SPECTRUM RIGHTS IN OUTER SPACE: INTERFERENCE MANAGEMENT FOR LOW EARTH ORBIT (LEO) BROADBAND CONSTELLATIONS

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ABSTRACT

This article presents a comprehensive summary of the regulatory environment confronting low earth orbit, non-geostationary satellite orbit (LEO NGSO) communication satellites and critically evaluates analogies from terrestrial spectrum management as possibilities for LEO NGSO satellites. This analysis provides a framework for empirical analysis of the alternatives considered.

Keywords: spectrum, spectrum management, low earth orbit, mega-constellations, FCC

Recent years have seen a rapid rise in low earth orbiting, non-geostationary satellite orbit (LEO NGSO) communication satellites. A majority of the NGSO satellites operate in LEO, which according to the European Space Agency refers to an altitude lower than 1,000 km that can be as low as 160 km above Earth.[1] Since 2016, the Federal Communications Commission (FCC) has received applications for US market access from more than

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1. https://www.esa.int/ESA_Multimedia/Images/2020/03/Low_Earth_orbit.

twenty distinct networks seeking authorization to launch and operate more than a total of 70,000 satellites.[2] These authorizations were allocated in four "processing rounds" from 2016 to 2021, with more rounds planned given the continued demand for access rights. This process has been used to promote the development of space satellite constellations as well as to enable expansion of existing networks. For example, in March 2017, OneWeb filed an "instant petition" to the FCC's November 2016 processing round of "NGSO-like" satellite applications for approval of its NGSO fixed-satellite service (FSS) system consisting of 720 satellites. This granted OneWeb similar rights as other NGSO systems licensed or granted during the processing round. Subsequently, OneWeb requested a modification in May 2020 to increase its constellation to 6,372 satellites, which was deferred.[3]

For these satellite networks, commonly referred to as mega-constellations because they may involve thousands of satellites to enable broadband access, coexistence and interference mitigation between existing and planned satellite and terrestrial networks are key concerns. As mega-constellation networks progress in their development and deployment of their networks, they are required by Article 9 of the International Telecommunication Union (ITU) Radio Regulations and the FCC to conduct good-faith coordination to prevent the occurrence of harmful interference. As the density of satellites increases, however, potential interference events increase, marking the transition from relative spectrum abundance for NGSO satellites to enhanced spectrum scarcity. The assertion seems obvious to say that the lack of reporting of interference does not mean to imply that interference has not occurred and that a remedy was achieved behind closed doors. One might assume that reporting of interference would cause the 1/n rule to be applied, which may not be desirable for either party involved. For this reason, the authors are interested in understanding how disputes are resolved with interference, as well as in considering whether there is reason to be concerned that the 1/n rule appears to not be invoked. For example, it may be too punitive, which forces overreliance on private agreements. On the other hand, a punitive feature that promotes "private" solutions may be a

2. Anargyros (Argyris) Kriezis and Whitney Q. Lohmeyer, "U.S. Market Access Authorization Timeline Analysis for Megaconstellation Networks," *Olin Satellite + Spectrum Technology & Policy Group (OSSTP)*, Olin College of Engineering, Needham, MA (2022).

3. Federal Communications Commission, "WorldVu Satellites Limited, Petition for Declaratory Ruling to Modify the U.S. Market Grant for the OneWeb Ku-band and Ka-Band NGSO FCC System: Order and Declaratory Ruling," (Washington, DC: FCC, April 28, 2023), accessed December 1, 2023. https://docs.fcc.gov/public/attachments/DA-23-362A1.pdf.

beneficial design feature. Such considerations can inform ongoing conversations about the design of rules governing interference among mega-constellations. Thus, one of the authors' objectives is to clarify the significance of rules that have yet to be triggered, as well as to consider alternatives.[4]

Another of their objectives is to ensure they accurately describe the rationale for the current and proposed FCC rules governing space satellites in LEO. The purpose of the FCC's rules is to define constraints under which the parties will negotiate a cooperative agreement to share spectrum during those times when satellites from different operators line up in the field of view of an Earth-based antenna. Although that approach is reasonable and arguably efficient, the authors emphasize that there are opportunities to consider ways that those negotiations may be improved, as well as to consider whether there is even a need for the 1/n rule, as well as to consider alternative ways to promote the reasonable goal of decentralized coordination and cooperation among satellite operators. In this review, the authors will analyze the existing rules and propose potential improvements as well as alternatives, while acknowledging the merits of the current and proposed regulations.

This article is organized as follows. The authors first provide a technical and regulatory overview of NGSO systems, with emphasis on the emergence and evolution of the current regime, which includes the current 1/n rule and processing rounds to manage outer space spectrum use. They then provide an economic framework to analyze spectrum based on the logic of the commons, analyzing the economic problem of spectrum management. This is a situation in which spillovers diminish the value in using a natural resource, in this case, spectrum in LEO. After describing the problem of managing multiparty access to spectrum in outer space, the authors consider alternative frameworks for governing terrestrial spectrum: nonexclusive authorizations, database-aided spectrum access, and excludable, tradable rights. Each constitutes a potential alternative to the 1/n rule. After describing these options, they consider prospects for a priority access system to manage spectrum. By articulating these alternatives to the 1/n rule, their research offers insight into the institutional possibilities that can inform FCC rulemaking and motivates the need for empirical analysis of these alternatives.

4. From a more technical game theoretic perspective, the fact the rule has not been invoked does not necessarily mean that it has had no effect as it establishes a "disagreement point" that may influence the outcome of bargaining among the operators. This is a standard concept in the game theory literature. See, for example John F. Nash, "The Bargaining Problem," *Econometrica* 18, no. 2 (1950); Kenneth Binmore, Ariel Rubinstein, and Asher Wolinsky, "The Nash Bargaining Solution in Economic Modelling," *The RAND Journal of Economics* 17, no. 2 (1986).

Technical and Regulatory Overview of NGSO Systems

The ITU codifies interference limits from satellite networks into terrestrial networks in Article 21 of the Radio Regulations and interference from NGSO networks into geostationary (GSO) satellite networks in Article 22 of the Radio Regulations.[5] Article 21 specifically defines power flux density (PFD) limits, implying contours within which harmful interference with terrestrial networks is avoided. These limits are not statistical, or temporal, in nature and account for the satellite power from an NGSO network into a terrestrial receiver.[6] On the other hand, Article 22 defines equivalent power flux density (EPFD) limits, which are statistical and complex in nature and similarly aim to avoid usage that generates harmful interference with GSO networks.

A clear methodology for computing interference from NGSO networks into other NGSO networks is not currently defined at the ITU, or nationally under agencies like the FCC. As such, the interoperation of NGSO networks and coordination and coexistence of such networks have recently been a focus area of discussion among regulators and operators.[7] In December 2021, the FCC initiated a Notice of Proposed Rulemaking (NPRM) to facilitate the deployment of both existing and future NGSO systems to provide certainty around spectrum-sharing requirements.[8] In April 2023, the FCC followed this with a Report and Order (R&O), along with an accompanying Further Notice of Proposed Rulemaking (FNPRM), which sought additional comments in this area.[9]

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5. International Telecommunication Union (ITU), *Radio Regulations* (2020), accessed December 1, 2023. http://handle.itu.int/11.1002/pub/814b0c44-en.

6. Ibid.; Anargyros Kriezis, Rohil Agarwal, Celvi Lisy, Olivia Seitelman, Regan Mah, Utsav Gupta, and Whitney Q. Lohmeyer, "Power Flux Density (PFD) Compliance Validation of FCC's Ka-band NGSO Processing Round Participants," *2021 IEEE Aerospace Conference*, 2021, accessed December 1, 2023, https://ieeexplore.ieee.org/document/9438491.

7. Douglas Brake, *Spectrum Policy and the Future of Satellites, Aspen Institute, Communications and Society Program. Report from the 2018 Aspen Institute Roundtable on Spectrum Policy*, August 2019, https://www.aspeninstitute.org/publications/spectrum-policy-and-the-future-of-satellites/.

8. Federal Communications Commission, "Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed Satellite Service Systems" (Washington, DC: FCC, December 15, 2021), accessed December 8, 2023, https://docs.fcc.gov/public/attachments/FCC-21-123A1.pdf.

9. Federal Communications Commission, "Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems: Report and Order and Further Notice of Proposed Rulemaking" (Washington, DC: FCC, April 21, 2023), accessed December 1, 2023, https://docs.fcc.gov/public/attachments/FCC-23-29A1.pdf.

