

NIST Technical Note 2240

Radio Spectrum Occupancy Measurements Amid COVID-19 Telework and Telehealth

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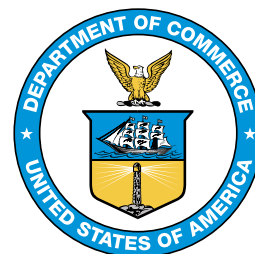
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Preface

While the long author list of this report reflects the scope of its technical effort, it neglects the indispensable contributions of other staff at NIST.

The rapid deployment of the distributed spectrum sensing network was only possible because of the fast response of our administrative staff. Ally Esquibel was exceptionally responsive in ordering a large number of parts in record speed. This was executed within the boundaries of the stay-at-home policies in place during the spring of 2020, thanks in large part to the dedicated attention and help from our administrators and management.

The project received invaluable coordination support during its startup. Early efforts, in particular by Sarah Hughes and Joanne Krummel, brought in personnel and resources which ensured that the project could proceed quickly and at scale.

We sincerely appreciate the understanding and support of the administrative and technical staff of our local hospital. They took time to enable us to perform our measurements even amid the strenuous demands of health care during the COVID-19 pandemic.

The scoping of the project was informed substantially by the background research performed by Regina Avila of the NIST library. The technical team thanks her for her work.

Finally, the core technical team is also grateful for the helpful technical and moral advice and discussions with John Ladbury and group leader Jason Coder, of the Communications Technology Laboratory at NIST.

Abstract

During the COVID-19 pandemic, the National Institute of Standards and Technology (NIST) began a targeted campaign of measurements of averaged power and occupancy rate in the radio spectrum. The purpose was to sample real environments to offer timely insights into data infrastructure where it might be strained by stay-at-home and quarantine orders. The findings from this study could be applied to testing to support network resilience and receiver immunity in future stay-at-home disaster scenarios.

Researchers who began working from home found themselves embedded in examples of the field sites that needed to be studied. Measurements began in 13 residential sites after a rapid engineering development effort, followed by spot measurements at a local hospital in the Denver metropolitan area. The study targeted radio frequency allocations that support key wireless data infrastructure. These included the cellular network bands below 1 GHz, and the unlicensed bands that support wireless local-area network (WLAN) and wireless personal area network (WPAN) traffic near 2.4 GHz and 5 GHz. The principal test locations were the home telework sites of NIST research staff, postdoctoral researchers, graduate and undergraduate students, and summer high school interns. Measurements continued where possible from late spring in 2020 until the autumn of 2021.

This report details the study and its results, beginning from its conception and specification and continuing through its execution to a summary analysis of the resulting data, which is also publicly available [1]. The key observations are as follows:

- In uplink channels of cellular frequency bands, as well as unlicensed radio bands, sensors observed low rates of occupancy. Transmissions that did occur appeared as short bursts: in all cases the 90th percentile of the transmission duration was no greater than 4 ms.
- In downlink channels of cellular frequency bands, occupancy rates were high, reflecting nearly continuous broadcasting.
- A strong diurnal characteristic was observed, with average downlink power levels reduced by approximately 5 dB between 23:30 and 07:30 local time.

These characteristics were broadly similar across all residential and hospital sites. The specific distributions of these parameters can now be used to help design test cases to ensure the continued resilience of wireless infrastructure in residential or health care shelter-in-place scenarios. In particular, we conclude with recommendations about the burst timing parameters for emulating the observed traffic in electromagnetic compatibility testing.

Through the development of the distributed sensor network, the team also produced new contributions to engineering and metrology for these problems. These included

- techniques for tuning sensors when precision laboratory calibration is not available,
- calibration methods for assembled software-defined radios (SDRs), and
- assessments of the performance of spectrum sensors in the field.

These may be developed further in the future as general-purpose approaches.

Table of Contents

Preface	v
Abstract	vi
List of Acronyms	x
List of Figures	xxii
List of Tables	xxiii
1 Introduction	1
1.1 Industry Background	1
1.2 Prior Work	1
1.3 Outcomes	1
1.3.1 Report Overview	2
2 Test Scope	3
2.1 Measurands	3
2.1.1 Band Power	3
2.1.2 Occupancy Rate	3
2.1.3 Network Traffic Profiling Parameters	4
2.2 List of Radio Frequencies Under Test	4
2.3 Coverage in Time and Frequency	4
2.4 Location	6
2.4.1 Residential Telework Sites	6
2.4.2 Hospital Site	6
3 Test Engineering	8
3.1 Goals and constraints	8
3.2 Design of the Sensor for Radio Band Power Sensor	8
3.2.1 Software-Defined Radio Receiver	10
3.2.2 Receive Architecture	10
3.2.3 Receive Antennas	11
3.2.4 Detection	11
3.2.5 Sensor Tuning	11
3.2.5.1 Settling Time	11
3.2.5.2 Sample Rate	11
3.2.5.3 Gain	14
3.2.5.4 Filtering	14
3.3 Network Data Traffic Profiling	15
3.3.1 Radio Configuration	15
3.3.2 Data Filtering	15
3.4 Deployment and Operation	16
3.4.1 Band Power Data and Privacy	16
3.5 Gain and Noise Calibration	16
3.6 Operating Procedure	17
3.6.1 In-Situ Noise Calibration of SDRs	17
3.6.2 Field Data Acquisition with SDRs	18

4	Band Power Data	19
4.1	Sample Distributions of Band Power Across Site and Frequency	19
4.1.1	Sample Sizes by Site and Date	19
4.1.2	Comparisons Between Frequency Bands	19
4.1.2.1	Dynamic Range Characteristics	19
4.1.2.2	Typical Power Level Incidence	19
4.1.3	Qualitative Features by Frequency Band	20
4.1.3.1	LTE Bands: Uplink Channels	20
4.1.3.2	LTE Bands: Downlink Channels	25
4.1.3.3	2695 MHz Passive Services Band	25
4.2	Sample Characteristics of Dwell Window Time Series	27
4.2.1	Time Series Representation	27
4.2.2	Time Duration of Occupancy Events Across Site and Frequency	27
4.2.2.1	LTE Bands: Uplink Channels	27
4.2.2.2	2.4 GHz ISM Channels	28
4.2.2.3	5 GHz U-NII Bands	30
4.3	Case Study at Site 1	32
4.3.1	LTE Bands: Uplink Channels	32
4.3.2	LTE Bands: Downlink Channels	32
4.3.3	2.4 GHz ISM Band	34
4.3.4	2695 MHz Passive Services Band	36
4.3.5	5 GHz U-NII Bands	36
5	Network Profiling Data	40
5.1	Summary of Cellular Data	40
5.2	Summary of WLAN Data	43
6	Conclusion	45
6.1	Findings	45
6.2	Application to Resilience Testing	45
6.2.1	Existing Test Standards	45
6.2.1.1	Tests for Medical Equipment	45
6.2.1.2	Tests for Household Products	46
6.2.2	Implications of the Test Data	46
6.3	Challenges and Future Direction	46
6.3.1	Analysis of Averaged Band Power	47
6.3.2	Sensor Noise De-embedding	47
6.3.3	Sensor Performance and Calibration	47
	References	48
A	Sensor Tuning and Performance	51
A.1	Tuning the Settling Time Delay	51
A.2	Dead Time Performance	51
A.3	Noise performance	51
B	Calibration and Uncertainty	55
B.1	Microwave Network Model of the SDR	55
B.1.1	Available Power (Wave)	56

B.2	Calibration with Known Input Signals	57
B.3	Uncertainty	58
B.3.1	Uncertainty Due to S-parameter Measurements	58
B.3.2	Uncertainty Due to Unknown x_1	58
B.3.3	Uncertainty Due to Power Measurements	59
C	Sample Data Verification in the 2695 MHz Passive Service Band	61
C.1	Spurious Readings	61
C.2	Time Stability of Power Readings	61
D	Sample Power Distributions by Site	65
	Residential Site 0	65
	Residential Site 1	72
	Residential Site 2	72
	Residential Site 3	78
	Residential Site 4	84
	Residential Site 5	90
	Residential Site 6	96
	Residential Site 7	102
	Residential Site 8	108
	Residential Site 9	114
	Residential Site 10	120
	Residential Site 11	126
	Residential Site 12	132
	Hospital Site	138
E	Network Profiling Data by Site	141
	Cellular Network Profiling	141
	WLAN Profiling	141

Acronyms

AP	access point	OFDM	orthogonal-frequency division multiplexing
BS	base station	OTA	over the air
COTS	commercial off-the-shelf	PII	personally-identifiable information
DL	downlink band	RAT	radio access technology
EVM	error vector magnitude	RB	resource block
FDD	frequency-division duplex	RIV	resource indication value
FIR	finite impulse response	RF	radio frequency
GPS	global positioning system	RSSI	received signal strength indicator
IQ	in-phase and quadrature	SDR	software-defined radio
IMD	intermodulation distortion	SF	survival function
ISM	industrial, scientific, and medical	TTI	transmission time interval
LTE	long-term evolution	U-NII	unlicensed national information infrastructure
MAC	medium access control	UE	user equipment
MCS	modulation coding scheme	USB	universal serial bus
MIMO	multiple-input multiple-output	WLAN	wireless local-area network
NIST	National Institute of Standards and Technology	WPAN	wireless personal area network

List of Figures

2.1	The structure of a shuffled frequency sweep in time and frequency.	6
2.2	Test locations of measurements at the hospital site.	7
3.1	An assembled sensor node, with an SDR enclosed inside the transparent enclosure. The antennas shown were the omni-directional models used in the residential telework setting.	9
3.2	Block diagram of the radio front-end architecture of a sensor node	10
3.3	The GNURadio flow graph for real-time energy detection in software. In this software, only the unit prefix is shown for unitary quantities. Parameter values here are applied in the following units: gain in linear power (“Low Pass Filter”) or dB (all other blocks); sample rates, bandwidths, and frequencies in Hz; times in s; and all other quantities are unitless.	12
3.4	Example of the real time display of band power readings shown on a sensor node during operation. The time span is one stepped frequency sweep. The top (red) trace indicates the in-phase and quadrature (IQ) sample peak, while the botto (blue) is the average channel power reported in the paper. (The actual sweep time is greater than 6 s, because the hardware settling time on frequency changes was typically 250 ms.)	13
3.5	Sensor readings at 884.5 MHz taken 1.5 m away from a 701.5 MHz user equipment (UE). At 60 dB gain (bottom/blue line), the sensor showed poor frequency selectivity. Reducing the gain to 15 dB (top/green line) mitigated the impact.	14
3.6	A low-pass filter with 2x decimation achieved downsampling from 8 MHz to 4 MHz, reducing the volume of data while removing high frequency noise. The result was a reduction in noise power by 9.4 dB.	15
3.7	A sensor node connected to 50 Ω input terminations for input noise calibration.	17
4.1	Overview of size of the data set as distributed across time and site, from 2020-06-09 through 2021-09-22. Sample counts from each site are summed across all frequencies.	20
4.2	Mean of each site’s empirical survival functions of band power, categorized by center frequency. This averaging illustrates the stress on receivers’ dynamic range experienced in these environments. To illustrate rare events, the traces are transformed onto a logarithmic vertical axis.	21
4.3	Empirical survival functions of band power per site, categorized by band activity. To illustrate rare events, the traces are transformed onto a logarithmic vertical axis.	22
4.4	Mean of each site’s empirical survival functions of band power, categorized by center frequency. This averaging illustrates the stress on receivers’ dynamic range experienced in these environments. To emphasize the most common levels band power, the vertical axis is on a linear scale.	23
4.5	Empirical survival functions of band power per site, categorized by band type. To emphasize the most frequently sampled values of band power, the vertical axis is on a linear scale.	24
4.6	Empirical survival function of band power in LTE uplink channels relative to the interference floor, by frequency (left) and site (right). On the left, counts were summed from all sites, and on the right, counts were summed across all center frequencies in the band from 2020-06-09 through 2021-09-22.	25
4.7	Histogram heat maps of samples received in each LTE downlink channel by time of day. Sample counts are summed across all sites within the period of 2020-06-09 through 2021-09-22.	26
4.8	Example time series of band power, acquired starting on 2020-11-06. Close views are shown spanning the duration of 1 dwell window on the left. These were least and most occupied dwells within their 24-hour acquisition period, indicated with the vertical lines on the right.	27
4.9	Example heat map of band power envelopes in dwell windows (vertical axis) progressing in time across 1 day in 2020 (horizontal axis). In order to make the short transmissions visible on the horizontal time scale, the data are shown binned into 10-minute maxima. The vertical dashed lines correspond with the traces shown in Figure 4.8 (left).	28
4.10	Empirical survival functions of occupancy duration in LTE uplink channels across all dates. The distribution in each plot is split across the variable as shown in the legend; otherwise an occupancy threshold is set to -60 dBm and data is aggregated across all sites and frequencies.	29
4.11	Empirical survival functions of occupancy duration aggregated across all 2.4 GHz ISM channels and all dates. The distribution in each plot is split across the variable as shown in the legend; otherwise an occupancy threshold is set to -60 dBm and data is aggregated across all sites and frequencies.	30

4.12	Empirical survival functions of occupancy duration in 5 GHz unlicensed national information infrastructure (U-NII) bands across all dates. The distribution in each plot is split across the variable as shown in the legend; otherwise an occupancy threshold is set to -60 dBm and data is aggregated across all sites and frequencies.	31
4.13	Histogram heat maps of band power at 842.5 MHz from site 1 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	32
4.14	Histogram heat maps of band power at 701.5 MHz from site 1 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	33
4.15	Empirical survival functions of band power in uplink channels of long-term evolution (LTE) bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	33
4.16	Histogram heat maps of band power at 739.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE downlink bands at this site.	34
4.17	Histogram heat maps of band power at 866.3 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE downlink bands at this site.	34
4.18	Empirical survival functions of band power in downlink channels of LTE bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.	35
4.19	Histogram heat maps of band power at 2462.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	35
4.20	Histogram heat maps of band power at 2412.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	35
4.21	Empirical survival functions of band power in ISM bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.	36
4.22	Histogram of band power measured in the 2695 MHz passive service band at site 1. At this sample size, quantization is observable below -130 dBm/4 MHz.	37
4.23	Histogram heat maps of band power at 2695.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	37
4.24	Histogram heat maps of band power at 5170.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	38
4.25	Histogram heat maps of band power at 5775.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	38
4.26	Empirical survival functions of band power in U-NII bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.	39
5.1	Histograms of LTE uplink resource grants from the hospital site on 2020-12-07 observed at 739.0 MHz	41
5.2	Histograms of LTE downlink resource grants from the hospital site on 2020-12-07 observed at 739.0 MHz	41
5.3	Histograms of LTE uplink resource grants from site 07 observed at 739.0 MHz	42
5.4	Histograms of LTE downlink resource grants from site 07 observed at 739.0 MHz	42
5.5	Received power levels by transmission source in WLAN measured from the hospital site on 2021-09-24 data at 2412.0 MHz	43
5.6	Data rate by transmission source in WLAN measured from the hospital site on 2021-09-24 data at 2412.0 MHz	43
5.7	Histogram of packet types observed in WLAN measured from the hospital site on 2021-09-24 data at 2412.0 MHz	44
5.8	Histograms of WLAN data rate and payload sizes from the hospital site on 2021-09-24 observed at 2412.0 MHz	44
A.1	Maximum power at 2695 MHz in all readings through November 2020, by time elapsed in the dwell window. Holdoff time was set to 195 ms to remove the noise plateau from published data.	52

A.2	Distribution of the time duration between frequency steps, including acquisition time and settling holdoff time for transients.	53
A.3	Simulation results of a SDR with 40 dB gain and 5 dB NF. The detection bandwidth is set to 10 MHz. The 95th quantile indicates the confidence level of the receiver to determine the input signal level.	54
B.1	The scattering parameter model of noise waves at the sensor input, used as the basis for the sensor calibration. The shaded region indicates the SDR receiver.	56
B.2	Waves generated by a source being delivered to a load. Both source and load present reflections, which are non-idealities that must be accounted for through calibration.	57
C.1	Empirical survival functions of band power in the passive services band at 2695 MHz, both across all sites (left) and categorized by site (right). To illustrate rare events, plots average of the SF from each site (left) are shown on a logarithmic vertical axis. The SF of all samples received, shown with linear scale (right), emphasizes the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.	62
C.2	Histogram heat map of all band power samples in the passive services band at 2695 MHz, summed across all sites on each calendar day. Spurious high readings (around 1 part in 10^6) were acquired mostly in September through November of 2020.	62
C.3	Histogram heat map of all band power samples in the passive services band at 2695 MHz, summed across all sites by time of day with bin size 10 minutes. Spurious high power samples (around 1 part in 10^6) were acquired mostly during daylight and early evening hours.	63
C.4	Long-term stability in band power sensed at 2695 MHz. To improve clarity on this time scale, averaging was applied to reduce variance. The mean was computed on the center 2 quartiles of each dwell window, and the traces are a 1 hour moving mean of this dwell average. The result here encapsulates the full data set, categorized by site.	64
D.1	Histogram of band power samples in downlink channels in LTE downlink bands relative to the site noise and interference level at site 0, as gauged by the peak histogram level in each dwell window.	65
D.2	Plots of empirical survival functions of band power in downlink channels in LTE downlink bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	65
D.3	Histogram heat maps of band power at 821.3 MHz from site 0 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	66
D.4	Histogram heat maps of band power at 782.0 MHz from site 0 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	66
D.5	Plots of empirical survival functions of band power in uplink channels in LTE bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	66
D.6	Histogram heat maps of band power at 887.5 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	67
D.7	Histogram heat maps of band power at 739.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	67
D.8	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 0, as gauged by the peak histogram level in each dwell window.	67
D.9	Plots of empirical survival functions of band power in downlink channels in LTE bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	68
D.10	Histogram heat maps of band power at 2412.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among industrial, scientific, and medical (ISM) bands at this site.	68
D.11	Histogram heat maps of band power at 2462.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	68
D.12	Plots of empirical survival functions of band power in ISM bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	69
D.13	Histogram heat maps of band power at 2695.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	69

D.14	Histogram of band power measured in the 2695 MHz passive service band at site 0.	69
D.15	Histogram heat maps of band power at 5210.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	70
D.16	Histogram heat maps of band power at 5775.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	70
D.17	Plots of empirical survival functions ofband power in U-NII bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	70
D.18	Histograms (left) and empirical survival functions (right) of all samples received in site 0 in each type of band under test.	71
D.19	Histogram heat maps of band power at 842.5 MHz from site 2 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	72
D.20	Histogram heat maps of band power at 701.5 MHz from site 2 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	72
D.21	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	73
D.22	Histogram heat maps of band power at 739.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	73
D.23	Histogram heat maps of band power at 887.5 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	73
D.24	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 2, as gauged by the peak histogram level in each dwell window.	74
D.25	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	74
D.26	Histogram heat maps of band power at 2462.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	74
D.27	Histogram heat maps of band power at 2437.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	75
D.28	Plots of empirical survival functions ofband power in ISM bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	75
D.29	Histogram heat maps of band power at 2695.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	75
D.30	Histogram of band power measured in the 2695 MHz passive service band at site 2.	76
D.31	Histogram heat maps of band power at 5240.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	76
D.32	Histogram heat maps of band power at 5795.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	76
D.33	Plots of empirical survival functions ofband power in U-NII bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	77
D.34	Histograms (left) and empirical survival functions (right) of all samples received in site 2 in each type of band under test.	77
D.35	Histogram heat maps of band power at 782.0 MHz from site 3 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	78

