Spectrum Rights in Outer Space

Interference Management for Mega-constellations

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Abstract

The rapid increase in low earth orbiting, non-Geostationary (NGSO) communication satellites raises concerns related to the coordination of radio frequency access across competing NGSO systems. Responding to an April 2020 petition by SpaceX, the FCC issued a Notice of Proposed Rulemaking NPRM (FCC 21-123) aimed at updating its NGSO spectrum sharing rules in the relevant frequencies (which involve ten distinct bands between 10 and 51 GHz).[2] In this paper, we examine the rights regime proposed by the FCC and, guided by empirical evidence, propose alternatives that may better resolve the challenges confronted. Spectrum policy for satellite systems has been a topic for regulators for several decades, and the new satellite system, radio technologies, and spectrum sharing approaches make the topic ripe for reconsideration.

Currently, NGSO Fixed Satellite Service (FSS) spectrum is allocated in processing rounds to qualified applicants without explicit protection for incumbents having rights issued in prior rounds. FCC rules first encourage co-frequency operators in certain bands to resolve interference privately (self-governance); failing coordination agreement, the Commission imposes a “1/n rule”. Under the 1/n approach, if the level of interference (“system noise temperature”) rises above a specified level due to the entry of additional wireless users, then access rights to the band(s) in question will be segmented, each of the n systems given access

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[2] FCC 21-123, fn. 30.

to 1/n of the allocated band. This creates a number of implications, including: (1) a potential disincentive to invest in these services given the insecurity of existing access rights; and (2) opportunities to force fragmentation, hobbling competitors' bandwidth access. This rule also assumes that rival systems value spectrum usage equally, which is unlikely. As a result, alternative approaches may be more economically efficient than the 1/n rule.

Recent innovations in coordinating spectrum sharing, such as database-mediated access or sensing-based approaches, could be relevant here and merit examination in the NGSO context. Because the FCC's NPRM proposes to protect systems from prior rounds from those in subsequent rounds, it creates a tiered rights structure similar in some ways to CBRS; services now deployed under this regime may illustrate regulatory options for NGSOs. Finally, we examine the utility of congestion metrics such as interference to noise ratio (I/N), and "system noise temperature" as a basis for the 1/n rule.

1. Introduction

Since 2016, the Federal Communications Commission (FCC) has received applications for U.S. market access from more than twenty distinct networks seeking authorization to launch and operate more than a total of 70,000 satellites (Kriezis and Lohmeyer, 2022). These applications occurred across four distinct Processing Rounds denoted with the year in which the Processing Round took place and the frequency band that it considered: 2016 Ku-/Ka-band, 2017 V-band, 2020 Ku-/Ka-band and 2021 V-band. For these satellite networks, commonly referred to as 'mega-constellations' because they may involve thousands of satellites to deploy broadband, coexistence and interference mitigation between existing and planned satellite and terrestrial networks is of key concern.

As mega-constellation networks progress in the development and deployment of their networks, they are required by the International Telecommunications Union (ITU) and the FCC to conduct good-faith coordination in order to prevent the occurrence of harmful interference[3] . As the density of satellites increases, however, the likelihood of interference events increases, marking the transition from spectrum abundance for NGSO satellites to spectrum scarcity. Currently under the Commission's Part 25 Rules, if networks interfere, they must either coordinate with each other explicitly or evenly divide the spectrum among them (the "1/n rule"). Since the deployment of the latest generation of mega-constellations, consisting of operators like OneWeb and SpaceX's Starlink, the "1/n rule" has not been invoked.[4]

This paper reviews the current FCC rules for spectrum access rights, which evolved in an environment where there were relatively few satellites, and then considers how those rights might adapt given the dense satellite deployments now being constructed. The need for

[3] See Article 9 of the ITU Radio Regulations (ITU, 2020).
[4] Note that the fact that 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 [Nash 1950].

enhanced coordination appears likely, but the implications of alternative policy options are complicated.

2. Background

The International Telecommunications Union (ITU) codifies interference limits from satellite networks into terrestrial networks in Article 21 of the Radio Regulations, and interference from non-geostationary satellite (NGSO) networks into geostationary (GSO) satellite networks in Article 22 of the Radio Regulations (ITU 2020). Article 21 specifically defines power flux density (PFD) limits, within which if a satellite network complies, no harmful interference should result into terrestrial networks. These limits are not statistical, or temporal, in nature and account for the satellite power from an NGSO network into a terrestrial receiver (ITU (2020), and Kriezis et.al. (2021). On the other hand, Article 22 defines equivalent power flux density (EPFD) limits, which are statistical and complex in nature, and aim to ensure that no harmful interference is caused into victim GSO networks.

