

Sophisticated Wireless Interference Analysis: A Case Study for Spectrum Sharing Policy

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Abstract

Access to sufficient wireless spectrum is important for sustaining the growth of wireless broadband and enabling next-generation wireless technology. However, freeing additional spectrum for wireless broadband is often a difficult and contentious process. As policymakers look to new mechanisms of sharing spectrum to meet growing wireless needs, the specific terms of sharing are central to the utility of the wireless resource. For this reason, nuanced understanding of interference risks - which drive spectrum sharing policies - is needed to maximize the productive use of the spectrum.

Commonly proffered interference analyses are static and simplified, while the real world of wireless is dynamic and ever changing. Improving the technical information on which policymakers rely is therefore critical to the success of spectrum sharing as a policy strategy.

In this paper, we demonstrate how sophisticated simulation of wireless coexistence can yield important insights, in contrast to simplified models normally offered by advocates. We focus on a portion of the 5 GHz Wi-Fi band, which is crucial for enabling capacity and throughput, and is the global home to the next-generation mass market Wi-Fi standard known as 802.11ac.

In this analytic context, outdated FCC rules designed to protect

mobile satellite service (MSS) from harmful interference rendered Wi-Fi access to 100 megahertz of the band, known as UNII-1, unsuitable for wide-scale deployment. Today, a single MSS company occupies this entire 100 megahertz, and a far lower level of MSS utilization exists than assumed would be the case when the FCC established rules many years ago.

Our paper develops a sophisticated coexistence simulation, which shows that satellite phone users are extremely unlikely to experience any service diminution (harmful interference) as a result of liberalized Wi-Fi access to UNII-1. This analysis was submitted to the FCC in January 2014, and served as the primary basis for action to expand Wi-Fi access to UNII-1 in March of that year.

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Table of Contents

1	Executive Summary.....	5
2	Spectrum Sharing: The Concept and The Practice.....	6
3	Dynamic Understanding of Interference in the 5 GHz Wi-Fi Band	10
3.1	Overview of the Dynamic Method	11
3.2	Components of the Simulation	12
3.2.1	Tracking the Globalstar Constellation	12
3.2.2	Simulating Wi-Fi Deployment.....	13
3.2.3	Characterizing the Wi-Fi Signal.....	15
3.3	Putting the Components Together: Simulating Wi-Fi “Noise”	18
3.4	Results: Translating Wi-Fi “Noise” to Globalstar Capacity	22
3.5	Sensitivity of Results.....	24
4	Themes and Lessons Learned	26
4.1	An Aversion To Simple Bright Lines.....	26
4.2	Attention to Shifting Marketplace Circumstances.....	26
4.3	Use of Powerful Tools	27
4.4	The Next Frontier of Spectrum Sharing.....	27
5	Conclusion.....	28

1 Executive Summary

Wi-Fi now carries the majority of Internet traffic and is therefore crucial to the functioning of modern economies. Yet the resource that enables Wi-Fi use – wireless spectrum – is scarce. Additional spectrum capacity is required to sustain wireless growth and enable new technologies like 802.11ac, the next-generation mass market Wi-Fi standard that is designed for gigabit speeds.

The FCC has proposed to expand Wi-Fi access in the 5 GHz band, which is the global home to 802.11ac technology. Doing so will require sharing wireless frequencies with other users, as Wi-Fi has done since its inception.

This makes the 5 GHz wireless band a prominent example of a shift in spectrum policy toward sharing among services. Spectrum sharing is often cast as a means to expand wireless access to new uses in a manner that would not be possible under a fragmented, siloed allocation regime where systems and services enjoy their own exclusive access. Sharing also offers the prospect of more rapid access to spectrum, a means to bypass the time-consuming process of relocating systems from one frequency band to another.

The efficacy of spectrum sharing is highly situation specific, however. Spectrum sharing is, in essence, a parsing of usage rights. This parsing must be done in a manner that maximizes net benefits and utility. A key input to determining the proper balance of rights is the risk of harmful interference among systems. A thorough understanding of system interactions can therefore provide policymakers with the tools needed to maximize use of the spectrum.

This paper outlines a sophisticated interference analysis that enabled the proper balance of rights in the 5 GHz band between Wi-Fi and the primary user, a mobile satellite company. In this context, we demonstrate that historic restrictions on Wi-Fi designed to protect the satellite system were overly conservative, and that liberalized terms of access for Wi-Fi users would not place the primary user at risk of harmful interference.

Therefore, in expanding Wi-Fi usage of the band consistent with this technical assessment, the FCC increased the productive use of the spectrum. In our view, this represents a successful instance of

spectrum sharing that can serve as a model as governments look to expand spectrum access for wireless broadband.

2 Spectrum Sharing: The Concept and The Practice

An important element of contemporary national economic policy is the expansion of access to spectrum to enable the continued growth of wireless broadband. As the President's Council of Economic Advisors put it:

“...the evidence is clear that the wireless industry is an important source of investment and employment, and that supporting the growth of this industry through new spectrum allocation is likely to generate substantial economic benefits.”¹

However, governmental processes to bring new spectrum to market are lengthy. For example, the FCC's 2014 auction of the PCS “H Block” was its first auction of new wireless broadband licenses since 2008.²

Recent history is consistent with past experience. As the FCC noted in its National Broadband Plan, spectrum has typically taken between six and thirteen years to make available.³ This lag is driven in large part by complexities in shifting legacy uses of spectrum to new bands or new systems, which is often a prerequisite to making available clean, exclusive spectrum for new uses.

Sharing spectrum resources among services has taken on new interest among communications policymakers. It is an attractive prospect to meet the rapidly growing need for wireless spectrum in a manner that avoids the drawn-out and sometimes contentious process of realignment and reallocation. Indeed, in a recent speech, NTIA Administrator Larry Strickling remarked, “Our long-term spectrum

¹ Council of Economic Advisors, “The Economic Benefits of New Spectrum for Wireless Broadband”, Executive Office of the President, February 2012.

² See fcc.gov/auctions for more information on spectrum auctions. The 2008 spectrum auction referenced here is the 700 MHz band, which was made available for mobile use as part of the nation's transition to digital television broadcasts.

³ National Broadband Plan, Chapter 5, “Spectrum”, Federal Communications Commission, 2010.

needs, both for industry and for government agencies, can only be met through sharing and we need a top-to-bottom commitment from everyone to make it happen.”⁴

The concept of sharing spectrum, however, can refer to any range of usage rights for new services. Sharing can occur in time, geography, or frequency, and a number of engineering and operational approaches can apply to each dimension. Spectrum may as a legal matter be allocated to more than one service, but the service of lower allocation priority (lesser interference protection) may be confined to such narrow usage parameters that the practical benefit of the allocation is limited.

Therefore, in spectrum sharing arrangements, care must be taken to maximize the productive use of the spectrum. This policy orientation is often informed by technical considerations relating to the risk of harmful interference.

Wi-Fi is an ideal case study in spectrum sharing. It is of lower legal status than other services in terms of interference protection, and thus has shared frequency bands since its inception. Yet it is central to the burgeoning wireless broadband ecosystem. Properly parsed usage rights can therefore yield significant benefits, while non-optimal rights can entail significant opportunity costs.