D.36	Histogram heat maps of band power at 821.3 MHz from site 3 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	78
D.37	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. .	79
D.38	Histogram heat maps of band power at 887.5 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	79
D.39	Histogram heat maps of band power at 866.3 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	79
D.40	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 3, as gauged by the peak histogram level in each dwell window.	80
D.41	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. .	80
D.42	Histogram heat maps of band power at 2437.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	80
D.43	Histogram heat maps of band power at 2462.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	81
D.44	Plots of empirical survival functions ofband power in ISM bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	81
D.45	Histogram heat maps of band power at 2695.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	81
D.46	Histogram of band power measured in the 2695 MHz passive service band at site 3.	82
D.47	Histogram heat maps of band power at 5230.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	82
D.48	Histogram heat maps of band power at 5190.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	82
D.49	Plots of empirical survival functions ofband power in U-NII bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	83
D.50	Histograms (left) and empirical survival functions (right) of all samples received in site 3 in each type of band under test.	83
D.51	Histogram heat maps of band power at 842.5 MHz from site 4 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	84
D.52	Histogram heat maps of band power at 709.0 MHz from site 4 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	84
D.53	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. .	85
D.54	Histogram heat maps of band power at 887.5 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	85
D.55	Histogram heat maps of band power at 751.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	85
D.56	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 4, as gauged by the peak histogram level in each dwell window.	86
D.57	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. .	86

D.58	Histogram heat maps of band power at 2437.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	86
D.59	Histogram heat maps of band power at 2462.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	87
D.60	Plots of empirical survival functions ofband power in ISM bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	87
D.61	Histogram heat maps of band power at 2695.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	87
D.62	Histogram of band power measured in the 2695 MHz passive service band at site 4.	88
D.63	Histogram heat maps of band power at 5190.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	88
D.64	Histogram heat maps of band power at 5230.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	88
D.65	Plots of empirical survival functions ofband power in U-NII bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	89
D.66	Histograms (left) and empirical survival functions (right) of all samples received in site 4 in each type of band under test.	89
D.67	Histogram heat maps of band power at 782.0 MHz from site 5 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	90
D.68	Histogram heat maps of band power at 821.3 MHz from site 5 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	90
D.69	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	91
D.70	Histogram heat maps of band power at 739.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	91
D.71	Histogram heat maps of band power at 751.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	91
D.72	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 5, as gauged by the peak histogram level in each dwell window.	92
D.73	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	92
D.74	Histogram heat maps of band power at 2412.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	92
D.75	Histogram heat maps of band power at 2462.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	93
D.76	Plots of empirical survival functions ofband power in ISM bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	93
D.77	Histogram heat maps of band power at 2695.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	93
D.78	Histogram of band power measured in the 2695 MHz passive service band at site 5.	94
D.79	Histogram heat maps of band power at 5170.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	94

D.80	Histogram heat maps of band power at 5240.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	94
D.81	Plots of empirical survival functions ofband power in U-NII bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	95
D.82	Histograms (left) and empirical survival functions (right) of all samples received in site 5 in each type of band under test.	95
D.83	Histogram heat maps of band power at 701.5 MHz from site 6 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	96
D.84	Histogram heat maps of band power at 842.5 MHz from site 6 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	96
D.85	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	97
D.86	Histogram heat maps of band power at 739.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	97
D.87	Histogram heat maps of band power at 751.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	97
D.88	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 6, as gauged by the peak histogram level in each dwell window.	98
D.89	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	98
D.90	Histogram heat maps of band power at 2412.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	98
D.91	Histogram heat maps of band power at 2437.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	99
D.92	Plots of empirical survival functions ofband power in ISM bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	99
D.93	Histogram heat maps of band power at 2695.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	99
D.94	Histogram of band power measured in the 2695 MHz passive service band at site 6.	100
D.95	Histogram heat maps of band power at 5170.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	100
D.96	Histogram heat maps of band power at 5775.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	100
D.97	Plots of empirical survival functions ofband power in U-NII bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	101
D.98	Histograms (left) and empirical survival functions (right) of all samples received in site 6 in each type of band under test.	101
D.99	Histogram heat maps of band power at 782.0 MHz from site 7 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	102
D.100	Histogram heat maps of band power at 701.5 MHz from site 7 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	102
D.101	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	103

D.102	Histogram heat maps of band power at 866.3 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	103
D.103	Histogram heat maps of band power at 734.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	103
D.104	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 7, as gauged by the peak histogram level in each dwell window.	104
D.105	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	104
D.106	Histogram heat maps of band power at 2412.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	104
D.107	Histogram heat maps of band power at 2462.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	105
D.108	Plots of empirical survival functions ofband power in ISM bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	105
D.109	Histogram of band power measured in the 2695 MHz passive service band at site 7.	105
D.110	Histogram heat maps of band power at 5170.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	106
D.111	Histogram heat maps of band power at 5775.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	106
D.112	Plots of empirical survival functions ofband power in U-NII bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	106
D.113	Histograms (left) and empirical survival functions (right) of all samples received in site 7 in each type of band under test.	107
D.114	Histogram heat maps of band power at 821.3 MHz from site 8 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	108
D.115	Histogram heat maps of band power at 709.0 MHz from site 8 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	108
D.116	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	109
D.117	Histogram heat maps of band power at 887.5 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	109
D.118	Histogram heat maps of band power at 751.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	109
D.119	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 8, as gauged by the peak histogram level in each dwell window.	110
D.120	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	110
D.121	Histogram heat maps of band power at 2412.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	110
D.122	Histogram heat maps of band power at 2462.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	111
D.123	Plots of empirical survival functions ofband power in ISM bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	111

D.124	Histogram heat maps of band power at 2695.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	111
D.125	Histogram of band power measured in the 2695 MHz passive service band at site 8.	112
D.126	Histogram heat maps of band power at 5170.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	112
D.127	Histogram heat maps of band power at 5795.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	112
D.128	Plots of empirical survival functions ofband power in U-NII bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	113
D.129	Histograms (left) and empirical survival functions (right) of all samples received in site 8 in each type of band under test.	113
D.130	Histogram heat maps of band power at 701.5 MHz from site 9 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	114
D.131	Histogram heat maps of band power at 709.0 MHz from site 9 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	114
D.132	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	115
D.133	Histogram heat maps of band power at 866.3 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	115
D.134	Histogram heat maps of band power at 751.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	115
D.135	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 9, as gauged by the peak histogram level in each dwell window.	116
D.136	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	116
D.137	Histogram heat maps of band power at 2437.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	116
D.138	Histogram heat maps of band power at 2462.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	117
D.139	Plots of empirical survival functions ofband power in ISM bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	117
D.140	Histogram heat maps of band power at 2695.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	117
D.141	Histogram of band power measured in the 2695 MHz passive service band at site 9.	118
D.142	Histogram heat maps of band power at 5190.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	118
D.143	Histogram heat maps of band power at 5795.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	118
D.144	Plots of empirical survival functions ofband power in U-NII bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	119
D.145	Histograms (left) and empirical survival functions (right) of all samples received in site 9 in each type of band under test.	119

D.146	Histogram heat maps of band power at 709.0 MHz from site 10 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	120
D.147	Histogram heat maps of band power at 842.5 MHz from site 10 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	120
D.148	Plots of empirical survival functions of band power in uplink channels in LTE bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	121
D.149	Histogram heat maps of band power at 751.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	121
D.150	Histogram heat maps of band power at 739.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	121
D.151	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 10, as gauged by the peak histogram level in each dwell window.	122
D.152	Plots of empirical survival functions of band power in downlink channels in LTE bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	122
D.153	Histogram heat maps of band power at 2412.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	122
D.154	Histogram heat maps of band power at 2437.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	123
D.155	Plots of empirical survival functions of band power in ISM bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	123
D.156	Histogram heat maps of band power at 2695.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	123
D.157	Histogram of band power measured in the 2695 MHz passive service band at site 10.	124
D.158	Histogram heat maps of band power at 5170.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	124
D.159	Histogram heat maps of band power at 5795.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	124
D.160	Plots of empirical survival functions of band power in U-NII bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	125
D.161	Histograms (left) and empirical survival functions (right) of all samples received in site 10 in each type of band under test.	125
D.162	Histogram heat maps of band power at 709.0 MHz from site 11 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	126
D.163	Histogram heat maps of band power at 701.5 MHz from site 11 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	126
D.164	Plots of empirical survival functions of band power in uplink channels in LTE bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	127
D.165	Histogram heat maps of band power at 866.3 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	127
D.166	Histogram heat maps of band power at 751.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	127
D.167	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 11, as gauged by the peak histogram level in each dwell window.	128

D.168	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	128
D.169	Histogram heat maps of band power at 2412.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	128
D.170	Histogram heat maps of band power at 2462.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	129
D.171	Plots of empirical survival functions ofband power in ISM bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	129
D.172	Histogram heat maps of band power at 2695.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	129
D.173	Histogram of band power measured in the 2695 MHz passive service band at site 11.	130
D.174	Histogram heat maps of band power at 5170.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	130
D.175	Histogram heat maps of band power at 5775.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	130
D.176	Plots of empirical survival functions ofband power in U-NII bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	131
D.177	Histograms (left) and empirical survival functions (right) of all samples received in site 11 in each type of band under test.	131
D.178	Histogram heat maps of band power at 701.5 MHz from site 12 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.	132
D.179	Histogram heat maps of band power at 709.0 MHz from site 12 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.	132
D.180	Plots of empirical survival functions ofband power in uplink channels in LTE bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	133
D.181	Histogram heat maps of band power at 887.5 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.	133
D.182	Histogram heat maps of band power at 734.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.	133
D.183	Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 12, as gauged by the peak histogram level in each dwell window.	134
D.184	Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	134
D.185	Histogram heat maps of band power at 2462.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.	134
D.186	Histogram heat maps of band power at 2412.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	135
D.187	Plots of empirical survival functions ofband power in ISM bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	135
D.188	Histogram heat maps of band power at 2695.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.	135
D.189	Histogram of band power measured in the 2695 MHz passive service band at site 12.	136

D.190	Histogram heat maps of band power at 5190.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.	136
D.191	Histogram heat maps of band power at 5775.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.	136
D.192	Plots of empirical survival functions ofband power in U-NII bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	137
D.193	Histograms (left) and empirical survival functions (right) of all samples received in site 12 in each type of band under test.	137
D.194	Empirical survival functions of band power in uplink channels in LTE bands at site hospital, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	138
D.195	Band power samples in downlink channels in LTE bands relative to the site noise and interference level at site hospital, as gauged by the peak histogram level in each dwell window.	138
D.196	Empirical survival functions of band power in downlink channels in LTE bands at site hospital, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	139
D.197	Empirical survival functions of band power in ISM bands at site hospital, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.	139
D.198	Histogram of band power measured in the 2695 MHz passive service band at site hospital.	139
D.199	Histograms (left) and empirical survival functions (right) of all samples received in site hospital in each type of band under test. No samples were collected in the U-NII or quiet bands in this site.	140
E.1	Histograms of LTE uplink resource grants from site 07 observed at 866.3 MHz	141
E.2	Histograms of LTE downlink resource grants from site 07 observed at 866.3 MHz	142
E.3	Histograms of LTE uplink resource grants from site 07 observed at 731.5 MHz	142
E.4	Histograms of LTE downlink resource grants from site 07 observed at 731.5 MHz	143
E.5	Histograms of LTE uplink resource grants from site 07 observed at 751.0 MHz	143
E.6	Histograms of LTE downlink resource grants from site 07 observed at 751.0 MHz	144
E.7	Histograms of LTE uplink resource grants from site 11 observed at 739.0 MHz	144
E.8	Histograms of LTE downlink resource grants from site 11 observed at 739.0 MHz	145
E.9	Histograms of LTE uplink resource grants from site 11 observed at 866.3 MHz	145
E.10	Histograms of LTE downlink resource grants from site 11 observed at 866.3 MHz	146
E.11	Histograms of LTE uplink resource grants from site 11 observed at 731.5 MHz	146
E.12	Histograms of LTE downlink resource grants from site 11 observed at 731.5 MHz	147
E.13	Histograms of LTE uplink resource grants from site 11 observed at 751.0 MHz	147
E.14	Histograms of LTE downlink resource grants from site 11 observed at 751.0 MHz	148
E.15	Received power levels by transmission source in WLAN measured from hospital 2021-09-24 data at 2437.0 MHz	148
E.16	Data rate by transmission source in WLAN measured from hospital 2021-09-24 data at 2437.0 MHz	149
E.17	Histogram of packet types observed in WLAN measured from hospital 2021-09-24 data at 2437.0 MHz	149
E.18	Histograms of WLAN data rate and payload sizes from hospital 2021-09-24 observed at 2437.0 MHz	149
E.19	Received power levels by transmission source in WLAN measured from hospital 2021-09-24 data at 2462.0 MHz	150
E.20	Data rate by transmission source in WLAN measured from hospital 2021-09-24 data at 2462.0 MHz	150
E.21	Histogram of packet types observed in WLAN measured from hospital 2021-09-24 data at 2462.0 MHz	150
E.22	Histograms of WLAN data rate and payload sizes from hospital 2021-09-24 observed at 2462.0 MHz	151

List of Tables

2.1	List of frequencies under study	5
3.1	Sensor node specification and performance at the deployed 15 dB gain setting	9
3.2	Measurement receiver component listing	10

Chapter 1

Introduction

The start of the COVID-19 pandemic caused most staff at National Institute of Standards and Technology (NIST) to work from home beginning in March, 2020. While they minimized or eliminated time spent at the NIST site, the agency – like the broader public – worked to prepare safety measures for a safe return. During this time, most staff teleworked from home.

With this as a backdrop, NIST undertook a program of technical projects focused around the novel coronavirus in and around Boulder, Colorado [2]. This location was notable on the national scale: one analysis of census data reported that the Boulder area experienced the highest rate of telework in the United States [3].

1.1 Industry Background

Stay-at-home orders that began in March 2020 led to several abrupt shifts in data consumption.

One significant shift in this period was toward remote work. Initial reports suggested that the telework rate in the U.S. increased from less than 4% in 2019 to 50% in April 2020 [4]. Meanwhile, press reported that broadband service experienced a 47% increase in data consumption [5] and 53% increase in calls placed over Wi-Fi [6]. As a result of this added load, urban broadband users experienced decreases in broadband data throughput between 10% and 40% [7].

Because internet service for most households passes through Wi-Fi, impacts on mobile networks were less significant. Industry reported an increase in cellular voice and data traffic by 20%-25% [8].

The volume of data traffic in telehealth settings increased as well. A retrospective analysis by the U.S. Department of Health and Human Services reported a 63-fold increase in Medicare health appointments, and 32-fold increase for behavioral health [9]. Meanwhile, the U.S. Department of Veterans Affairs reported an elevenfold increase in the number of telehealth appointments [10].

1.2 Prior Work

Several publications reported on spectrum occupancy measurements performed in residential settings. These were performed in many countries internationally [11, 12, 13, 14, 15]. However, these tended to be performed outdoors, in the vicinity of housing rather than inside, where the equipment is used.

Data collected in hospitals is more sparse. Two studies focused on the 2.4 GHz ISM band [16, 17]. Few publications address other frequency bands.

1.3 Outcomes

This report details the experimental efforts undertaken to fill the above gaps by assessing occupancy in the radio spectrum. The approach was to use low-cost sensors to assess this environment inside 13 residences and outside of one hospital. The types of contributions that resulted from this test campaign included:

1. A public dataset of the channel power measurement data, collected during the first half of the pandemic in residential environments and outside a hospital [1]
2. Development of sensor tuning methods that could be applied at home without precision test equipment
3. Development of precise sensor calibration techniques, which were executed on returning to the laboratory at NIST in Boulder
4. An analysis of the statistical characteristics of occupancy across site, frequency band and time.

Testing during the COVID-19 pandemic emergency makes the results well suited toward future applications in testing network resilience and device immunity for disasters that require inhabitants to stay at home. This could be accomplished by adopting the occupancy characteristics identified in this report in immunity test standards such as IEC 60601-1-2 [18] (medical equipment) and CISPR 14-2 [19] (household devices).

During the course of this campaign, we also developed new sensor test and calibration methods suited for limited access to precision lab measurements. These included:

- techniques for tuning sensors when precision laboratory calibration is not available,
- calibration methods for assembled software-defined radios (SDRs), and
- assessments of the performance of low-cost spectrum sensors in the field.

These methods may be applied in other test campaigns for which precision calibrations are too costly or time consuming to perform at the beginning of tests.

1.3.1 Report Overview

Detailed discussion of the procedures, results, and conclusions are organized in this report as follows:

- Chapter 2 specifies the technical parameters of the test
- Chapter 3 details the design and test characterization of the sensors used in the campaign
- Chapter 4 summarizes the data collected by the sensors
- Chapter 5 summarizes ancillary network traffic profiling data
- Chapter 6 discusses the overall findings and how they could be applied to testing to support network resilience and receiver immunity in future stay-at-home disaster scenarios

Further details of the approach and resulting data are presented in the appendices:

- Appendix A details the sensor frontend tuning methods developed for these tests
- Appendix B describes the sensor calibration methods
- Appendix C shows sensor validation methods and results based on the field data
- Appendix D gives occupancy data plots of measurement data from sensors residential and hospital site
- Appendix E presents network profiling data collected with a network test instrument at the hospital site.

Chapter 2

Test Scope

The test scope is the context for the test data published in [1], and which is the basis for the analysis presented in the remainder of this report.

2.1 Measurands

This section establishes mathematical and physical definitions for the parameters that were measured and reported in this study.

2.1.1 Band Power

Band power refers to the power integrated across 4 MHz of sensing bandwidth in the sensor. This is in most cases smaller than the regulatory band allocation, or the channel bandwidth, due to limitations of the sensor (see Section 3.2). The center frequency of the sensor was aligned with the expected center frequency of the radio activity in the band.

Each band power measurement is evaluated as the time-average of power readings in a time bin of duration 500- μ s. This time bin duration is equivalent to the aperture time in an average power sensor. Physically, this power level is a guided-wave *available power* that is calibrated to the antenna output (Section 3.5). Each band power reading, P , was computed from complex-valued samples of the baseband receive waveform, x_n , as

$$P = \frac{A}{N} \sum_{n=1}^N ||x_n||^2, \quad (2.1)$$

in linear power units. Here, $||\cdot||$ represents complex magnitude, and A is a frequency-dependent correction to physical input power that is determined from laboratory calibration. Each bin contains $N = 2000$ samples that were acquired at 8 MS/s, and then digitally filtered to 4 MHz bandwidth and downsampled to 4 MS/s. This was the greatest feasible sampling rate based on technical limitations that are described in Appendix A.