Clear methodology for computing interference from NGSO networks into other NGSO networks is not currently defined at the ITU, or nationally under administrations like the FCC. As such, the interoperation of NGSO networks, and coordination and coexistence of such networks has recently been a focus area of discussion amongst regulators and operators (Brake 2019). In December 2021, the FCC initiated a Notice of Proposed Rulemaking to facilitate the deployment of both existing and future NGSO systems in order to provide certainty around spectrum sharing requirements (FCC 2021b).

a. NGSO Systems: Technical & Regulatory Overview

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.

Geostationary systems (GSO) consist of satellites orbiting at 35,678 km above the sea level, the altitude at which the orbital period of the spacecraft is equivalent to the rotation of the earth underneath it. This technology permits a single satellite to supply services over a large footprint approximately ⅓ of the Earth in size; video transmissions from just a handful of orbiting craft supply the entire continental United States, e.g., with hundreds of channels of video programming from two competing networks, around the clock. The set-up 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.

NGSO networks consist of satellites orbiting at altitudes other than 35,678 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 66 NGSO satellites that was proposed in the 1980s and deployed in the 1990s (Bloom 2017). The latest generation of Low Earth Orbit (LEO) NGSO systems are oriented toward providing satellite-based broadband and consist of hundreds to thousands of satellites.

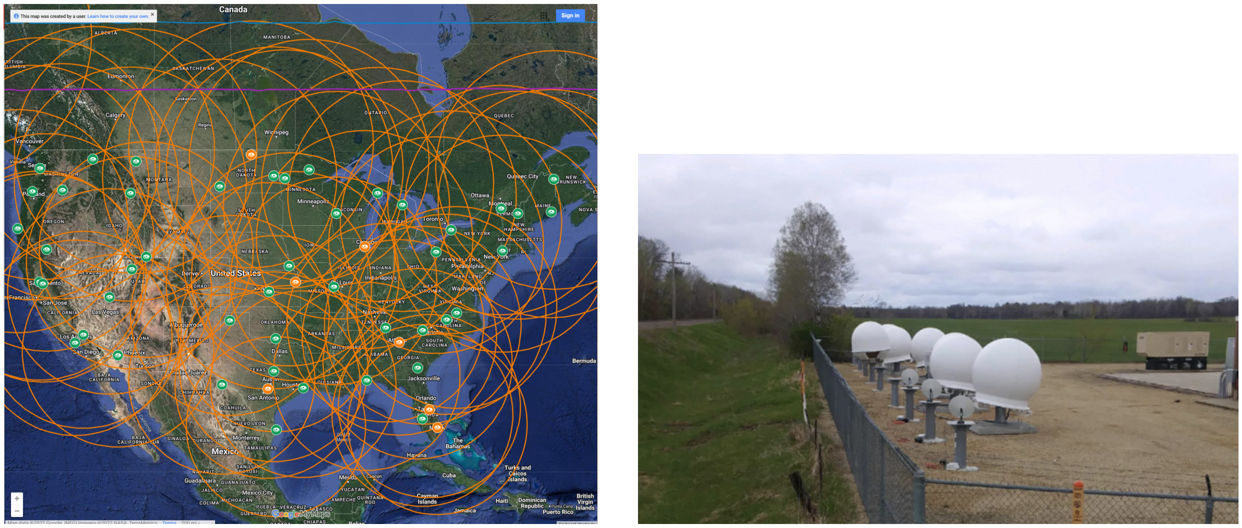
To provide Internet service, end users communicate with a satellite using a user terminal. The signal is sent to a satellite within line of sight. The satellite then relays the packets to a gateway that is connected to the Internet via fiber or to other satellites using inter-satellite links (ISLs), and then routed to a gateway. Response packets follow 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[5].

Figure 1 - Starlink user terminal (retrieved 28 June 2022)

In general, offering low-cost user terminal solutions is still one of the primary technical challenges with deploying these networks. GSO systems tend to use a single parabolic dish, which as previously mentioned maintains fixed pointing relative to the satellite. Due to tracking requirements, NGSO user terminals require two parabolic dishes to maintain connection to the spacecraft during handovers. Phased array technology, shown in Figure 1, enables the use of a single aperture system, but is challenging to offer for less than $500 per unit without selling the device at a loss[6].

As noted, on 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, WI. It is clear from this image that these gateway stations are fixed capital investments, a significant fraction of an NGSO network, which consists of sunk costs.

[5] We provide examples from Starlink because, at the time of this writing, they are the only system serving customers.
[6] At the time of this writing, Starlink sells its terminal for $599.



