA users as a type of SCM that can be incorporated in the SAA that a SAS issues to the CBSDs, or if multiple CBSDs are under the control of a proxy manager, to that proxy manager. The SAA contract is between the SAS operator and the CBSDs. The SAS operator acts as a centralized band manager for the spectrum that is available to GAA operators, which is the spectrum that is not utilized by either incumbent operators or PAL licensees on a temporally-changing and geographically-localized basis.

The design of the SAS for CBRS is specific to that band and impacts the protocols and capabilities that CBSD devices and their operators have to be able to comply with to take advantage of the opportunity to use CBRS spectrum. The SAS issues time-limited authorizations for CBSDs to operate in the available GAA spectrum but the precise design of the "SAAs" issued and how they are managed by different SAS operators is not fully automated and to the extent it has been automated, it is not standardized nor fully specified across different SAS operators.[62] In short, the SAS framework remains a work-in-process driven by top-down policy reforms. Our SCM/SAA work is intended to provide more generalized tools to make it easier for market participants and others to take advantage of and contribute to the development of sharing of CBRS and other spectrum where multiple classes of heterogeneous radio users might co-exist constructively (rather than destructively). That is simultaneously a technical challenge for interference management and an economic and regulatory policy market design challenge.

Although the CBRS framework has provided an important step towards enabling temporal sharing among multiple tiers of users with different levels of priority (incumbents, PALs, and GAA), researchers have already noted shortcomings with the CBRS framework that have limited its success to date.[63] The SCM/SAA framework offers a framework for understanding how the CBRS approach might be improved and potentially rendered applicable for other bands.[64] For example,

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[62] For an earlier discussion of how time-limited leases might be used to manage complex radio behaviors, see Chapin & Lehr (2007)

[63] See Berry, Hazlett et al. (2023).

[64] For example, the abstraction of the SCM/SAA design is inherently more flexible and general than the CBRS/SAS design. The SCM/SAA is not band-specific nor usage or business model specific. More detailed SCMs with more information about radio needs, capabilities, and operating behaviors could be considered and exploited to identify additional sharing opportunities. The SCM/SAA approach provides the

extending the CBRS/SAS management model is being considered for other spectrum bands such as the 3.1-3.45 GHz band and 7.125-8.4 GHz band identified in the recent national spectrum strategy.[65] In these bands there are different incumbent users, and a more developed SCM/SAA framework could provide a more efficient approach to time-based sharing.

In the following, we offer several examples of how the SCM/SAA approach might be useful for addressing challenges with the current CBRS framework:

(1) Issue: Usability of interruptible spectrum by commercial users

For traditional wireless operators, an issue with CBRS is that temporal sharing of spectrum as in CBRS does not provide predictable access to spectrum to PAL or GAA users.[66] Cellular service providers have argued that a lack of predictability is not compatible with the business model that depends on their ability to provide a high quality of service to their customers. The reason for this is that federal incumbent users have strict priority access to the spectrum but are under no obligation to provide advance warning as to when and where they might decide to require exclusive access to the spectrum. Consequently, a PAL or GAA radio has no guarantee over how much access to spectrum it will receive in an area where incumbent federal user operations may occur. Using SCMs/SAAs could facilitate alternative arrangements to the strict priority scheme used in CBRS. For example, an incumbent could specify that interruptions to spectrum access would only happen during a certain fraction of time during any month via an SAA, which could also include a penalty for violating this that might sufficiently compensate commercial operators, while still being acceptable to Federal incumbents to create a win-win situation for all users.[67] These parameters could be negotiated between an incumbent and a new entrant as part of the establishment of the SAA.

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opportunity to experiment with finer-grained and more contextually rich information about the radios needs and operating behaviors than is baked into the initial implementations of CBRS SAS and CBSD operation. That flexibility allows partially-separable experimentation with the technologies, business models, and market needs to determine what sharing approaches are most useful in different contexts.

