The Current and Future State of Non-Geostationary Orbit (NGSO) Fixed-Satellite Service (FSS) Interference Regulation Metrics

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I. Introduction

Since humans first started launching satellites, space has become an increasingly critical part of our everyday lives. With thousands of satellites scheduled to be launched in the coming years, there grows an increasing risk of interference between co-frequency satellite operators. To avoid such interference, radio frequency spectrum is regulated by government entities: the Federal Communications Commission (FCC) in the United States; and the International Telecommunications Union (ITU), globally. Recent growth in the space telecommunications sector is giving rise to increasingly large and complex Non-Geostationary Orbit (NGSO) Fixed-Satellite Service (FSS) systems. As a result, spectrum sharing rules within the United States require review in order to promote competition from new operators while protecting existing systems from harmful interference.

In December 2021, the FCC released a Notice of Proposed Rulemaking (NPRM) on revising spectrum sharing rules for NGSO FSS systems, which questioned whether current standards, particularly interference-to-noise, will suffice as a metric in evaluating modern satellite systems [1]. The FCC also asked for comments on how spectrum sharing rules and metrics may be revised. This paper discusses the following topics: the current metric (interference-to-noise) for preventing harmful interference; contemporary concerns with that metric; alternative metrics proposed by commenters in response to this NPRM; and the FCC's decision to move forward with a degraded throughput methodology.

A. The Current Metric: Interference to Noise

A key metric used to regulate and assess the likelihood of interference from NGSO FSS systems into earth stations is the interference-to-noise ratio (I/N). I/N compares the strength of an interfering signal, I, to the strength of the background thermal noise, N, of a system and is determined similarly to a link budget calculation between a satellite 'interferer' and a 'victim' earth station, as shown in Figure 1[2].

The ITU defines parameters for a generic fixed service earth station to be used as the victim in these calculations [3]. Examples of I/N calculations may be found in [4]. The I/N metric is used by both the FCC and the ITU: the FCC uses I/N to determine whether coordination with other co-frequency operators is necessary [5]; meanwhile, in ITU-R F.1495 [6], the ITU defines time-based regulations with explicit I/N values that should not be exceeded beyond brief periods of time. The effectiveness of I/N as a metric to regulate interference between modern satellite systems was called into question by the FCC in its December 2021 Notice of Proposed Rulemaking (NPRM) on revising spectrum sharing rules for NGSO FSS systems [1]§.

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§At 17-21, "Level of Protection for Earlier-Round Systems"

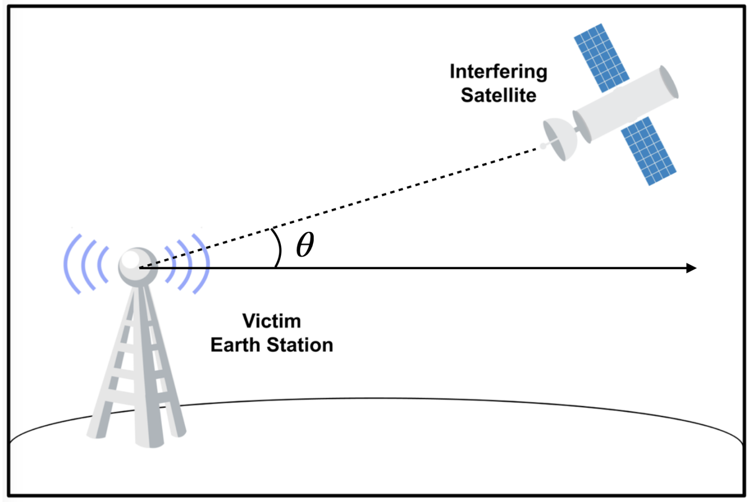

Fig. 1 Geometry of satellite interference into a victim Earth station.

II. NGSO FSS Spectrum Sharing Rules

A. Rulemaking Timeline

Since 2017, the FCC has sought to update rules governing NGSO FSS spectrum sharing. This process has unfolded over a variety of announcements and petitions, which will be explained in brief below. A timeline of these document releases is shown in Figure 2.

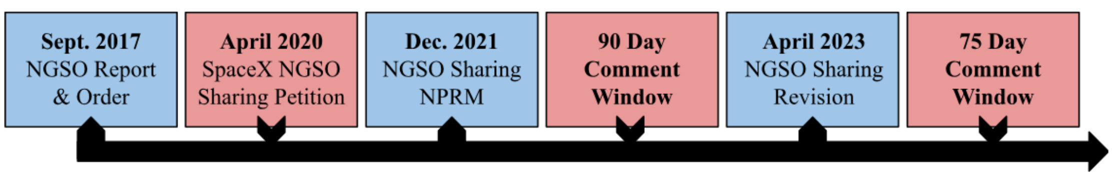

Fig. 2 Timeline of FCC Rulemaking on NGSO FSS Spectrum Sharing.

On September 27, 2017, the FCC released a Report and Order, which updated rules for NGSO FSS Systems (this report is hereafter referred to as the "2017 NGSO Report & Order" [5]). This Report and Order sought to remove regulatory obstacles for companies proposing to provide satellite broadband internet access by updating frequency allocations in the Ka-band, power limits, and spectrum sharing and service rules to facilitate these emerging systems.

On April 30, 2020, SpaceX petitioned the FCC to clarify spectrum sharing obligations among systems authorized through different processing rounds (this petition is hereafter referred to as the "2020 SpaceX NGSO Sharing Petition" [7]). In this petition, SpaceX proposed using an I/N interference limit to define the obligations of later-round systems to protect earlier-round systems. I/N is relied upon as the key metric to define a variety of regulations for parties operating within the same or adjacent frequency bands, and is used by both the ITU and FCC.