The FCC has proposed to expand Wi-Fi access to the 5 GHz band as a means to ensure adequate capacity for this increasingly important element of the wireless broadband ecosystem, and to fully enable the next generation of Wi-Fi technology, known as 802.11ac or “gigabit Wi-Fi.”⁵ The 5 GHz band is shared between Wi-Fi and many other services with higher regulatory status. The specific terms of access for Wi-Fi vary as a function of the FCC’s determination of protections needed for these higher-status systems.

⁴ Remarks by Lawrence E. Strickling, Assistant Secretary of Commerce for Communications and Information, “The Spectrum Sharing Paradigm”, NTIA/NIST Innovative Spectrum Sharing Technology Day, Department of Commerce, Washington, DC November 5, 2013.

⁵ For a discussion of Wi-Fi capacity trends and 802.11ac spectrum needs, see The Need for Wi-Fi Spectrum, section 2 of Alderfer et al., “Toward Expanded Wi-Fi Access in the 5 GHz Band”, July 2013, appended to Reply Comments of the National Cable and Telecommunications Association in Federal Communications Commission ET Docket No. 13-49.

A component of the FCC's proposal involves updating the terms of access for Wi-Fi in the 5150-5250 MHz band, known as UNII-1. The restrictions placed on Wi-Fi in this band were specified over 15 years ago, and were intended to provide conservative protections to the nascent Mobile Satellite Service (MSS) that uses the band for its ground station feeder uplinks, which are one link in their duplex (satellite phone) system.

Since the time these rules were put in place, wireless broadband has become central to economic activity in much of the world, with Wi-Fi serving as the primary means to connect online.⁶ In addition, the past 15 years have provided a basis for assessing the technical and economic role of MSS. During that period, several MSS companies have declared bankruptcy, and their spectrum, underutilized, has been repurposed. The overall subscribership of satellite communications remains limited.⁷ In fact, only one MSS provider remains an active user of the UNII-1 band. Given the disparity between expectations and reality about the usage of MSS, the FCC deemed it appropriate to reassess its rules in the UNII-1 band.⁸

Globalstar is the sole remaining MSS operator using 5 GHz, and in reaction to the FCC proposal to expand Wi-Fi use of UNII-1, repeatedly asserted that expanding Wi-Fi access will result in harmful interference to its duplex system, which serves approximately 85,000 customers globally.⁹ These concerns took several forms.

⁶ According to the 2013 Cisco Visual Networking Index, Wi-Fi now carries almost half (49%) of all Internet Protocol traffic worldwide, compared to 48% over fixed lines and 3% over mobile.

⁷ For example, three satellite companies discontinued operations in 2005 and returned their spectrum to the FCC, which was subsequently reassigned to ICO Satellite Service and TMI Communications, two remaining companies. These two companies then, in turn, went bankrupt, and were purchased by Dish Networks. Recognizing that satellite service was not the highest use of the spectrum, the FCC converted the spectrum to terrestrial use, creating what is now known as the AWS-4 band. See FCC 12-151, Report and Order and Order of Proposed Modification, December 12, 2012. https://apps.fcc.gov/edocs_public/attachmatch/FCC-12-151A1.pdf

⁸ Federal Communications Commission ET Docket No. 13-49, "In the Matter of Revision of Part 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band", February 20, 2013.

⁹ Note that a simple subscriber count implicitly overstates the actual usage of Globalstar's duplex system; most subscribers will generally use the service when out of range of terrestrial communications, so simultaneous usage is likely to be much lower than total subscriber counts.

In May 2013, Globalstar submitted technical analysis to the FCC indicating that as few as 201 Wi-Fi access points could harm their duplex system.¹⁰ This claim entailed a narrow and imprecise definition of interference, premised on a generic ITU-developed standard for noise as measured at the satellite. In a July, 2013 paper, we outlined how this approach does not appropriately account for the technical characteristics of the Globalstar system, and does not seek to forecast the outcome of central policymaking importance, which is the potential impact to satellite phone users.¹¹ Through a sensitivity analysis of Globalstar's technical work, we showed that even hundreds of millions of Wi-Fi access points deployed in UNII-1 would be unlikely to cause harmful interference, when considering the system as a whole.

In November 2013, Globalstar filed a second technical analysis at the FCC.¹² Significantly, Globalstar adopted our approach for analyzing the risk to the system as a whole, rather than a generic, single-link, ITU-specified noise floor recommendation.¹³ This is the correct framework for analyzing Globalstar's bent-pipe satellite system, and took the technical debate toward greater specificity and accuracy.

However, Globalstar's conclusions with regard to sharing with Wi-Fi in UNII-1 remained pessimistic. Specifically, Globalstar claimed that expanding Wi-Fi access to UNII-1 would reduce the capacity of their satellite phone system by approximately 56%. The balance of this paper describes a subsequent technical analysis conducted by the authors, which simulated the real-world interaction between the two systems.

Actual real-world data on system interactions is often difficult to obtain in FCC proceedings, particularly where new allocations or uses are concerned. Incumbent providers resist the new entrant and provide simplified, assumption-driven analysis to outline interference risks. A better technical understanding of these risks is therefore crucial to expanding access for new uses. In the present case study, our analysis provided the FCC with a basis for expanding Wi-Fi access

¹⁰ Comments of Globalstar Inc., ET Docket No. 13-49, May 28, 2013.

¹¹ Rob Alderfer, Dirk Grunwald, and Kenneth Baker, "Toward Expanded Wi-Fi Access in the 5 GHz Band", July 2013.

¹² Supplemental Comments of Globalstar Inc., ET Docket No. 13-49, November 29, 2013.

¹³ See p.10 of the "Roberson Report", appended to Supplemental Comments of Globalstar Inc., November 29, 2013, wherein an expression of total system carrier to noise ratio is documented.

to UNII-1, making this a successful instance of spectrum sharing policy, and one that has lessons for future FCC proceedings.

3 Dynamic Understanding of Interference in the 5 GHz Wi-Fi Band

The radio frequency environment in which all wireless communication takes place is complex and ever changing. Definitive statements of interference risk therefore by nature rely on a simplified understanding of the wireless environment. Wireless policy is optimally developed with a more nuanced understanding of interference risk, particularly where spectrum sharing is undertaken to meet critical national needs. Absent real-world information on system interactions, this means that sophisticated simulation of the interference environment is necessary.

For this reason, we endeavor to present a careful simulation of coexistence between Globalstar's duplex system and Wi-Fi use of UNII-1. Such a simulation moves beyond the static presentations typically proffered in FCC proceedings, and toward a dynamic understanding of how key parameters change over time.

In the context of UNII-1 coexistence, this means accounting for the impact to each of Globalstar's 24 active satellites,¹⁴ individually and collectively, by determining their orbital position and sensitivity to Wi-Fi access points at any given time, with a realistic understanding of how Wi-Fi is deployed geographically and used temporally, among other factors. This is a complex undertaking, but one that is necessary for understanding the true risk of interference to Globalstar's duplex system, upon which a framework for coexistence can be built.

This approach represents a progression in the state of the art of interference analysis, beyond simplistic models and toward an understanding of realistic interactions. Through this simulation we find confirmation that UNII-1 technical rules can be updated to enable greater Wi-Fi use without significant risk to Globalstar.

¹⁴ Globalstar has 84 total satellites, but we incorporate only the 24 that we believe are currently in use for duplex service.