[65] See NTIA (2023).

[66] See Recon Analytics (2022) and Dano (2022).

[67] We characterize this a potential win-win for Federal and commercial users because it expands the negotiating space between Federal and commercial users in ways that could allow each to be better off, relative to the current bargaining situation. Some might argue that neither party really wants to make co-existence work since both prefer incompatible worlds – cellular operators want exclusive licensed access while federal users do not want to share. Resolving those debates is beyond the scope of this paper, but enabling the SCM/SAA framework would provide a research-based approach for further resolving those issues and unpacking further complexities of the problem. For example, federal users are concerned that rendering their usage of CBRS spectrum fully predictable would cause a national security risk. The partial predictability that the hypothesized solution with moderate penalties (or, compensation to commercial operators when SAA interruption guarantees are violated by federal users at those users discretion) would ameliorate the predictability needs claimed by cellular operators while still preserving the discretionary flexibility for federal users. Precisely where the hypothesized SAA might settle is a matter for further discussion, possible simulation, and research.

(2) *Issue: initial CBRS aggregate interference calculations overly conservative, leaving potentially usable spectrum under-utilized*

A related issue with CBRS is that the aggregate interference calculations used in CBRS to determine which users need to vacate the spectrum has been viewed as overly conservative, leading to less utilization of the spectrum.[68] Examples of this include not accounting for time division duplex (TDD) operation of the CBSDs (i.e. the fact the CBSDs use different time-slots to transmit and receive) or the loading factor of CBSDs (i.e. a given CBSD may not have full traffic load most of the time). Recently, the NTIA has established new guidelines that account for such issues and shown that by doing this SAS administrators should be able to serve approximately 72 million more people without needing them to suspend transmissions to protect incumbents.[69] This is analogous to adopting a more specific form of a SCM which includes additional information about the deployed CBSDs.

The guidance from NTIA specifies certain parameters for TDD split and network loading to use. A more general approach is to allow a provider deploying CBSDs to specify these parameters for their deployment (in the form of a SCM). This in turn might allow a provider to tune these parameters so e.g., they could operate with a lower network loading to enable some CBSDs to continue operating in the presence of a federal user if this was economically beneficial. Moreover, the decision of what parameters to include in such a SCM, could vary with location.[70] For example, a deployment far from any federal incumbent might not need to specify as much information as it would not be pre-empted from transmitting. Alternatively, these types of parameters could be dynamically adjusted based on feedback from a SAS, so that for example, when a federal incumbent is present, a CBSD reduces its network loading or changes its TDD split so that it can continue operating, where the SCM/SAS construct could be used to specify the details of such an approach. This can be viewed as a way of "relaxing" the impact of the strict incumbent protections within CBRS.

To illustrate the potential advantages of such relaxation, Mu and Berry (2024) considered a simple market model for competing wireless service providers (SPs) that utilize both a temporally shared band of spectrum (e.g., a CBRS PAL license) and exclusively licensed spectrum controlled by the service providers.[71] The underlying market is modeled via a framework of Cournot competition with congestion as in Berry et al. (2020), where each SP specifies a quantity of customers to serve. Customers in turn pay a service price that depends on a market clearing price (determined by an underlying demand function) and a congestion cost that models the quality of service they obtain. The congestion cost for a given SP in Mu and Berry (2024) depends on the spectrum holdings of the SP (both proprietary and shared) as well as the impact of the incumbent protection on the shared band.

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[68] See FCC Technological Advisory Council (2022).

[69] See NTIA (2024).

[70] The decision of what to include would also need to be balanced with considerations of the complexity of the corresponding aggregate interference calculations.

[71] Here we use SP to refer to Service Providers, but the type of SP we have in mind is closest to today's Mobile Network Operators (MNOs), which we discuss elsewhere in the paper.