The FCC responded to SpaceX's petition on December 15, 2021 with a NPRM on revising spectrum sharing rules (this NPRM is hereafter referred to as the "2021 NGSO Sharing NPRM" [1]). This NPRM proposed two key changes: 1) to limit the FCC's default procedure for resolving spectrum-splitting conflicts to systems authorized within the same processing round, and 2) that later-round systems should protect earlier-round systems but that this protection should sunset after a period of time. Over the following three months the FCC solicited comments and feedback from industry and the general public.

Finally, on April 21, 2023 the FCC released a Report and Order which revised spectrum sharing rules for NGSO FSS Systems (this report is hereafter referred to as the "2023 NGSO Sharing Revision" [8]). This report adopted three key changes: 1) a degraded throughput methodology to clarify the protection obligations between systems authorized through different processing rounds, 2) a protection sunset period, and 3) clarification that operators must coordinate with each other in good faith. In addition, the FCC sought additional comments on "which specific metrics should be used to define the protection afforded to an earlier-round NGSO FSS system from a later-round system" as well as recommendations for the implementation of a degraded throughput methodology.

Prior to the 2023 NGSO Sharing Revision [8], operators applying for licenses who sought to use the same frequency ranges as pre-existing systems were considered by the FCC on a case-by-case basis, and codified rules for the protection of pre-existing systems did not exist [5]*. Furthermore, existing rules and considerations were based on I/N as a metric for evaluating interference (as opposed to the degraded throughput methodology introduced in the 2023 NGSO Sharing Revision). In order to understand the motivation for using degraded throughput as a metric, it is first necessary to understand the benefits and problems with I/N. Historically, regulating bodies have relied upon two types of I/N spectrum sharing regulations: the I/N coordination trigger and the dynamic I/N threshold. Although the FCC has not adopted dynamic thresholds, both coordination triggers and dynamic thresholds will be explained below as both are relevant to the ongoing evolution of interference regulations.

B. The I/N Coordination Trigger

The 'coordination trigger' requires parties operating in the same frequency to coordinate their transmissions if certain I/N levels are exceeded. In Appendix 8 of the Radio Regulations [2], the ITU defines an I/N value of -12.2 dB (a 6% increase in noise temperature $\Delta T/T$) as the threshold for triggering co-frequency coordination actions. The process for conducting this coordination is described in Article 9 of the ITU Radio Regulations [9].

The FCC has similarly adopted -12.2 dB as a threshold for triggering coordination, though it requires a different set of actions than the ITU. The FCC's current spectrum sharing rules encourage completing coordination agreements between NGSO FSS operators †. Unlike the ITU, the FCC offers no prescribed method for coordinating, and coordination agreements are negotiated between operators. However, an operator may still become licensed without coordination agreements if they demonstrate that they will not cause harmful interference to other existing systems [1]‡.

If a victim receiver experiences I/N levels in excess of -12.2 dB due to interfering emissions from another NGSO FSS system, and coordination can not be reached, then a "default spectrum splitting" procedure defined by the FCC goes into effect. This default procedure takes each of the n operators involved and confines each operator to $1/n$ of the assigned spectrum. Operators may transmit only in the narrow band ($1/n$) while the threshold is exceeded, but full-band operation may resume once action has been taken to end the interference and the threshold is no longer being exceeded, as shown in Figure 3 [1]§. Operating with decreased bandwidth reduces performance, so this default spectrum splitting procedure encourages coordination agreements between system operators to avoid band segmentation.

C. Dynamic I/N Thresholds

The ITU has also defined I/N levels which transmitters are allowed to exceed as long as they are exceeded only up to a specified period of time. An example of permissible interference level regulations can be found in ITU-R F.1495 [6], which defines the following criteria to protect fixed service operations within the 17.7-19.3 GHz band:

Long-term	I/N should not exceed –10 dB for more than 20% of the time in any year.
Short-term	I/N should not exceed +14 dB for more than 0.01% of the time in any month, and I/N should not exceed +18 dB for more than 0.0003% of the time in any month.

Dynamic I/N analysis uses a probabilistic approach to verify compliance with these time-based regulations. In dynamic I/N analysis, a number of datapoints are randomly sampled across a range of input variables (for example, picking random points in time over the course of a year and looking at the satellites' positions at each time). The goal of this simulation is to accumulate a dataset that representatively describes the I/N levels that the constellation will produce.

For each randomly sampled set of variables, the I/N value is calculated and added into a time-weighted function which describes the percent of time that the I/N level is predicted to be some value. This time-weighted distribution function is then aggregated into a cumulative distribution function which represents the percent of time that the I/N is predicted to exceed some value. An example of a cumulative probability distribution function of I/N is shown in

*At 59-61, "Applications after a Processing Round"
†See [5] at 49, "Default Sharing"
‡At 16, "Protection of Earlier-Round Systems from Later-Round Systems"
§At 5-6, "NGSO FSS System Spectrum Sharing Overview"