Technical and Regulatory Overview of NGSO Systems

Satellite networks typically send information via a satellite between terrestrial equipment located at the user's premise such as a home, aircraft, or vessel and larger Earth stations, known as gateways, which are connected to fiber-optic lines.[10] GSO systems consist of satellites orbiting at 35,678 km above the sea level, the altitude at which the orbital period of the spacecraft matches the rotation of the Earth underneath it. This technology permits a single satellite to supply services over a large footprint, approximately one-third of the Earth in size; for example, video transmissions from just a handful of orbiting craft supply the entire continental United States with hundreds of channels of video programming from two competing networks, around the clock. The setup is well suited for video, given that it is generally a one-way service. But for interactive services, the latency of transmissions going to such altitudes can be highly disruptive, creating demand for lower-latency solutions.[11]

NGSO networks consist of satellites orbiting at altitudes other than 35,678 km, mostly in near-circular low earth orbits (LEOs) with an apogee less than 2000 km. These have been used for applications such as geolocation, Earth observation, and low latency communications such as text and broadband. The use of NGSO satellite constellations to promote low latency communications originated commercially with Iridium, a system of sixty-six NGSO satellites that was proposed in the 1980s and deployed in the 1990s (Bloom 2017). A prevailing use case for the latest generation of LEO NGSO systems is oriented toward providing satellite-based broadband and consists of hundreds to thousands of satellites.

To provide internet service, end users communicate with a satellite by a user terminal. The signal is sent to a satellite via line of sight. The satellite then relays the packets to a gateway that is connected to the internet via fiber or to other satellites using intersatellite links. Response packets follow

10. All satellite networks have command and control links while some have broadcast links to provide broadband services; however, not all satellite networks broadcast. For example, Planet has a network of satellites that image the earth, are NGSO, have participated in processing rounds and have a spectrum need to get a significant volume of data to the ground in a timely manner.

11. Low latency is only one element and important for applications such as video conferencing, audio communications and high-speed trading. One also should consider the GSO range is 20× larger than the LEO range so the pathloss for the link increases by 400× (23 dB).

a similar route, though the end user may receive the return packets from a different LEO satellite. Due to the orbit of the NGSO satellites, terrestrial Earth station antennas are required to track satellites across the sky, as opposed to GSO systems, in which the Earth stations maintain a fixed pointing orientation. Figure 1 provides an example of SpaceX's Starlink user terminal. As of 2022, this was the primary system serving Starlink customers.

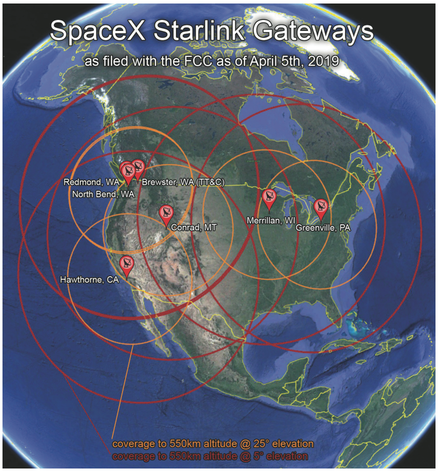
As noted, the other end of the communications link is the gateway. Figure 2(A) provides a schematic of Starlink's gateway locations over the United States. The concentric circles illustrate the coverage provided by each gateway; when a satellite is in this circle, it will be visible to that ground station. Figure 2(B) is an image of the Starlink gateway site in Merrillan, Wisconsin. These stations require fixed and sunk capital outlays that constitute a significant fraction of an NGSO network's total cost.

As of May 2024, Starlink had progressed furthest in deploying NGSO broadband services, reporting three million subscribers. The increase was also rapid, with subscribership increasing by 50% in the 8 months prior, across nearly 100 countries and 7 continents.[12] In the United States,

FIGURE 1 Starlink User Terminal (Accessed June 28, 2022)

Source: Credit: By Steve Jurvetson from Los Altos, USA - A Bright New Day for Broadband — Starlink, CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=105132633. https://en.wikipedia.org/wiki/Starlink#/media/File:A_Bright_New_Day_for_Broadband_%E2%80%94_Starlink_(51016637753).jpg

12. Surur, "Starlink Announces 2 Million Active Subscribers: Growth Going Geometric," *BigTechWire* (September 24, 2023), accessed December 1, 2023, https://www.bigtechwire.com/2023/09/24/starlink-announces-2-million-active-subscribers-growth-going-geometric/.



(A)

(B)

FIGURE 2 Starlink Gateway (A) Locations in the Continental United States and (B) Merrillan, Wisconsin, Gateway Site (Accessed June 28, 2022).

Sources: (Figure A) Megaconstellations (@Megaconstellati) via X. https://x.com/Megaconstellati/status/1114534342624194560/photo/1. (Figure B) r/SpaceXLounge via Reddit (user w_line) https://www.reddit.com/r/SpaceXLounge/comments/gkkm9c/starlink_base_station_photos_from_the_location_of/

Starlink is active in forty-eight states. As of May 2024, it has just over 6,000 operational satellites in orbit.

NGSO Spectrum Usage Environment

Interference mitigation from gateway antennas may be less technically challenging, given the high gain beams and specific geographic locations of the relatively fewer number of gateway locations that are needed for a constellation (150 globally for Starlink in December 2023).[13] Interference from user terminal service links, on the other hand, tends to be more challenging to coordinate, as user beams blanket the Earth globally. It is also possible that user terminals from various providers may be colocated, simultaneously servicing customers.

While the specifics of the sharing arrangements between NGSO systems and between NGSO and GSO systems are highly specific to each system, an initial review of the applications indicates that most NGSO systems will seek to avoid interference with GSO systems, and in doing so

13. Starlink, "Starlink Ground Station Locations: An Overview," Starlink Insider, Accessed December 1, 2023, https://starlinkinsider.com/starlink-gateway-locations/.

comply with the ITU's Article 22 EPFD limits by designing constellations such that multiple beams can cover a given location. In turn, this enables operators to intelligently steer the beams of their spacecraft and their ground stations (both gateways and user equipment) to prevent in-line events between NGSO and GSO systems (in-line events between such systems occur where beams for the two systems overlap causing interference). For NGSO systems operating between 400 and 2,000 km, in-line events are on the order of seconds, as a different satellite passes overhead within a few minutes, and spot-beams deploy multiple-color frequency reuse. Satellites providers have economic incentives to maximize capacity, which they accomplish by reusing frequency with spot-beams arranged into densely packed grids of beams, with each beam assigned to a channel to mitigate interference. When colors are assigned to these systems of reuse patterns to visualize "ownership," the system is referred to as a multicolor frequency reuse pattern. Grids with more colors can decrease interference, albeit at the expense of lower frequency reuse. Conversely, grids with fewer colors can increase frequency reuse, yet this results in heightened interference.[14] Similar strategies might be deployed for avoiding interference with other NGSO systems, though band segmentation is raised as a possibility as well. In the latter case, applicants are not proposing specific sharing arrangements, but they rely instead on explicit coordination discussions as the specifics of each system operation impacts coexistence.

The frequencies in use for these NGSO FSS networks are:

- Ku-band: 10.7–12.7 GHz (spacecraft-to-Earth, or downlink) and 14.0–14.5 GHz (Earth-to-spacecraft, or uplink)
- Ka-band: 17.8–18.6 and 18.8–20.2 GHz (Earth-to-spacecraft) and 27.5–30.0 GHz (spacecraft-to-Earth)
- Q-band: 37.5–42.5 GHz (spacecraft-to-Earth)
- V-band: 47.2–50.2 GHz and 50.4–51.4 GHz (Earth-to-spacecraft)

Continuing with the authors' example, SpaceX's Starlink uses the Ka-band frequencies for feeder links to many of the gateways illustrated in Figure 2; the Ku and Ka bands are used for transmissions to user terminals.

14. Craig Miller, "How and Why Commercial High-capacity Satellites Offer Superior Performance and in the Future Space Threat Continuum," *32nd Space Symposium, Technical Track*, 2016.