(a) (b)

Figure 2(a,b) - Starlink gateway (a) locations in the CONUS[7] and (b) Merrillan, WI gateway site (retrieved 28 June 2022).

As of May, 2022, Starlink had progressed furthest in its deployment of the NGSO Fixed Satellite Service (FSS) operators, and reported 400,000 subscribers (up from 250,000 two months prior) in 36 countries.[8] In the U.S., Starlink is active in 48 states. According to this May 2022 report (based on an ex parte FCC filing), it has launched approximately 2500 satellites.

b. NGSO Spectrum Usage environment

Interference mitigation from gateway antennas is 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 (53 for Starlink in CONUS at the time of this writing). Interference from user terminal service links, on the other hand, is far more challenging to coordinate, as user beams blanket the earth globally. It is also possible that user terminals from various providers may be co-located, 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 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

[7] https://www.google.com/maps/d/u/0/viewer?mid=1H1x8jZs8vfjy60TvKgpbYs_grargieVw&ll=40.415314768793245%2C-94.56437201645632&z=5)

[8] Michael Sheetz, "SpaceX's Starlink Satellite Internet Surpasses 400,000 Subscribers," CNBC (May 25, 2022).

prevent in-line events between NGSO and GSO systems. For NGSO systems operating at approximately 1,000 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. 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 rely instead on explicit coordination discussions since the specifics of each system operation impact coexistence.

The particular frequencies in use for these NGSO FSS networks are:

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

Continuing with our example, SpaceX's Starlink uses the Ka band frequencies for many of the gateways illustrated in Figure 2 for feeder links.

c. 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*, ΔT/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)[9].

Thus, 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. That being said, band segmentation occurs for both parties, so coordination is generally approached in earnest, as band segmentation would likely prevent either party from continuing to serve broadband, and from closing their business case. Interestingly, the CFR makes no statement about the verifiability of an interference event.

The "1/n" Rule

The established rule specifies that, in the event of unacceptable interference and lacking agreement for 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 share constituting 1/n of the

[9] This approach was first adopted in the FCC's Ku Band Report and Order and Further Notice of Proposed Rulemaking (FCC, 2002). Thus, it is understandable why this regulatory approach would serve as the starting point for regulations for the NGSO/LEO systems.

available bandwidth). The satellite licensees then select their band in order of their system launch.[10] Once the interference levels are no longer exceeded, the operators may resume using the entire frequency band. Key attributes of the 1/n rule invoke the following questions and implications:

- The rule does not specify who measures the increase in I/N or how the 1/n should be applied. Is the spectrum segmentation nation-wide or is it specific to the locality of occurrence?
- The rule does not account for who is responsible for 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.
- The rule assumes that all operators' transmissions are equally valuable.

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 of the systems are fully deployed.

At the time of the four processing rounds, application fees were $471,575 per application, and also required applicants to post a bond within 30 days of application grant. This bond escalates to $5M 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, incentivizes operators to over-file 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 & Hill (1990) involves homesteading land in the American West. 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. Though care is required in generalizing from the experience of terrestrial property rights to access rights in outer space, a relevant consideration is whether the pre-emptive rights established by the FCC’s 1/n rule will result in similar resource dissipation.

[10] 47 CFR § 25.261. 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.” As discussed in Brake (2019), this precedence based on application is deeply rooted in satellite policy beginning at the International Telecommunications Union.

Overview of FCC's NPRM

The goal of the NPRM is to facilitate the deployment of both existing and future NGSO Fixed Satellite Service (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 coordination be limited to systems authorized in the same round?

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 provides no incentives for incumbents to improve the technology of the space segment to be more flexible or more tolerant of other systems. This might be addressed through sunsetting the rights of incumbents, which is also raised in the NPRM.

- 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.

- 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 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?

3. Economic Considerations with the Current System of Outer Space Access Rights

Space provides opportunities for innovation and productive social growth. At the same time, space has features of a common pool resource and hence is subject to concerns about a tragedy of the outer space commons. Spacefaring implicates risks involving both physical collisions (space debris) and radio interference. Both are discussed in the FCC approval of the

SpaceX application (FCC 2018) and in the FCC's Report and Order And Further Notice of Proposed Rulemaking In the Matter of Mitigation of Orbital Debris in the New Space Age (FCC 2020). The NPRM discusses changing the rights regime described above 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.[11] 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 these to be property rules, which include exclusive rights, restrictions on particular activities, or governance arrangements to manage commons (Lueck & Miceli, 2007). Exclusive rights assign ownership to individual users, whereas governance involves opportunities for individuals to work out arrangements, including through sharing rules. The economic problem to be addressed is whether rights of holders conflict such that outputs created, by the sum of the parties, is diminished relative to an alternative rule regime (Coase 1959, Hazlett 2005).