3.1 Overview of the Dynamic Method

Our goal in this analysis is to determine a realistic upper-bound level of interference risk to Globalstar's duplex system, in order to gauge the likelihood of an impact to satellite phone users.¹⁵

To facilitate this, we track the path of each of the 24 satellites in Globalstar's constellation as they orbit the Earth, which enables us to know how many Wi-Fi access points each satellite "sees" at any given point in time. With information about Wi-Fi deployment, both in total number and in geographic distribution, we calculate the distance of each access point to each satellite at any given time to obtain a true understanding of Wi-Fi signal path loss, and integrate information about the likelihood of signal losses due to ground clutter. We can account for characteristics of Wi-Fi antennae, and for the episodic usage of Wi-Fi by consumers. In this manner we characterize the level of Wi-Fi "noise" added to Globalstar's constellation.

Next, we translate this simulation of noise to duplex system capacity impact using a link budget provided by Globalstar.¹⁶ This provides a framework for estimating the impact to end users of the satellite system. We note, however, that we have no basis for judging the accuracy of Globalstar's link budget. It is possible that the duplex system has more margin for noise than estimated using this framework, and therefore the capacity impact estimates we present here may overstate what might be realized in the real world.

We present a means of simulating real-world coexistence in UNII-1, though we do make several simplifying assumptions in the presentation to avoid arbitrary precision. Where simplifying assumptions have been made, they are clearly identified and calibrated to avoid understating interference risk. For example, we assume that all access points transmit at 1-watt power, which as the maximum power typically used by Wi-Fi, is highly unlikely to be observed across all deployments even if allowed by FCC rules. In calibrating our parameters to the upper end of the possible, we note that even our simulation may be interpreted as an overstatement of interference risk. We acknowledge this and do not intend to set precedent for assumption calibration in other interference analyses.

¹⁵ We also explore both peak and average levels of interference risk; we find average levels to be significantly lower than peak.

¹⁶ Supplemental Comments of Globalstar Inc., ET Docket No. 13-49, November 29, 2013.

Rather, we conduct a thought experiment to determine the upper bound of interference risk, based on simulated real-world interactions.

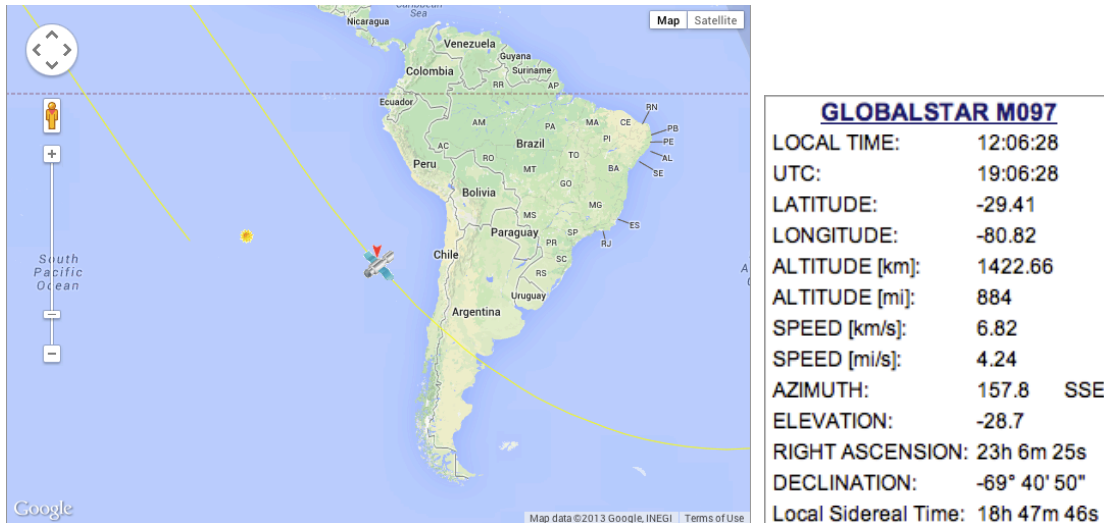
This simulation involves several large and dynamic data sets, as well as significant computation. IPython was used as the software tool to bring this data together in the simulation and produce results.¹⁷

3.2 Components of the Simulation

We now describe the key components of the simulation and the values we associate with each driver in our presentation.

3.2.1 Tracking the Globalstar Constellation

We begin with an inventory of the Globalstar constellation of non-geostationary, low Earth orbit satellites. Each of Globalstar's 24 satellites can be tracked in real time using publicly available information.¹⁸ For example, at approximately 19:00 UTC on December 31st, 2013, Globalstar satellite M097 was orbiting off the Pacific coast of South America at 1422 km altitude, as seen below.

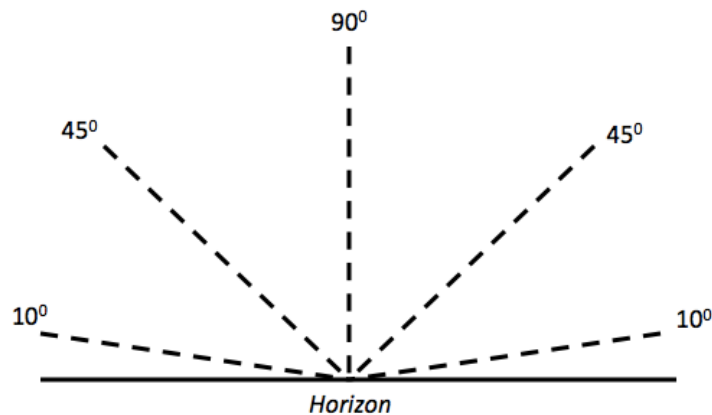


Snapshot of A Satellite in the Globalstar Constellation

¹⁷ IPython is a powerful open source computing resource, supported in part by Microsoft and the Sloan Foundation. See: <http://ipython.org>

¹⁸ Found at: <http://www.n2yo.com/satellites/?c=17>

Globalstar has described each satellite in the constellation as having a 5800 km wide spot (diameter) for receiving signals from Earth. Satellite phone signals at the edges of this spot are unlikely to complete a reliable link; in general, an elevation angle above 10 degrees is needed to communicate with the satellite.¹⁹



Angles Above Horizon: Illustrative Reference

For this reason it would be reasonable to assume that Wi-Fi access points at an elevation angle lower than 10 degrees would not generate noise into a Globalstar satellite. However, to ensure that we are not understating the potential risk of interference, in our presentation we will assume that all access points within the 5800 km spot of a satellite will be seen.

3.2.2 Simulating Wi-Fi Deployment

We then gather an estimate of the number of outdoor Wi-Fi access points that will be deployed, and where they will be deployed. For purposes of our current presentation, and again to avoid understating risk, we will carry forward the assumption of outdoor access point density used by Globalstar in its previous analysis, but refine it for greater geographic granularity.

Globalstar assumed approximately 16 access points per square kilometer for every urban area in the United States, as derived from their analysis of Google's Wi-Fi network deployment in Mountain View,

¹⁹ For more information on Globalstar's system characteristics, see "Description of the Globalstar System", December 7, 2000, at: <http://gsproductsupport.files.wordpress.com/2009/04/description-of-the-globalstar-system-gs-tr-94-0001-rev-e-2000-12-07.pdf>

California. However, an entire urban statistical area²⁰ was used to define urbanicity and generalize this observation across the country, despite variation in population density throughout urban areas. For example, the suburbs surrounding urban cores are included in the defined urban area, and in Globalstar's analysis a uniform access point density would apply throughout that area. In addition, Globalstar's analysis did not assume any access points were deployed outside of these areas (i.e., in rural areas).