Each band power measurement can be interpreted as band-limited to 4 MHz (i.e., center frequency $\pm$ 2 MHz) centered at the radio frequency (RF) center frequencies listed by Section 2.2. However, spurious energy readings can result when energy from powerful carriers outside of the band under study. This occurs despite the sharp roll-off of the digital filter because low-cost SDRs hardware tends to exhibit limited frequency selectivity, and because the front-end preselect filters have wide bandwidth to support the tuning range under study.

2.1.2 Occupancy Rate

The band occupancy rate in this report is empirical and derived from band power. As such, it is not measured directly, but is a consequence of the power readings. It is a statistic defined in terms of a sequence of M band power readings, P_m , and an occupancy threshold reference power, P_{occ} , as

$$\text{Occupancy rate} = \frac{\#\{P_m : P_m > P_{occ}\}}{M}. \quad (2.2)$$

The notation $\#\{P_m : \text{condition}\}$ here should be interpreted the total number of samples for which P_m meets the specified condition. The choice of P_{occ} can be tailored to the coexistence interactions in a specific scenario or protocol standard. Because we wish to provide data without constraining to a specific application, the simple analysis in this report gives occupancy rate for several values of P_{occ} selected above the sensor noise level. Values for more specific P_{occ} can be computed using the published data.

2.1.3 Network Traffic Profiling Parameters

Network traffic profiling was carried out by a commercial instrument for over the air (OTA) wireless testing. The protocol layers information can give more details about downlink communication as well as a way to predict the uplink spectrum occupancy. The instrument supported 5G NR, 4G long-term evolution (LTE), and 802.11 wireless local-area network (WLAN). The instrument was able to decode only LTE cellular and WLAN activity in our residential tests. Results from these radio access technologies are included in the released dataset. This tool gives us some sense for the interaction between the physical and communication layers independent of the receivers and transmitters.

The instrument hardware and software implementations are proprietary, so we are not able to verify its occupancy and data rate outputs independently. The data were collected for diagnostic interest, and are included in the data set to serve as a complement to the power data in future analyses. As such, within the context of this report, the traffic profiling data should be interpreted qualitatively.

2.2 List of Radio Frequencies Under Test

The focus is on frequencies that were motivated by the data traffic loading trends mentioned in Section 1.1. Ideally, this would include frequency coverage across all WLAN bands as well as 4G cellular bands¹. In practice, we had to limit the range of frequencies under study, because we were constrained by the available stock of commercial bandpass filter parts.

Table 2.1 gives the complete list of frequencies tested in this study. They are split into two groups:

1. Lower-frequency LTE uplink and downlink bands between 700 MHz and 900 MHz; and,
2. Higher-frequency bands that include WLAN activity in the industrial, scientific, and medical (ISM) and unlicensed national information infrastructure (U-NII) bands, as well as a passive service that is protected from transmission.

The lower bands in this frequency list are focused toward cellular, and the upper bands toward WLAN. This grouping is meant to allow separate front-end filtering, which helps ensure that cellular and WLAN readings cannot invalidate each other on power overload events. The passive service band is included as a way to check for overload events in the high band frequency group, due to its broad bandwidth.

2.3 Coverage in Time and Frequency

Each sensor node stepped through each frequency listed in Section 2.2. This constituted one sweep. In order to reduce possible statistical bias from unmeasured external effects, the list order was randomized at the start of each of these sweeps. Each node repeated this process for the full duration of data acquisition.

The process is illustrated in more detail by Figure 2.1. The sensor acquires a time series of band power readings (implemented according to Subsection 2.1.1) during the dwell period provided by each frequency step. While time bins in this time series are fully contiguous, there was substantial “dead time” between frequency steps in order to accommodate settling time in the receiver (Section A.2).

¹This study was undertaken just before wide deployment of 5G new radio.

Measurement		Typical transmissions			
Band center	Bandwidth	RAT	Resource	Duplex	Bandwidth
701.5 MHz	4 MHz	LTE FDD	Band 12	Half (Up)	5 MHz
709 MHz	↓	LTE FDD	Band 12	Half (Up)	10
731.5 MHz		LTE FDD	Band 12	Half (Down)	5
739 MHz		LTE FDD	Band 12	Half (Down)	10
751 MHz		LTE FDD	Band 13	Half (Down)	10
782 MHz		LTE FDD	Band 13	Half (Up)	10
821.3 MHz		LTE FDD	Band 26	Half (Up)	10
842.5 MHz		LTE FDD	Band 5	Half (Up)	5
866.3 MHz		LTE FDD	Band 26	Half (Down)	10
887.5 MHz		LTE FDD	Band 5	Half (Down)	5
(a) Channels in lower LTE bands					
2412 MHz	4 MHz	WLAN 802.11	Chans. 1-3	Half	20, 22, 40
	↓	BLE	Chans. 4-6	↓	2
		Bluetooth classic	Chans. 9-13		1
2437 MHz		WLAN 802.11	Chans. 4-8	Half	20, 22, 40
		PAN BLE	Chans. 15-16	↓	2
		PAN Bluetooth classic	Chans. 35-38		1
2462 MHz		WLAN 802.11	Chans. 9-13	Half	20, 22, 40
		PAN BLE	Chans. 27-29	↓	2
		PAN Bluetooth classic	Chans. 59-63		1
(b)Channels in 2.4 GHz ISM bands					
2695 MHz	4 MHz	Transmissions not permitted [20]			
(c) Radio-astronomy, earth-exploration satellite, and space research (“passive services”) band					
5170 MHz	4 MHz	WLAN 802.11	Chan. 34	Half	20, 40
5190 MHz	↓	WLAN 802.11	Chan. 38	↓	20, 40, 80, 160
5210 MHz		WLAN 802.11	Chan. 42		20, 40, 80, 160
5230 MHz		WLAN 802.11	Chan. 46		20, 40, 80, 160
5240 MHz		WLAN 802.11	Chan. 48		20, 40, 80, 160
5775 MHz		WLAN 802.11	Chan. 155		20, 40, 80, 160
5795 MHz		WLAN 802.11	Chan. 159		20, 40, 80, 160
(d) Channels in 5 GHz U-NII bands					

Table 2.1: List of frequencies under study

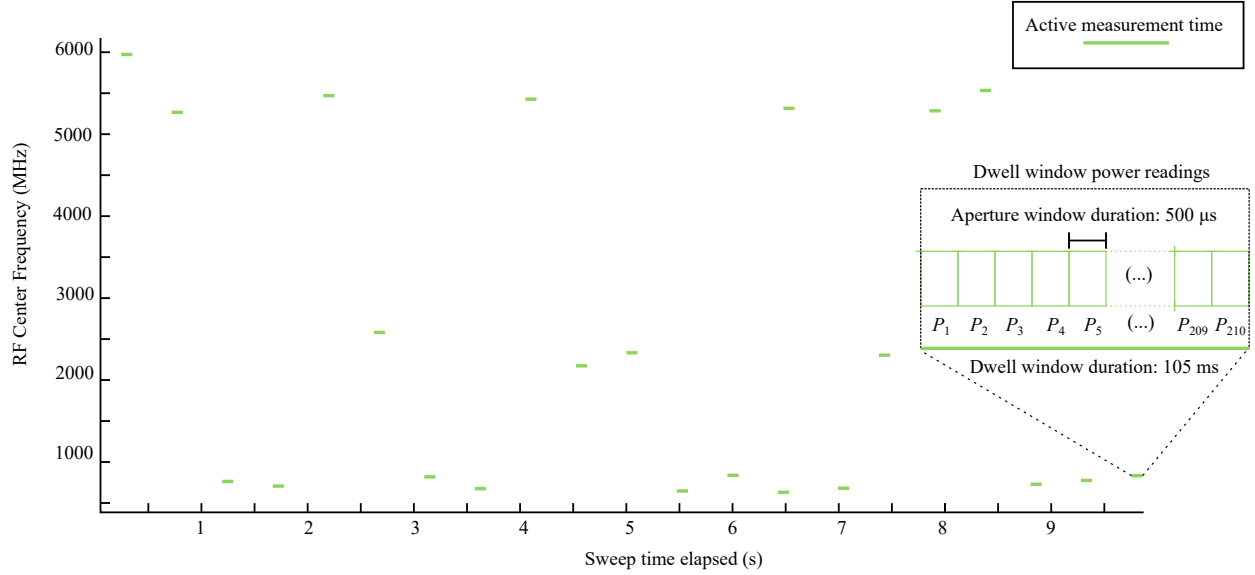


Figure 2.1: The structure of a shuffled frequency sweep in time and frequency.

2.4 Location

2.4.1 Residential Telework Sites

These sites were 13 different homes of NIST staff, research associates, and student interns. The staff live in and around the cities of Boulder and Denver, Colorado, in the United States. The specific details of these locations are not released with the data. However, these sites included examples of single- and multi-family homes, single- and multi-story structures.

Data were collected for as long as was practical at each site. The resulting data set spans June 2020 to August 2021. Sensors were placed on the ground level or 2nd floor in these structures, except one, which was in a basement.

2.4.2 Hospital Site

Additional data were collected from the parking lot of a private hospital in Boulder County, Colorado, with its permission. An approximate topology for the test site is given by Figure 2.2.

The data here were collected during short visits, not as an ongoing activity as was the case for the residential environments. The data included captures of power data with extended dwell periods. During these periods, network traffic profiling data was collected with the wireless test instrument described in Section 5.1. These provided the distribution of a limited number of samples of cellular and WLAN orthogonal-frequency division multiplexing (OFDM) traffic data.

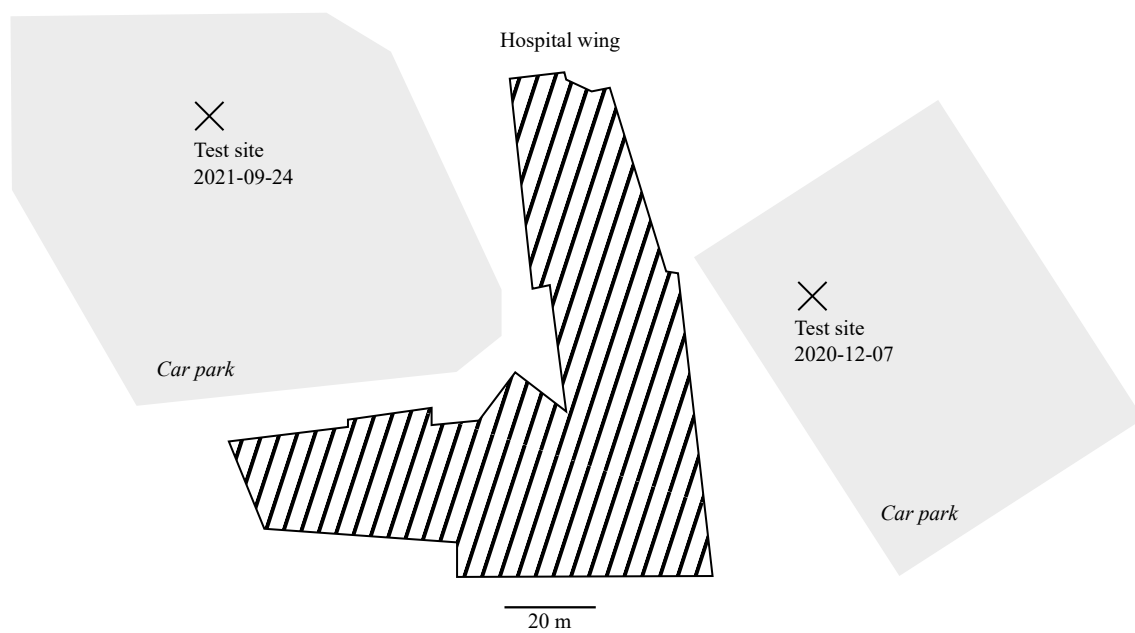


Figure 2.2: Test locations of measurements at the hospital site.

Chapter 3

Test Engineering

The measurements required a distributed sensing network, comprising nodes that share the same specification. This section details the development of this sensing network: the engineering practice needed for rapid design and deployment of the nodes and network, resulting challenges, and resulting performance.

3.1 Goals and constraints

The practical constraints on the sensing network as a whole were largely determined on the scale of the individual nodes. Significantly, each node must

1. operate connected to users' employer-issued home computer without impeding concurrent office work as normal;
2. minimize strain on data upload backhaul, including hardware and configuration of computer networking and internet service in the test site;
3. respect the privacy of the tester and other surrounding spectrum users;
4. be rapidly deployable; and,
5. maintain ongoing measurement uptime for long-term data captures.

The residential test sites present an environment that is heterogeneous and unknown, across several test factors that could impact the interpretation of the results. These uncontrolled factors include

1. wireless data traffic distribution
2. unknown magnitude of electromagnetic field strength outside the frequency band of interest
3. processing performance of the employer-issued computer hosting the experiment

These should be considered when drawing conclusions from the measurement data.

3.2 Design of the Sensor for Radio Band Power Sensor

The goal of rapid deployment drove the decision to use SDRs even before detailed specifications could be developed. There was only time to purchase commercial off-the-shelf (COTS) hardware that had immediate availability. Further, by the spring 2020, the region surrounding the NIST Boulder labs were subject to stay-at-home orders, limiting the availability of laboratory access. As a result, testing, tuning, and calibration were limited to simple checks at home, and mass-produced SDRs packaged with integrated RF frontends and digitization became appealing.

General requirements for the performance of a node are given by Table 3.1. The tuning frequency range is focused on widely-used cellular and unlicensed bands below 6 GHz. This range is supported by related families of SDR products from various vendors that share a common line of COTS agile transceiver chips. Within these product families, we selected a model that was readily obtainable from multiple vendors at that time. It satisfied the remaining specifications as well.

<i>RF and sampling</i>	
RF receive channels	2
RF frequency tuning range	RX1: 700 MHz - 900 MHz RX2: 2 GHz - 6 GHz
Sample rate	4 MHz (downsampled from 56 MHz)
Out-of-band IP3 (701.5 MHz)	-12.4 dBm [21]
Input compression level (701.5 MHz)	-20.9 dBm [21]
Dead time between measurements	77% (see Section A.2)
Digitized sample depth	12 bits
<i>Data streaming</i>	
Host-SDR connection	USB
Data rate	8 MS/s
<i>Host PC Software</i>	
Real-time DSP	GNUradio
Programming language	Python

Table 3.1: Sensor node specification and performance at the deployed 15 dB gain setting



Figure 3.1: An assembled sensor node, with an SDR enclosed inside the transparent enclosure. The antennas shown were the omni-directional models used in the residential telework setting.

Function	Sensor Design [†]	Make	Model
LTE Passband Filter (Channel 1)	A	Mini-Circuits	ZX75BP-750-S+
	B	Mini-Circuits	VLF-800+ and SHP-600+
WLAN Passband (Channel 2)	A, B	Mini-Circuits	ZX75HP-2400-S+
SDR Receiver	A, B	Nuand	BladeRF 2.0 micro
Antennas	A, B	Taoglas	Apex II TG.35

[†]Due to parts availability, two versions of the sensor, “A” and “B,” were fielded. These used different passband filters.

Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Table 3.2: Measurement receiver component listing

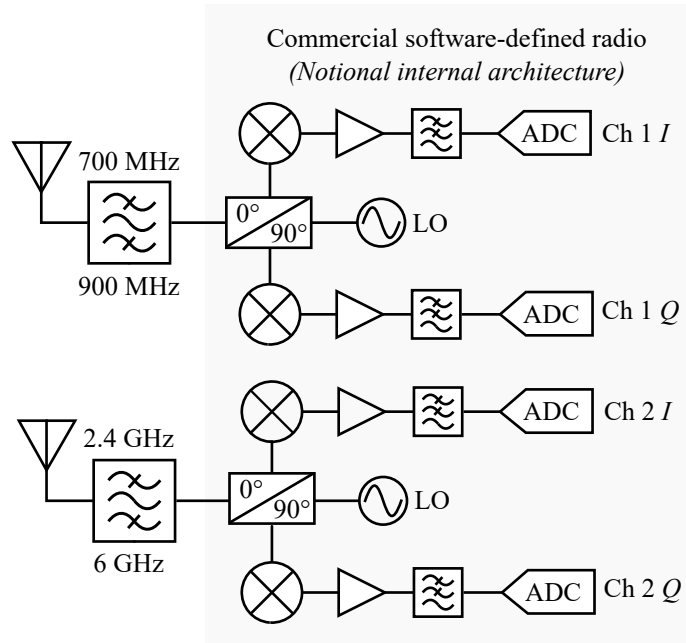


Figure 3.2: Block diagram of the radio front-end architecture of a sensor node

3.2.1 Software-Defined Radio Receiver

The SDR encapsulates all of the radio receive electronics in each sensor node. It is pictured as part of a node in Figure 3.1. Its specifications are listed by Table 3.2.

3.2.2 Receive Architecture

The simple architecture of the receive front-end is illustrated by Figure 3.2, mostly implemented in the SDR. Reception is banded across the two available receive channels: channel RX1, a low band below 900 MHz and channel RX2, an high band from 2.4 GHz and above. The preselect filters mitigate intermodulation distortion (IMD) products from far outside the center frequency tuning range indicated each channel. In effect, this isolates cellular input signals from signal overload in the unlicensed bands, and vice-versa.

This choice of receive topology was determined in part by the immediate availability of COTS filter parts during the design process. With more lead time available, this design could be improved by replacing the two filters with a single diplexer. The two paths of the diplexer could pass the bands shown in Figure 3.2, but share a single input connection

to require only a single input antenna.

3.2.3 Receive Antennas

The COTS antennas shown are planar bowtie designs printed with broadband matching structures. Like the preselect filters, the selection was limited to products that were immediately available in quantity during the design of the sensor node.

3.2.4 Detection

The direct-conversion quadrature receiver in each SDR channel includes an integrated analog-to-digital converter. The digitized samples, which are complex-valued voltages with arbitrary scaling, stream to a host computer via universal serial bus (USB). There, GNURadio software applies a signal flow graph (Figure 3.3) to process the signal stream in real time. In each sweep, the radio steps through a freshly shuffled sequence of frequencies, lingering at each to acquire channel power for the dwell period of 300 ms. The time duration of each of these dwell windows is subdivided into a sequence of bins of length 0.5 ms, which we refer to as apertures, following microwave power measurement terminology. The average power computed with Equation 2.1 in this time window is the band power. Each dwell window consists of 600 of these aperture bins, though most of these are discarded to permit settling time between dwell windows (see Subsubsection 3.2.5.1). For later diagnostic purposes, the flowgraph also records the peak value of IQ sample power for each dwell window. These power readings stream to a binary file together with time and frequency tags.

3.2.5 Sensor Tuning

3.2.5.1 Settling Time

The settling time after changing frequency to start a new dwell is non-deterministic. This is mitigated somewhat by waiting for the SDR to indicate “ready” status, yet transient power readings still occurred for an inconsistent period after this flag is set. The sensing acquisition software included a fixed settling wait time of 100 ms per dwell window before collecting data, which was an initial attempt to avoid spurious transients.

Sensing data collected in the field presented another opportunity to tune the sensing behavior. Section A.1 details dwell windows in the quiet band data at 2695 MHz, and shows that transients last up to another 195 ms after the start of acquisition. As a result, we omit the first 195 ms of recorded data per dwell window, leaving the last 105 ms of band power samples as the recorded data.