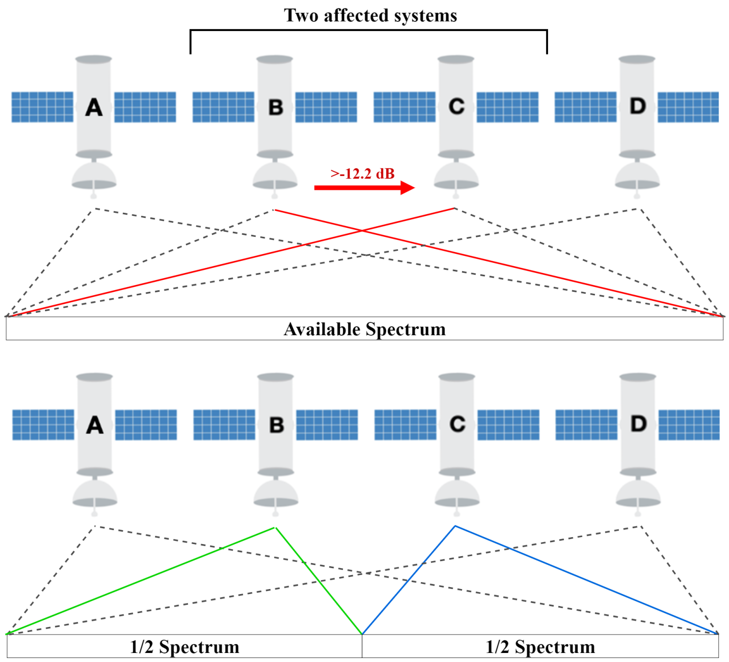

Fig. 3 Interference triggering the default spectrum splitting procedure. (Top) Four satellite networks (A-D) share a common spectrum band. In the event of interference between networks B & C, each of these two networks is confined to 1/2 of the available spectrum, while networks A & D retain full access to the spectrum (bottom).

Figure 4. To show compliance to a dynamic I/N threshold, the probability of exceeding the I/N value must be lower than the permissible percentage of time, which is visually represented by the calculated I/N not crossing over the red line delineating the long- and short-term limits. In Figure 4, the system complies to the permissible interference level in ITU-R F.1495.

The ITU defines I/N analyses as being calculated between an interfering operator against a generic fixed service victim earth station, rather than real-world systems [3] (the implications of this will be discussed later in this work). It is notable that dynamic I/N regulations deliberately allow operators to produce large I/N levels for brief periods of time.

D. Applications after a Processing Round

The FCC licenses NGSO FSS operators in "processing rounds" that occur on an irregular basis triggered by either a new applicant or the FCC itself [1] *. In the 2017 NGSO FSS Report and Order [5], the FCC did not define spectrum sharing rules for later-round applicants seeking authorization in the same frequency bands as operators authorized through earlier processing rounds. Instead, the FCC ruled that the default spectrum-splitting rule would be "initially limited" to applicants in the same processing round, but did not codify this in its published rules. Additionally, the FCC ruled that later applicants had to be considered on a case-by-case basis at that time to protect expectations and investments while still allowing for new entry [5] †. In the 2023 NGSO Spectrum Sharing Revision, the FCC ruled that the default spectrum-splitting rule will be limited to applicants in the same processing round, and that later-round applicants will be required to protect earlier-round applicants from harmful interference.

III. Notice of Proposed Rulemaking on Revising Spectrum Sharing Rules

On April 30, 2020, SpaceX filed a petition for rulemaking to revise and clarify spectrum sharing rules among co-frequency NGSO FSS systems authorized through different processing rounds ("2020 SpaceX NGSO Sharing Petition" [7]). In this petition, SpaceX argued that the FCC can not indefinitely maintain a case-by-case approach and must establish uniform procedures for later-round systems. Additionally, SpaceX argued that clarifying the

*At 3-4, "Processing Round Procedure Overview"
†At 61, "Applications after a Processing Round"

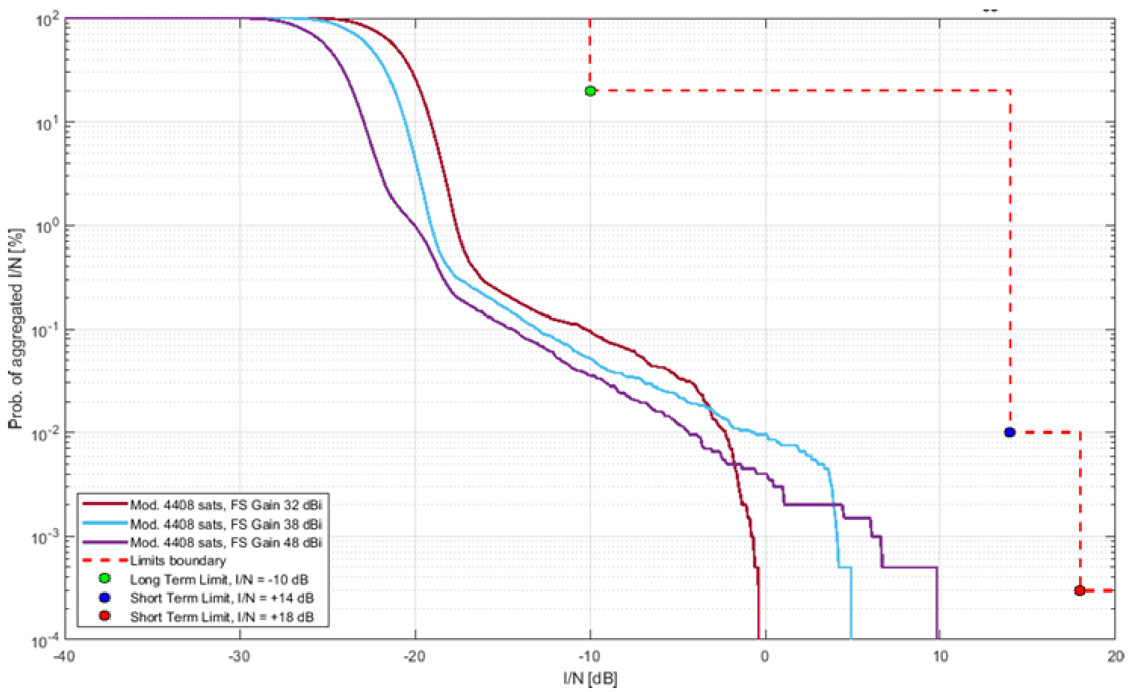

Fig. 4 Dynamic I/N and ITU-R F.1495 permissible interference limits, with axes of probability of aggregated I/N [%] versus I/N [dB] [10].

spectrum sharing obligations of later-round applicants and codifying protection of earlier-round systems would increase certainty about the future spectrum sharing environment [1], which may be helpful to both current operators and prospective entrants. On December 15, 2021 the FCC released the Notice of Proposed Rulemaking on Revising Spectrum Sharing Rules for NGSO FSS Systems in response to SpaceX's petition ("2021 NGSO Sharing NPRM" [1]).