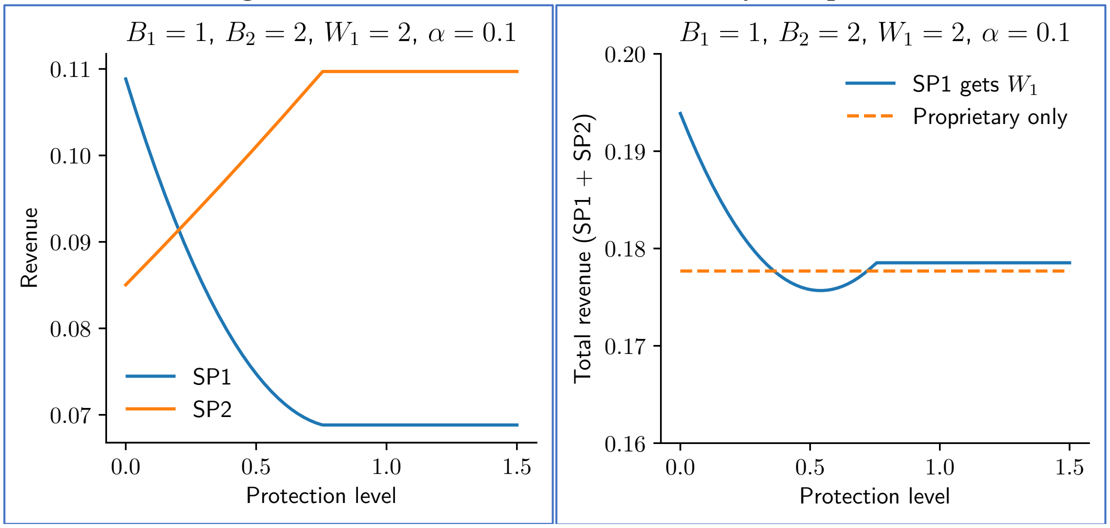
Figure 3 below shows an example of this model for a setting where there are two SPs in the market, SP1 and SP2. SP1 is a "small" SP with 1 unit of proprietary bandwidth and SP2 is a "large" SP with 2 units of bandwidth. Additionally, SP1 has access to a shared band of spectrum with 2 units of bandwidth that is intermittently available (SP2 does not have access to any shared band). The left-hand side shows the individual revenue of the two providers versus the level of incumbent protection. When this level is greater than 0.75, SP1 has to completely vacate the spectrum when the incumbent is active. For protection levels less than 0.75, SP1's revenue increases as it is able to still utilize the shared band when the incumbent is present but at a reduced level. While SP1's revenue increases with lower levels of incumbent protection, SP2's revenue decreases as SP1 becomes more competitive. The right-hand side of this figure shows the total revenue summed across the SPs versus the incumbent protection level. Additionally, this plot shows the SPs total revenue when they each have only proprietary spectrum (the dotted red line). When the level of protection exceeds 0.75, there is little revenue gained by adding this shared spectrum to the market. As the protection level gets smaller, notice that the total revenue initially *decreases* and in some cases is lower than that obtained when there is no shared spectrum. Apparently, in these ranges the revenue lost by SP2 due to greater competition exceeds that gained by SP1. This can be viewed a type of Braess Paradox, where adding effectively more spectrum to the market leads to a reduction in revenue.[72] However, when the incumbent protection level is low enough, the sum revenue increases.

What this work demonstrates are the complex incentive dynamics that may create inefficiencies (such as Braess Paradox) when top-down regulatory policies designed to expand spectrum use efficiency result in aggregate welfare losses. When Braess Paradox applies, expanding spectrum resources can lead to less welfare efficiency but the circumstances where that may occur are not obvious. The SCM/SAA framework, by allowing market participants to dynamically exchange information and negotiate a contract, the externalities that are driving the paradoxical result can be internalized.[73]

[72] Braess (1968) first identified this type of paradox in the context of transportation networks. For applications to wireless, see Nguyen et al. (2016) and Adams & Yoo (2023).