3.2.5.2 Sample Rate

Ideally, the instantaneous sensing bandwidth would exceed the full bandwidth of signals of interest in these bands, such as an LTE channel (5 MHz or 10 MHz in this case) or non-overlapping WLAN channel (20 MHz or 40 MHz). This was limited in practice by the computing power available from the slowest available host computer. Further, the slowest available host computer needed to be able to perform typical office teleworking tasks during data acquisition.

The upper bound on the filtered sample rate was determined by increasing the data rate on a “slow” host computer until it could no longer process samples in real time, indicated by output buffer over-runs in the SDR. This threshold was determined to be approximately 6 MS/s. Reducing this to 4 MS/s, the value used in field measurements as listed in Table 3.1, was subjectively sufficient to allow concurrent office telework with most available hosts.

Spectrum sensing by sampling at a rate below the signal bandwidth is known as sub-Nyquist sampling [22]. This is a common approach to detecting the presence of a signal; due to the Parseval identity, the energy detected this way is simply the subset of total energy that is distributed inside the radio passband. The total energy in the band can be estimated from this data, but requires some assumptions about the spectrum parameters of the full-bandwidth signal.

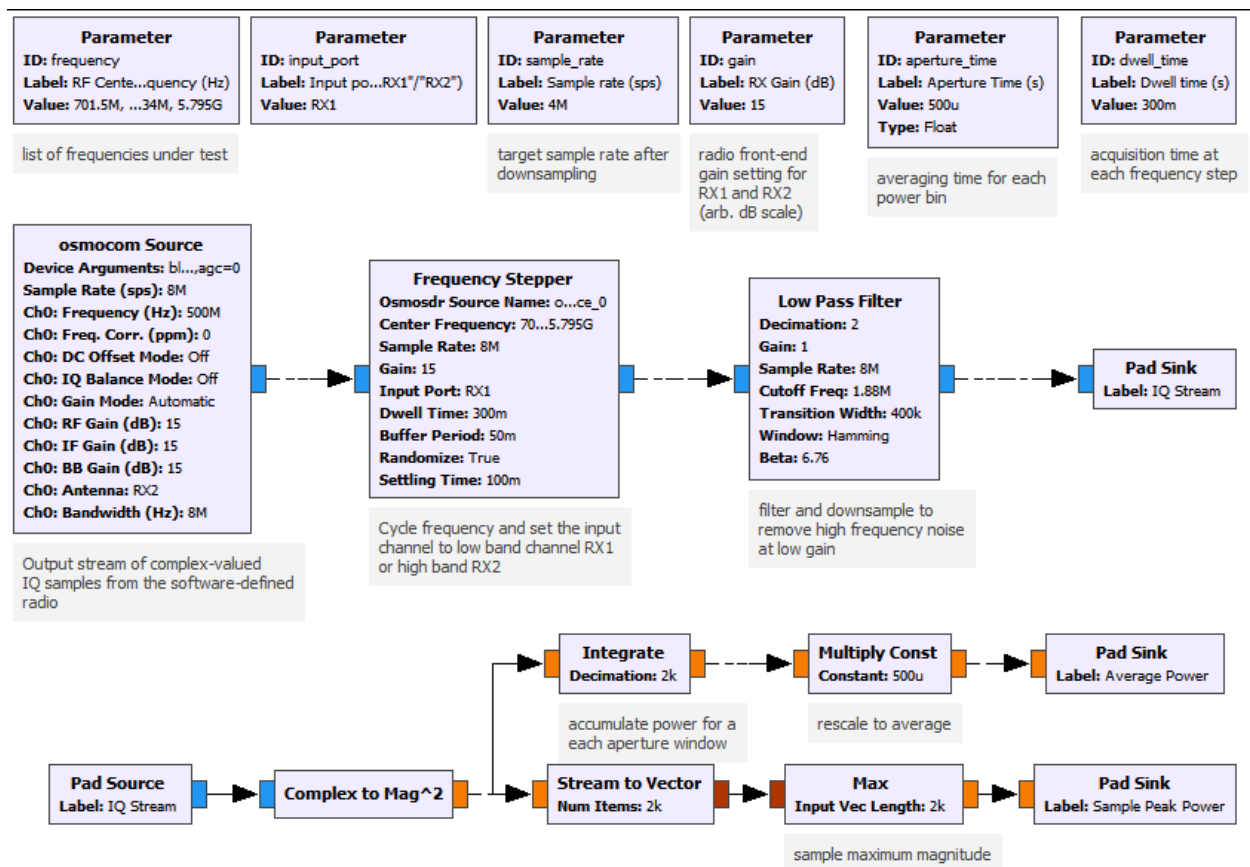


Figure 3.3: The GNURadio flow graph for real-time energy detection in software. In this software, only the unit prefix is shown for unitary quantities. Parameter values here are applied in the following units: gain in linear power (“Low Pass Filter”) or dB (all other blocks); sample rates, bandwidths, and frequencies in Hz; times in s; and all other quantities are unitless.

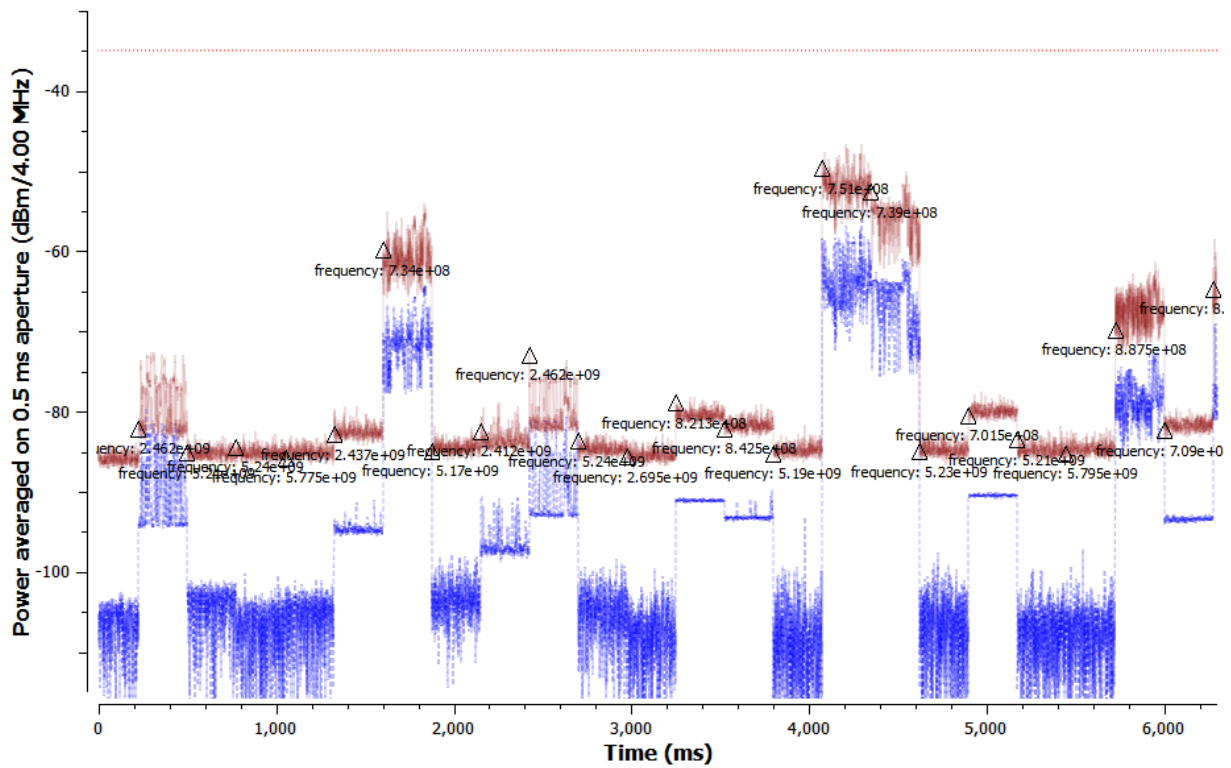


Figure 3.4: Example of the real time display of band power readings shown on a sensor node during operation. The time span is one stepped frequency sweep. The top (red) trace indicates the in-phase and quadrature (IQ) sample peak, while the botto (blue) is the average channel power reported in the paper. (The actual sweep time is greater than 6 s, because the hardware settling time on frequency changes was typically 250 ms.)

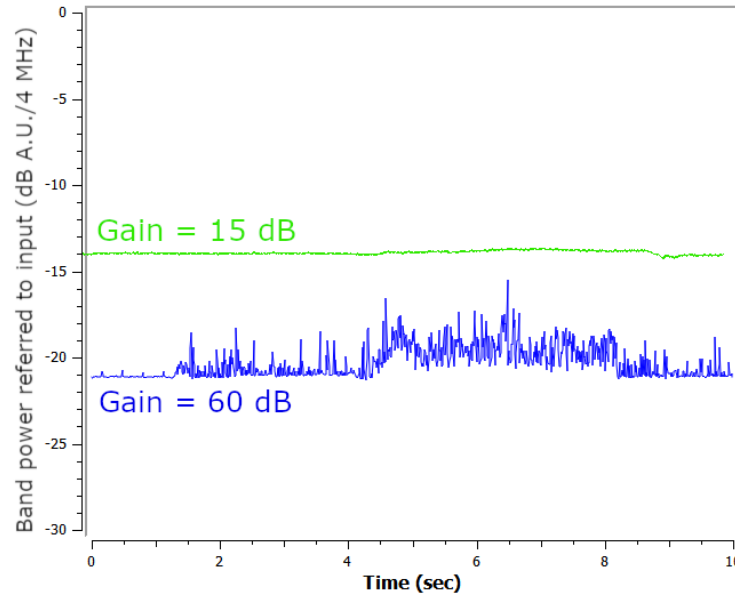


Figure 3.5: Sensor readings at 884.5 MHz taken 1.5 m away from a 701.5 MHz user equipment (UE). At 60 dB gain (bottom/blue line), the sensor showed poor frequency selectivity. Reducing the gain to 15 dB (top/green line) mitigated the impact.

3.2.5.3 Gain

A judicious front-end gain setting leverages the full dynamic range of the SDR. High gain maximizes sensitivity, but leaves the receiver vulnerable to spurious IMD power readings caused by high-power signals outside of the sampling band. Conversely, low gain improves sensor response to powerful radio activity, but at the cost of increased noise figure and thus reduced sensitivity.

Optimization in a laboratory would best balance this trade-off, but in the spring of 2020, this was not accessible. Instead, for this campaign, the approach was to reduce gain until noise and distortion from nearby wireless equipment was too small to observe in a real-time spectrum display. Figure 3.5 illustrates the end result of this process at 15 dB.

To help ensure valid data collection, we needed to develop a test procedure to avoid sensor overload from powerful signals outside of the center frequency of the channel. These overloads, which may be a symptom of spectral regrowth or sampling artifacts, cause spurious high power level readings and therefore false positive occupancy. The mitigation approach was to establish a minimum separation distance between the sensor and household electronics that support wireless capabilities. After trials at different separation distances with a cellular phone and a laptop, using both cellular and WLAN channels, we set this minimum distance at 1.5 m. At this distance, the perturbation of noise power in all bands under test was less than 3 dB.

3.2.5.4 Filtering

The flowgraph needed to include signal processing to address high-frequency noise produced by the SDR at low gain settings. Figure 3.6 demonstrates this problem: at 15 dB gain, the spectral density of noise at higher frequencies in channel RX1 was 18 dB greater than the center 50% of the band. RX2 did not suffer this problem, though its noise floor was consistently higher, as shown by Section A.3. This behavior was consistent across SDR units. Filtered downsampling, as illustrated in the figure, mitigated this problem. The low-pass finite impulse response (FIR) filter removed the high-frequency energy from baseband.

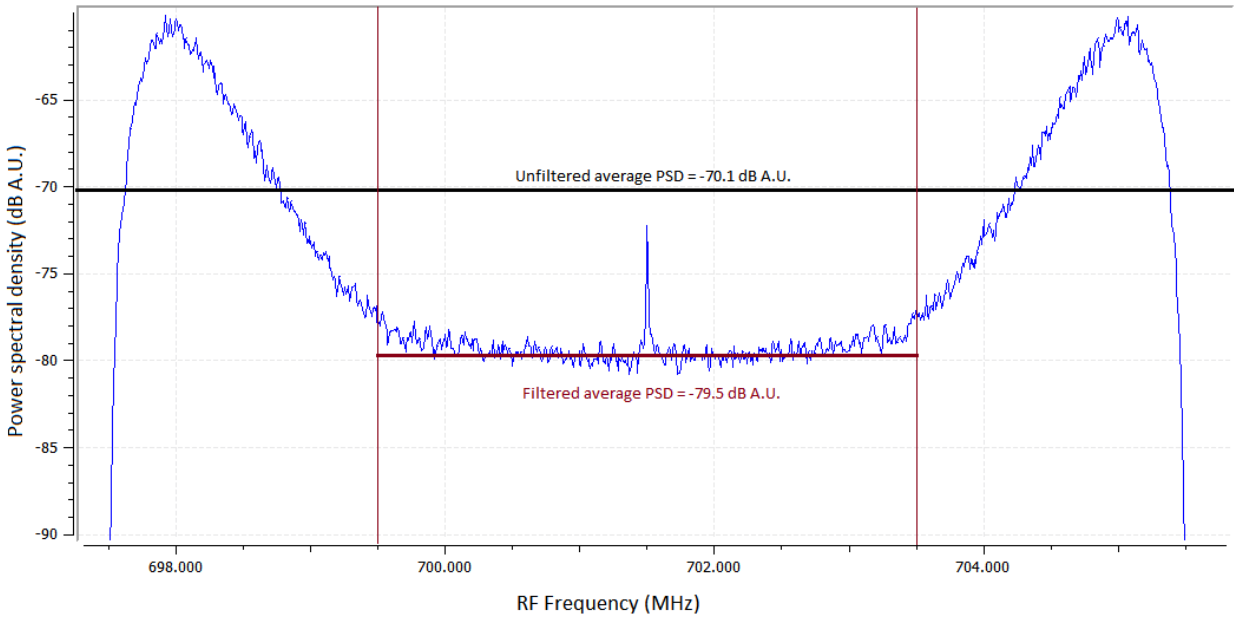


Figure 3.6: A low-pass filter with 2x decimation achieved downsampling from 8 MHz to 4 MHz, reducing the volume of data while removing high frequency noise. The result was a reduction in noise power by 9.4 dB.

3.3 Network Data Traffic Profiling

The OTA wireless analyzer acts as a passive receiver of a base station, access point, or client signals. It provides detailed diagnostic information about the amount of data passing over the air, the number of unique network nodes, and modulation characteristics. It is a passive tool that needs to be configured for the type of intended wireless communication type, frequency, and bandwidth.

The resulting information is anonymized, and the instrument was not capable of decoding user data. This was enforced in part because we lacked all of the protocol and cryptographic key parameters to do so. However, we also replaced all potentially identifiable metadata; namely, MAC addresses were replaced with randomized user IDs when monitoring WLAN networks.

3.3.1 Radio Configuration

The antennas connected to the instrument were the same as those used in the band power sensors. The only RF configuration supported is the center frequency and gain. In operation, the center frequency was set before data collection, and the gain was adjusted to search for sufficiently high input signal.

3.3.2 Data Filtering

To optimize the use of memory and reduce the duration of post-processing of the collected logs, we applied data filtering to limit the capture to the most important outputs. Decoding a stream of all details from the received baseband waveforms may requires large memory usage and would force a reduction in the duration of data collection.

We configured filters in the wireless analyzer to capture the following parameters from physical-layer OTA captures of cellular and WLAN traffic:

1. Spectrum occupancy
2. Frequency
3. Bandwidth

4. Modulation
5. Error vector magnitude (EVM)
6. Power
7. Received signal strength indicator (RSSI)
8. Throughput
9. Downlink control message for uplink spectrum allocation (LTE only) by user

In order to preserve privacy of users in these networks, we replaced each personally-identifiable data in each capture, such as medium access control (MAC) address, with unique integer numbers.

3.4 Deployment and Operation

3.4.1 Band Power Data and Privacy

Responsible data collection requires careful attention to personally-identifiable information (PII).

The radio sensing equipment itself collects readings of averaged power, and the local time and radio frequency at which the reading was collected.

The radio sensing equipment does not collect location data, including by use of global positioning system (GPS), cellular, or WLAN, or other signals. A person with access to the collected radio sensing information would be able to make a reasonable guess about whether there is generally WLAN or LTE traffic near the monitoring station, but not be able to decode any of the information being transmitted over the air, and not be able to determine unique identity information about observed transmitters. The computer software that operates the radio sensing equipment needs internet access only to upload the data. No information (about the tester or otherwise) is logged from this computer except the clock time to record the local time of the collected data (as mentioned above), and a pseudo-random cryptographic hash unique to the tester's login name to distinguish data collected by different testers.

An anonymized table of metadata about each monitoring station was stored on firewalled NIST network file storage.

3.5 Gain and Noise Calibration

The principal goal of the calibration procedure is to determine the correction offsets that are needed to transform the SDR output data into measurements of physical power at the input of the SDR. This correction value is the gain A in the calculation of band power (Equation 2.1).

Gain calibration typically requires metrology instruments in a controlled laboratory setting. During the early stages of the pandemic, it was impractical to perform these measurements on all sensor units. Instead, we performed detailed calibration measurements on two units, including an assessment of uncertainty. As a result, in the propagation of uncertainty in each sensor unit, an additional uncertainty term needs to be included in order to account for manufacturing variability between units. Past experience suggests that a reasonable estimate for the standard uncertainty of this variability should be on the order of approximately 3 dB. It may be worthwhile to study this further in the future.

Detailed calibration principles and techniques are documented in Appendix B. In essence, we need to resolve two unknowns by introducing two known noise signals to the SDR. The SDR gain and noise was extracted from the following equations.

$$G = \frac{P_{meas}^{hot} - P_{meas}^{cold}}{M_{in}^{hot} P_{in}^{hot} - M_{in}^{cold} P_{in}^{cold}}, \quad (3.1a)$$

$$P_{eqn} = \frac{M_{in}^{hot} P_{in}^{hot} P_{meas}^{cold} - M_{in}^{cold} P_{in}^{cold} P_{meas}^{hot}}{M_{in}^{hot} P_{in}^{hot} - M_{in}^{cold} P_{in}^{cold}}, \quad (3.1b)$$

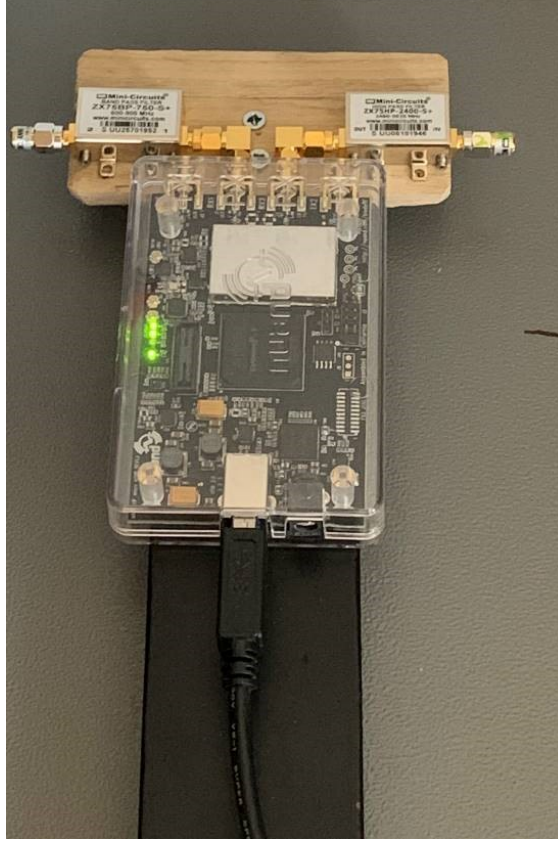


Figure 3.7: A sensor node connected to 50 Ω input terminations for input noise calibration.