SpaceX's proposals and the FCC's responses can be summarized in the following manner:

1) SpaceX proposed that the existing spectrum-splitting procedure should be limited only to systems authorized within the same processing round, eliminating the current method of "case-by-case" evaluation of later-round applicants. The FCC responded favorably and proposed to adopt this as a rule.
2) SpaceX proposed that later-round NGSO FSS systems should protect earlier-round systems up to a specified I/N level, but that this protection should sunset after a period of time. The FCC agreed that later-round applicants should be required to protect earlier-round systems by both coordination agreements and a quantitative limit, but did not necessarily agree that I/N was the most appropriate metric to use in defining this limit and invited comments on the matter. The FCC responded favorably to sunsetting this protection after a period of time, and called for further comments on sunsetting of protections.
3) SpaceX proposed requiring operators to share beam-pointing data in order to facilitate interference analysis. The FCC did not favor this proposal due to concern about competitive harm.

A. Shortcomings of I/N

In the 2021 NGSO Sharing NPRM, the FCC expressed apprehension at using I/N as a metric. These apprehensions emerged from the FCC's seeking to balance effective protection, encouraging coordination, and reducing burdens on new applicants. The full text of the relevant paragraph is reported here:

> *Beyond the initial difficulty of developing such an I/N limit for protection of NGSO FSS systems, commenters raise potential shortcomings of an I/N approach. Because the I/N limit would reflect generic NGSO system parameters and not the parameters of the NGSO system to be protected, it could provide insufficient protection to an NGSO system with especially sensitive antennas. Adoption of an I/N limit could also discourage coordination if either the earlier-round licensee or later-round licensee preferred to operate*

within the I/N limit rather than a negotiated alternative. Requiring applicants to perform interference analyses for the potentially thousands of satellites authorized through previous processing rounds, many of which may never be launched, could also place undue burdens on new entrants, especially those with limited resources. [1]*

B. Invitation for Comments

Given the potential downsides of I/N as a metric, the FCC invited comments in response to the 2021 NGSO Sharing NPRM on a number of specific topics. These included suggestions for continuing to use I/N as well as recommendations for alternative metrics that might be used to modernize and address the FCC's concerns appropriately [1]†. Specifically, these topics are:

1) What I/N limit might be appropriate to protect NGSO FSS systems.
2) What amount of time might be appropriate for a system to exceed the I/N limit.
3) What standard antenna mask and noise temperature might be appropriate in calculating I/N.
4) Whether to adopt alternative interference criteria based on a percentage of degraded throughput. The FCC notes that this "may be appropriate because most, if not all, modern NGSO systems will use adaptive coding and modulation (ACM) to allow maintaining a satellite connection in spite of signal degradation, but at lower throughput rates."
5) What limits may be appropriate if using degraded throughput as the criteria.
6) The suitability of degraded throughput in general, including "the burdens of computing any limit" under an alternative metric.
7) Whether the degraded throughput analysis should consider unavailability as well.

The former three topics seek comment on rule revision if I/N remains the key metric of interest for determining harmful interference. The latter four topics address the alternative metric of degraded throughput.

IV. Proposed Future Regulations

In response to the FCC's 2021 NGSO Sharing NPRM, comments were submitted from private companies and public interest organizations (PIOs) [11–27]. A summary of comments is shown in Table 1. Although specific proposals and areas of focus differed between commenters, feedback generally centered around alternative metrics, specific I/N limits, and how to apply rules between early and later applicants in order to protect earlier-round systems from later-round systems. Various metrics proposed by commenters included specific thresholds for static and dynamic I/N limits, degraded throughput, and a 75/25 spectrum splitting procedure in which, during an interfering event, earlier round systems would be entitled to 75% of the available spectrum while later round systems would be confined to 25%. A summary of comments is shown in Table 1. Companies shown on the table provided specific comments on the 75/25 spectrum split, the continuing use of I/N as a metric, or degraded throughput as an alternative metric. Comments from Astra, Inmarsat, Mangata, SpaceLink, and Telesat did not provide specific comments on these metrics. These proposed metrics are discussed in greater detail in the following subsections.

Table 1 Summary of comments in response to the 2021 NGSO Sharing NPRM.

Metric	Advocates	Opponents
75/25 Spectrum Split	Boeing, O3b	None
Static I/N	Kepler, OneWeb, SN	Boeing, O3b, Telesat, PIOs, Viasat, Kuiper
Dynamic I/N	SpaceX, Hughes, AST	Boeing, O3b, Telesat, PIOs, Viasat, Kuiper
Degraded Throughput	Intelsat, PIOs, Viasat, Kuiper, AST	Hughes, O3b

*At 18, "Level of Protection for Earlier-Round Systems"
†At 20-21, "Level of Protection for Earlier-Round Systems"

A. 75/25 Spectrum Splitting

Boeing and O3b proposed granting earlier-round systems 75% of the available spectrum during an interfering event (thus confining later round systems to 25% of the spectrum). While this plan may initially sound unfair, it eliminates the need for complex and burdensome calculations and utilizes a projection that later-round systems will require less bandwidth to provide the same service as earlier round systems on account of more advanced technology. Both companies proposed this splitting procedure in response to perceived problems with existing metric proposals: Boeing specifically opposed I/N, while O3b opposed both I/N and degraded throughput. In this context, the proposal of an entirely different band-splitting plan is sensible.