Analysis of the Current Regime

The current sharing regime, codified in 25.261 of the Commission's Rules in force, requires the following:

> Absent coordination between two or more satellite systems, whenever the increase in system noise temperature of an *Earth station receiver, or a space station receiver for a satellite with on-board processing, of either system*, $\Delta T/T$, exceeds 6 percent due to interference from emissions originating in the other system in a commonly authorized frequency band, such frequency band will be divided among the affected satellite networks. (47 CFR 25.261, emphasis added.)[15]

This approach was first adopted in the FCC's Ku-Band Report and Order and FNPRM.[16] Thus, it is understandable why this regulatory approach would serve as the starting point for regulations for the NGSO systems. In the absence of coordination, a private resolution between at least two operators, either a satellite or an Earth station of any competitive system, may declare an interference event that initiates band segmentation. Band segmentation only applies to transmissions associated with the in-line event. As it terminates when the in-line event terminates, it would not necessarily prevent parties from continuing to serve broadband or close their business case but would require some changes to their operations.

15. In contrast with bent-pipe satellites (those that relay signals from one ground station to another), satellites with on-board processing use various signal processing and compression techniques to reduce the amount of data transmitted to the ground. The reason why on-board processing is necessary is because the amount of raw data generated by instruments often exceeds what can be transmitted to the ground. Besides signal processing and compression, success depends on high-speed data links, large on-board storage capacity, and sufficiently fast data signal processors. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Onboard_Data_Processing/What_is_On-board_Data_Processing.

16. Federal Communications Commission, "The Establishment of Policies and Service Rules for the Non-Geostationary Satellite Orbit, Fixed Satellite Service in the Ku-Band, Further Notice of Proposed Rulemaking" (Washington, DC: FCC, 2002), accessed December 1, 2023, https://www.fcc.gov/document/establishment-policies-and-service-rules-non-geostationary-0.

The "1/n" Rule

To understand the current proposal, it is useful to consider its progression. The previous version of the 1/n rule spoke explicitly of "in-line interference events," stating that an interference event occurred whenever the angular separation of two satellites of different operators fell to 10 degrees or less. Interference events could trigger a "coordinate or split" rule. Such a rule does not require sensors or measurement: with knowledge of the orbits of the relevant satellites and the location of ground stations, such events are anticipated.

The established rule specifies that, in the event of unacceptable interference and lacking agreement for the resolution of the conflict by rival systems, rights to use the band will be divided equally across all "n" NGSO operators involved in the conflict (each allocated 1/n of the available bandwidth). Specifically, the FCC states "such frequency band will be divided among the affected satellite networks." In this context, n is the number of entities involved in an incident of harmful interference. The threshold for such a conflict is achieved when "the percentage increase in system noise temperature of an Earth station receiver, or a space station receiver for a satellite with onboard processing, of either system, $\Delta T/T$, exceeds 6% due to interference from emissions originating in the other system in a commonly authorized frequency band."[17] The FCC action is triggered in the event these entities, each of which require a license prior to launch, do not reach a coordination agreement. The satellite licensees then select their band in order of their system launch.[18] The relevant satellite coordination rule is "if $\Delta T/T$ is less than 6 percent, there will be no problem and no need for further analysis."[19] Table 1 describes the key differences in the previous rules (in operations from 2013 to 2017) and the current rules for interference dispute resolution in NGSO FSS operations across several dimensions, including scope, coordination procedures, default procedures, and sunsetting.

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17. Federal Communications Commission, "Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems" (April 21, 2023).

18. Part 25.261 of the commission's rules states that this ranking "will be determined by the date that the first space station in each satellite system is launched and capable of operating in the frequency band under consideration."

19. See ITU Radio Regulations, Appendix 8, Method of calculation for determining if coordination is required between geostationary-satellite networks sharing the same frequency bands. The FCC discusses the rational for the shift from angle separation to the $\Delta T/T$ criterion at https://www.federalregister.gov/d/2017-26532/p-32.

TABLE 1 Differences between Previous and Current Rules for Dispute Resolution

	Previous Rule	**Current Rule**
Scope	The rule applied to NGSO FSS satellite networks operating in specific assigned frequency bands, namely the 28.6–29.1 GHz or 18.8–19.3 GHz bands	The current rule applies to NGSO FSS operations worldwide, regardless of processing round status, under a commission license or US market access grant
Coordination	Coordination procedures were required among affected satellite networks to resolve interference issues, with a default procedure outlined	Good-faith coordination is mandated for the use of commonly authorized frequencies among NGSO. FSS licensees and market access recipients, irrespective of processing round status
Default Procedure	In the absence of coordination between satellite systems, frequency bands would be divided among affected networks based on the date of the first space station launch and operation	Frequency bands will be divided among affected networks when the increase in system noise temperature due to interference exceeds 6 %, with selection of spectrum based on launch dates and capability of operating in the frequency band
Sunsetting	No provision for sunsetting is mentioned in the previous rule	Ten years after the first authorization or market access grant in a processing round, systems approved in that round will no longer be required to protect earlier-round systems and instead will share spectrum under the default procedure

Once the interference levels are no longer exceeded, the operators may resume using the entire frequency band. The new rule states that the segmentation is specific to the stations involved in the given interference event with language stating that the affected station(s) of the respective satellite systems may operate in only the selected (1/n) spectrum associated with its satellite system while the $\Delta T/T$ of 6 percent threshold is exceeded and that all affected station(s) may resume operations throughout the assigned frequency bands once the threshold is no longer exceeded.

The authors focus on three attributes of the 1/n rule that may pose challenges for mitigating interference or enforcement. The first is that the proposed and previous rules rely heavily on the ability of operators to anticipate and avoid interference. Both rules do not require determining which satellite operator is the source of interference. Unlike with space debris, where there is some precedent for assigning liability, the rules governing interference impose sharing rules without regard for which party took the triggering actions.

There is reason to believe the rule creates a framework to avoid interference. The 10-degree rule enables calculation of interference events, and operators can calculate $\Delta T/T$ events—and, through the coordination process, avoid them. The reason why these events may be anticipated and avoided is because (1) the relevant radio propagation laws are free-space propagation (mostly, there are some issues with atmospheric effects at low elevation angles, rain, etc.), (2) the location of transmitters and receivers is known, and (3) the technical characteristics of the systems are known to the participants even if they do not know the specific modulation schemes.

The extent to which the framework can prevent interference is a rather strong assumption. LEO is increasingly crowded. The number of satellites and user terminals continues to increase dramatically with increasingly complex antenna beam patterns. Even though the satellites' positions are generally known, the positions of user terminals and the instantaneously steerable antenna patterns are not public knowledge. In what follows, the authors suggest that this gap—clear provisions for identification of who is the source of interference—is a significant issue from an institutional design perspective.

A related second issue is that the rule does not address the challenges of identifying the satellite networks involved in interference incidents, especially the interference source(s), whose transmissions are highly directional and often in short bursts. Even with the strong assumption that interference events are a subset of in-line events, there remains the possibility of three or more satellites being approximately aligned, making the identification of the actual interference source a technical challenge.

A third issue is that the proposed rule and the previous rule do not have a clear way to discern the value of an operators' transmission. What the rule does is assign equal "rights" to each licensee. In the event of interference, the operators essentially divide the spectrum. In this sense, it is an imposed sharing rule.

One potential response is that the operators could bargain, in Coasean fashion, to redefine liability. This is because the Coasean solution presumes that the final allocation does not depend on how liability is assigned. However, the 1/n rule is different in that it is not an assignment of liability: it is a rule that imposes sharing in the event of interference, without assigning liability. That can become significant to the extent the satellite activities of operators have different values. In such instances of interference, the rule could impose disproportionate costs on one of the operators. Although bargaining could overcome these costs, the point is that the regulations can be improved by reducing rather than increasing the "transaction costs" of governance of interference. If one assumes that the rules and technology are clear enough that the operators will always avoid this situation, then this concern is not an issue. But if interference does occur, then the implementation of the rule will be inefficient, inequitable, or both (inefficient in that interference could undermine socially valuable satellite operations, and inequitable in the sense that the operators who invest more to provide valuable services are disproportionately harmed).

The "Processing Round" Approach

The FCC adopted the approach to process NGSO systems in "processing rounds." A processing round is initiated when an operator files an application with the FCC for specific frequency bands (subject to processing round rules). When this is issued as a public notice, other potential operators may file an application to be considered with the initial (or "lead") applicant. This approach enables the FCC to be responsive to potential system operators and allows the operators' visibility into the (potential) technical and competitive environment that they may face when all the systems are fully deployed.