Here P_{in}^{cold} and P_{in}^{hot} represent the power values of two dissimilar input signals. P_{meas}^{cold} and P_{meas}^{cold} are the corresponding output power readings from the SDR. The mismatch factors M account for the power delivery correction at the junction.

While P_{eqn} “falls out” of this calibration naturally, giving SDR receiver noise power, we needed calibration data for every unit to apply denoising to improve the sensor dynamic range. As a result, we used the *in-situ* noise calibration that was performed in the field for each sensor node (Subsection 3.6.1).

These calibration measurements were performed in the small-signal regime of the receivers. In this regime the gain is assumed to be constant with power. Even though the gain setting of the SDR was left constant across frequency, the calibration was repeated separately for every RF center frequency, in order to accommodate the realistic frequency response.

3.6 Operating Procedure

3.6.1 In-Situ Noise Calibration of SDRs

The additive noise power level intrinsic to the sensor receiver and its thermal environment needs to be characterized to improve measurement sensitivity by denoising in post-processing. A calibration process is performed to assess this for each sensor node before spectrum data collection, then again after measurements are complete. This calibration determines the power input-equivalent power level of additive noise inside the hardware at room temperature.

The calibration procedure was as follows:

1. Unscrew and remove each antenna from the filter input
2. Replace with matched terminations, finger-tightened to avoid damage from excessive torque (Figure 3.7)
3. Run calibration script, saving calibration data
4. Disconnect the matched input terminations and replace with the antennas

At completion, calibration data is saved for later application in post-processing.

3.6.2 Field Data Acquisition with SDRs

After the noise calibration is completed, sensor nodes were placed to prepare for data acquisition. The two antennas were oriented as shown in Figure 3.1. The sensor node has to be located near the host computer, in order to connect by USB. Within this constraint, each tester identified a test location for the sensor node that was at least 0.5 m from wireless transmission sources, to avoid saturating the receiver. It was also placed on a dielectric surface for consistency between test setups.

Chapter 4

Band Power Data

4.1 Sample Distributions of Band Power Across Site and Frequency

4.1.1 Sample Sizes by Site and Date

The number of band power samples collected across the duration and location of the test are shown by Figure 4.1. The trend on the time scale of months was toward fewer sites producing data; this echoes the decreasing fraction of work time that employees and associates spent teleworking. However, many other factors also impact the number of sites collecting data. For example, many students participating in the summer of 2020 completed internships and left NIST to return to school in the autumn, ending their participation in the sensing effort. Hence, the number of active sites was largest July and early August, and some of the variability in the number of samples produced in different sites. Further, some test participants needed to pause data acquisition during work hours to use their computer for their normal office and research work; in some cases this resulted in inconsistency in resuming the test afterward. This also further exaggerated the variability in the total number of data samples among the different sites.

4.1.2 Comparisons Between Frequency Bands

4.1.2.1 Dynamic Range Characteristics

One use for the sample distributions is to inform dynamic range requirements for future tests in this type of residential environment. The data support this type of effort with a total number of band power readings on the order of 10^9 per frequency. This gives statistical sensitivity in detecting the incidence of the most powerful band power readings, which causes varying amounts of spurious power to bleed into in other bands inside the receiver. This is the non-linear process of spectral regrowth. Because this spurious power is added inside the sensor and not present in the environment, it is a well-known source of bias in power readings for any radio spectrum assessment. It is therefore helpful to consider the distribution of band power from prior tests in an electromagnetic environment when tailoring the dynamic range of sensors for future tests of similar environments.

To support dynamic range assessment for high reliability spectrum sensing, consider empirical survival functions shown on logarithmic scales. The plots in Figure 4.2 illustrate these by center frequency, grouped by band type. In order to weight the characteristics of each test site equally, these curves are the mean of the empirical survival functions computed for each site. This averaging results in increased variability at lower sample incidences (particularly at rates less frequent than 1 in 10^7) due to the finite number of sample sites and the relatively small number of samples acquired in sites 2, 4, 6, and 8.

4.1.2.2 Typical Power Level Incidence

In many applications it is more informative to consider dynamic range in terms of the most likely range of band power levels. This could include wireless coexistence scenarios in which a consistent level of interference is accepted, such as mobile networks that experience interference due to frequency-reuse among cells, or in coexistence realized by distributed channel-sensing schemes such as WLAN. As another example, low-power devices that harvest ambient wireless energy for the internet of things [23, 24] are concerned to first order with time-average of power level above

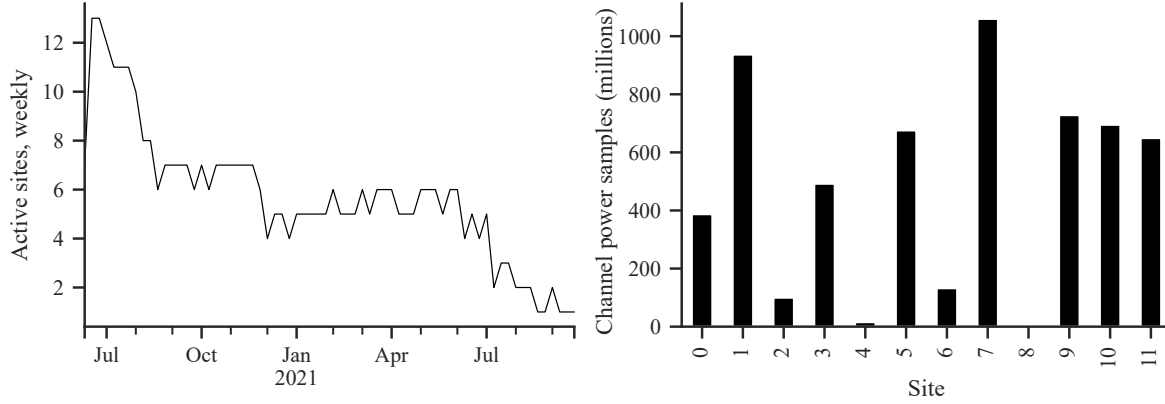


Figure 4.1: Overview of size of the data set as distributed across time and site, from 2020-06-09 through 2021-09-22. Sample counts from each site are summed across all frequencies.

a minimum harvesting threshold.

To emphasize the most likely values, the data from Figure 4.2 and Figure 4.3 are re-plotted in Figure 4.4 and Figure 4.5 on linear vertical scales.

High measured power levels were most frequent in ISM bands, followed by LTE downlink and U-NII bands; the lowest rate of incidence was in LTE uplinks. Most of these could be explained by data traffic offloading from cellular to WLAN in this residential setting, since standards prescribe similar uplink power levels from mobile devices in both radio access technologies (RATs). Meanwhile, LTE downlink broadcasts in these LTE base stations include all traffic in the sector, and thus are not significantly affected by the shift in traffic at these individual sites.

4.1.3 Qualitative Features by Frequency Band

4.1.3.1 LTE Bands: Uplink Channels

The sources of LTE uplink transmissions are smartphones, tablets, and other LTE UEs. Like the other data network RATs, the transmission events are short and infrequent bursts, as observed for example in [25]. This is demonstrated by the bulk statistics. In Figure 4.4, fewer than 1% of detectable power samples in LTE uplink channels were stronger than -68 dBm; yet, above this threshold, the logarithmic view in Figure 4.2, there is a long tail of increasingly powerful burst events that also become increasingly infrequent.

The long tail in band power survival functions can be explained by the mobility of the UEs. The large number of combinations of position and orientation of UEs relative to the sensor antennas of each test site create a wide range of different propagation loss conditions. None of the other bands are pure uplink, making this tail longer than any others.

Another distinct LTE uplink characteristic is the presence of an interference floor, which consists of power levels with low variance. To illustrate this, Figure 4.6 shows some normalized survival functions at each center frequency. The denominator of the normalization was the 20-minute rolling median of the power level in the strongest histogram bin at 0.25 dB resolution. This normalization was performed separately for each frequency and site, and then summed in each of these categories to give the resulting survival functions. This result represents a simple estimate for the background interference level, leveraging the robust median statistic to reject the samples that were infrequently occupied. Averaged across all sites (on the left), 90% of band power samples were within ± 1 dB of this rolling median level at each frequency. This inter-quantile distance varied slightly by site, but the trend held tightly.

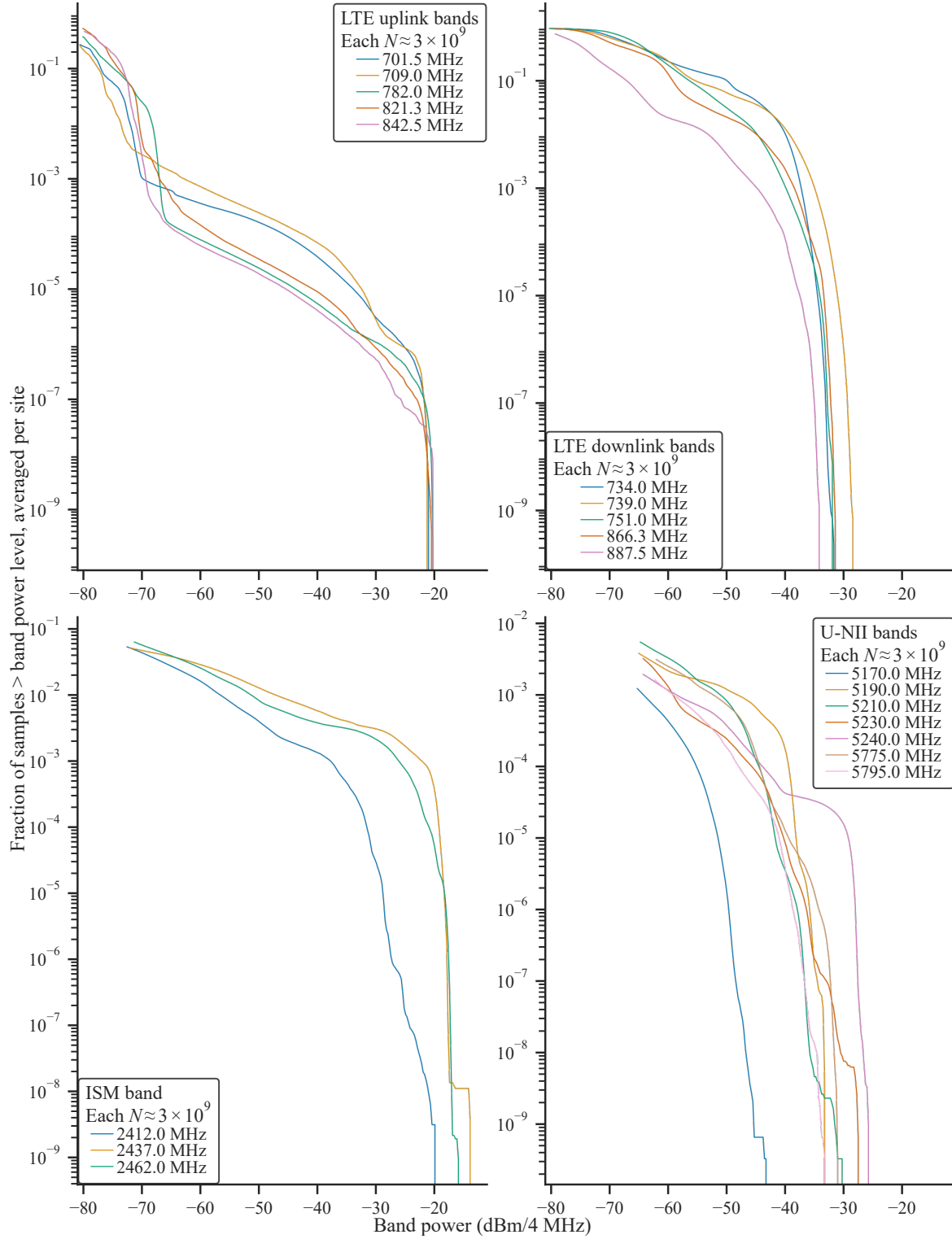


Figure 4.2: Mean of each site's empirical survival functions of band power, categorized by center frequency. This averaging illustrates the stress on receivers' dynamic range experienced in these environments. To illustrate rare events, the traces are transformed onto a logarithmic vertical axis.

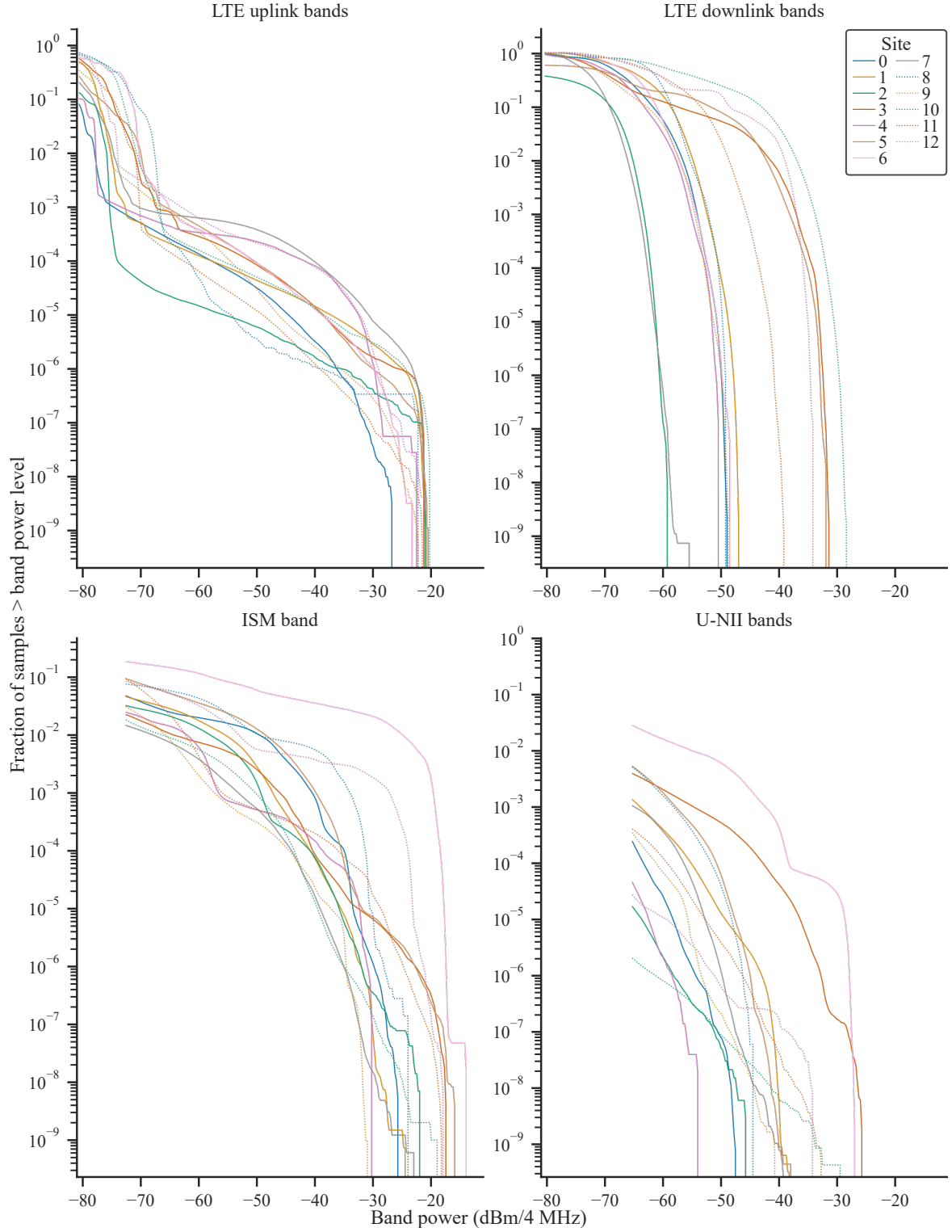


Figure 4.3: Empirical survival functions of band power per site, categorized by band activity. To illustrate rare events, the traces are transformed onto a logarithmic vertical axis.

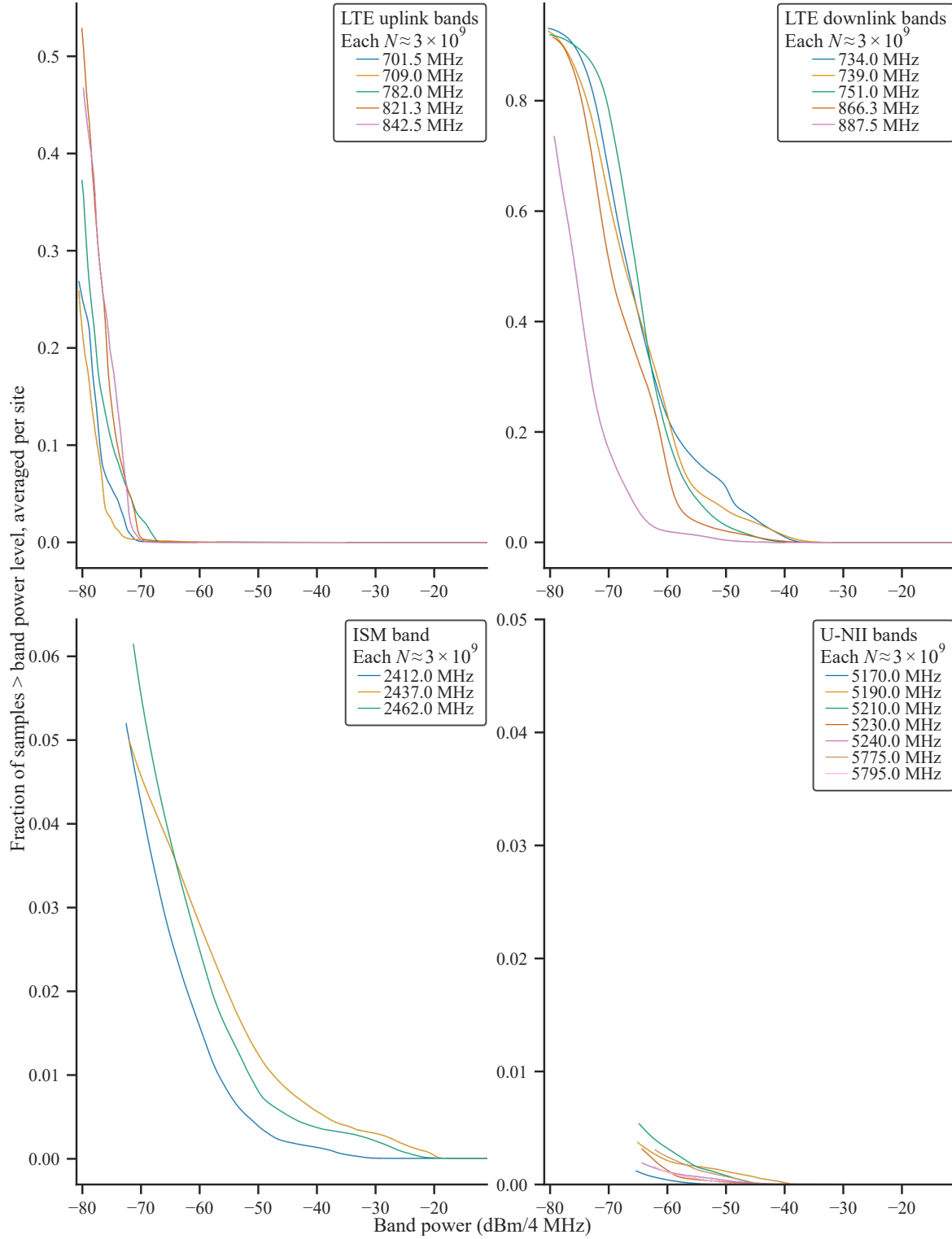


Figure 4.4: Mean of each site's empirical survival functions of band power, categorized by center frequency. This averaging illustrates the stress on receivers' dynamic range experienced in these environments. To emphasize the most common levels band power, the vertical axis is on a linear scale.