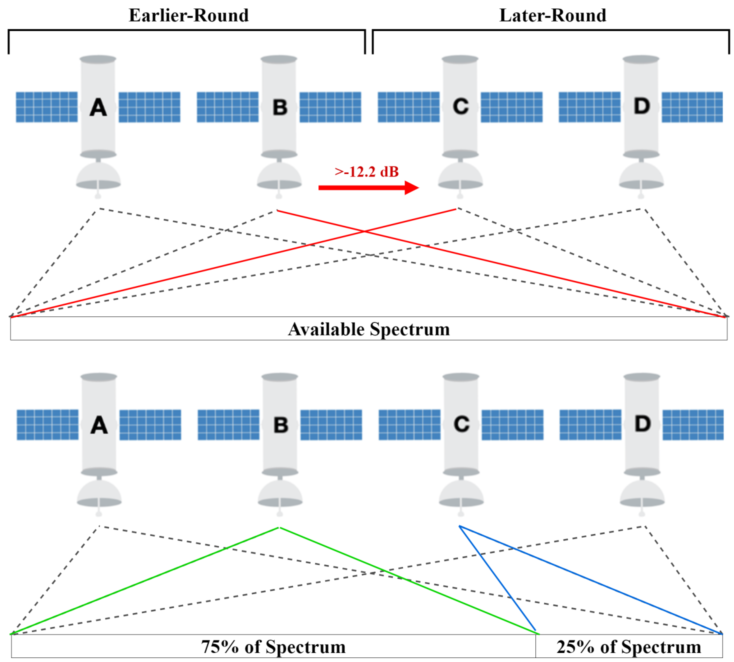

Fig. 5 Interference triggering a 75/25 spectrum split as proposed by Boeing and O3b. (Top) Four satellite networks (A-D) share a common spectrum, with networks A & B being processed in an earlier round than networks C-D. In the event of interference between B & C, earlier-round system B is confined to 75% of the spectrum and later-round system C is confined to 25% of the spectrum, while networks A & D retain full access to the spectrum (bottom).

B. Specific I/N Thresholds

Before 2023, static I/N was the sole metric used to regulate NGSO FSS interference in the United States. Same-round applicants have been required to adhere to a -12.2 dB static I/N limit to prevent interference with each other, while interference between operators of different rounds was handled on a case-by-case basis by the FCC. Three commenters advocated for the use of static I/N limits and proposed specific thresholds while five commenters opposed using I/N as a metric.

Advocates of I/N included Kepler, OneWeb, and SpinLaunch/SN Space Systems, though the three parties differ on whether the static limit should be increased or decreased. Kepler proposed that subsequent applicants should not exceed -15.2 dB I/N into earlier round systems, effectively tightening the limit for later-round applicants. By contrast, OneWeb and SpinLaunch/SN Space Systems expressed that the existing -12.2 dB limit was “overly conservative” and SN specifically advocated raising the limit to 1 dB, a significant loosening of interference restrictions. Additionally, SpaceX, Hughes, and AST each suggested adoption of dynamic I/N limits, though proposed no specific limits.

Opponents of I/N included Boeing, O3b, Telesat, ViaSat, Kuiper, and public interest organizations (PIOs). Telesat, O3b, and Boeing argue that I/N thresholds do not effectively protect real-world systems because they are calculated with respect to a generic victim system. Boeing, specifically, notes that this simultaneously results in over-protection of robust systems and under-protection of sensitive systems. ViaSat and PIOs both argue that any I/N limit will lead to spectral inefficiency. PIOs, which are interested in maximizing throughput for customers, point out that conservative I/N values result in unused spectrum capacity that could be more fully utilized with coordination agreements. Taken together, detractors argue that static I/N limits do not protect all systems equally and do not maximize efficient use of spectrum.

C. Alternative Metrics

Proposals of alternative metrics to static I/N generally centered around degraded throughput (also referred to as 'spectral efficiency'), which quantifies the amount of data that a satellite can transmit in a certain amount of frequency.

Opponents of degraded throughput included Hughes and O3b. O3b argued that it is impractical to define a standard for degraded throughput because calculating degradation would require an excessive level of knowledge about every operator's links. Hughes argued that spectrum efficiency metrics are flawed because they benefit some technologies over others and proposed instead to use a combination of dynamic I/N and equivalent power flux density (EPFD) limits.

Advocates of degraded throughput include Intelsat, Viasat, AST, Kuiper, and PIOs. Viasat and Public Interest Organizations (PIOs) point out that because degraded throughput can be calculated with respect to real world systems, they allow interference to be regulated with respect to–and potentially up to the limit of–causing actual harm. This, in turn, allows spectrum to be more efficiently utilized. IntelSat and Kuiper also note that degraded throughput would take into account robustness from modern adaptive coding and modulation (ACM) techniques that allow satellites to actively adapt performance in response to interfering events. AST and Kuiper proposed specifically that the FCC adopt ITU degraded throughput limits as laid out in Article 22.5L [28].

All taken together, these proposals indicate growing concern with I/N as a regulating metric and an increased support for degraded throughput. Kuiper's comments to the FCC included a detailed proposal for using degraded throughput alongside a link unavailability metric to establish a regulation that protects modern systems over both long and short time spans.