At the time of the four processing rounds discussed in the introduction, application fees were $471,575 per application, and required applicants had to post a bond within thirty days of application grant. This bond escalates to $5 million over the course of five years. These fees are not dependent on the size of the constellation and given the nature of the limited application window of processing rounds, as well as the precedent that systems can be modified down the road so long as they do not increase the interference environment of the originally filed system, operators are incentivized to overfile for large systems to ensure network flexibility.

An important economic question is whether this approach dissipates resources. In many situations, a "race for access rights" will be socially expensive. The example given in Anderson and Hill involves homesteading land in the American West.[20] Claimants were induced to settle unproductive land (incurring negative returns until, say, the railroad connected their town or region to the large markets of the Midwest and East) simply to be awarded property rights. The losses were costly; an alternative means of awarding rights may have more efficiently established ownership. The most significant lesson from homesteading was that settling property rights disputes by incentivizing expenditures of real resources (those invested prematurely in agricultural production and residential buildouts, in the Anderson and Hill example) may incur significant social costs. Lacking offsetting benefits in a particular context, rules that quickly establish access rights while avoiding expensive development races are then relatively efficient. Although care is required in generalizing from the experience of terrestrial property rights to access rights in outer space and there are potentially important differences—just because a company overfiles does not mean that they have to launch satellites, which would lessen the issue of expending real resources in the FCC case compared to homesteading—a potentially relevant consideration is whether the preemptive rights established by the FCC will result in similar resource dissipation.

Recent Changes/Proposals

As mentioned, the FCC recently went through a process of revising the rules around NGSO spectrum sharing. During this process, the FCC considered changes to its policy related to the spectrum-splitting procedure (that is, to its 1/n rule), the protection of earlier-round systems from later-round systems, the sharing of information among operators, and the sunsetting of protection. In the 2023 Report and Order, the FCC adopted changes that require NGSO FSS licensees to coordinate on their use of commonly authorized frequencies, with a sunsetting provision that would eventually transition from protection to spectrum sharing with

20. Terry Anderson and P. J. Hill, "The Race for Property Rights," *Journal of Law & Economics* 33, no. 1 (1990).

earlier-round systems.[21] Another provision was considered that would require NGSO FSS licensees or market access recipients to certify coordination agreements with earlier-round systems or submit compatibility showings to prevent harmful interference. The rule specifies that if earlier-round systems become operational after a later-round system, later-round licensees must submit a certification of coordination or compatibility within sixty days.[22]

Overview of the FCC's Recent Rule Making

The goal of the FCC's recent rulemaking on NGSO spectrum sharing is to facilitate the deployment of both existing and future NGSO FSS systems by providing certainty around spectrum-sharing requirements as well as incentives for technological innovation. Some key questions that arise in the 25.261 regime include:

- Should the default spectrum-splitting procedure be limited to systems authorized in the same round?

The FCC's 2023 Report and Order established such a limit.[23] The rationale in support of this approach is that, under present technology, the deployed satellites may not be easily modifiable to accommodate a changed interference environment that would occur with the systems approved after an incumbent. It also reflects administrative efficiency in situations where spectrum access is not contentious; existing licensees operate and worry about certain constraints later if circumstances in the spectrum environment change. On the other hand, this may provide weak incentives for incumbents to conserve the spectrum space (perhaps by investing in technology upgrades) or to be more tolerant of other systems. The FCC addressed this issue by sunsetting an incumbent's protections ten years after "the first grant in a subsequent processing round."[24] In-orbit lifetimes of LEO satellites are limited by, for example, atmospheric drag and in many

21. Federal Communications Commission, "Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems" (April 21, 2023).

22. Ibid., Para. 14.

23. Ibid., Para. 9.

24. Ibid., Para. 29.

instances, the lifetimes of these satellites will be short, which means that earlier-licensed operators will often be rebuilding systems (and potentially upgrading them) within the ten-year window.[25]

- Is the current coordination trigger of a 6% increase of the noise floor appropriate, given current technology?

There are several alternative possibilities regarding triggers for intervention. Some possibilities include a throughput-based metric. The FCC did not make changes to how this rule is triggered.

- How should earlier-round systems be protected from later-round systems?

For a satellite system launched in an earlier round, should it be guaranteed protection from later-round systems and how should this guarantee be enforced? The rationale for doing this is that some degree of protection to provide predictability of their service may be needed to justify the expense incurred in launching the service. A cost of such protection is again that it may diminish incentives for incumbents to efficiently manage their spectrum use. The FCC codified this protection by requiring any later-round system to demonstrate that it will protect earlier-round systems.[26] A related question addressed is how to quantify the protection level provided to earlier-round systems (e.g., should this depend on the interference-to-noise level or the system throughput). The FCC decided to adopt a "degraded throughput" metric but is still seeking input for how this will be implemented.[27]

- What can be done to facilitate information sharing?

There are benefits to information sharing among providers. For example, information regarding beam-pointing (how the spectrum resources are being used) could facilitate better coordination. Similarly, time patterns of frequency usage might be confidentially shared to identify points of congestion or abundance. To this end, what is useful information to share

25. The reduced launch costs for LEOs also contributes to this as it lowers the incentive to design satellites for longer lifetimes.

26. Ibid., Para. 14.

27. Ibid., Para. 19.

to coordinate spectrum usage? How and with whom should this information be shared? What kind of protections do operators have for this potentially proprietary information? Information-sharing requirements were not adopted at this time, although there was a requirement that operators engage in "good-faith coordination."[28] Such coordination may include industry custom that contributes to spontaneous information sharing. For example, SpaceX states its current coordination practices include sharing frequencies for uplink and downlink transmissions, relevant noise temperature values, relevant power density values, and several other categories of cooperative information sharing.[29] The presence of these customs does not mean that codifying information sharing is recommended, which may hinder technological advances. Rather, they illustrate that the FCC may consider seeking to preserve them or avoid policymaking that undermines spontaneous information sharing.

Economic Considerations Regarding Outer Space Access Rights

Space provides opportunities for innovation and productive social growth. At the same time, space is potentially a common-pool resource subject to destructive conflicts in the absence of institutions to govern access to and relationships in space. This feature gives rise to concerns about resource dissipation in the outer space commons, a byproduct of externalities that reduce the value of space as an input into various productive missions.

Spacefaring implicates risks involving both physical collisions (space debris) and radio interference. Both are discussed in the FCC approval of the 2018 SpaceX application and in the FCC's Report and Order and FNPRM.[30] (Here the authors deal with the spectrum issues, but do not doubt that the orbital debris issue invokes the need for social coordination,

28. Ibid., Para. 21–24.

29. SpaceX letter of March 15, 2023, in IB 21-456 docket.

30. Federal Communications Commission, "Space Exploration Holdings, LLC, Application for Approval for Orbital Deployment and Operating Authority for the SpaceX NGSO Satellite System: Memorandum Opinion, Order and Authorization" (Washington, DC: FCC, 2018), Accessed December 1, 2023, https://www.fcc.gov/document/fcc-authorizes-spacex-provide-broadband-satellite-services; Federal Communications Commission, "Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking" (Washington, DC: FCC, 2020), accessed December 1, 2023, https://www.fcc.gov/document/fcc-updates-orbital-debris-mitigation-rules-new-space-age-0.

as well.[31]) The FCC's 2023 Report and Order codifies the rights regime described earlier to a temporal access rights regime, where earlier applicants enjoy superior rights to subsequent applicants, while the 1/n rule still applies to applicants within the same processing round. The report and order further indicates that this temporal rights regime has in fact been implemented in recent NGSO licensing decisions. However, it was not stated in the relevant rule. The proposal adopted here makes this temporal priority explicit. This section sets the stage for alternative governance regimes by considering general economic considerations as well as issues with the current regime.

In general, economists consider access restrictions to be property rules, which include exclusive rights, limits on activities, or governance arrangements to manage commons.[32] Exclusive rights assign ownership to particular parties, whereas governance involves opportunities for multiple stakeholders to work out arrangements, including through sharing rules. The economic problem to be addressed is whether transaction costs—the expense of coordinating activities—which includes the value of outputs lost due to either restrictions or damage from harmful interference, are economically deployed. This is determined by identifying the resulting sum of the values obtained via the coordination. The maximum net output implies minimization of transaction costs. Lesser totals imply higher costs, with diminished value creation relative to a more efficient framework.[33]

The economic regime governing satellites leans toward governance, with a focus toward licensing and self-governance. The increase in demand for satellites has made space an increasingly scarce resource. To address conflicts in orbital positions and frequency use, the FCC licenses new systems. However, all the proposed systems use the same frequency bands for up- and downlinks, so congestion in spectrum usage among NGSO licensees is to be worked out through self-governance, or where self-governance fails, through the algorithmic application of the 1/n rule.