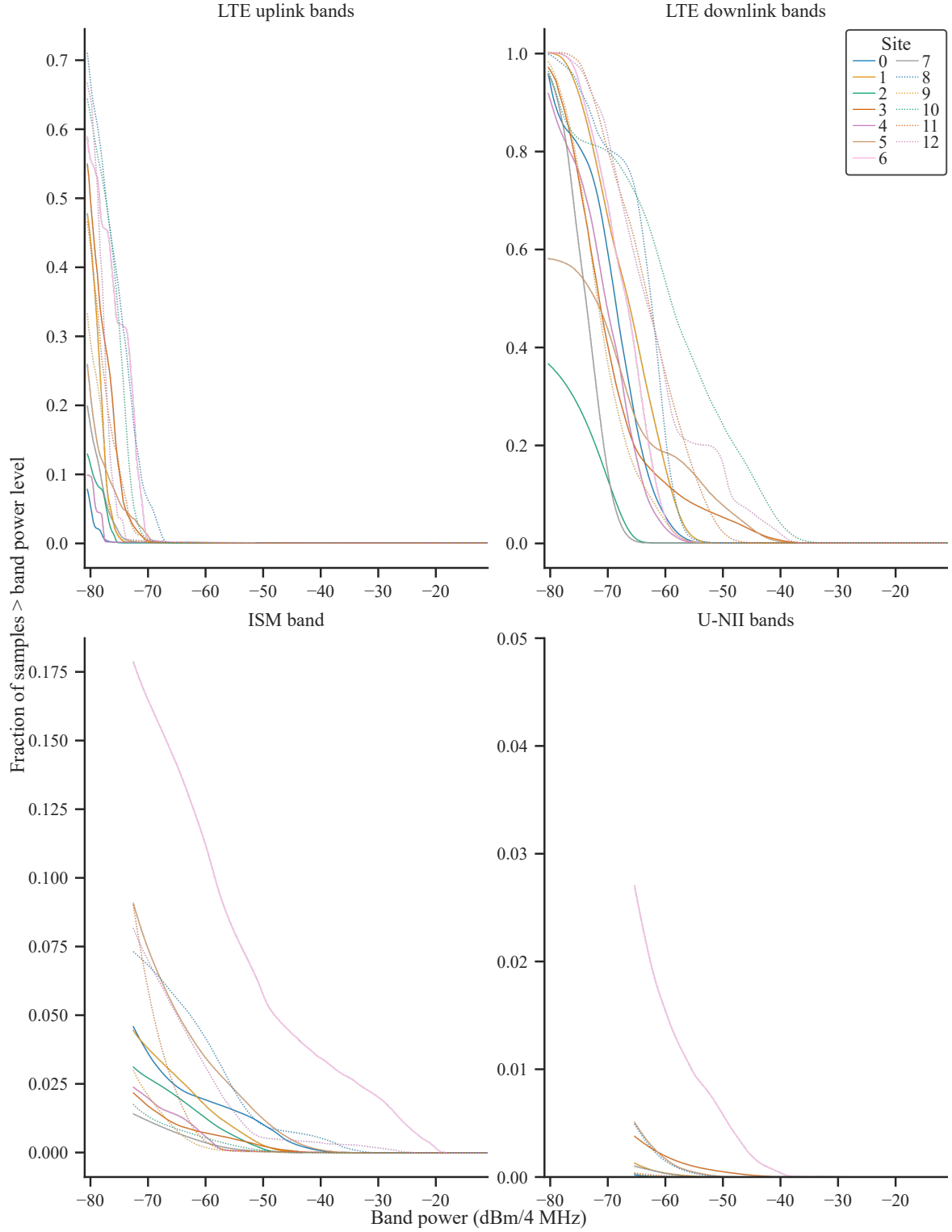


Figure 4.5: Empirical survival functions of band power per site, categorized by band type. To emphasize the most frequently sampled values of band power, the vertical axis is on a linear scale.

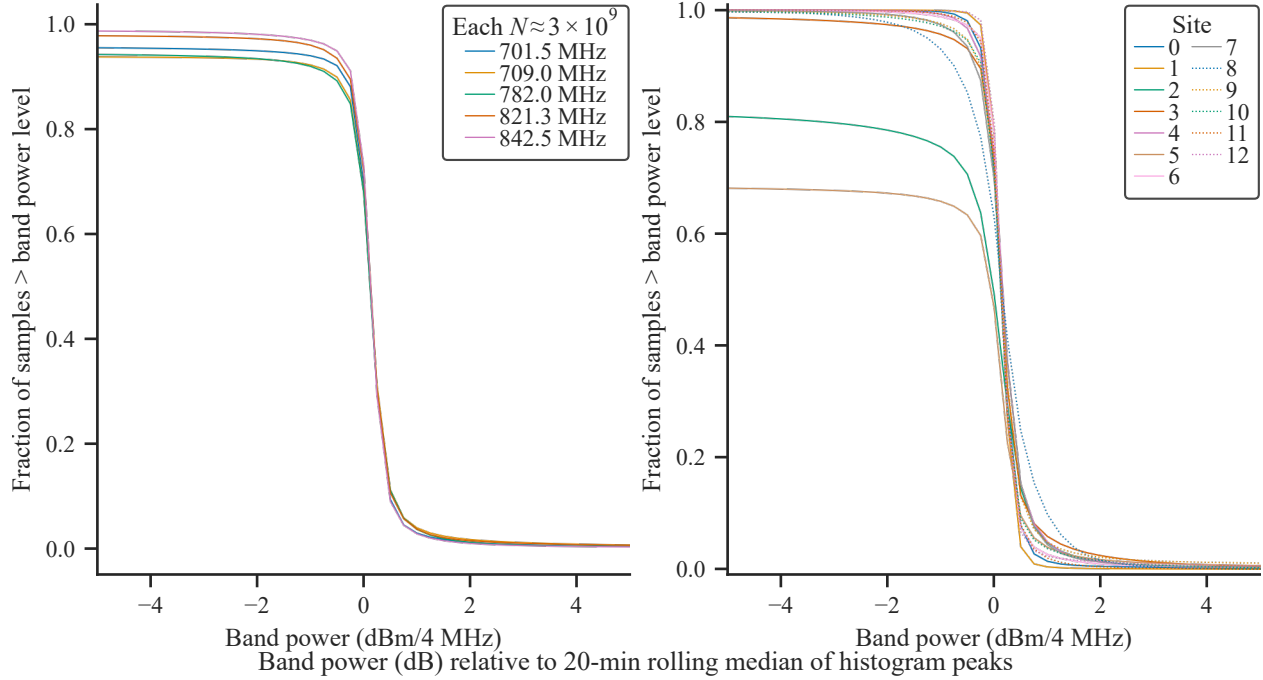


Figure 4.6: Empirical survival function of band power in LTE uplink channels relative to the interference floor, by frequency (left) and site (right). On the left, counts were summed from all sites, and on the right, counts were summed across all center frequencies in the band from 2020-06-09 through 2021-09-22.

4.1.3.2 LTE Bands: Downlink Channels

Transmissions in LTE downlink channels originate from cellular base stations (BSes). The locations of these tend to be fixed. The propagation path between each combination of BS and sensor is therefore also fixed, to the extent that each sensor was left undisturbed for the duration of the test. The base station broadcasts at least *some* power nearly continuously; these broadcasts include data and control for all UEs in the cell, and other broadcast waveforms for synchronization and channel sounding. In general, we expect that each base station broadcasted all of the downlink band (DL) waveforms to each UE in its cell, because multiple-input multiple-output (MIMO) was not widely deployed in LTE networks at the time of this test, and so DL transmissions in each cell are sent to all UEs.

The broadcast nature of the downlink led us to expect a power sample survival function distribution with similar curves among the different sites, and a steady, monotonic decrease, without the long tails at infrequent power levels observed in the uplink. This is borne out by the plots in Figure 4.3. The reasons for this trend are not clear, but could be an interesting subject for future work.

We observed a strong diurnal characteristic which was in general common among the different LTE downlink channels. It is illustrated by Figure 4.7. Power levels were more likely to be approximately 5 dB weaker between 23:30 and 07:30.

4.1.3.3 2695 MHz Passive Services Band

We use data from the passive services allocation at 2695 MHz to help validate field data from the deployed sensors. Appendix C presents this analysis in detail.

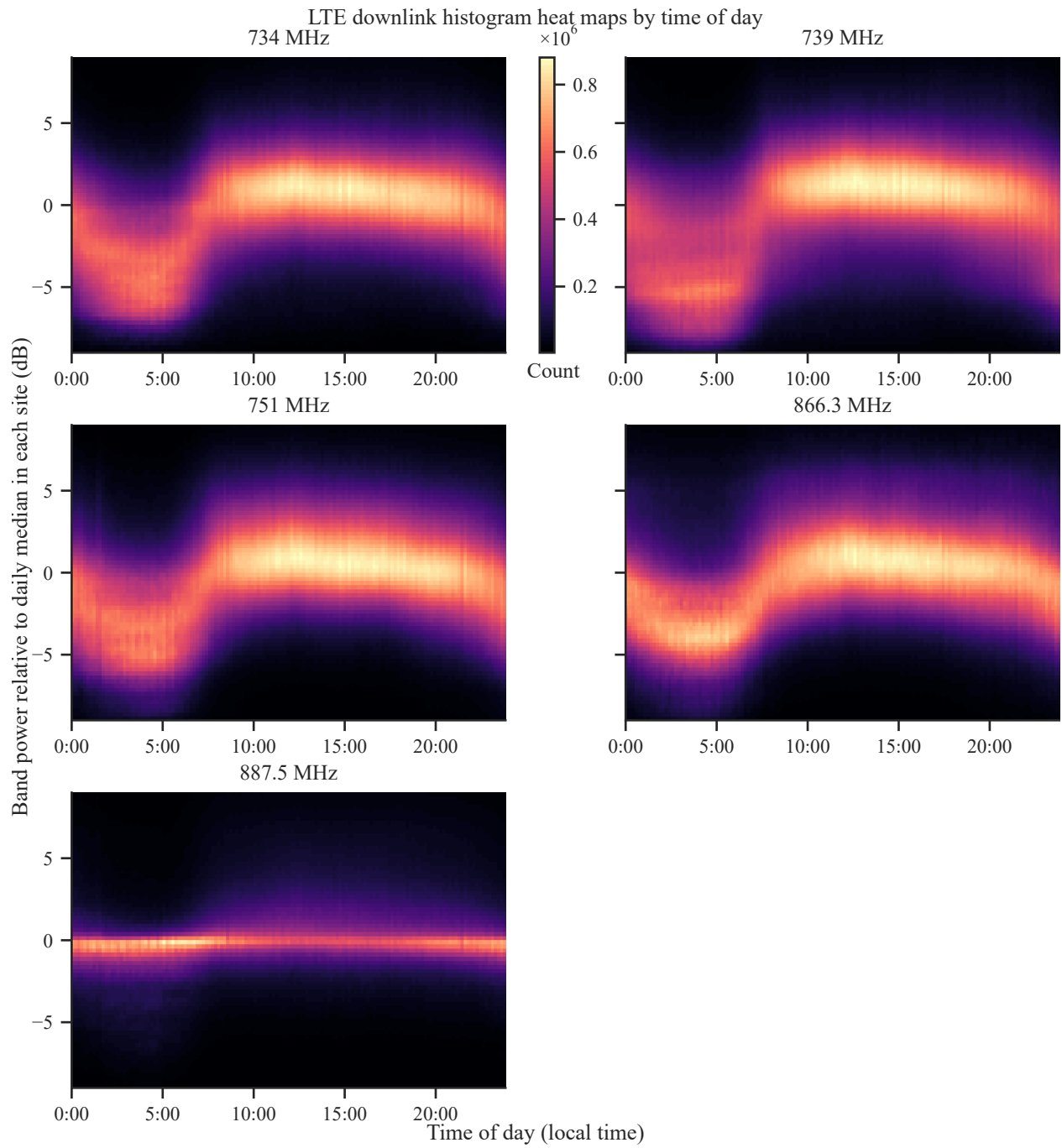


Figure 4.7: Histogram heat maps of samples received in each LTE downlink channel by time of day. Sample counts are summed across all sites within the period of 2020-06-09 through 2021-09-22.

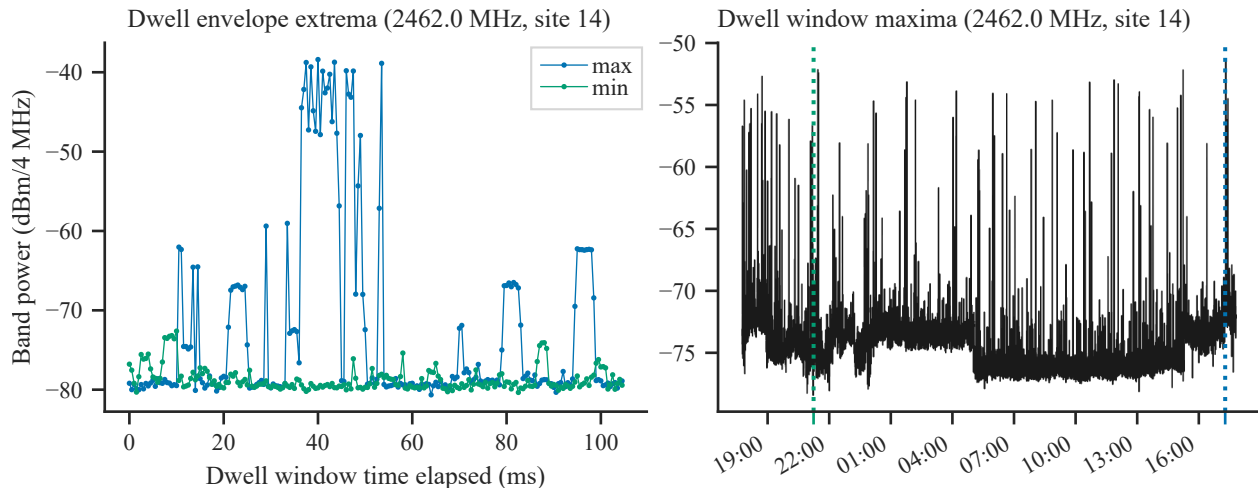


Figure 4.8: Example time series of band power, acquired starting on 2020-11-06. Close views are shown spanning the duration of 1 dwell window on the left. These were least and most occupied dwells within their 24-hour acquisition period, indicated with the vertical lines on the right.

4.2 Sample Characteristics of Dwell Window Time Series

4.2.1 Time Series Representation

The time series of band power data in each dwell window offers opportunities to study the impulsivity of channel occupancy. The time resolution of 0.5 ms is small enough to match the scale of the LTE transmission time interval (TTI). The 100-ms dwell window duration is also long enough to capture multiple LTE frames (10 ms) or WLAN frames (no longer than 5.5 ms in IEEE 802.11ac).

Figure 4.8 illustrates time series examples collected in the ISM band. The ‘max’ time series (i.e., with the greatest peak reading on 2020-11-06) had wide excursions span from the noise level near -80 dBm/4 MHz at the low end up to peak burst levels of -40 dBm/4 MHz. The noise level between transmissions in the ‘min’ time series matches that in the ‘max.’ Qualitatively, then, we’d conclude for this example that the channel consists of impulsive transmissions amid an otherwise quiet channel.

The most direct representation of the same data is illustrated by the heatmap in Figure 4.9. The low incidence of the more powerful readings, shown in lighter colors, is clear in this format. Occupancy events are illustrated here split across long time bins (horizontal axis) and time elapsed on the shorter dwell window axis (vertical axis). These events tended to occur in several bursts spread out over the course of each 10-minute bin. The location of the events on the vertical axis seemed uncorrelated; this is expected because the sensor is not time synchronized and exhibits random time delay variability in each frequency change. This behavior was typical. In response to this trend, in the remainder of the report, our approach is to reduce the data in each dwell window into an distribution.

4.2.2 Time Duration of Occupancy Events Across Site and Frequency

The occupancy duration was computed as described in Subsection 2.1.2. This was performed for all types of frequency bands except those that contained LTE downlink channels — these bands are characterized by nearly continuous broadcasting, for which the calculation of occupancy does not give meaningful results.

4.2.2.1 LTE Bands: Uplink Channels

Empirical survival functions of occupancy durations (Figure 4.10) demonstrate primarily that transmissions were typically short on the time scale of the collected power samples. At threshold level of -60 dBm, half of transmissions

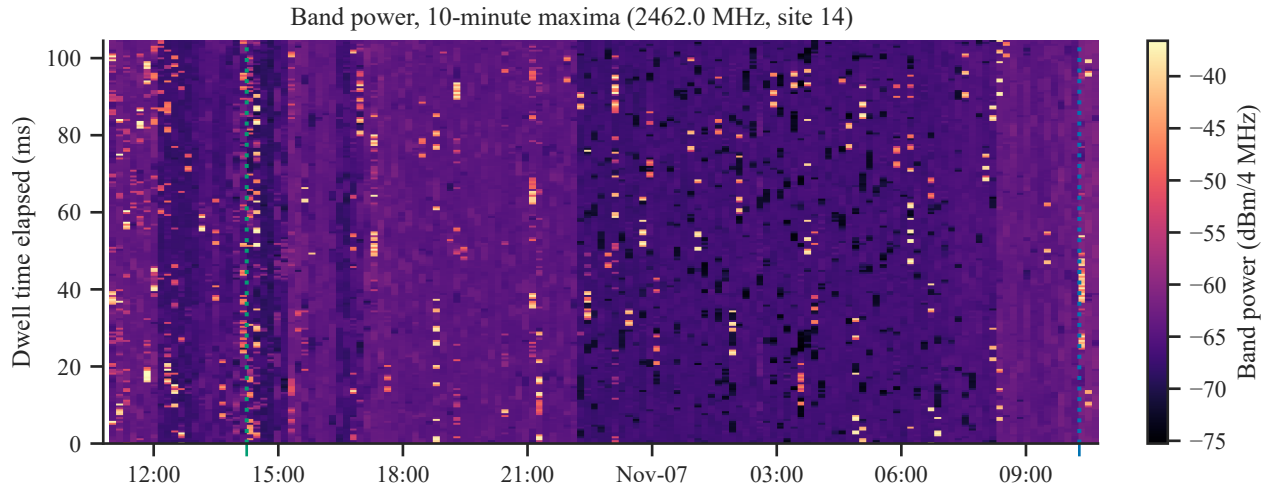


Figure 4.9: Example heat map of band power envelopes in dwell windows (vertical axis) progressing in time across 1 day in 2020 (horizontal axis). In order to make the short transmissions visible on the horizontal time scale, the data are shown binned into 10-minute maxima. The vertical dashed lines correspond with the traces shown in Figure 4.8 (left).

were 1 ms or shorter, and only 10% exceeded 3 ms.