[73] Of course, it is also worth noting that the SCM/SAA capabilities could also be used to implement a cartel solution that might be more profitable for the SPs, but fail to maximize total welfare and support equilibria with undesirable distributional implications. Thus, enabling the SCM/SAA capabilities does not eliminate the need for top-down regulatory oversight and transparency to monitor that the framework is not abused to facilitate the creation and maintenance of market power.

Figure 3 : Example of service provider revenues in a market equilibrium versus the protections level for the incumbent. The left-hand side shows the individual revenue of the two providers, while the right-hand side shows the total revenue of both providers.



4.2. Coexistence of equal priority users

Another area in which SCM/SAAs may improve spectrum utilization is in offering new ways that "equal priority networks" can co-exist in the same spectrum band. Examples of this include the coexistence of multiple GAA networks in CBRS[74] or coexistence of networks in unlicensed bands such as the recently opened 6 GHz band.[75]

One way that multiple entities can operate networks in such bands is via channel selection. For example, in the case of multiple GAA users in CBRS seeking to operate using a 10MHz channel, a SAS can attempt to assign them into different channels. Likewise, with WiFi deployments, different networks can select different WiFi channels to promote coexistence. However, such an approach has a limit in that if there are enough networks operating in a given location, there may not be adequate channels available for them to each use distinct channels. Moreover, to support high data rates, networks may want larger channel bandwidths. For example, while legacy WiFi systems used 20 MHz bandwidth, newer standards support larger bandwidths, with WiFi 7 allowing channels of up to 320 MHz. Likewise, a CBRS network based on LTE or 5G can utilize carrier aggregation to operate over multiple GAA channels. Given a fixed bandwidth, using larger channels means that there will be fewer non-overlapping channel assignments available.

[74] GAA coexistence has been highlighted as an area that the initial CBRS standards did not adequately address (FCC TAC, 2022; Berry et al., 2023). The most common deployments of CBRS area based on 4G/5G cellular standards that do not utilize techniques such as listen-before-talk to share spectrum. Hence, when multiple entities are operating CBSDs in the same spectrum the performance of their networks can significantly degrade. There are efforts underway to improve this (cite https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8191409/).

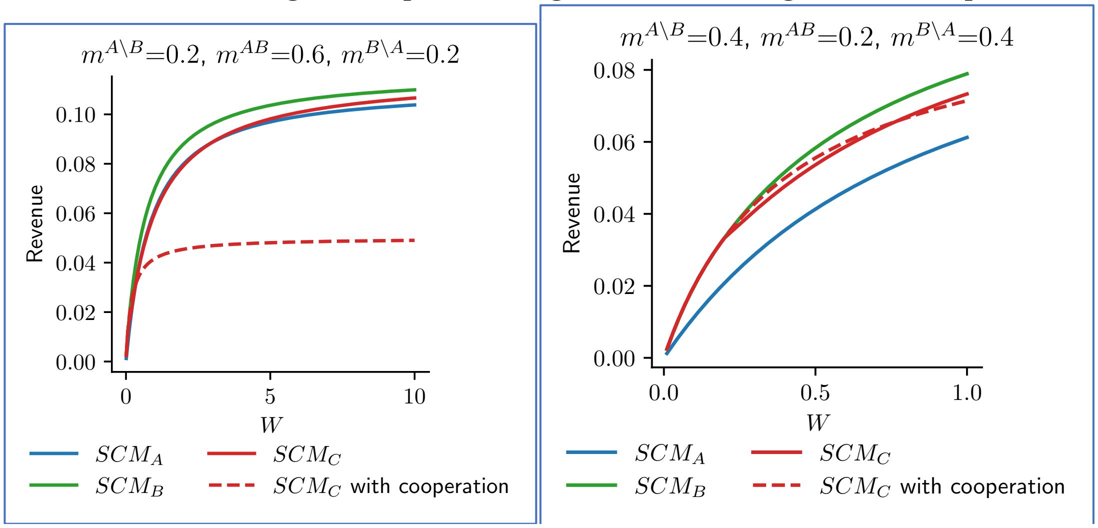
[75] Unlike CBRS, unlicensed technologies such as WiFi do utilize basic coexistence techniques such a listen-before-talk. The performance of these networks can still degrade in area of dense deployments. SCMs/SAAs offer a way to increase coordination in such settings.