Economists use the term "property rights" in connection with regimes to determine usage priorities. But it is important to note that the licenses for these systems are *operating* licenses and refer to permissions to build,

31. Space is a commons in that it can be subject to overuse and misuse absent rules governing access to it.

32. Dean Lueck and Thomas J. Miceli, "Property Law," in *Handbook of Law and Economics Vol. 1*, ed. A. Mitchell Polinsky and S. Shavell (Amsterdam: Elsevier, 2007).

33. Ronald H. Coase, "The Federal Communications Commission," *Journal of Law & Economics* 2 (1959); Thomas W. Hazlett, "Spectrum Tragedies," *Yale Journal on Regulation* 22 (2005).

launch, and operate a network of satellites. The NGSO systems then fall under a nonexclusive spectrum-management regime. Commonly assigned channels have been widely used in maritime and aviation communications. Amateur radio is another example of this sort of regime.[34]

Property rights tend to adjust in response to the changing economic environment. The key driver prompting such social movement is a shift in the balance between supply and demand, as when a previously abundant resource becomes scarce.[35] In this case, demand exceeds supply, and rules to prioritize access often become worth their cost. These costs involve defining, distributing, trading, using, and then enforcing the property rights created. Such undertakings can help guide competitive actions in productive ways, not in *eliminating* interference between users; as such property rules inherently exclude some activity choices while favoring others. Efficiency is enhanced when more valuable options are revealed and chosen, versus alternatives.[36]

The ongoing effort by regulators to establish additional access rules in satellite bands appears to reflect changing scarcity conditions. The value dissipation problem addressed was classically formulated in Garrett Hardin's "tragedy of the commons."[37] For Hardin, a tragedy of the commons is the tendency to overuse resources in the absence of effective systems to manage access to those resources. In this case, space may be considered the commons. Regulatory efforts to shape access rights, undertaken in the United States by the FCC, involve an array of options, each of which constrains "open access" in some respect.

Traditional licenses define appropriate uses of a particular channel and limit the use of a given frequency, at particular times, in stated geographic

34. Pedro Bustamante, William Lehr, Ilia Murtazashvili, Ali Palida, and Martin BH Weiss. "Polycentric Governance in the Amateur Radio Community: Unassigned Spectrum and Promoting Open Innovation," *2022 Telecommunications Policy Research Conference* (Washington, DC, 2022).

35. Harold Demsetz, "Toward a Theory of Property Rights," *American Economic Review* 57, no. 2 (1967); Terry Anderson and P. J. Hill, "The Evolution of Property Rights: A Study of the American West," *Journal of Law & Economics* 18, no. 1 (1975); Gary Libecap and James L. Smith, "The Economic Evolution of Petroleum Property Rights in the United States," *Journal of Legal Studies* 3, no. S2 (2002).

36. Coase, "The Federal Communications Commission."

37. Garrett Hardin, "The Tragedy of the Commons," *Science* 162, no. 3859 (1968). The title of his famous article has been criticized as mis-stated; Hardin actually described a situation where there were no ownership rights. Conversely, a commons typically depicts a common property control structure (with resource rules managed by a group of owners).

space. Rights may be assigned either exclusively or to multiple entities (as when access rights overlap, often the case in satellite bands). Flexible-use licenses are assigned exclusively, and delegate discretion over how frequencies are utilized to the wireless licensee, who then selects the services, technologies, and business models deployed. This authority can also be used to coordinate spillovers with adjacent (or other) rights holders, often by aggregating rights via merger. The frequency spaces allotted to such licenses may be intensively shared by users, with the license holder being a coordinating agent. Competition between such agents (de facto spectrum owners) governs the optimization process. Such rights are a relatively recent policy innovation and have developed in parallel with a switch from fiat rights assignments to competitive bidding (auctions), most notably for those licenses used by mobile services networks. Auctions for orbital slots, and complementary spectrum allocations, were implemented in FCC auctions 8, 9, 15, and 52 (completed July 2004), but were then discontinued in favor of administrative assignments.

One reason given for avoiding satellite rights auctions is that they are impractical given the high capital expenditures associated with launching and constructing networks.[38] However, given that such costs impact bids, high postauction costs make licenses more affordable (i.e., lowers winning bids). Moreover, mobile networks are themselves costly to construct—not only in physical capital, but also in the price of licenses. The 2021 auction for 5G licenses, FCC auction 107, cost US cellular operators some $94 billion.[39] An alternative to either of the earlier mentioned is the license-exempt model, in which the regulator grants nonexclusive use rights but imposes usage restrictions—power limits being the most common, but technical standards and sharing protocols (perhaps with dynamic communications with a network controller) among them. Such an approach can mitigate certain transaction costs associated with acquiring licenses while implicating other costs (such as those imposed by the regulatory restrictions, as well as by contracting obstacles among the overlapping rights holders).

38. TRAI, the regulator in India, was however debating the use of auctions to assign satellite licenses in 2023.

39. W. Lohmeyer, P. Post, G. Miner, L. Heinrich, Y. Mao, J. Musey, and G. Aher, "Auction 107 (C-Band): Policy Overview and Closing Bid Price Analysis of Expedited Access due to $9.7B in Accelerated Relocation Payments to Incumbent Satellite Operators," SSRN 2022, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4177518.

Self-Governance and Information Sharing

With the earlier-mentioned aspects in mind, the authors can offer some preliminary thoughts on the current regime, starting with self-governance and information sharing. As they proceed, it is important to keep in mind that they consider some of the potential issues theoretically, while emphasizing how well each potential issue is relevant in practice in orbital space satellite communities. One strategy for resolving coordination and interference disputes is self-governance, which has mitigated conflicts in certain spectrum-sharing situations. (A coordination agreement between SpaceX and OneWeb was recently concluded, for instance.[40]) As Ostrom emphasized, self-governance often occurs in the context of polycentric systems of governance where resolution of conflict depends on the behavior of community members and of the broader legal and social framework.[41] While information sharing among NGSO operators can promote more successful coexistence, numerous operators urged the FCC that if it required information sharing, it must be done so in a manner that preserved confidentiality of the operators' end users.[42]

Incentive Analysis

Beyond issues with self-governance, the authors consider some mechanism design issues. Economists use incentive analysis to examine what stakeholders might be motivated to do based on the net expected returns of potential actions. It does not attempt to predict the behavior of any actor. The FCC, as the regulator, must consider behaviors that the industry may not normally exhibit, and incentive analysis can be a helpful tool to understand these outliers. Of special note are mechanisms to address externalities. Uncompensated interference is an outcome that does not enter an operator's decision process (much like pollution for power plants prior to emissions caps). This may allow a satellite operator to treat bandwidth as "free" when it is, in fact, contentious (valuable at the margin to other

40. Josh Dinner, "SpaceX and OneWeb tell the FCC Their Broadband Megaconstellations Can Coexist," Space.com, June 21, 2022, https://www.space.com/spacex-oneweb-satellite-internet-constellation-coexistence.

41. E. Ostrom, "Beyond markets and states: Polycentric governance of complex economic systems," *American Economic Review* 100, no 3 (2010): 641–72.

42. Federal Communications Commission, "Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems" (April 21, 2023), Para. 23.

parties), and effectively blocks rival wireless services that could use the bandwidth to produce more value. For social efficiency, rights and regulations should support mechanisms that internalize externalities, prompting actors to face prices that reflect true opportunity costs, or benefits, of given actions.