The economic regime governing satellites leans toward governance, with a focus towards 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 of 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, launch and operate a network of satellites. From a spectrum perspective, the NGSO systems fall under an unassigned spectrum management regime (Weiss et.al., 2021) in that no operator has exclusive rights to any "parcel" of electrospace (i.e., a time, space, frequency block). Amateur radio is another example of this sort of regime (Bustamante et. al., 2022).

Property rights tend to adjust in response to the changing economic environment, an adaptive feature of a market system. The key driver prompting such social movement is a shift in the balance between supply and demand, as when a previously abundant resource – where rival activities can coincide without significant conflict – becomes scarce (Demsetz 1967; Anderson & Hill 1975; Libecap & Smith 2002). In this case, demand exceeds supply, and coordinating rules to prioritize access often become worth the cost of organizing. These costs involve defining various rights, distributing such rights to particular parties, and then enforcing the rules established. 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, but in facilitating the most valuable resource employments

[11] The NPRM indicates that this temporal rights regime has in fact been implemented in recent NGSO licensing decisions. However, it is not currently stated in the relevant rule text. The proposal here is to make this temporal priority explicit.

(Coase 1959). The ongoing effort by regulators to establish additional access rules in satellite bands reflects the changing scarcity conditions, and can address the value dissipation problem associated with certain types of rivalry – "tragedy of the commons" (Hardin 1968). Regulatory efforts to shape access rights, undertaken in the United States by the FCC, involve an array of options, each of which constrains non-exclusive 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 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. The frequency spaces allotted to such licenses may be intensively shared by users, but the license holder is a coordinating agent; competition between such agents governs the optimization process. Such rights are a relatively recent innovation, and have enabled a switch from administrative allocations to competitive bidding (auctions) for licenses issued by regulators, most notably for those licenses used by mobile services networks. The authors note that auctions have not been implemented for satellite systems, given the high capital expenditures associated with building out and launching the networks, and will likely not be implemented in the future. An alternative to either of the above is the license-exempt model, in which the regulator grants non-exclusive use rights but imposes generally 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 are imposed by the rigidities of allocation rules by central authority).

a. Self-governance and information sharing

With the above in mind, we can offer some preliminary thoughts on the current regime, starting with self-governance and information sharing. As we proceed, it is important to keep in mind that we consider some of the potential issues theoretically, while emphasizing how well each potential issue is relevant in practice in orbital space satellite communities. The initial strategy for resolving coordination and interference disputes is self-governance, or coordination, which has proven useful in addressing conflicts in many spectrum sharing situations (Sandvig 2004). A coordination agreement between SpaceX and OneWeb was recently concluded that addresses spectrum conflicts between these two systems[12]. As Ostrom (1990) 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. While information sharing amongst NGSO operators can promote more successful coexistence, numerous operators urged the FCC that if it required information

[12] See https://www.space.com/spacex-oneweb-satellite-internet-constellation-coexistence (retrieved 5 July 2022). The terms of the sharing agreement were not disclosed. Note that this agreement does not address sharing with other NGSO constellations in the same band, so it is an incomplete governance arrangement.

sharing to do so in a manner that preserved confidentiality of the operators end users (Astra and Mangata comments on (FCC 2021b)). The only economic question is the costs: if sharing information is too costly, or if enforcement of information sharing is too costly, then the additional requirements could undermine efficiency.

b. Incentive Analysis

Beyond issues with self-governance, we can consider some mechanism design issues. Economists use incentive analysis to examine what stakeholders might be motivated to do based on the returns and the costs that they experience based on potential actions. It does not attempt to predict the behavior of any particular actor. The FCC, as the regulator, must consider behaviors that the industry does not normally exhibit, and incentive analysis can be a helpful tool to understand these outliers. Of special note are mechanisms to address externalities, which would include uncompensated interference. 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 parties), and effectively blocks rival services from producing more valuable communications. For social efficiency, rights and regulations should support mechanisms that internalize externalities, allowing (indeed, forcing) actors to face accurate prices that reflect the true opportunity costs of given actions. The various rules applied, however, will not be free to impose or enforce, and transaction costs of alternatives will influence social efficiency

In this instance, the 1/n rule allocates access rights but may not disincentivize interference[13]. That is, first, because the marginal satellite that generates sufficient traffic 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, such that the parties would not make deals where, predictably, those with higher demands would out-bid those with less valuable traffic. Third, the 1/n rule assigns rights based on *claims* of interference, which may lead to incoherence in the enforcement of the rule On the other hand, the streamlined nature of the overall process – relaxed FCC oversight until a situation of possible congestion, then a numerically simple rule is imposed to separate competing systems – may dominate. If so, the transactional economies of the FCC's proposed rules would be advantageous. In other words, the 1/n rule is quick and simple to implement, allowing for rapid mitigation of interference events; it is possible to imagine that negotiated approaches to mitigate interference events would be more costly and time consuming to implement.