When multiple networks share the same channel(s) in a given area, there performance will degrade as traffic on one network creates interference on the others. Approaches, like listen-before talk used in WiFi help to mitigate the impact this interference, but still lead to a degradation in throughput as when one network is operating in a given band, other networks must be silent. As shown in Adams and Yoo (2023) and Nguyen et al. (2016), the common degradation due to shared spectrum can also have a market impact on the resulting profits of firms using this shared spectrum. Namely, these works consider a model for competition where again users are sensitive to congestion. As the spectrum is shared, the congestion depends on the traffic of *every* service provider using the band so that when one SP increases its traffic, this degrades the service of all the other SPs and leads to lower SP revenue.

The results in Adams and Yoo (2023) and Nguyen et al. (2016) assume that SPs using shared spectrum do not coordinate and have coverage identical coverage areas. We have been considering similar models in which SPs may utilize different types of SCMs/SAAs to coordinate their operations and further have distinct but partially overlapping coverage areas.[76] More precisely, we again adopt a model of Cournot competition with congestion between two competing SPs. Now the congestion experienced by a user depends on if they are being served in the coverage area of one SP or both SPs. Figure 4 below shows that total revenue obtained by the two SPs versus the amount of shared bandwidth W under different SCM/SAAs, where in the figure on the left the two SPs have a large overlap of coverage, while on the right the overlap is smaller. SCM_A corresponds to a case where the two SPs each agree to use half the bandwidth, where the bands used do not overlap. SCM_B corresponds to the cases where the two SPs divide a dedicated portion of the bandwidth over the area where their coverage overlaps and use the entire remaining bandwidth outside of that area. Here we show the revenue obtained under the revenue optimal split of the bandwidth for each value of W. SCM_C corresponds to a case where the both SPs use the entire band, but offer different prices for service for users in the overlapping area and users outside of the overlapping area. Finally, SCM_C *with cooperation* refers to a case where the two SPs agree to not serve any users in the overlapping area. Note that implementing these SCMs requires that the SPs exchange information about their transmitter locations and power levels to determine the coverage areas. Some of these cases such as SCM_C *with cooperation,* also requires that the SPs agree on constraints on how they will compete. When there is large overlap (left), SCM_C *with cooperation* gives the lowest revenue, while SCM_B generally gives the largest revenue. When there is a smaller overlap (right), SCM_A gives the lowest revenue, while SCM_B gives the largest revenue. Note in this case that SCM_C *with cooperation* at times gives more revenue than SCM_C.