V. Kuiper's Proposal: Degraded Throughput

In response to the FCC's NPRM, Amazon Kuiper proposed regulations that define an allowable increase in unavailability and throughput degradation that interferers may cause to a victim system (Kuiper refers to this pair of regulations together as a "degraded throughput metric") [18]. In particular, Kuiper suggests an interference threshold providing that a later-round NGSO FSS system may cause: "(1) at most an increase of 3% of the time allowance for the earlier-round system's lowest carrier-to-noise ratio (C/N) value; and (2) at most a 3% reduction in the time-weighted average spectral efficiency of an earlier-round system, calculated on an annual basis." Kuiper argues this metric would be more spectrally efficient than I/N as it takes into account the actual design and operation of existing systems. Kuiper's proposal also matches provisions in Article 22.5L of the ITU Radio Regulations which protect GSO operations from NGSO systems in V-band [28], so adopting degraded throughput in this manner would advance the harmonization of FCC and ITU rules [18].

Kuiper's proposed regulations rely upon using the carrier-to-noise ratio (C/N) to evaluate harmful interference. C/N evaluates the strength of a signal between a transmitter and a receiver, effectively measuring the performance of the link between them. Specifically, C/N is the ratio between received transmitting signal strength and received noise. C/N and I/N are calculated in an identical manner: the difference is that C/N measures the strength of a desired signal while I/N measures the strength of an interfering or unwanted signal.

Spectral efficiency, colloquially referred to as throughput (hence the term 'degraded throughput'), is a measure of the amount of data in bits per second (bps) that a satellite can transmit in a unit reference of spectrum (Hz) and can be calculated as a function of C/N [29, 30]. Throughput and C/N are calculated probabilistically, the output being a time-weighted function which shows the frequency distribution and can be visualized on a histogram as shown in Figure 6. Part one of Kuiper's proposal limits the reduction in the time-weighted average throughput that an interfering system may cause to a victim system, which protects the victim system against long-term interference impacting data throughput.

Although limiting throughput degradation alone prevents long-term interference, an additional limit on the time allowance for link unavailability helps to fully protect victim systems [18]. The amount of time that a victim system operates at or below its lowest C/N value is also known as the time allowance for link unavailability. Link availability is a binary value stating whether a communications link can be maintained [30]. When a link falls below its minimum C/N value, the system cannot effectively transmit data at the designed rates. Link unavailability may be caused by combinations of factors including path length, weather conditions, and interfering systems. Setting a time allowance

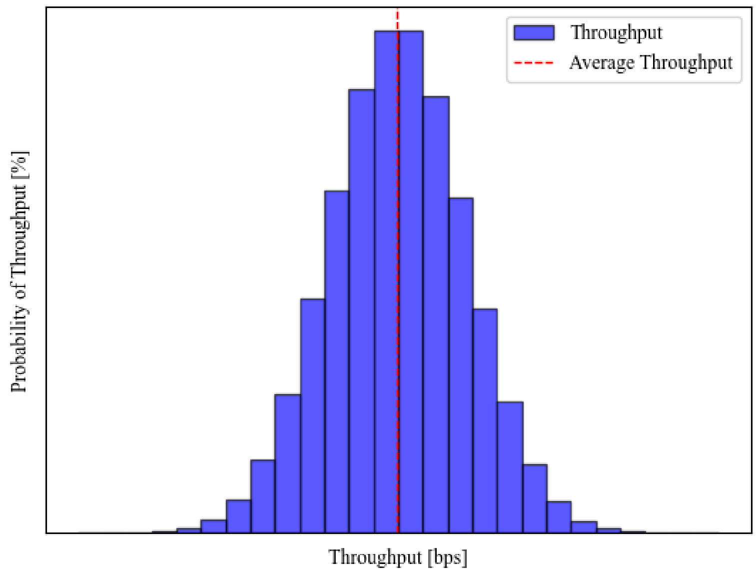

Fig. 6 Time-weighted throughput and time-weighted average throughput.

that an interfering system may cause link unavailability to a victim system, as Kuiper does in part two of their proposal, protects the victim system against short-term high intensity interference [18]. A graph demonstrating unavailability is given in Figure 7. Example code for calculating link status and carrier to noise plus interference ratio is published by MathWorks at [31].

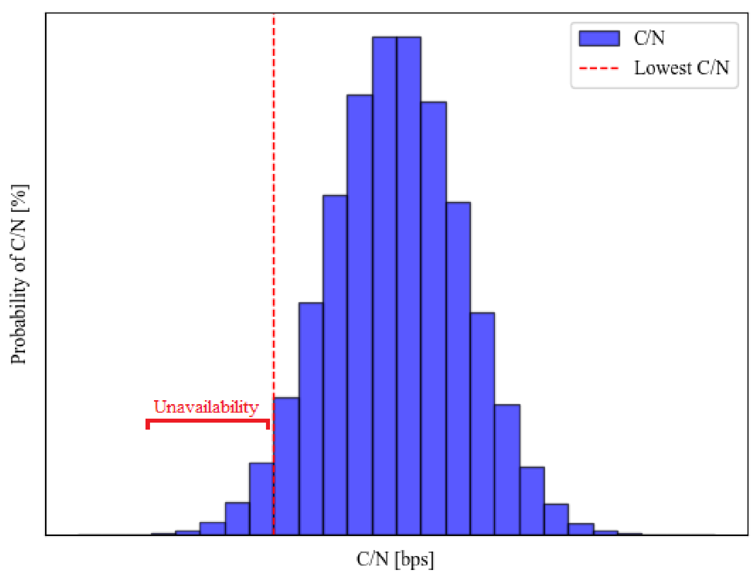

Fig. 7 Time-weighted C/N, showing that unavailability occurs when C/N is less than the lowest C/N threshold.