Our simulation enables greater granularity in access point density by using zip code tabulation areas (ZCTAs) from the US Postal Service and Census Bureau.²¹ ZCTA data entails both population and area data at a much more detailed level than broader urban areas used by Globalstar – there are 33,120 ZCTAs across the United States, whereas there are only 486 urban statistical areas.

Using ZCTAs, we can distribute access points across the nation according to population density. To do so, we will use an urban / suburban / rural breakdown, with 16 APs per square km in urban areas, 10 APs per square km in suburban areas, and 1 AP per square km in rural areas.

This more granular approach to estimating access point density yields a total number of approximately 3,120,000 APs. As noted earlier, our simulation accounts for the specific geographic distribution of these APs by ZCTA – therefore, we know the angle and distance of each AP to every Globalstar satellite at any given point in time. To enhance accuracy in distance calculations, we account for ground elevation in each ZCTA as well.²²

While 3.12 million APs is less than the 4.4 million assumed in the aggregate by Globalstar in its technical analysis, we observe that no adjustment has been made for the significant proportion that are likely to be deployed indoors (and thus pose no risk to Globalstar). This factor is significant; for example, industry-consensus interference

²⁰ For more information on how urban areas are defined, see US Census Bureau, "Growth in Urban Population Outpaces Rest of Nation, Census Bureau Reports", March 26, 2012, at: http://www.census.gov/newsroom/releases/archives/2010_census/cb12-50.html

²¹ ZCTA data available at: <http://www.census.gov/geo/reference/zctas.html>

²² Elevation data from the US Geological Service, found at: http://gisdata.usgs.net/xmlwebservices2/elevation_service.asmx

modeling generally assumes approximately 95% of APs are deployed indoors.²³ In effect, therefore, our simulated population of APs deployed has significant allowance for Wi-Fi growth.

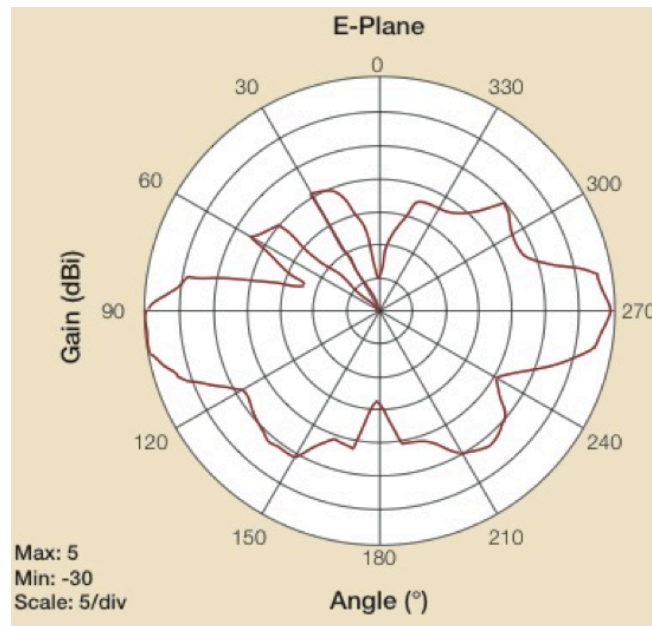
3.2.3 Characterizing the Wi-Fi Signal

There are several discrete considerations in characterizing the Wi-Fi signal. First and most straightforward is the assumed transmit power. For purposes of our simulation, we will assume that every one of the 3,120,000 APs is transmitting at 1 watt, the maximum power typically used by Wi-Fi. While this is not a realistic scenario – even if FCC rules allow for 1 watt transmit power, many access points will operate well below that level – we use this base parameter to avoid understating interference risk.

Also relevant to determining the level of Wi-Fi signal seen at the satellite is the antenna pattern, or the amount of gain from the AP in different directions. For this parameter, we will use a common antenna pattern as seen in a Ruckus AT-0636-VP access point.²⁴ As shown in the diagram below, most signal is directed outward and downward, to serve users on the ground. At nadir (zero degrees in the figure below), the signal is reduced by 25 dBi. This antenna pattern helps us determine the level of signal directed at each Globalstar satellite as it makes its orbit and positions itself at different angles to each AP.

²³ Document 4-5-6-7/CG-Cisco, ITU-R Study Groups, October 2, 2013.

²⁴ The Ruckus AT-0636-VP has an omnidirectional antenna. Specs are available here: <http://www.ruckuswireless.com/products/external-antenna-options>



Representative 5 GHz Wi-Fi Antenna Pattern

In addition to transmit power and antenna pattern, another factor impacting the Wi-Fi signal seen at the satellite is the level of ground clutter. At low elevation angles of below 10 degrees, ground clutter may reduce the Wi-Fi signal by 10 dB. As the satellite reaches higher elevation angles clutter will have less impact on the Wi-Fi signal, and we assume that angles of 30 degrees or higher will have no associated clutter losses.²⁵ This is a relatively conservative clutter loss construct; outdoor deployments in areas with tall buildings will entail greater losses and will experience them at much higher angles.

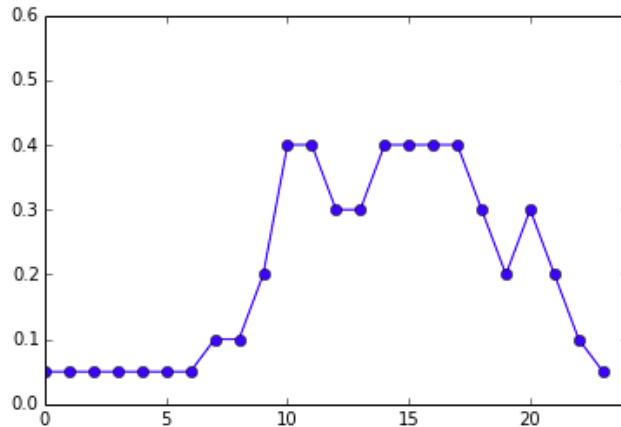
Also of importance to characterizing the Wi-Fi signal is the duty cycle, or the proportion of time that access points will be transmitting. Empirical studies have observed peak duty cycles of 10% at the 95th percentile.²⁶ The impact to Globalstar's duplex system will be driven not by a static duty cycle number, but by human usage of Wi-Fi in real time.²⁷ For this reason it is appropriate to characterize duty cycles

²⁵ Yoshikawa & Kagohara, "Propagation characteristics in land mobile satellite systems", IEEE 39th Vehicular Technology Conference, 1989.
<http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=40130>

²⁶ Joseph, W. et al., "Determination of the duty cycle of WLAN for realistic radio frequency electromagnetic field exposure assessment", Progress in Biophysics and Molecular Biology, 2012.

²⁷ Hourly activity based on usage patterns depicted by Rodrig et al., "Measurement-based Characterization of 802.11 in a Hotspot Setting", presented at SIGCOMM, 2005. Note that

over a 24-hour period that depict higher usage at peak periods, which will vary by time zone. Again, to be conservative we will choose a higher peak than empirical observations suggest – 40%, rather than 10% as the literature (Joseph et al) indicates is the true statistical peak. The 24-hour duty cycle distribution is shown in the figure below.