There are a few broader issues to consider. First, if there is not an interference problem, why not wait for increasing demand to provide a framework? Since the amount of interference depends in part on technology as well as on access rights, changes in technology imply standards should be continually adapting (Werbach 2011). This is the most significant rationale to consider in a non-exclusive access rights model (e.g., the "spectrum anarchy" discussed by Bustamante et.al. (2021)) and its relationship to more centralized regulations. The alternative

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[13] For the systems currently approved, the 1/n rule is sufficiently costly in reduced capacity that spurious claims are unlikely.

consideration (and the answer to the question posed above) 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, congestion management seems to be based on a *claim* of interference by one of the parties. For a claim to be credible, it should be supported by data that conforms to agreed-upon measurements transparent across all parties (and the regulatory authority). Because this is based on unilateral claims, strategic falsification is a risk, though, because these operators are dealing with each other repeatedly, this (i.e., falsification) may not be a dominant strategy (Axelrod 2006).

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. If this occurs (i.e., the events passed) and the remediation mechanism is triggered, then it is best thought of as an ex post consequence of interference rather than a mechanism to mitigate current interference. It is important to note that band segmentation plays a punitive role in ex post enforcement, unlike real time mitigation (Polinsky and Shavell, 1998; Polinsky and Shavell, 2000).

There are additional issues with the 1/n rule that each involve incentives. One issue is that non-exclusive access may undermine agreements to split bands in response to interference claims. One might imagine agreements among the operators that bargain for different priority should at least one claim interference and invoke the 1/n rule. A problem is that n may vary and there can be new entrants, due to non-exclusive access, so that rights post-band-splitting are not protected, thereby reducing incentives for private arrangements to address interference. Another is that the splitting rule does not account for the size of the network. If Network A is a mega-constellation with 10000 satellites and Network B has 1000 satellites, they still split the band by n=2.

4. Alternative Models of Access Rights

With the general issues raised above in mind, this section outlines options for access rights as the density of orbiting spacecraft increases. This progresses from distributed, light interference management to centralized interference management. Currently, because only a small number of constellations have started launching satellites, interference does not appear to be a major issue, and as long as that continues to be the case, the light interference management schemes discussed here, loosely based on non-exclusive 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 centralized schemes become potentially useful.

a. Non-exclusive access

Despite Hardin's (1968) concern about a tragedy of the commons, open or non-exclusive access is appropriate when spectrum is abundant and interference events and packet collisions do not significantly affect application performance and associated economic benefits. As previously mentioned, power masks are already in place in order 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 WiFi. 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 launching satellites dominates the cost of more sophisticated interference management schemes. However, if the satellite density continues to increase without bound, 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.

Non-exclusive access aligns with prevailing public international space law. According to the Outer Space Treaty (United Nations 1966), "exploration and use of outer space…shall be carried out for the benefit and interests of all countries…" In addition, the treaty prohibits "national appropriation of outer space." Arrangements that more clearly align with prevailing international regimes have advantages as far as implementation.

b. 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, or control signaling). This information could then be used to assess the likelihood and consequences of future interference events, and promote more centralized interference management schemes that avoid interference, analogous to the Spectrum Access System (SAS) in CBRS. We discuss this in more detail below.

Sensors can be deployed at various locations to identify and characterize interference events, and to reduce incentives to mis-declare such events or exaggerate their effects. These may only detect signal strength across the allocated band and along certain directions, and hence could be relatively inexpensive. With many sensors deployed near a ground station, or across a coverage area, it may be possible to support claims that an interference event has occurred, and to provide some information about the source location. Sensor and database specifications could be part of an industry standard, analogous to WiFi standards.

The FCC NPRM asks whether information about beam directions should be shared by incumbents in order to avoid interference by entrants in subsequent rounds. More generally, databases for resource management across multiple service providers may request information about satellite trajectories, coverage and resource utilization. This information is likely to be considered proprietary, possibly revealing information about market share in particular locations, which can pose a strong disincentive to share. 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 [Grissa 2021].