The split plots support further conclusions:

- The variation with the choice of threshold power level was minor. For transmissions shorter than 2 ms, there seemed to be little correlation between the threshold level and the distribution. This trend held even at low threshold power levels corresponding with greater path loss over a larger potential coverage area. This implies that the radio signal environments in the uplink channels across the different sites principally exhibit impulsive occupancy statistics. For transmissions longer than 2 ms, lower threshold power levels did correspond with a clear trend toward longer estimates of occupancy duration. These cases warrant further investigation.
- The strongest impact in occupancy duration comes with center frequency. This may be a side effect of different base station configurations applied by the different cellular networks operating these channels. It is likely that this variability is related to the (smaller) variability that is visible among the different sites, since there is likely to be a correlation between the site and the most active cellular network activity.

While the minimum transmission period on the frequency-division duplex (FDD) LTE resource grid is defined by the TTI, which is 1 ms, many instances of shorter occupancy time were observed. Most of these cases were at 701.5 MHz, which produced nearly twice the number of transmission events as any other frequency. This may indicate that the operator of the mobile network operating at this frequency has enabled sounding reference signal (SRS) transmissions on this channel, though this would need to be confirmed by other measurements.

4.2.2.2 2.4 GHz ISM Channels

The occupancy duration distributions are shown for 2.4 GHz channels in Figure 4.11. The splits with site and frequency are shown substantially different characteristics compared to the LTE uplink.

- While the variation with the choice of threshold power level was again minor, threshold setting at lower levels produced a more consistent trend toward larger occupancy duration estimates. This may imply that there are typically a greater number of ISM transmitters active in each band and that the channels are less purely impulsive than the LTE uplink channels.
- There was no discernable difference between the distributions of the duration estimates among the different chan-

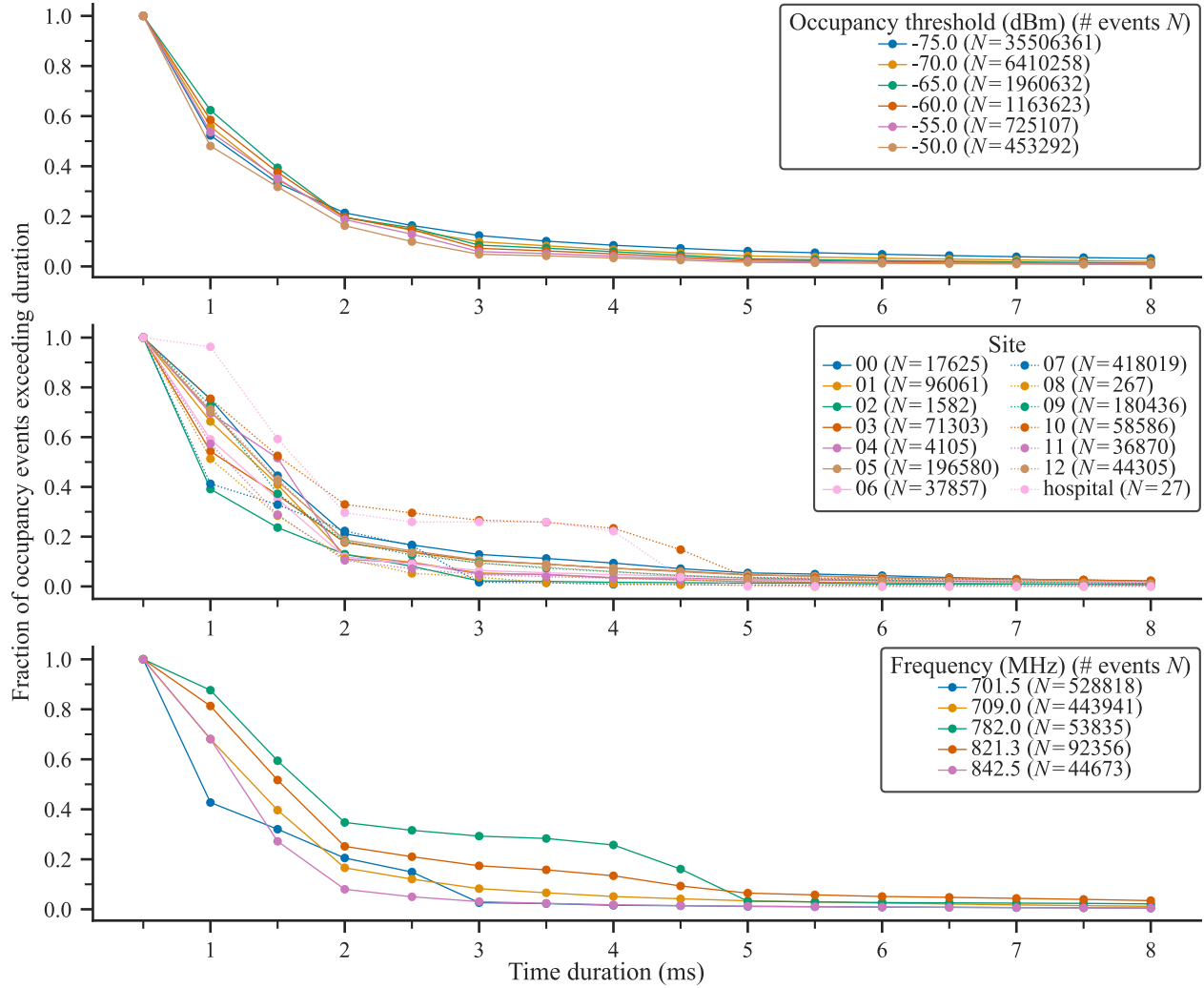


Figure 4.10: Empirical survival functions of occupancy duration in LTE uplink channels across all dates. The distribution in each plot is split across the variable as shown in the legend; otherwise an occupancy threshold is set to -60 dBm and data is aggregated across all sites and frequencies.

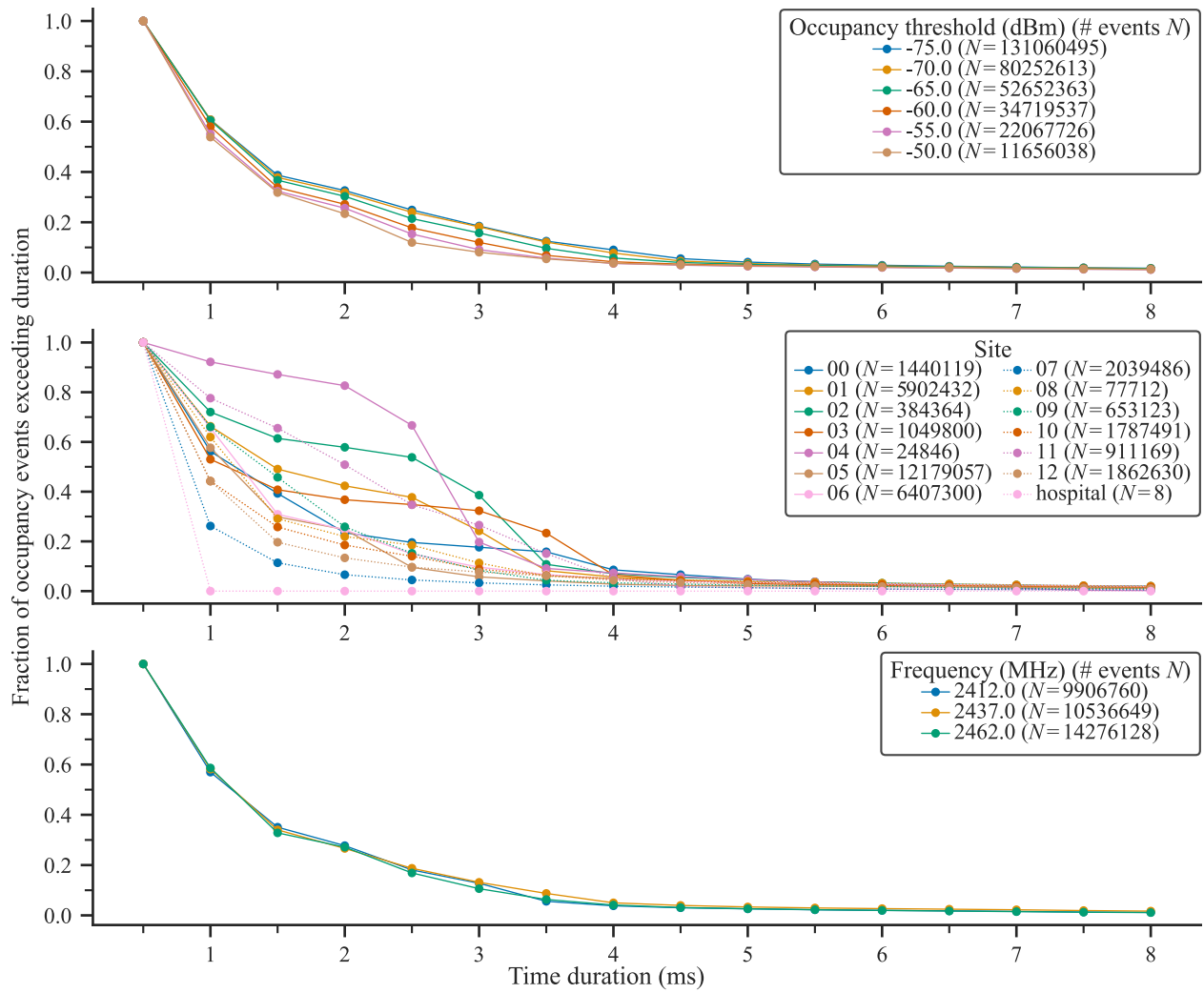


Figure 4.11: Empirical survival functions of occupancy duration aggregated across all 2.4 GHz ISM channels and all dates. The distribution in each plot is split across the variable as shown in the legend; otherwise an occupancy threshold is set to -60 dBm and data is aggregated across all sites and frequencies.

nels.

- The distributions were dramatically different at different sites between the range of 1 ms to 4 ms. These may be a symptom of the type of wireless equipment in use and/or the data traffic patterns at these different sites.

In all, only 10% of estimated occupancy durations exceeded 3.5 ms.

4.2.2.3 5 GHz U-NII Bands

Distributions in the 5 GHz channels are given by Figure 4.12. Transmissions in this band were the shortest among all of the different types of channels under study. Fewer than 10% of transmission events corresponded with estimated occupancy durations longer than 2 ms.

In this band, as in the 2.4 GHz ISM band, the location was the variable with the greatest impact on the distribution. This occurred principally only between 1 ms and 1.5 ms.

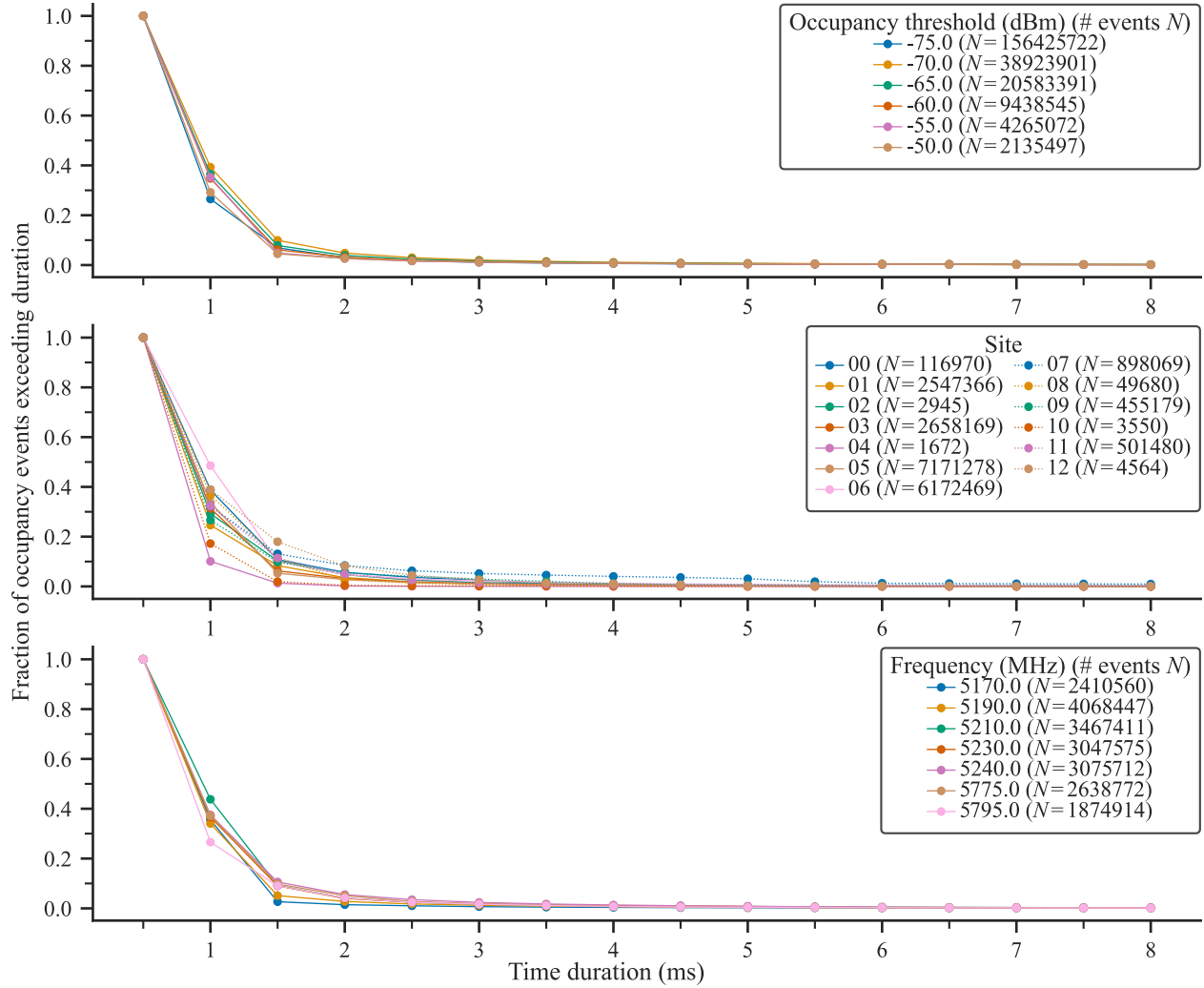


Figure 4.12: Empirical survival functions of occupancy duration in 5 GHz U-NII bands across all dates. The distribution in each plot is split across the variable as shown in the legend; otherwise an occupancy threshold is set to -60 dBm and data is aggregated across all sites and frequencies.

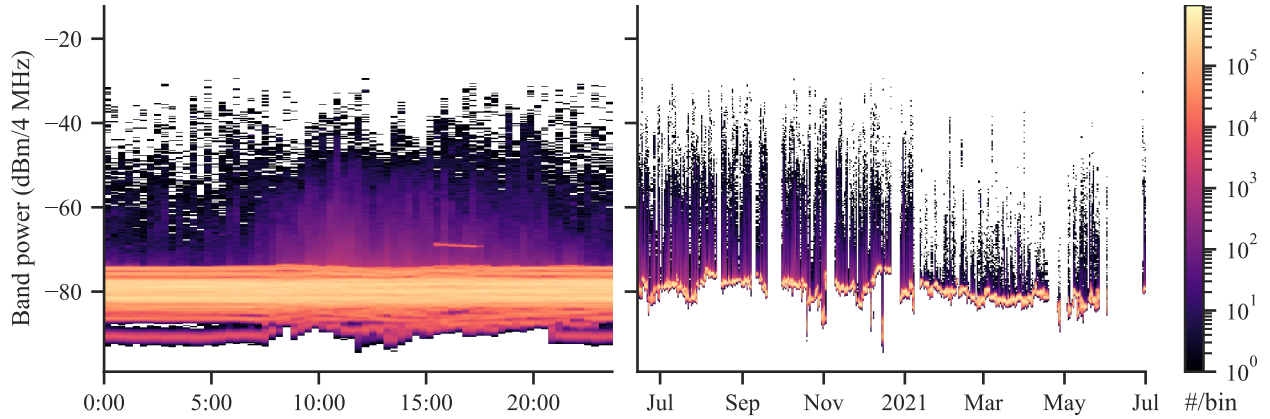


Figure 4.13: Histogram heat maps of band power at 842.5 MHz from site 1 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

4.3 Case Study at Site 1

The focus so far on bulk dataset statistics clouds the features that are unique to each test site. In order to consider this further, we take site 1 as a case study here, which produced a balance of a significant volume of data, a few visible gaps, and coverage through the end of the data set.

4.3.1 LTE Bands: Uplink Channels

Figures 4.14 and 4.13 show the time progression of histograms at 701.5 MHz and 842.5 MHz. These frequencies exhibited the lowest and highest peak band power readings at this site. The left sides of these plots show that more powerful band power samples were more likely to be received during daylight hours, where higher sample counts at power levels above the noise floor (up to around $10^2/10$ min) were observed than at night. The activity at 842.5 MHz became less significant at the beginning of the 2021 calendar year, which may hint at a change in band uplink channels by nearby equipment.

The underlying time-progression of the noise and interference is visible on the right sides of Figures 4.13 and 4.14. The central value of this power level changed on the scale of days, varying within a range of approximately 10 dB. Since the thermal noise in the sensor is stable (see Subsection 4.3.4), we conclude that this floor is either background energy received over the air, or spectral regrowth produced in the sensor.

Uplink band power readings at this site only rarely exceed the interference and noise floor (see Subsubsection 4.1.3.1, Figure 4.6) in any of the channels. Aggregated across time, the fraction of band power levels greater than this noise floor was between 10^{-3} and 10^{-4} , shown by Figure 4.15. These events were too infrequent to be visible on the linear scale.

The empirical survival functions for these bands and the other LTE uplink frequencies are compared in Figure 4.15. The maxima at both 842.5 MHz and 709 MHz were more than 25 dB above that of 701.5 MHz. This hints that LTE UEs nearest this sensor operated at the first two bands.