Wi-Fi Duty Cycles Over A 24-Hour Period

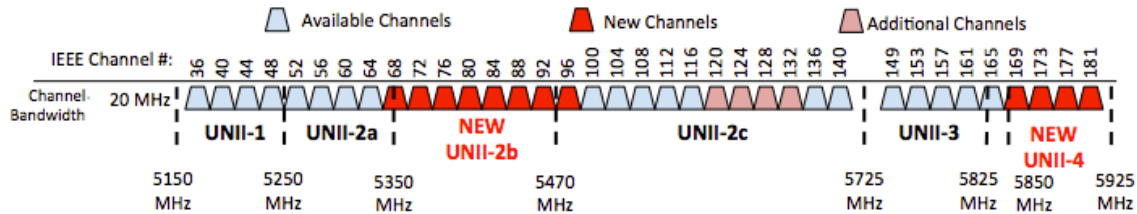
Finally, we must also know how many channels are in use by the access point, in order to determine the possible concentration of Wi-Fi signal in the UNII-1 band that is shared with Globalstar. Most APs that use the 5 GHz band rely primarily on the UNII-3 sub-band because of its favorable access rules; in addition, APs also use the 2.4 GHz ISM band. Recognizing that the FCC is considering how best to expand Wi-Fi access, we will use a range of channels in our presentation.

In our base case, twelve 20 MHz channels are in use, consisting of the three non-overlapping channels in the 2.4 GHz band, as well as UNII-1 and UNII-3 in 5 GHz. Currently available UNII-2 channels (UNII-2 a and c) are not included in our base case because of the unique restrictions that apply to their use; however, these channels are authorized for use outdoors, so we do incorporate them into the upper bound of our range of channel availability.²⁸ In addition, the FCC may make other Wi-Fi spectrum available – another eight channels in UNII-2b, and four more channels in UNII-4 -- which we

measurements were taken indoors in a conference setting with high demand that is not representative of outdoor usage levels, but temporal patterns provide a basis for analysis.

²⁸ UNII-2 channels require the use of Dynamic Frequency Selection (DFS) protocols. Anecdotal evidence suggests that these DFS channels are not widely used in practice.

also include in the upper bound of our range. This provides a range of spectrum availability between twelve and thirty-nine 20 MHz channels.²⁹ The 5 GHz IEEE Wi-Fi band plan is shown below for reference.



Wi-Fi Band Plan at 5 GHz

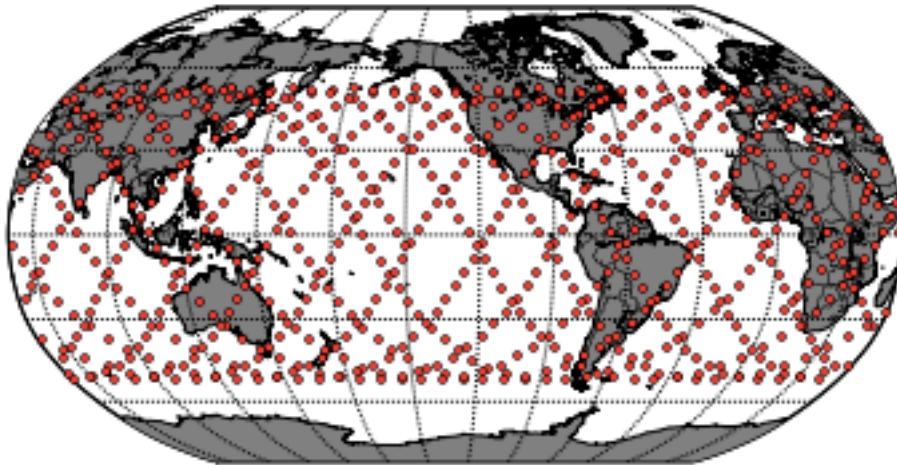
3.3 Putting the Components Together: Simulating Wi-Fi “Noise”

With the above components, we are able to simulate the level of Wi-Fi interference to each Globalstar satellite at any given point in time from any access point on the ground, accounting for how Wi-Fi use at different times of the day and in different locations will impact a satellite orbiting the Earth at over 15,000 miles per hour.

To do this, we begin by choosing a specific satellite to track, a specific period of observation, from a specific location on the ground.

In our presentation we begin by tracking Globalstar satellite M088; the path of which over a 24-hour period is as follows:

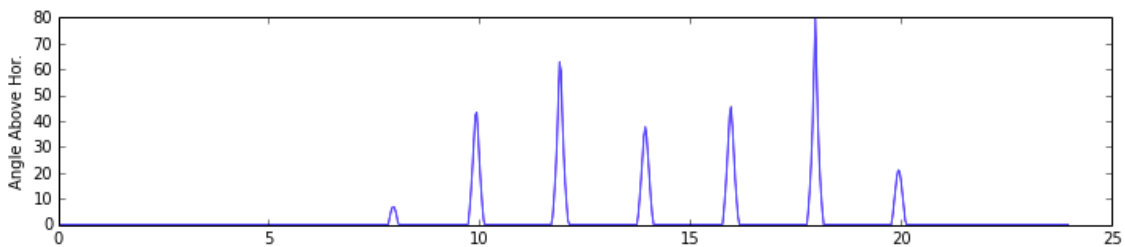
²⁹ This does not include the up to 150 megahertz of spectrum that the FCC has proposed to make available for Wi-Fi-like service at 3.5 GHz, or any other potential future Wi-Fi spectrum. Including potential future spectrum would further reduce Wi-Fi “noise” in UNII-1, since the usage would be spread across greater bandwidth.



24-Hour Path of Globalstar Satellite M088

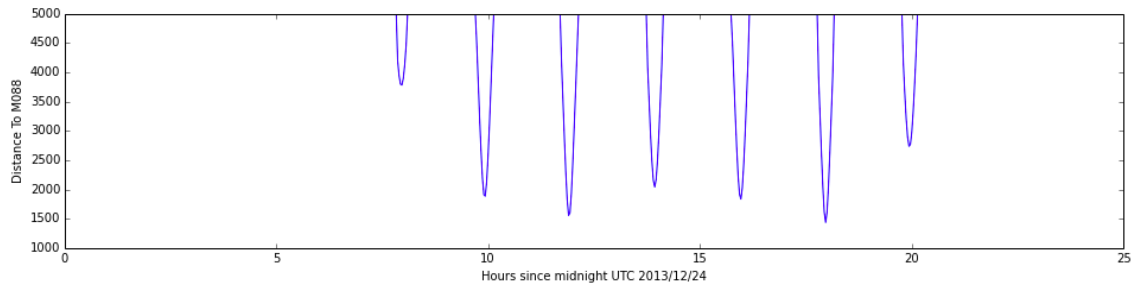
We will observe M088 from Lebanon, Kansas, the geographic midpoint of the United States. This will enable the satellite to see the entire contiguous states – and all APs within it -- when the satellite is close overhead.

On any given day, the angle from Lebanon to the satellite will change rapidly as the satellite orbits. The following figure shows the angle of M088 to the ground throughout the day. Note that for most of the day, the angle is zero (or lower) and the satellite is out of sight. For brief periods the satellite moves overhead of our chosen location; at its closest point, around 17:00 UTC, the satellite is 80 degrees to Lebanon.