A standard for sensors and databases could set requirements for sensor sensitivity and specify sensor outputs along with protocols for storing and maintaining this data, identifying interference events, and conducting resource management. The sensors and database systems could then be supplied by third-party providers. A difference from current WiFi protocols for unlicensed access is that the satellite protocols would have to account for priority rules for incumbents versus newer entrants. Those could serve as the foundation for more centralized interference management and resource allocation protocols as the density of satellites increases.

c. 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 cell or amateur radio). As spectrum use increases, non-exclusive access may lead to poor performance in terms of latency and throughput and thus to efforts to more clearly define access rights in space. Efficiency can potentially be improved through centralized 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” (Huber 1997), the licensee with exclusive, flexible-use rights enables rival uses (adjusting 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 can be inefficient to assign a particular satellite provider exclusive rights to a band globally, and so interference must be managed across different providers and across different national legal and regulatory regimes.[14]

Thus, for satellites, exclusive use would serve as a means for interference protection, and perhaps less so as a means for enabling centralized resource optimization. One approach for achieving this function is to allow priority access rights to be traded: providers would be able to negotiate for priority in a particular region of space, time, frequency. 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 exchange their priorities at

[14] This is one of the reasons for use of the “unassigned” spectrum management regime in this case (Weiss et.al. 2021).

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 aspects of property rights law, where exclusive rights are granted to agents who first make productive use of the resource. Allowing priorities to be traded creates a market for those rights, which then allows a provider to trade off the cost of interference protection with the cost of launching additional satellites and equipment upgrades.

As satellite traffic grows and interference becomes more problematic, enforcement of priority rights may require a database and centralized decision-making for channel allocations as previously described for open access, analogous to an SAS in CBRS. A database of this nature, applied to satellite systems is likely unrealistic given current technology, feedback times for telemetry and telecommand, and nuances to predicting orbital locations. Should these technical challenges be overcome in the future, the database could store priority assignments across time, frequencies, and directions, and would make dynamic channel assignments given incoming requests. Specification and coordination of the databases and associated resource allocation mechanisms would likely have to be developed as an industry standard.

A database scheme and protocol for resource management may take advantage of advances 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.

4 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, such that a new satellite beam transits over head every ten seconds and a new spacecraft every few minutes; 2) many directional, extremely long-distance links cross paths and transmission footprints are large.

Any harm due to undesirable interference occurs *only* at the location(s) of the impacted receiver(s), not at the location(s) of the transmitter(s) or anywhere in the space in between. A coordination arrangement could define access rights at (potential) receiving locations, referred to as a form of spectrum usage right (SUR) in [Ofcom2006]. Separate rights are then defined for the two directions in the case of a two-way communication link, which often use different slices of spectrum.[15] To be more specific, rights on ground, and in space, can be defined similarly as they are for cellular services, i.e., the right to impinge a given geographical area on earth with radio waves subject to certain power-spectral constraints. This way, rights on ground 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 convenient and sufficient to only define the transmission rights. With moving receivers in outer space and long-range highly-directional links, however, a beam direction towards one's own satellite becomes interference when another operator's satellite comes close to the first position. Thus, it is hard to forestall interference by constraining the transmitters only, without specifying the receivers' positions as a function of time and their interference tolerance. To protect exclusive access rights, technologies need to be developed to determine interference levels and identify interference sources to facilitate enforcement.

As long as 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. 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, develop industry standards, and to seek mediation for interference mitigation and remediation, with the court system and/or the FCC as the last resort;
- 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;
- Access rights in regions with more traffic and profit could be valued more in the market, which incentivizes spectrum resources to be put to the most productive use;
- In regions with light traffic, it may not be worth the cost to enforce rights, so that non-exclusive access is a likely outcome;

[15] If two-way communication occurs only over a relatively short range, i.e., the transceivers are near each other, it is convenient and sufficient to define one right/license without separating the two directions. This is indeed the situation in cellular networks.

5. Discussion and Recommendations

Space governance involves two tragedies of the commons: physical debris and spectral interference. Physical debris has been of special concern with the increase in mega-constellations, as thousands of ships to provide for Internet broadband exacerbated a Space Age tragedy of the commons (David 2021). Despite concern that mega constellations pose specific risks for debris (Boley and Byers 2021), spectral interference has received less attention.

The current FCC rulemaking addresses interference and NGSO sharing. Since conflicts amongst NGSO constellations are currently not much of an issue because these systems are still in the early stages of development and deployment, an opportunity for experimentation exists, where decentralized approaches may be tried and then compared to conventional licensing. The NPRM focuses largely within a satellite system licensing regime, not a broad spectrum licensing regime. Consideration of a more decentralized perspective given the demand for space satellites is already regulated and there are alternatives to licensing that could incorporate greater self-governance is recommended.