Taken together, these two limits (degraded throughput and link unavailability) fully define protections for victim systems. For instance, a 3% reduction in throughput alone may result in more than a 3% reduction in link availability and therefore negatively impact the service availability of the victim system beyond an acceptable level. Hence, distinct requirements for unavailability and throughput reduction are both necessary in order to create a complete measure of both long-term and short-term interference which is comparable to a dynamic I/N threshold.

A. Benefits of Degraded Throughput

Modern NGSO satellites are subject to dynamic effects. Satellites in non-geostationary orbits are subject to dynamic path loss due to changing path length and elevation angle, and phased arrays are subject to changes in antenna gain due to antenna scan angle. Systems operating in higher frequency bands have to overcome atmospheric conditions including rain attenuation which can cause signal degradation and unavailability [18]. To withstand these dynamic effects and continue to maintain service, modern satellites use adaptive control and modulation (ACM) to actively adapt their signals to balance link availability and throughput [29].

A degraded throughput methodology would recognize that NGSO FSS systems already must withstand signal degradation due to path length changes and link unavailability due to weather effects, which makes them also tolerant to interference from other NGSO FSS systems causing decreases in link availability or throughput. In contrast, an absolute measure of interference such as I/N does not take into account the resiliency built into NGSO systems' design [18].

Degraded throughput and unavailability measure the effect of interference on a system by comparing the performance that a system expects to achieve against the performance it would achieve with the interference of another system. Tailoring interference protections to measure the operational effects on victim systems rather than needlessly constraining interfering systems maximizes spectrum sharing among operators and allows for more efficient use of spectrum [18].

B. Drawbacks of Degraded Throughput

Potential drawbacks to degraded throughput include the complexity of calculation, the use of generic or system specific parameters, and establishing strict definitions of minimum C/N.

1. Complexity of Calculation & System Parameters

The complexity of preventing interference between NGSO systems has grown alongside the need to maximize the use of shared spectrum. One drawback of degraded throughput is that it is more complex to calculate than I/N, which places a greater burden on entrants. However, an important part of how to calculate degraded throughput is still undecided: it is unclear whether the FCC will require the use of generic or specific system parameters for degraded throughput analysis. The FCC accepts filings that are based on either system-specific or ITU-recommended generic parameters, including a standard reference antenna mask and noise temperature value [3].

Using generic system parameters could ease the burden placed on entrants, but would not guarantee effective protections for all systems. If generic parameters are set for a highly sensitive system, then the protection level would likely be conservative for most systems, though would not ensure protection for systems more sensitive than the generic. Conversely, using specific system parameters would require later-round applicants to calculate degraded throughput for each operating earlier-round system using each system's specific link parameters. However, tailoring to specific system parameters is precisely what makes degraded throughput superior at assessing the impact to performance of a system and allows for maximizing shared spectrum use. The decision of whether to use generic or specific system parameters is a tradeoff between reducing burden to applicants versus protecting all systems equally and promoting spectral efficiency.

2. Strict Definitions

Another limitation of degraded throughput is that there does not currently exist a guideline for defining the minimum C/N of a system; unavailability does not refer to a complete outage, but rather a system operating below its 'nominal' or advertised ability. A loose definition of minimum C/N opens a potential loophole in which an operator, not acting in good-faith, defines an arbitrarily high minimum C/N value for itself to place restrictions on competitors.

C. Additional Sources of Support

In addition to public and private sector commenters expressing support for degraded throughput, international parties have expressed support for degraded throughput as an appropriate metric for protecting modern satellite systems. The ITU has adopted degraded throughput in Article 22.5L of the ITU Radio Regulations for the protection of GSO operations from NGSO systems in V-band [28]. Furthermore, ITU-R Recommendation S.2131 endorses a degraded throughput metric for determining satellite interference [29].

The FCC's own Technological Advisory Council (TAC) has endorsed degraded throughput as an interference criteria for NGSO satellite systems [32]. In October 2020, the United States government recommended that the ITU adopt degraded throughput for assessing NGSO-NGSO interference, asking the ITU "to consider a single-entry metric of a 3% increase in unavailability and a 3% allowance in the reduction of the time-averaged weighted degraded throughput" [33].

D. Sources of Potential Bias

Kuiper's license was granted during the Ku-/Ka-band processing round that closed in May 2020. As a result, Kuiper self-acknowledges that it is currently "the sole operator required to accommodate operational, earlier-licensed systems under existing spectrum sharing rules" [18]. In other words, Kuiper is currently the only operator that is both seeking protection from future systems while being required to protect earlier systems. In this position, Kuiper argues that it can "offer a unified proposal that serves the public interest" [18].

Being a private corporation, however, Kuiper has an inherent interest in advocating for rules that advantage its own system. Kuiper has stated support for applying updates to the NGSO FSS rules across all operators, regardless of processing round [18]*. In this case, earlier round systems would receive no grandfathering or special protections, but would be subject to the same protections and restrictions as Kuiper and all future applicants.

VI. Methodology Considerations

The FCC sought public comments in response to the 2023 NGSO Sharing Revision about "appropriate values and assumptions" to be used under a degraded throughput methodology, and to which interference thresholds later-round NGSO FSS systems must adhere [8].