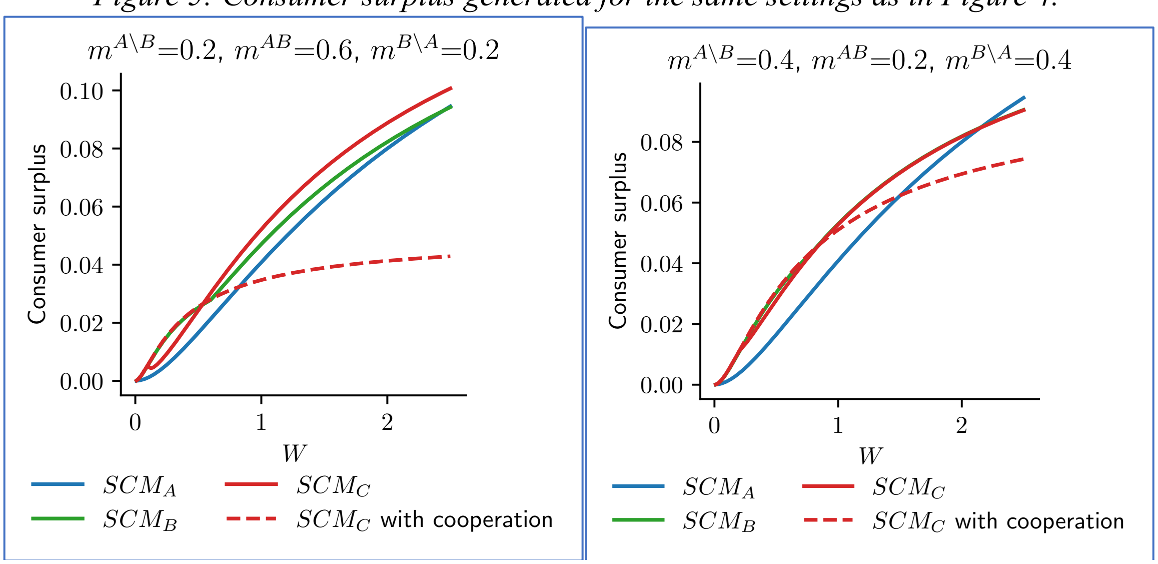
[76] A detailed analytical formulation of this model is provided in Mu et al. (2024).

Figure 4: Revenue obtained under different SCM/SAA models when two competing SPs share a single band of spectrum with partially overlapping coverage. The left-hand side is an example where the SPs have a large overlap in coverage, while on the right, the overlap is smaller.



Using this framework, we can also characterize the consumer surplus generated in the market using different types of coordination. An example of this is shown in Figure 5 for the same settings as in Figure 4 (in this case we optimize $\mathrm{SCM_B}$ for the optimal consumer surplus). When there is large overlap (left), *SCM_C* gives the largest surplus when there is enough spectrum being shared. However, when the spectrum is limited, *SCM_C with cooperation* gives more surplus, even though in this case the SPs are agreeing to not serve a set users. Similar trends hold when there is smaller overlap (right), except in this case when the amount of bandwidth becomes large enough, *SCM_A* gives the largest surplus. These results illustrate that the type of coordination desired varies with both the settings (e.g. the amount of overlap) and with the objective (e.g. revenue or consumer surplus). SCMs/SAAs provide a general framework that can be adapted to these different settings.

Figure 5: Consumer surplus generated for the same settings as in Figure 4.



4.3. Perspectives and the road ahead

Due to their declarative nature, SCMs can transform several spectrum use regulatory processes to become more data driven while also enabling the setup of negotiation mechanisms between spectrum-using entities to facilitate the establishment of sharing arrangements. Those entities can use the SAA capabilities to exchange technical information via SCMs to facilitate identifying the technical parameters to define a set of spectrum use boundaries. The SAA mechanisms can include the communication of non-technical business-relevant information related to economic incentives, monitoring mechanisms and penalties (or rewards) that the parties involved in a negotiation can agree to in order to enable spectrum sharing (or trading and leasing) interactions.

The SCM/SAA framework enables flexibility of spectrum use across all dimensions of the spectrum space that two or more entities that use spectrum can use to define the technical and business related (economic incentives/penalties and enforcement mechanisms) items that can enable new and innovative spectrum sharing interactions and/or market-based mechanisms for spectrum use.

Nowadays, regulations for the operations of RF systems in particular bands such as those for CBRS or the 6 GHz bands define maximum levels of aggregate interference for receivers, methods for a Spectrum Access Systems (SAS) or Automated Frequency Coordinator (AFC) to compute protection areas for incumbents, maximum response times to vacate a channel when required by an incumbent, etc. In many instances, some of these limits are overly conservative and if in a particular case two or more entities agree to a new set of operational limits and boundaries of spectrum use to enhance their technical and economic use of the spectrum then the SCM/SAA framework could provide the mechanisms for such "new" spectrum operations. Overall, with the SCM/SAA framework regulators would have an incentive to allow more flexible and fast-evolving uses of spectrum while continuing to be key participants in the spectrum use ecosystem.