In this instance, the 1/n rule allocates access rights but may not efficiently coordinate interference. That is, first, because the marginal satellite that generates sufficient traffic so as to exceed the FCC's critical threshold for noise stands to gain (1/n band rights) as per the action. Second, the new constraint is applied generally to all operators, creating free rider problems—those which could, at low cost, resolve current disputes may gain by rejecting such solutions to benefit from the regime shift (to 1/n). Third, the 1/n rule assigns rights based on predicted interference, where prediction is becoming increasingly difficult as the number of satellites and user terminals rapidly increases. Subjective or forecast claims of interference, not based on actual data, tend to be easy to assert and relatively difficult to evaluate and adjudicate. In rulemaking proceedings, interference is defined ($\Delta T/T$ rule) and the involved parties either must agree on how to resolve the conflict or they have to fall back to the default rule. Although such processes can be effective, a challenge is that they require the operators to agree even though they do not have data. For that reason, there may be opportunities to further require "objective" measures of the sources of interference. Indeed, such subjective considerations have been used strategically in FCC proceedings to block competing spectrum-based applications or achieve other strategic goals.[43]

Any satellite operators that are currently approved will be subjected to the 1/n rule in the event of interference. To an extent, operators are expected to work this out through good-faith coordination. However, if they cannot, then the division will be imposed in equal measure, which the authors suggest is costly. To the extent they want to avoid these costs, the system encourages operators to work things out. The authors' contention is not that this is a problem, but that there is uncertainty, including arising from perceived "spurious" claims that cannot be resolved through self-governance or voluntary coordination.

43. Philip J. Weiser and Dale N. Hatfield, "Policing the Spectrum Commons," *Fordham Law Review* 74, no. 2 (2005); Thomas W. Hazlett and Michael J. Marcus. "Why Couldn't the FCC and FAA Solve Their 5G Problem?" *Regulation* 45 (2022). In this sense, the FCC proposed rule avoids some of these problems.

On the other hand, the FCC offers a streamlined nature to the dispute-resolution process. This features relaxes FCC oversight until a situation of possible congestion develops, then encourages self-governance (good-faith negotiations), and then supplies a backstop to such remedies (when not achieved) in the form of a numerically simple rule. This could be an advantage: the 1/n rule, being simple to implement, potentially incentivizes dispute resolution and then is invoked at seemingly low cost when such methods fail.

The authors highlight several issues for consideration. First, if disputes do not appear to be an issue even though interference events, or satellites operating within 5 to 10 degrees, are common, why not wait for the emergence of issues before revising the rules or developing a new framework? Agreements by OneWeb and SpaceX recognize that interference and operations often get close and have developed coordination plans.[44] If the rules appear to work, the question is simply, "What is the problem that needs fixing?"[45]

There is much to be gained by encouraging operators to work things out because of the dynamic nature of spectrum management. As the amount of interference depends in part on technology as well as on access rights, changes in technology imply standards should be continually adapting.[46] This is the most significant rationale to consider in a nonexclusive access rights model, e.g., the "spectrum anarchy" discussed by Bustamante et al. and its relationship to more centralized regulations.[47] Still, there is reason to be fearful of the extent to which regulations provide an uncertain framework in the event of harmful interference. The answer to the question

44. For background, see https://spacenews.com/starlink-and-oneweb-reach-spectrum-coordination-plan/.

45. The straightforward response in the property rights literature is that property rules are not costless to create or administer, so premature efforts (undertaken before it is certain that such rules are beneficial) may entail wasted investments. Further, when actual conflicts develop that are, efficiently, mitigated via new rules, the market will have evolved and new options for coordination may well be more economical to adopt than the mechanisms previously understood. And, of course, with real disputes actually forming the contours of the interference problem, the nature of the conflict will be seen, measured, and adjudicated with better information. This is a key consideration in legal controversies generally, as the common law generally resists using resources of courts to decide issues before they are "ripe."

46. Kevin Werbach, "The Wasteland: Anticommons, White Spaces, and the Fallacy of Spectrum," *Arizona Law Review* 53, no. 1 (2011).

47. P. Bustamante, M. Gomez, I. Murtazashvili I, and M. Weiss "Spectrum anarchy: why self-governance of the radio spectrum works better than we think," *Journal of Institutional Economics* 16, no. 6 (Dec. 2020): 863–82.

posed earlier is that reducing spillovers, as when the 1/n rule confines satellite operators' emissions in defined spaces, will strengthen incentives for innovation by reducing free riding, which occurs when transmissions by Operator A create harmful congestion for Operators B, C, and D.

Second, for congestion claims to be credible, they should be supported by data that conforms to transparent measurements. When disputes are triggered by unilateral claims, strategic behavior (e.g., pursuing extremely low probability claims of damage) is a risk to the process. A countering effect, though, may be supplied by the fact that the satellite licensees in question here deal with each other repeatedly, such that disingenuous claims may not be a dominant strategy.[48] Here a fault tolerant consensus protocol can also be adopted for "good-faith" operators to reach consensus about each claim, provided that most of them have reliable measurements.[49]

Third, time is of the essence as far as interference management is concerned. If the response to interference does not occur rapidly, then the events that triggered a congestion claim may have passed. Here, the distinction between real-time mitigation and ex post enforcement is significant. If the enforcement is triggered after events passed and the remediation mechanism is triggered at that time, then such a mechanism is best thought of addressing harm from interference rather than a mechanism to mitigate current interference in real time. It is important to note that band segmentation plays a punitive role in ex post enforcement, unlike in real-time mitigation: the latter focuses on addressing interference when it occurs, while the former imposes penalties after the fact.[50] As currently implemented, the 1/n rule appears to be targeting real-time mitigation as it is only imposed for the duration of the interference event. Additionally, nonexclusive access may undermine agreements to split bands in response to interference claims. One might imagine agreements among the operators that bargain for different priorities in the event that one of them claims harm from interference and invokes the 1/n rule. The authors have in mind contract negotiations that

48. Robert Axelrod, *The Evolution of Cooperation* (Revised Edition) (New York: Basic Books, 2006).

49. Arman Mollakhani and Dongning Guo, Fault-Tolerant Spectrum Usage Consensus for Low-Earth-Orbit Satellite Constellations, arXiv, 2024. Available Online: https://arxiv.org/abs/2312.05213v2..

50. A. Mitchell Polinsky and Steven Shavell, "Punitive Damages: An Economic Assessment," *Harvard Law Review* 111, no. 4 (1998); A. Mitchell Polinsky and Steven Shavell, "The Economic Theory of Public Enforcement of Law," *Journal of Economic Literature* 38, no. 1 (2000): 45–76.

occur offline. Terms might include particular regions (time–frequency–orbital positions) over which the negotiated priorities apply along with the contract duration.

A problem is that networks may vary (with new entry), such that rights post-band-splitting are not protected, thereby reducing incentives for private arrangements to address interference. Further, the splitting rule may not account for the size of the network. There are ambiguities in the proposed rule. If interpreted as a split of the entire band, then the rule would appear to be unnecessarily harsh. For example, if network A is a mega-constellation with 10,000 satellites, Network B has 1,000 satellites, and there are no other licensed operators, the band is split in half despite the lopsided service requirements of the two systems. However, another reading of the rule is that it is a split in a single satellite from each operator. Under that interpretation, the spectrum is only split in half for those satellites (typically two) involved in the interference event and not for the other satellites that are not dealing with interference. There is also a potential fairness issue in that the large constellation may have more alternative satellites that it can use to serve a given user or ground station. If the smaller constellation does not have such options, the reduction in bandwidth may hurt the smaller constellation more. As these outcomes may be wasteful or inequitable, the only suggestion here is that the FCC clarifies to ensure the latter is what is meant by the rule.

Alternative Models of Access Rights

With the preceding general issues in mind, this section outlines options for access rights as the density of orbiting spacecraft increases. This progresses from distributed, light interference management to "proactive interference management." The reason the authors refer to it as proactive interference management rather than a "centralized" system is that, given the enormity of outer space and the fact that interference events are local, a completely centralized solution is unlikely to be feasible. For example, decentralized mechanisms based on fault tolerance consensus among operators (implemented by a blockchain system), are proactive, although not quite centralized.

Currently, because only a small number of constellations have started launching satellites, interference does not appear to be a major issue, and if that continues to be the case, the light interference-management schemes discussed here, relying largely on overlapping, nonexclusive access rights, are likely to be sufficient. It is only in the scenario where interference events become more frequent and problematic in terms of application performance that more sophisticated schemes become efficient.

Nonexclusive Access

Open or nonexclusive access is appropriate when spectrum is abundant, and additional governance schemes are relatively expensive. As previously mentioned, power masks are already in place to protect terrestrial and GSO systems, respectively. The power mask may be dynamically adjusted according to the protocol or detection of interference events, and random-access protocols could be specified as an industry standard, analogous to Wi-Fi. A potential disadvantage is the latency associated with acknowledgments and timeouts built into random-access protocols.