A. Rain Attenuation

An important modeling choice is whether to include signal degradation caused by rain. In probabilistic analysis, rain attenuation can be accounted for by using a model that estimates its effects over a period of years [30] [34]. Rain attenuation can have a significant effect on signal strength, especially in higher frequencies. Some systems are able to compensate for rain attenuation by increasing transmission power dynamically, which is called uplink power control (UPC). While adding rain attenuation makes the model more realistic, it also brings the threshold for unavailability closer for interfering systems and impacts spectral efficiency in a non-linear manner [29]. Depending upon the specific systems and thresholds used, adding rain attenuation into the calculation of degraded throughput may tip the result into noncompliance.

B. Aggregate Interference

It is possible that the aggregate interference from multiple constellations into a victim system may reach harmful levels even while the thresholds for single-system interference are not exceeded. Degraded throughput methodology may be expanded to include multiple interfering constellations, increasing the complexity of the model. Some questions that have not yet been answered are which interfering systems would be obligated to decrease their interference and how a regulation on aggregate interference might be defined.

C. Modeling Assumptions

The importance of defining modeling assumptions should not be understated. The goal of probabilistic simulation is to accumulate a dataset that appropriately represents the level of interference that a constellation will produce. However, the results of probabilistic analysis are sensitive to the assumptions made in setting up the model. Defining the assumptions which have the strongest effect on the results may be prioritized, and worst-case assumptions may be preferred in order to prevent underestimating interference impact. For example, C/N and I/N are highly sensitive to the off-axis angle (the angle between the satellite's beam and the boresight of the earth station antenna), so one may assume worst-case pointing angles rather than randomized pointing angles in order to avoid underestimating potential interference. However, worst-case assumptions may unnecessarily increase restrictions on interfering systems' transmissions.

In SpaceX's 2020 dynamic I/N analysis [10], SpaceX calculated the interfering signal strength by assuming worst-case pointing angles and considering the beams from eight satellites with the smallest off-axis angle, as well as the contribution of the sidelobes from all other satellites within view. SpaceX only accounted for eight beams in this analysis because their system operates with a maximum of eight co-frequency beams per spot. During normal operations, one may assume that there are not eight co-frequency beams pointed constantly at the same place on earth throughout the entire year. Nonetheless, modeling their worst-case mode of operations allowed SpaceX to simplify their model, justify their modeling decisions, and be assured that they did not underestimate interference.

*At IV. "Rule Changes Adopted in this Proceeding Should Apply to All NGSO FSS Licensees"

D. Threshold Values

Kuiper proposed 3% thresholds for both throughput degradation and link unavailability, the same as ITU provisions in Article 22.5L for the protection of GSO operations in V-band [18]. Whether this 3% threshold is also appropriate for regulating interference into NGSO systems in the Ku- and Ka-band is unclear, considering that there are differences in the design and goals of GSO and NGSO systems. Further modeling and analysis may be required to determine appropriate threshold values.

E. Degraded Throughput Analysis Tool

In order to reduce the burden on entrants and clearly define a degraded throughput methodology, it may be beneficial to create a software tool which performs a degraded throughput analysis and determines compliance. This idea is not unprecedented; for example, the ITU's has worked to develop a software tool for equivalent power flux density (epfd) validation [35]. A degraded throughput tool could have standard input and output file formats, allowing NGSO system operators to publish and share the information necessary for this analysis in a concise manner.

VII. Conclusion

In its 2017 NGSO FSS Report and Order [5], the FCC did not clearly define spectrum sharing rules for later-round systems in anticipation of setting more specific rules at a future date. Now, over five years later, NGSO systems are being deployed and the FCC has gained experience navigating contemporary processing rounds and handling later applicants. It is time to revise the spectrum sharing rules to clarify the obligations of later-round systems.

Until this point, I/N has been the only metric used for NGSO interference quantification, but it is becoming clear that I/N is an increasingly poor metric. Commenters state that I/N limits do not protect all systems equally, can lead to inefficient use of spectrum, and do not take advantage of the resilience of systems using ACM. Respondents to the FCC's December 2021 NPRM commented on I/N and proposed alternative regulation metrics. Proponents of I/N offered arguments for both raising and lowering the existing limit, whereas opponents of I/N were largely unified in the aforementioned criticisms.

An alternative proposal that garnered attention was degraded throughput. Degraded throughput is a metric with public, private, and international support. Unlike I/N, degraded throughput takes into account modern systems' resilience and relates directly to the impact to performance of the victim system. Degraded throughput is likely to increase spectral efficiency and would unify FCC regulations with international standards. In its response to the 2021 NPRM, Kuiper presented a detailed proposal for twin unavailability and throughput metrics to ensure long term and short term protections to existing systems. However, degraded throughput remains burdensome due to the complexity of calculation. Using generic system parameters to lower this complexity could simultaneously provide insufficient and excessive protection to existing systems while failing to maximize spectral efficiency. Additionally, the current definition of unavailability and guidelines for defining minimum operable signal strength have not been strictly defined and potential loopholes exist without careful definitions for both.

Degraded throughput as a replacement for I/N metrics in regulations could hold the promise of increasing spectral efficiency and modernizing satellite interference regulation. However, further clarification and specificity about the methodology for calculation is needed.

Acknowledgments

This paper was derived from work performed in the Spring 2023 Satellite Systems course at Olin College of Engineering and from research activities in the Olin Satellite + Spectrum Technology & Policy (OSSTP) Group. This work was supported by funding from an Amateur Radio Digital Communications (ARDC) grant and the National Science Foundation (NSF) SII-Center: SpectrumX – An NSF Spectrum Innovation Center Grant. The authors thank Ken Mentasti at Mangata Networks and Alex Epshteyn at Amazon's Project Kuiper for personal correspondence throughout the research phase of this project.

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