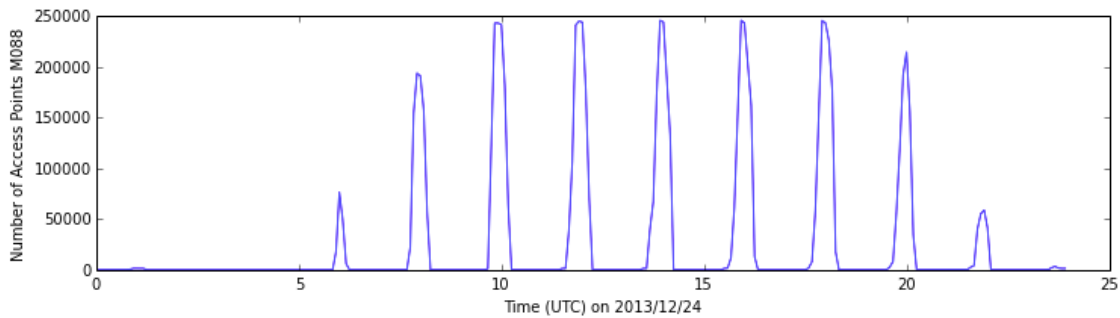
Angle of M088 to Lebanon, Kansas Throughout the Day

As M088 approaches Lebanon, the distance varies inversely with the angle, as shown in the figure below. At 17:00 UTC, M088 is at its closest point to Lebanon, at approximately 1800 km.



Distance of M088 to Lebanon, Kansas Throughout the Day

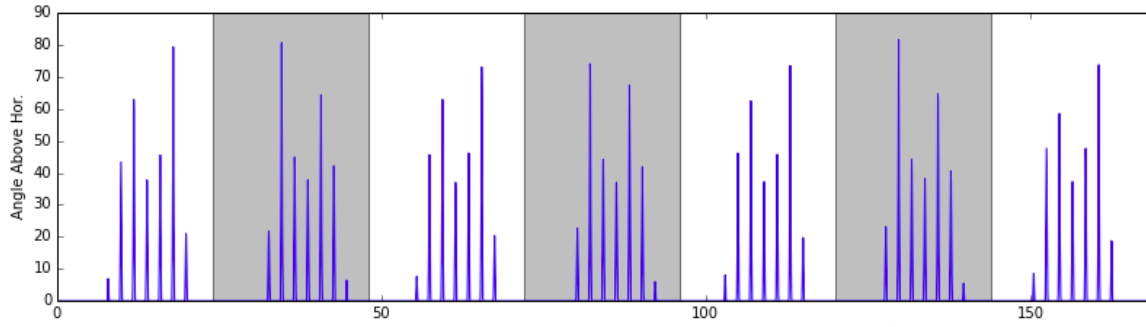
Coincident with its orbit over Lebanon, M088 is able to see Wi-Fi access points throughout the United States. The following figure shows the number of APs in view of M088 throughout the day, normalized to each of the twelve primary 20 MHz Wi-Fi channels in use today.



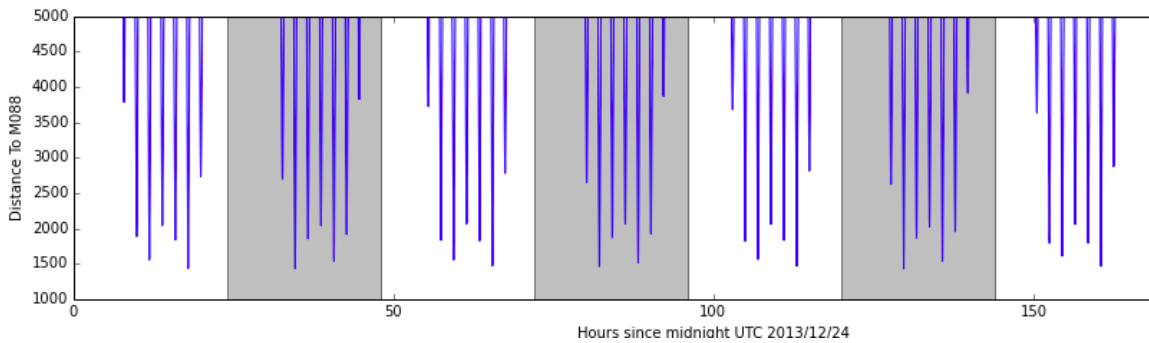
Number of APs seen by M088 As It Orbits Lebanon Throughout the Day³⁰

To ensure that we are not choosing an unrepresentative 24-hour period of observation, we also observe the satellite over the course of a week. As shown in the below rendering of elevation angles and distances, the 24-hour periods are similar. This therefore means that the number of access points seen by the satellite is relatively consistent from day to day.

³⁰ In this figure the peak number of APs by 20 MHz channel of 250,000 translates to 3 million total APs across all Wi-Fi channels.

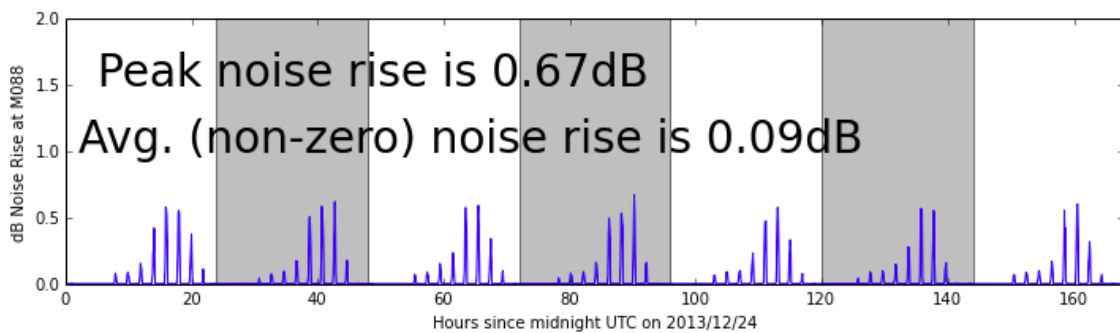


Angle of M088 to Lebanon Over A Week³¹



Distance of M088 to Lebanon Over A Week

We can then estimate the Wi-Fi noise added to Globalstar’s uplink as seen at M088 by accounting for the characteristics of the Wi-Fi signal specified earlier, such as the antennae pattern, duty cycle, and transmit power. As shown in the following figure, when the satellite is closest to Lebanon (nearly overhead), and Wi-Fi usage is highest, the level of noise seen at the satellite peaks. This noise level is relatively low, however, reaching only 0.67 dB.

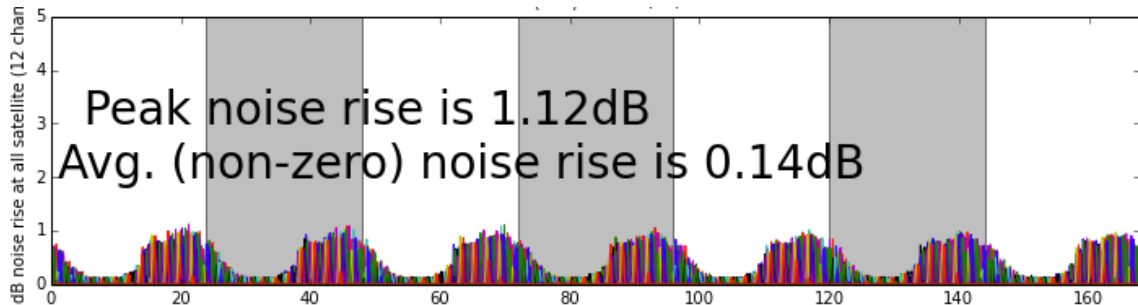


Uplink Noise Rise to M088 Over A Week

This analytic process can be repeated for all satellites in the Globalstar constellation to obtain a sense of the system-wide impact. This is depicted below, with each color representing a different