Light interference management with adaptive power masks may be cost-effective for mitigating sporadic, infrequent interference events, and may serve as a long-term solution if the cost of more sophisticated interference-management schemes proves prohibitive. However, if the satellite density continues to increase, at some point, more careful interference management may become desirable. The associated cost of using the spectrum should then be reflected in the operator's economic calculations to trade off spectrum usage with the number of satellites in orbit. With more sophisticated interference management and improved incentives to mitigate spillovers, operators may make such investments and improve overall system throughput. Improvements may come from upgraded technologies, spectrum-economizing applications, or reductions in the number of satellites.[51]

Database-Aided Interference Detection and Avoidance

As interference events become more frequent, it becomes useful to identify the nature of those events: the sources of interference, including locations in time, space, frequency, duration of the event, and the functions or associated applications of the interfering streams (broadband access, backhaul,

51. The relationship between the number of satellites and value of interference management is subtle. For a given demand, increasing the number of satellites may make interference management easier—with a larger number of alternative pathways—or more difficult—with more traffic from additional directions.

or control signaling). This information could then be used to assess the likelihood and consequences of future interference events and promote more effective coordination. This is the intended design of the Spectrum Access System (SAS) used in Citzens Broadband Radio Service. The authors discuss this approach here.

Sensors can be deployed at various locations to identify and characterize interference events and to reduce incentives to make false declarations or exaggerate their effects. Again, with good information about satellites orbits and the characteristics of the relevant radio systems, the parties can jointly decide on a contingency plan and hence avoid interference events. Nonetheless, the declarations in the event of interference are based on subjective calculations. This creates the potential for guile. One reasonable response is that doing anything more to detect interference would require expensive systems of sophisticated satellites that are capable of pinpointing detection. This suggests that, even if the uncertainty discussed earlier is present, that the current system which presumes the operators know enough—and have enough incentive—to develop fairly complete contingency "contracts" may be efficient.

On the other hand, the authors emphasize that the cost of sensors is to be determined. Those sensors may only need to detect signal strength across the allocated band and along certain directions, and hence each sensor could be relatively inexpensive.[52] A crucial difference between CBRS and NGSO systems is that the latter often consists of a small number of operators, where each operator controls a large network of ground stations and satellites, which communicate with a very large number of user terminals. The millions of user terminals can also be a major source of sensing data, although for such data to be useful, operators would have to be willing to share it. Such an extensive sensing network could support claims that an interference event has occurred, and to provide some information about source locations. Sensor and database specifications could be part of an industry standard, analogous to Wi-Fi standards. On the other hand, the combined knowledge of radio propagation and radio interference mechanisms, and the deterministic nature of satellite orbits, along with observation of system performance, could reduce incentives to make "false" or "exaggerated" declarations, even in the absence of the aforementioned systems of sensors.

52. The sensor itself may be relatively inexpensive but the cost goes up significantly if it needs to be hosted on a platform in orbit.

Another issue is locating which satellites are interfering. The FCC's 2021 NPRM asks whether information about beam directions should be shared by incumbents to avoid interference by entrants in subsequent rounds. More generally, databases for resource management across multiple service providers may request information about satellite orbits, coverage and resource utilization. Satellite orbits are publicly available, and the satellites must be in the spaces allocated (perhaps subject to small variations that would not significantly affect interference patterns).[53] The ITU's treaties on radio regulation emphasizes allocation of frequencies and coordination of orbital positioning of different satellites, which are accomplished through space plans that define frequencies and orbital resource usage.[54] Knowing this information alone is not sufficient for determining interference events; these will depend on the directions of the beams from these different satellites, which is not publicly available. The UN Office for Outer Space Affairs report in November 2023 recognized there is substantial national diversity in reporting requirements.[55] Hence, an evolving area is not only monitoring, but also in standardizing what must be reported.

Here there may be opportunities to deploy technologies that can register interference events and identify interfering parties without revealing more detailed proprietary information about traffic patterns.[56]

A standard for sensors and databases could set expectations, if not requirements, for sensor sensitivity, specifying outputs along with protocols for storing and maintaining data, identifying interference events, and conducting resource management.[57] The sensors and database systems could then be supplied by third-party providers. A difference from current Wi-Fi protocols for unlicensed access is that the satellite protocols would have

53. Note that LEO orbits change due to satellite drag, so NGSO orbits are continually evolving and lowering in altitude. This is not the case for GSO systems, which have fuel for station keeping so they stay at a fixed location for their operational lifetime.

54. https://www.itu.int/hub/2023/01/satellite-regulation-leo-geo-wrs/.

55. UN Office for Outer Space Affairs, *Registration of Objects Launched into Outer Space Stakeholder Study*, November 2023.

56. M. Grissa, A. A. Yavuz, B. Hamdaoui, and C. Tirupathi, "Anonymous Dynamic Spectrum Access and Sharing Mechanisms for the CBRS Band," *IEEE Access,* 9 (2021), https://doi.org/10.1109/ACCESS.2021.3061706.

57. A major challenge lies in defining "harmful interference" in cataloguing such events. The FCC has never produced a general definition of the phenomenon, and for good reason: the damage inflicted in any given event may be suggested (with loose correlation) by technical observations but are primarily influenced by effects on economic values. These are not charted, of course, by spectrum sensors.

to account for priority rules for incumbents versus newer entrants. Those could serve as the foundation for more proactive interference management and resource-allocation protocols as the density of satellites increases.

A decentralized interference-management design has been proposed in Mollakhani and Guo. Operators run a Byzantine fault tolerant consensus protocol to reach consensus about spectrum usage (or its deviation from a prior agreement).[58] Such a consensus protocol, possibly assisted by smart contracts, may facilitate allocating or trading resources, as well as enforcement and governance.

Exclusive, Tradable Access Rights

Currently, access rights are established through authorizations to launch and operate a satellite network, similar to the licensed-but-unassigned spectrum in amateur radio. As spectrum use increases, nonexclusive access may lead to diminished performance in terms of latency and throughput, thus sparking efforts to define access rights more clearly. Efficiency can potentially be improved through dynamic resource assignments and scheduling, mitigating interference. This is an important feature of cellular systems. There, however, a provider is assigned licenses featuring exclusive frequency rights; while access can (and will) be shared with customers (including wholesale providers of network services), the licensee is the nexus of such contracts. As such, rights fragmentation is limited and the primary network acts as a coordinating agent in the optimization of fixed investments and complementary spectrum resources. Acting as a "mini-FCC," the licensee with exclusive, flexible-use rights enables rival uses (adjusting access pricing, bandwidth consumption, power levels, beams, and various technologies, etc.) to accommodate competing traffic demands. In contrast, because satellite transmissions are directional and can blanket the Earth, it may be less efficient—or politically difficult—to assign exclusive rights to a band globally.[59] Access must then be managed across different providers and across different national legal and regulatory regimes—amounting to an "unassigned" spectrum-management regime.[60]

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58. Mollakhani and Dongning Guo, "Fault-Tolerant Spectrum Usage Consensus for Low-Earth-Orbit Satellite Constellations."

59. Peter Huber, *Law and Disorder in Cyberspace: Abolish the FCC and Let Common Law Rule the Telecosm* (New York: Oxford University Press, 1997).

60. Martin BH Weiss, Ali Palida, Ilia Murtazashvili, Prashant Krishnamurthy, and Philip Erickson, "A Property-Rights Mismatch Approach to Passive-Active Spectrum Use Coexistence,"

One approach for enabling spectrum optimization allows priority access rights to be traded: providers would be able to negotiate for priority in a particular region of space, time, frequency. John Williams, in a 1986 FCC study of interference rules related to entrants in wireless markets starting in the late 1960s, emphasized that the FCC rules at the time did not mandate interference parameters. In fact, they did not provide any working definition of harmful interference, allowing individual licensees instead to set their own protections. In Williams' estimation, abuse and confusion had not happened as of the mid-1980s.[61] At the time of Williams' writing, the system did not appear prone to abuse or confusion. Although not required, a consensus appears to have emerged for adherence to a single, uniform set of interference criteria to facilitate coordination. This emerged from a process in which private parties were expected to resolve conflicts through negotiation.[62]

For satellites, outcomes could include agreeing not to transmit or reducing transmit power, as well as exchanging assigned priorities based on rounds. For example, providers A and B could agree to trade their priorities at particular times and locations with appropriate compensation (monetary or otherwise) from the low- to high-priority provider. In the next section, possibilities for defining the access rights in terms of constraints on transmit power or interference at particular times, frequencies, and locations are discussed. Defining the units of access rights in terms of regions in frequency, time, and locations, and adding the capability to trade those rights would facilitate the reallocation of spectrum in response to dynamically changing services and demand, analogous to secondary markets for terrestrial licensed spectrum.