5. Conclusions and Future Directions

The future of wireless services, technology, and markets will necessitate more active and dynamic management of spectrum resources on a finer-grained basis (in time, space, and usage context). That implies being able to share spectrum more intensively and in more ways than are currently being employed. Dynamic Spectrum Access (DSA) technologies already exist and are under further development to enable this capability, and in so doing, they help alleviate the scarcity of spectrum that has distorted competition, hampered innovation, and slowed the growth of wireless services and their contribution to economic growth. One critical impediment to the evolution towards a shared spectrum future has been legacy regulatory frameworks; however, top-down policy efforts to liberalize spectrum and transition more spectrum management responsibility for market-forces to manage have made significant progress toward addressing these impediments.

This paper describes research being undertaken as part of the NSF's National Radio Dynamic Zones (NRDZ) program to develop the bottom-up techno-economic capabilities to take advantage of the sharing possibilities unlocked by DSA technologies and regulatory reforms. The NRDZ-SBE work described here continues research to develp a Spectrum Consumption Model/Spectrum Access Agreement (SCM/SAA) framework and the software and modeling tools needed to make use of this framework. The SCMs provide a data model for sharing information regarding the technical operational details of radio devices relevant to managing the non-interfering co-existence of multiple, potentially heterogeneous radios and radio networks in a shared spectrum space. A 2017 IEEE standard now exists for SCMs with an updated version to be released later this year. In this paper we discuss efforts to develop the SAAs that would serve as the contracting mechanisms for using SCMs to manage spectrum in a spectrum space under different market designs and spectrum usage contexts, where the latter may vary by frequency band, service, industry or market structure.

We explain how the bottom-up capabilities of the SCM/SAA tools under development can complement top-down regulatory reforms intended to promote the transition to shared spectrum. In short, the SCM/SAA work is intended to expand opportunities for market players to more easily experiment with, researchers to investigate, and policymakers to stress-test alternative sharing business models, market designs, and technologies to help make existing technologies and policy advances (top-down) more promising. We illustrate our efforts with reference to how it may address challenges to sharing in the 3.5Ghz CBRS and 6GHz bands, and provide a peak at some preliminary results from theoretical and empirical work toward the application of the SCM/SAA concepts to those challenges. In short, the SCM/SAA is intended to provide the tools to render existing spectrum access rights regimes, instantiated in regulatory rules, more dynamic by allowing market participants to negotiate enforceable sharing contracts.

At this stage of the work, we do not have answers as to what forms of sharing will be most efficient or are likely to be most successful among real-world spectrum users. Lacking those answers, it is premature to conclude from this work what market designs and what balance between centralized v. decentralized, planned v. ad hoc, or automated sharing mechanisms may prove successful. The SCM/SAA tools are expected to advance work on building Digital Twin and agent-based modeling for simulating wireless environments and managing co-existence. We also expect to be building prototype and proof-of-concept radio experiments to exploit the NRDZ testbed efforts that are underway by the NSF.

The next stage of this work is to coalesce market design ideas into more concrete specifications of how SCM/SAAs may be implemented and tested in usage contexts of practical and real-world significance. The transition to a shared spectrum future requires the co-evolution of the technology, industry economics, and regulatory policies. This effort is focused on better integrating economic and policy considerations in the development of the technogy, and visa versa, so that policy and business strategies can better exploit promising new technologies. While it is clear where we want to go – i.e., toward more efficient spectrum sharing – and we know that that decision will necessitate adjustments in technology, business economics (business models, market designs), and policies, it is not yet clear how best to get there. Our work is to build the tools (theoretical, empirical, and software-based) to help us navigate that road.

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