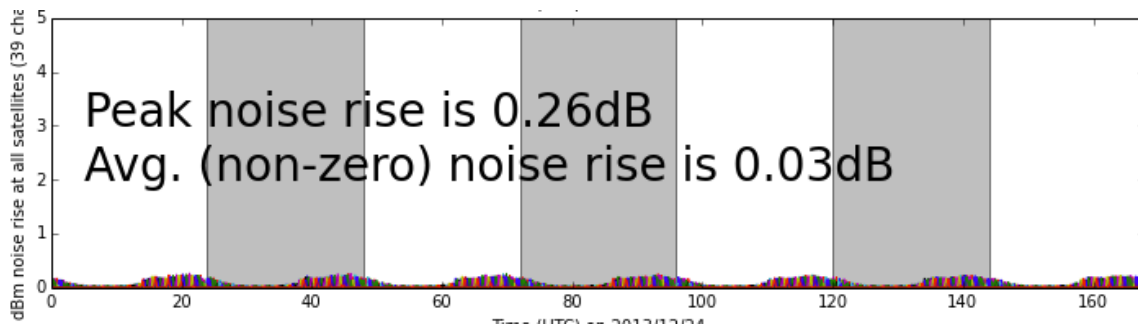
³¹ In graphics depicting week-long periods, 24-hour intervals indicated by shades.

satellite in the constellation. Note that the level of impact across all satellites is relatively uniform, and the peak uplink noise rise is approximately 1 dB.



Uplink Noise Rise to the Entire Globalstar Constellation Over A Week (12 Wi-Fi Channels in Use)

One can also obtain a sense of the impact if additional spectrum is available for Wi-Fi, which may be the case as the FCC expands Wi-Fi access across the 5 GHz band, and if currently available UNII-2 channels are considered. The effect would be to spread the signal across a greater range of bandwidth and further reduce the level of noise in Globalstar’s uplink. This is shown below, where the peak noise rise is reduced by 75%, relative to the 12-channel scenario shown above.



Uplink Noise Rise to the Entire Globalstar Constellation Over A Week (39 Wi-Fi Channels in Use)

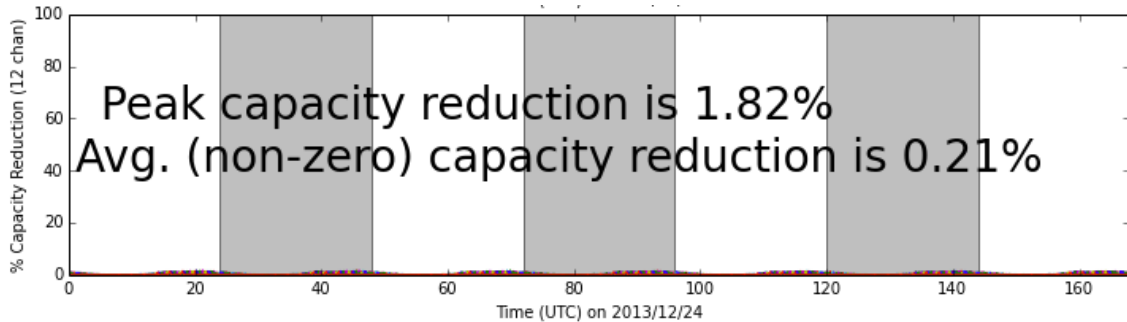
3.4 Results: Translating Wi-Fi “Noise” to Globalstar Capacity

The observations noted above are compelling: Millions of Wi-Fi access points deployed across the United States are likely to yield a very small amount of noise to the uplink in Globalstar’s duplex system. We will now translate the simulated uplink noise rise to an estimate of impact on end users, using the link budget provided by Globalstar. Our approach takes this link budget information on its face, without judgment as to its validity.

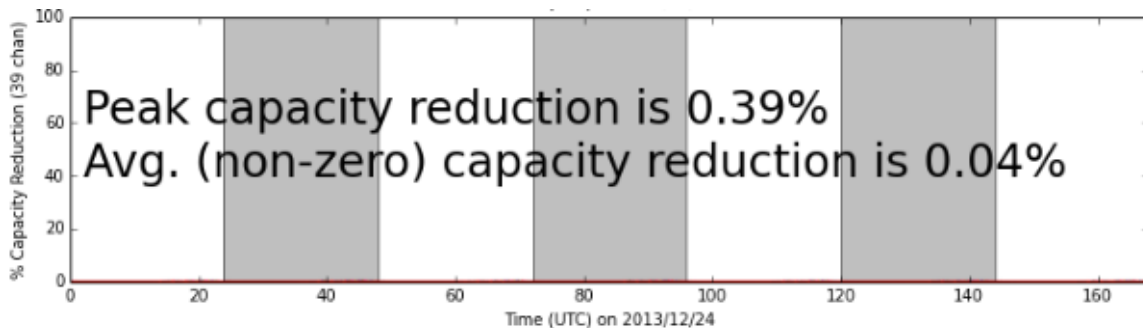
Globalstar states that the combined carrier-to-noise level (C/N, also expressed as E_b/N_o+I_o) with no additional interference from Wi-Fi is 1.01, which occurs when the downlink is 209.6 dBW/Hz.

The implication is that the Globalstar duplex system will increase uplink power to adjust for new Wi-Fi noise in order to maintain a C/N of 1.01, which then causes a reduction in capacity. We make no judgment on the validity of this claim, but we use the framework to estimate the amount of capacity that would be sacrificed by Wi-Fi deployment in our simulation.³²

We find that the peak amount of “capacity reduction” in the satellite system is 1.82% with twelve Wi-Fi channels in use, or 0.39% with thirty-nine Wi-Fi channels in use. This is shown in the following figures, again over the period of a week as satellites orbit and Wi-Fi use waxes and wanes.



Capacity Impact to Globalstar Constellation (12 Wi-Fi Channels in Use)



Capacity Impact to Globalstar Constellation (39 Wi-Fi Channels in Use)

³² The Roberson Report states that a 10 dB uplink noise rise translates to a 55.4% reduction in capacity. (See Table 2 of Roberson Report, p.15.) We use this ratio as the basis for our estimates.

These simulation results reveal how implausible, static assumptions drive an unrealistic (and overly pessimistic) assessment of interference risk and its potential impact. Globalstar estimated that over half of their system capacity could be put at risk by expansion of Wi-Fi access. Through more sophisticated analysis, we find the risk to be negligible.

Given the extremely conservative parameters of this simulation, which are reviewed in the next section of this paper, one might reasonably expect that the average capacity effects, rather than peak to be the more instructive output of the simulation (average is of course much lower than peak).³³ In any case, unless the satellite system is loaded to 98% capacity regularly – unlikely given its low subscribership – satellite phone users will experience no service diminution.³⁴

Therefore, there is little to no risk of harmful interference to Globalstar’s duplex system from expanding Wi-Fi access to UNII-1.

3.5 Sensitivity of Results

It is worth reviewing the many conservative parameters we have used in our presentation to avoid understating interference risk.

We have made no adjustment for the proportion of access points that may be deployed indoors, whereas well-over half of CableWiFi access points, for instance, are deployed indoors, and the broader population of access points are likely to heavily skew toward indoor deployment. In commonly accepted interference analyses, 95% of APs are assumed to be located indoors, so our presentation here is extremely conservative, and has significant allowance for Wi-Fi growth. Incorporating a proportion of indoor access points to the presentation would further reduce the impact of Wi-Fi on the Globalstar system.