Current rules give incumbents from earlier rounds priority over entrants in later rounds. This has its foundation in *right of first appropriation* principles found in property law.[63] Allowing priorities to be traded allows (even

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2021 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), 2021, Accessed December 1, 2023, https://ieeexplore.ieee.org/document/9677235.

61. John R. Williams, "Private Frequency Coordination in the Common Carrier Point-to-Point Microwave Service," Federal Communications Commission OPP Working Paper No. 21 (September 1986).

62. Thomas W. Hazlett, "The Wireless Craze, the Unlimited Bandwidth Myth, the Spectrum Auction Faux Pas, and the Punchline to Ronald Coase's 'Big Joke': An Essay on Airwave Allocation Policy," *Harvard Journal of Law & Technology* 14 (Spring 2001).

63. Dean Lueck, "The Rule of First Possession and the Design of the Law," *The Journal of Law and Economics* 38 (October 1995).

requires, for profit maximization) a for-profit provider to compare the benefits of interference protection against the costs of launching additional satellites and equipment upgrades, and choosing the more efficient path.

As satellite traffic grows and interference becomes more problematic, enforcement of priority rights may suggest that a centralized decision-making process for channel allocations (as with the SAS in CBRS) is a more efficient option. A database of this nature, applied to satellite systems, may be unrealistic given the current technology, feedback times for telemetry and telecommand, and nuances to predicting orbital locations. Should these technical challenges be overcome in the future, however, dynamic channel assignments could gain value.

Such a database controller for resource management may take advantage of advancements in scheduling and distributed interference management for terrestrial mobile networks. Those include utility-based scheduling algorithms that attempt to satisfy quality of service metrics when performing dynamic resource allocation across traffic requests. Here there is the possibility of allowing a provider to negotiate for resources on different time scales. As for CBRS, a challenge is to address the privacy and security concerns of the different providers while providing incentives to share information concerning traffic requests.

Possible Forms of Priority Access Rights

It is relatively challenging to define exclusive access rights in outer space: (1) Most transceivers in space are in NGSO orbits traveling at high velocities and transmit frequently and (2) many directional, extremely long-distance links cross paths and transmission footprints are large.

Harmful interference, generally speaking, occurs at the location(s) of the impacted receiver(s). A coordination arrangement could define access rights at (potential) receiving locations, referred to as a form of spectrum usage right (SUR) in Ofcom's 2006 report.[64] Separate rights are then defined for different directions in the case of a two-way communication link, yet an alternative would simply define and allocate distinct slices of spectrum. If two-way communication occurs only over a relatively short

64. Ofcom, *Technology-neutral Spectrum Usage Rights, Final Report* (London: Ofcom, 2006), Accessed December 1, 2023, https://www.ofcom.org.uk/__data/assets/pdf_file/0023/36527/final_report.pdf.

range, such as when the transceivers are near each other, it is convenient and sufficient to define one right without separating the two directions. To be more specific, rights on ground, and in space, can be defined similarly as they are for cellular services, namely, the right to impinge on a given geographical area on Earth with radio waves subject to certain power-spectral constraints. This way, terrestrial rights and rights in space are defined in a fundamentally consistent manner.

In contrast to the preceding arrangement, an alternative is to define rights to transmit at specified locations with (directional) power masks, without specifying rights at the receiving locations. In terrestrial cellular systems, radio links are short relative to the coverage of an operator's license in a typical area; hence it is proven sufficient to only define the transmission rights. With moving receivers and long-range, highly directional links in outer space, however, a beam aimed toward a receiving satellite becomes a source of interference to another operator's satellite if the latter moves into an in-line position (particularly if the latter satellite is receiving from a transmitter located in close proximity to the first transmitter).Thus, it is hard to forestall interference by constraining the transmitters only, without specifying the receivers' positions as functions of time and their interference tolerance. To protect exclusive access rights, methods need to be developed to determine interference levels and identify spillovers.

If transaction costs are low and access rights are clearly defined, regardless of their specific forms, the Coase Theorem suggests that rights will end up in their most socially beneficial configuration.[65] Specifically, well-defined access rights may also provide the following incentives and opportunities:

- Operators have incentives to detect and identify trespassers and seek remuneration for damages; at the same time, they may elect to tolerate trespassing to some degree should the cost of detection, forensics, and adjudication outweigh the loss of utility.
- Operators have incentives to reach coordination agreements, to develop industry standards, and to seek mediation for interference mitigation

65. The Coase Theorem, named for Ronald Coase, describes a situation where property rights are complete and can be costlessly exchanged. Under such conditions, individuals will reallocate rights to their highest valued uses (and users). This optimal outcome is dependent on unrealistic assumptions, and the degree of applicability (for the basic exchange model described) depends on the actual transaction costs involved. While Coase established the framework of the argument in his 1960 paper, the "Coase theorem" was a term developed and applied by others.

and remediation, with the court system and/or the FCC as the adjudicatory body for unresolved disputes.
- Operators have incentives to keep minimum angular distance between their satellites sharing the same spectrum, as well as to use narrow beams to avoid infringement of other operators' rights.
- Operators have incentives to squeeze more traffic into (and profits from) more popular, contentious communications routes, putting resources in highest valued uses.
- In regions with light traffic, it is worthless to vigorously enforce rights, leaving boundaries less important—an efficient outcome given the context.

Discussion and Recommendations

Space governance involves two tragedies of the commons: orbital debris and radio interference. Orbital debris has been of special concern with the increase in mega-constellations, as thousands of satellites to provide for internet broadband exacerbated a Space Age tragedy of the commons.[66] Recently, the FCC has included deorbit rules to address this in its satellite rulemaking, although orbital debris remains a concern from before the rules coming into existence. Given concern that mega-constellations pose specific risks for orbital debris, radio interference appears to have received less attention.[67] As NGSO constellations are still in the early stages of development and deployment, an opportunity for experimentation exists, where decentralized approaches that incorporate greater opportunities for self-governance may be tried and then compared to conventional access regimes.

The 2023 Report and Order begins to address the characteristics of a governance approach for NGSO systems. Key features are that the precedence established in earlier applications establish a ranking of choices made later, and that when bi-lateral coordination fails, the FCC determines the situation to trigger enforcement according to a fallback 1/n rule. As discussed earlier, the processing round approach incentivizes an "applications race,"

66. Leonard David, "Space Junk Removal Is Not Going Smoothly," *Scientific American* (July 30, 2021), https://www.scientificamerican.com/article/space-junk-removal-is-not-going-smoothly/.

67. Aaron C. Boley and Michael Byers, "Satellite Mega-Constellations Create Risks in Low Earth Orbit, the Atmosphere and on Earth," *Scientific Reports* 11 (2021): 10642.

with parties filing for rights enabling larger constellations than will likely be utilized. This provides option value, at low to no cost, for the filing parties. This not only clutters the administrative process with paper (real or virtual) but obscures actual demands, complicating coordination. Linking priority with the processing round protects engineering and capital investments of earlier-round companies but could disincentivize innovation by favoring incumbents. This disincentive could be removed if replenished satellites are not granted the same priority, an apparent rationale of the FCC's sunsetting of priority status adopted in 2023.

Another observation is that the 1/n rule as adopted addresses a situation that would last for a few seconds and would be localized to user stations in a particular geography. Nonetheless, interference may remain an issue. Even while conflicts are occurring with small probability, increases in the density of links further increases the probability of damaging interference or congestion. There are at least three implications for any coordination system (including the 1/n rule). One is identification of the location at which interference occurs and the satellites involved. Second, rapid localization and coordination (e.g., in milliseconds) can help mitigate interference events. Third is continuous monitoring of the spectrum usage environment. The authors' analysis suggests consideration of all three can inform future discussions of changes in rules in anticipation of increasing interference.

It is also important to consider that there are other ways to encourage more effective management of spectrum besides the ways discussed in this paper, including efforts to reduce interference through adoption of more efficient technology. For example, higher-gain antennas can improve system operation by allowing higher data rates at a given transmission power, resulting in less volume of space in which interference can occur. Analyzing these possibilities is beyond the scope of this article, although future research should consider incentives to adopt advanced technologies and more efficient models under rules designed by the FCC.

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