In essence, the NPRM begins to address the characteristics of a governance approach for NGSO systems: precedence of earlier round systems and consequences of failing to agree on bi-lateral coordination (i.e., the 1/n rule). As discussed above, the processing round approach incentives parties to file for rights for larger constellations than will likely be utilized. This obscures,and over-states the actual spectrum usage environment that systems are likely to encounter in operation, and needlessly complicates coordination Linking priority with the processing round protects engineering and capital investments of earlier round companies, but could disincentivize innovation. This disincentive would be removed if replenished satellites would not enjoy the same priority. Such sunsetting of the priority status is raised in the NPRM. However, if a sunsetting provision is poorly implemented it could also deter investment.

Another observation that is made is that the NPRM addresses a situation that is unlikely to occur, and, if it occurs, would last for a few seconds and would be localized to user stations in a particular geography. There are at least three implications for any coordination system (including the 1/n rule). One is identification...A second is localization...Thirdly, continuous monitoring of the spectrum usage environment. Our analysis suggests consideration of all three can inform future discussions of changes in rules in anticipation of increasing interference.

References

Anderson, Terry, and P.J. Hill. 1975. “The Evolution of Property Rights: A Study of the American West,” *Journal of Law & Economics* 18 (April): 163-79.

_____. 1990. “The Race for Property Rights,” *Journal of Law & Economics* 133 (April): 177-97.

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

Bloom, John. 2017. *Eccentric Orbits: The Iridium Story*. Grove Press, 2017.

Boley, Aaron C., and Michael Byers. 2021. "Satellite Mega-Constellations Create Risks in Low Earth Orbit, the Atmosphere and on Earth." *Scientific Reports* 11(1): 10642.

Bustamante, P., Gomez, M., Murtazashvili, I., & Weiss, M. 2020. "Spectrum anarchy: Why self-governance of the radio spectrum works better than we think". *Journal of Institutional Economics* 16(6): 863-882.

Bustamante, Pedro et al. 2022. "Polycentric Governance in the Amateur Radio Community: Unassigned Spectrum and Promoting Open Innovation"." In *Telecommunications Policy Research Conference*, Washington, D.C.

Brake, Douglas. 2019. *Spectrum Policy and the Future of Satellites, Aspen Institute, Communications and Society Program*. Available at: https://www.aspeninstitute.org/publications/spectrum-policy-and-the-future-of-satellites/

Coase, R.H. 1959. "The Federal Communications Commission". Journal of Law & Economics 2: 1-40.

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

Demsetz, Harold. 1967. "Toward a Theory of Property Rights," *American Economic Review* 57 (May): 347-59.

Federal Communications Commission. 2002. The Establishment of Policies andService Rules for the Non-GeostationarySatellite Orbit, Fixed Satellite Service in the Ku-Band, Report and Order, Further Notice of Proposed Rulemaking, FCC-02-123, 17 FCC Rcd 7841 (11).

_______. 2003. Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands, NPRM, DA/FCC #: FCC-03-289, Docket/RM: 03-237 (Released Nov. 2003).

______. 2020. In the Matter of Mitigation of Orbital Debris in the New Space Age Report and Order and Further Notice of Proposed Rulemaking FCC 20-54 (Released April 2020).

_______. 2018. Space Exploration Holdings, LLC, Application for Approval for Orbital Deployment and Operating Authority for the SpaceX NGSO Satellite System FCC-18-38, March 2018.

______. 2021a. In the Matter of Space Exploration Holdings, LLC, Application for Approval for Orbital Deployment and Operating Authority for the SpaceX NGSO Satellite System Supplement: Memorandum Opinion, Order and Authorization, IBFS File No. SAT-LOA-20161115-00118 (Released Mar. 29, 2021).

_____. 2021b. In the Matter of Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems: Order and Proposed Rulemaking, IB Docket No. 21-456 (Released Dec. 15, 2021).

Grissa, M., A. A. Yavuz, B. Hamdaoui and C. Tirupathi, 2021. Anonymous Dynamic Spectrum Access and Sharing Mechanisms for the CBRS Band," in IEEE Access, vol. 9, pp. 33860-33879, 2021, doi: 10.1109/ACCESS.2021.3061706.

Hardin, Garrett. 1968. "The Tragedy of the Commons," *Science* 162 (Dec. 13).

Hazlett, T.W. 2005. "Spectrum Tragedies," *Yale Journal on Regulation* 22 (Summer 2005), 242-74.