³³ We report non-zero averages of capacity impacts, which accounts only for the period of time in which the satellite is within site. This metric therefore avoids understating average impacts by including periods of time when the satellite is orbiting elsewhere.

³⁴ In addition to capacity impacts, Globalstar notes that small coverage reductions and greater satellite battery usage could result from expanded Wi-Fi use of UNII-1. We have insufficient information to verify these claims or assess them relative to the simulation presented here, though it is reasonable to assume that these effects are also negligible, given our findings vis-à-vis system capacity.

In our simulation all APs transmit at 1 watt, which is at the upper end of what Wi-Fi transmit power. Even when FCC rules allow for 1 watt transmit power on access points, many APs operate below the maximum threshold, as they do today for a number of network engineering reasons.

Our simulation also enabled Globalstar satellites to “see” APs anywhere above the horizon, rather than to cut off Wi-Fi signals below 10 degrees to correspond with the normal sight of satellite user terminals. In addition, we do not incorporate terrain information that would further reduce Wi-Fi signals.³⁵ In effect, our simulation intentionally over-estimates the proportion of access points that any satellite is likely to “see” in actuality.

All of these factors combine to a conservative simulation, and are presented here to demonstrate that a real-world simulation, even one that may be “worst case,” yields favorable prospects for coexistence.

We are confident that any reasonable set of inputs will yield the same conclusions we have reached. For instance, in our research we have run a version of the simulation that more closely adheres to the implausible assumptions used by Globalstar³⁶ and we achieved results that are not materially different, varying from our main capacity impact findings by only a percentage point or two.

In addition, we must also reiterate that the “capacity reduction” estimates we provide here rely on the link budget depicted by Globalstar, and we have undertaken no independent assessment of the validity of that link budget. We have used their noise-to-capacity ratio³⁷ and applied it to our simulation of uplink noise generation. Since capacity and coverage (range) are interrelated, valid questions may exist about the baseline from which Globalstar estimates capacity impacts.

³⁵ For example, Boulder, Colorado lies directly east of the Rocky Mountain foothills; Wi-Fi signals from Boulder are not likely to be visible to a satellite until it is well overhead.

³⁶ Such as 80% peak duty cycle and density of 16 access points per square kilometer across both suburban and urban areas.

³⁷ 10 dB addition of uplink noise = 55.4% capacity diminution. See Table 2 of November 2013 Globalstar ex parte, p.15.

4 Themes and Lessons Learned

In exposing how a dynamic and sophisticated understanding of interference risk can lead to optimal policy, our hope is to offer a mold for spectrum sharing as a framework for meeting the critical economic imperative of expanding spectrum access for wireless broadband. Technical rigor must be accompanied by a proper policy orientation, however, in order to achieve productive ends. With that in mind, we offer several thematic observations below, of both a technical and a policy nature, which can help to make this experience generalizable. We welcome input and further research to help build this experiential record.

4.1 An Aversion To Simple Bright Lines

A productive spectrum sharing arrangement was possible in the UNII-1 band because of the FCC's willingness to look beyond simple technical recommendations. In particular, blind fealty to the ITU recommendation for satellite-observed noise would have prevented expanded Wi-Fi use of the band. However, in recognizing that the ITU recommendation was not a reasonable guide to understanding true interference risk to Globalstar's particular system, the authors and the FCC set the stage for a more nuanced understanding.

4.2 Attention to Shifting Marketplace Circumstances

Another enabler of the positive outcome in the case study explored here was the FCC's consideration of how the communications marketplace had evolved since the time it first considered its technical rules. By restricting Wi-Fi to very low power levels and indoor-only use, the FCC many years ago had expectations about how the mobile satellite industry would grow. Over time, it became clear that satellite communications would serve a niche role, while terrestrial wireless broadband became central to American economic activity. This had real implications for the appropriate set of technical rules protecting satellite systems. Questioning the status quo in light of changed circumstances was therefore a prerequisite for achieving policy benefits.

4.3 Use of Powerful Tools

The overly-simplified interference analyses that are proffered in regulatory proceedings are often a function of the capabilities of the tools used to generate them. The system engineers and consultants that produce them often know that they do not represent a true picture of the real RF world, but ‘back of the envelope’ calculations, often done in Microsoft Excel, are offered as a means to present a simplified view. Some simplification is perhaps inevitable; even in our case study, some assumptions were made. However, aspiration to a realistic picture and use of sophisticated tools can make a significant difference in the conclusions one may draw. IPython, the tool used in our work, enabled the incorporation of detailed and numerous data sets to achieve a better approximation of reality. IPython is not the only tool that can have this impact, but it behooves researchers to explore complexity in their analysis, if only to test the limits of their conclusions.

4.4 The Next Frontier of Spectrum Sharing

We also offer suggestions for practical application of these lessons learned. Given the economic benefits associated with Wi-Fi and the as-yet unfinished business of expanding Wi-Fi access to the 5 GHz band as proposed by the FCC, it is logical to explore what insights may be gained through sophisticated interference analysis in this area.

The FCC has proposed expanding the 5 GHz Wi-Fi band to 5925 MHz, from its current limit at 5850 MHz. This would enable the use of a full 160 MHz 802.11ac channel, providing substantial consumer benefits. However, Wi-Fi use is to be expanded to this new band, known as UNII-4, on the condition of coexistence with an intelligent transportation concept known as Dedicated Short Range Communications (DSRC), which envisions vehicle-to-vehicle crash avoidance communications, among other things.

In the initial analysis, coexistence between DSRC and Wi-Fi should be workable: Both use 802.11 technology (DSRC uses a variant known as 802.11p), and DSRC has not yet been deployed, leaving flexibility for pre-operational technical planning between system engineers. The circumstances appear to be more easily conducive to a workable and productive sharing arrangement than was the case in UNII-1, where the primary incumbent operated a much different system (mobile

satellite) and had already deployed significant network infrastructure that cannot be modified (satellites orbiting in space).

We do not endeavor a thorough analysis of UNII-4 coexistence here; rather, we suggest it as a likely candidate for future technical analysis, in hopes of producing a similarly optimal outcome to expand Wi-Fi access in 5 GHz as was achieved in the UNII-1 case.

5 Conclusion

This paper offered a case study that demonstrates how a sophisticated understanding of interference risks can yield productive outcomes in spectrum sharing policy. We have demonstrated that Wi-Fi can successfully share the 5 GHz UNII-1 band with the primary satellite system under updated technical rules that remove limitations on Wi-Fi, such as outdoor use restrictions and onerous power limitations. This analysis served as the primary basis for the FCC's expansion of Wi-Fi access in March 2014.

The need for spectrum will continue to grow as a function of the increasing role of wireless broadband in modern economies, and governments will continue to look for new approaches to meet this need. Sharing spectrum resources, rather than maintaining siloed allocations, has received newfound policy attention in this regard. However, the efficacy and utility of spectrum sharing as a policy solution is highly situation-dependent, and a function of the specific rules put in place.

The parsing of usage rights in spectrum sharing is driven in part by technical considerations relating to the potential for harmful interference. Therefore, a nuanced understanding of system interactions and risks is critical to achieving optimal policy outcomes. Further research should further progress the state of the art in this regard; we suggest best practices and encourage further research of spectrum sharing in the 5 GHz band.