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

International Telecommunications Union (ITU) Radio Regulations, 2020. Available at http://handle.itu.int/11.1002/pub/814b0c44-en

Kolodzy, P. 2006. "Interference Temperature: a metric for dynamic spectrum allocation", International Journal of Network Management, vol. 16, no. 2, pp. 103-113.

Kriezis, A. et al., 2021. "Power Flux Density (PFD) Compliance Validation of FCC's Ka-band NGSO Processing Round Participants," 2021 IEEE Aerospace Conference (50100), pp. 1-14,

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

Libecap, Gary, and James L. Smith. 2002. "The Economic Evolution of Petroleum Property Rights in the United States," *Journal of Legal Studies* 31 (June): S589-S608.

Lueck, D. and Miceli, T. J. 2007. 'Property law', in Polinsky, A. Mitchell and Shavell, S. (eds), *Handbook of Law and Economics*, vol. 1. Amsterdam: Elsevier, pp. 183–257, 2007

Nash Jr, John F. 1950. "The bargaining problem." *Econometrica* (1950): 155-162.

Ofcom, 2006. Technology-neutral spectrum usage rights, Final Report, 1721/TNR/FR/1, 10th (February 2006).

Polinsky, A. Mitchell and Steven Shavell 1998. “Punitive Damages: An Economic Assessment” Harvard Law Review v. 111, No. 4.

Polinsky, A. Mitchell and Steven Shavell. 2000. "The Economic Theory of Public Enforcement of Law." Journal of Economic Literature, 38 (1): 45-76.

Sandvig, Chrisian. 2004. “An initial assessment of cooperative action in Wi-Fi networking.” Telecommunications Policy 28 (708): 579-602.

United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies Resolution 2222 (XXI), 1966 https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

Weiss, Martin; Palida, Ali; Murtazashvili, Ilia; Krishnamurthy, Prashant; Erickson, Philip “A Property-Rights Mismatch Approach to Passive-Active Spectrum Use Coexistence.” In: IEEE DySPAN, Dec 13, 2021.

Werbach, Kevin. “The Wasteland: Anticommons, White Spaces, and the Fallacy of Spectrum.” Arizona Law Review 53 (2011): 213.

To define receiver rights in the special case of NGSO systems, at least the following two forms of delineating rights in space are conceivable:

1) Divide the sky near the satellites' altitudes into cells. For example, a certain cell may be of *x* degrees longitude and *y* degrees latitude above Washington, DC, which more than covers that metropolitan area. If the spectrum is also divided into subbands of, say approximately 500 MHz each, then operators may acquire rights to transmit in some subbands to satellites as they fly above Washington, DC (and at the same time avoiding interference to neighboring regions). An operator may bid for a bundle of such rights to provide national, continental, or even global coverage. As satellites can switch channels as it crosses cell boundaries, an operator may acquire rights in different subbands in different cells to provide such coverage. An operator who has no right to transmit to satellite positions that cover Washington, DC may not provide services to that area. Yet another operator might lease from license holders or spectrum owners in order to serve some areas of interest. A small overlap of rights at the boundary between regions may be allowable as is the case in ground cellular networks.
2) An alternative is to define one unit of access right for each orbit. The FCC has granted such rights for GSO satellites, which are of course stationary in the sky. In contrast, an NGSO satellite's position orbit in the sky is a function of time. To also allow for minor orbit alterations and antenna beam widths, the right may cover a spatial band along the orbit. The right protects a region that "moves" with a satellite's planned orbit. In particular, a static directional transmission may infringe the right at one time (when the satellite flies into the beam) but not at other times. Since an operator currently needs approval to occupy an orbit, the approval process would also be a convenient time to parcel out spectrum access rights.[16] The advantage of such a definition is that the rights protect exactly the (moving) satellites rather than a stationary region. A pleasant consequence is that if a lone satellite is in a large region, its operator can transmit to it using all bands without infringing anyone's rights. There are potential conflicts, e.g., when two satellites are within a certain distance from each other, or when a beam's sidelobes cover an unintended receiver. In this case, if the incumbent orbit already has exclusive access right over a subband, then other operators need to yield. Alternatively, the newcomer could also lease a portion of the resources from the incumbent, or the incumbent could even allow open access if there is hardly contention.

The preceding definitions of rights, in the case of liberal licenses, enables an operator to acquire access rights on ground and in space in the market in order to provide network services. It also allows trading, leasing, or even open access (should the owner be so inclined) to spectrum resources. Moreover, it is conceivable that NGSO access rights be merged or further divided to facilitate their most productive use as technologies and economic conditions evolve.

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[16] Satellites may need to alter their orbits for a number of reasons. Rights should be defined to handle such changes.