4.3.2 LTE Bands: Downlink Channels

Site study in these frequencies gives some sense for variability in propagation losses at each site relative to the base stations. This is because downlink broadcasting was continuous, and some sensors are likely to be receiving the same broadcasts as a subset of other sensors. As a result, the shape of the distribution of many downlink power readings is very similar. The principal difference is simply the average levels at which they were received (e.g., Figure 4.7),

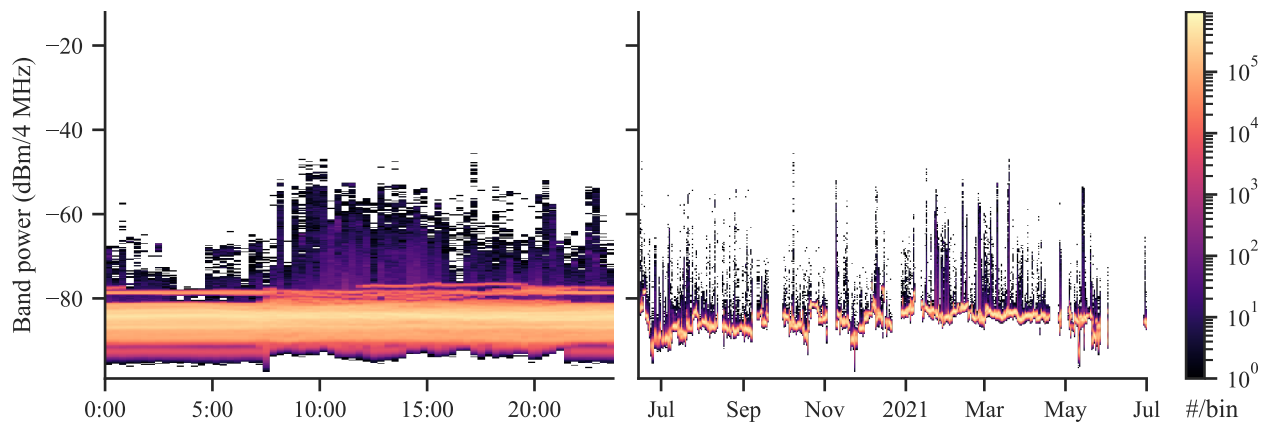


Figure 4.14: Histogram heat maps of band power at 701.5 MHz from site 1 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

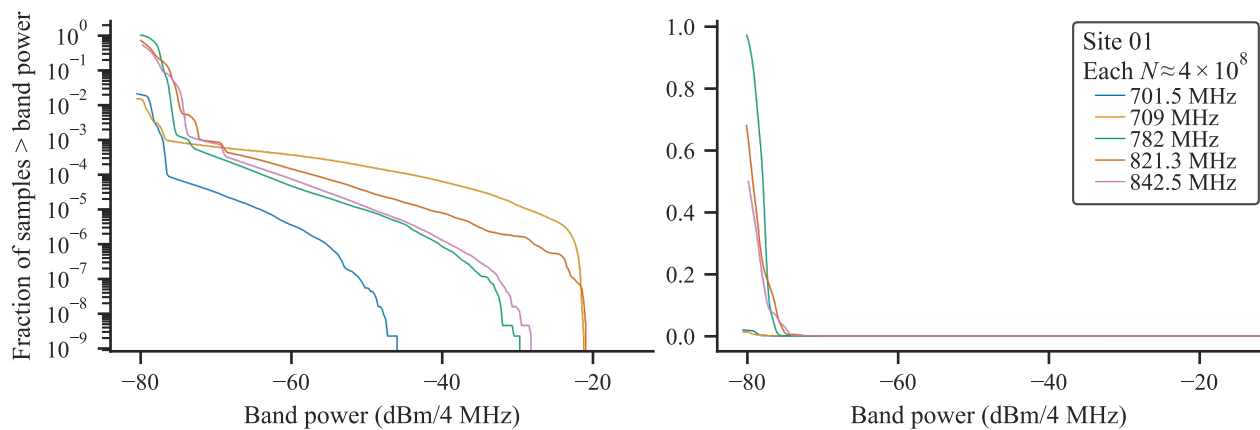


Figure 4.15: Empirical survival functions of band power in uplink channels of LTE bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

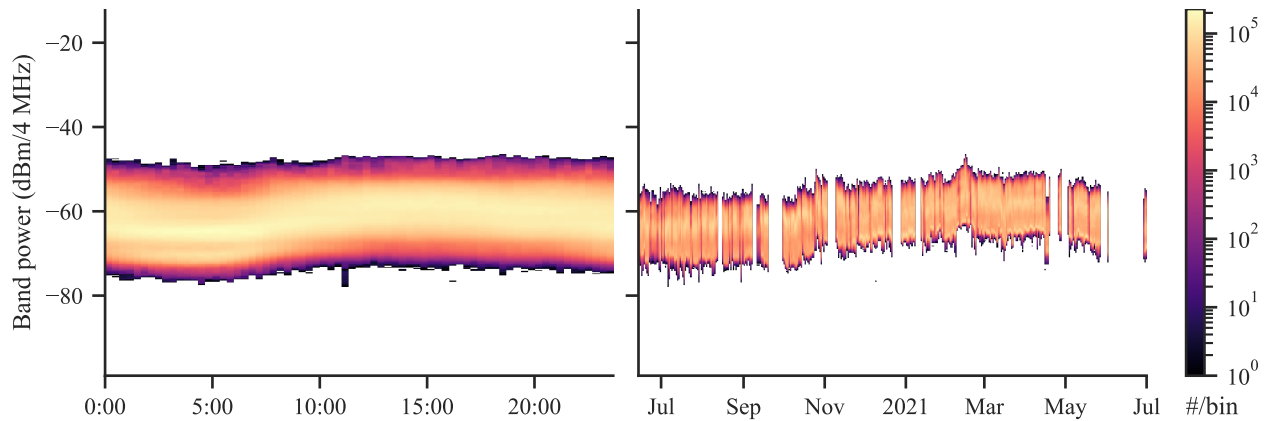


Figure 4.16: Histogram heat maps of band power at 739.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE downlink bands at this site.

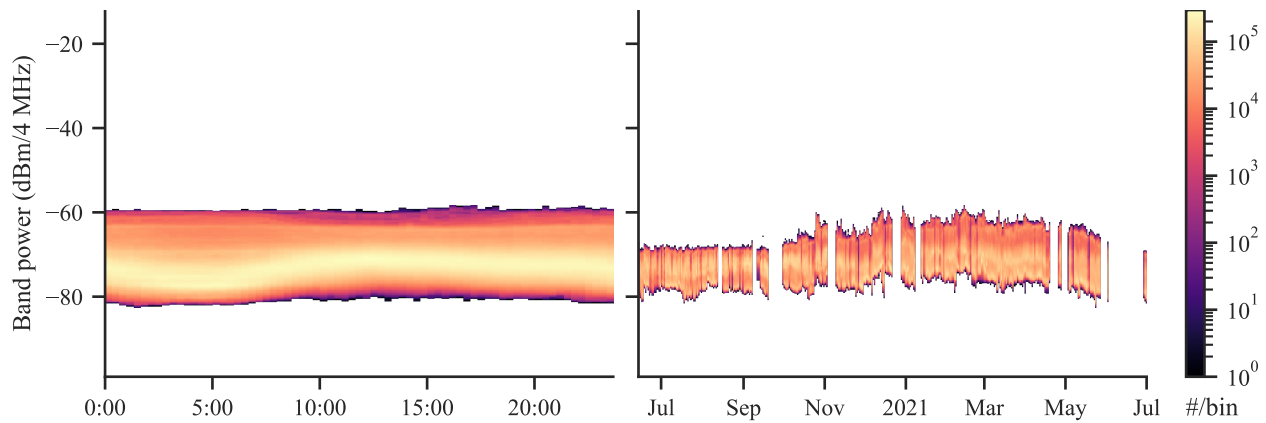


Figure 4.17: Histogram heat maps of band power at 866.3 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE downlink bands at this site.

visible as a shift on the horizontal axis.

The time progression of these distributions are illustrated by Figures 4.17 and 4.16, which show channels with contrasting power levels. The diurnal trend (left plots) matches the broader trends shown by Figure 4.7. The progression by date (right plots) suggests that the sensor was moved in early November 2020, when the received power increased.

The empirical survival functions are shown in 4.18, aggregated across all LTE downlink channels. The shape of the distribution was again very similar at each frequency, even at the tails. Further, 95% of samples at each frequency were distributed across a range of less than 10 dB. Both of these characteristics are a result of the fixed (non-mobile) nature of LTE downlink base stations.

4.3.3 2.4 GHz ISM Band

Figures 4.20 and 4.19 show the time progression of histograms in ISM channels.

The distributions binned by time of day (left sides) show 3 distinct power level regions. By approximate range of power level in dB, these are

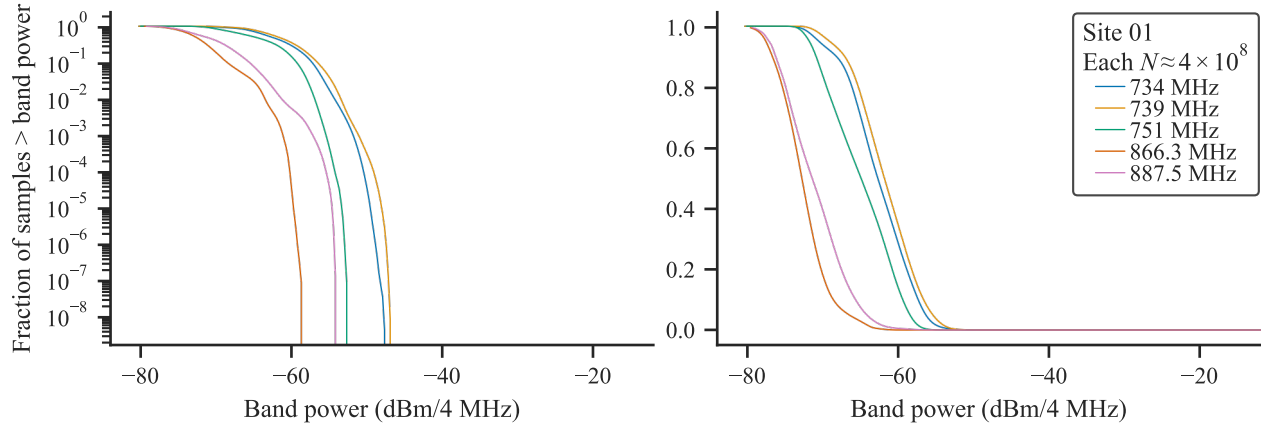


Figure 4.18: Empirical survival functions of band power in downlink channels of LTE bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.

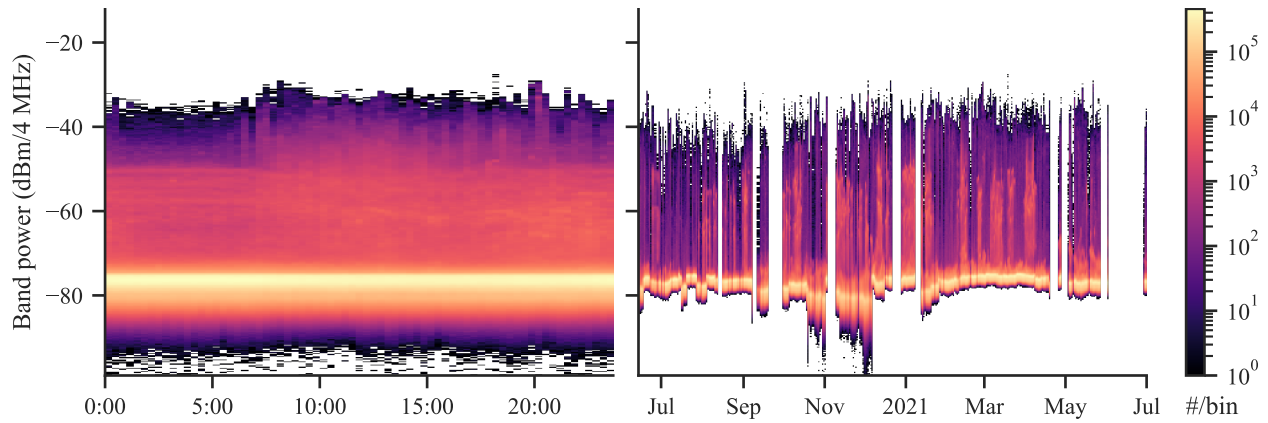


Figure 4.19: Histogram heat maps of band power at 2462.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

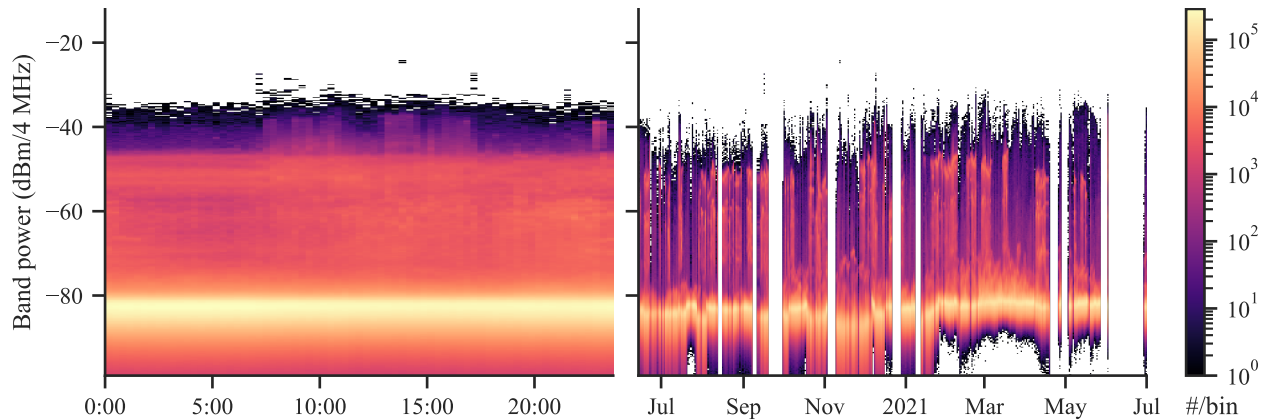


Figure 4.20: Histogram heat maps of band power at 2412.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

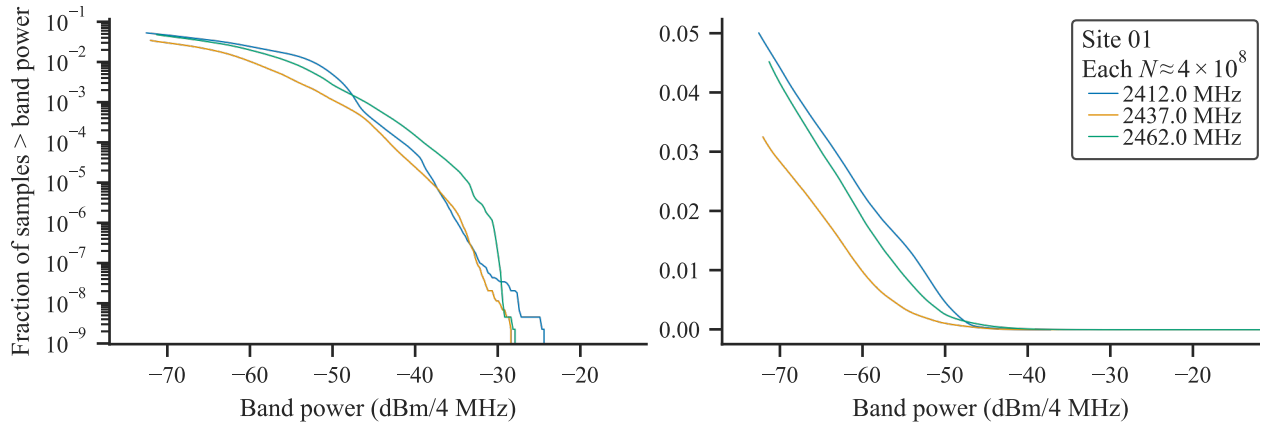


Figure 4.21: Empirical survival functions of band power in ISM bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.

- Below -75 dBm/4 MHz : thermal noise, which is roughly time-invariant;
- Between -75 dBm/4 MHz and -50 dBm/4 MHz : “background” levels, distributed with weak time dependence qualitatively uniform with power; and,
- Above -50 dBm/4 MHz : “foreground” levels from transmissions close to the sensor that vary strongly with time of day.

In all channels, the greatest variability by time of day is visible between about -50 dBm/4 MHz and -38 dBm/4 MHz , where there averaged more than an order of magnitude less activity between 00:00 and 06:00. Yet, the peak extrema (in black) are only weakly time variant. This suggests ongoing (though infrequent) keep-alive activity [26] from the wireless office equipment near the sensor overnight.

More trends are visible on the long time scale (right side) plots. In particular, 2412 MHz and 2462 MHz trade extended periods of more frequent occupancy. The duration of these high-occupancy periods is on a scale ranging from weeks up to about 1 month. This may represent the typical dwell time in a single channel for a WLAN access points (APs) at this site before automatically changing channel. Further insights might be gained on this by analysis across all sites, which is possible using the public data set.

The empirical survival functions of the bands in this site (Figure 4.21) suggest similar distributions even in the tails at high power levels. However, high power level readings at this site were most common at 2412 MHz (WLAN channel 1), and least likely to occur at the center frequencies (centered at WLAN channel 6).

4.3.4 2695 MHz Passive Services Band

The empirical distribution of power samples received at site 1 is shown first in aggregate across all time in the histogram of Figure 4.22. Because the histogram decays rapidly and monotonically from its peak, suggesting there no outliers above the detection floor and that the receiver was operating linearly (at least at this center frequency). The time progression of the histogram, when split across time as in Figure 4.23, further reinforces this conclusion. It is constant except for a temporary decrease by less than 2 dB that is visible in early 2021.

4.3.5 5 GHz U-NII Bands

The time structure of the empirical power sample distributions in site 1 are shown at contrasting frequencies by Figures 4.24 and 4.25. The channel with weaker peak readings, 5170 MHz, was active principally in the summer of 2020. In this channel, levels were rarely detectable above the noise floor after autumn of 2020. This is broadly similar to the tendency toward slow changes in occupancy for each of these channel on time scales of weeks to about a month.

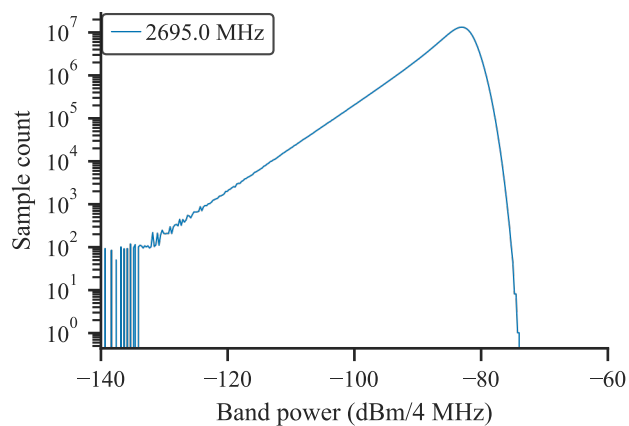


Figure 4.22: Histogram of band power measured in the 2695 MHz passive service band at site 1. At this sample size, quantization is observable below -130 dBm/4 MHz.

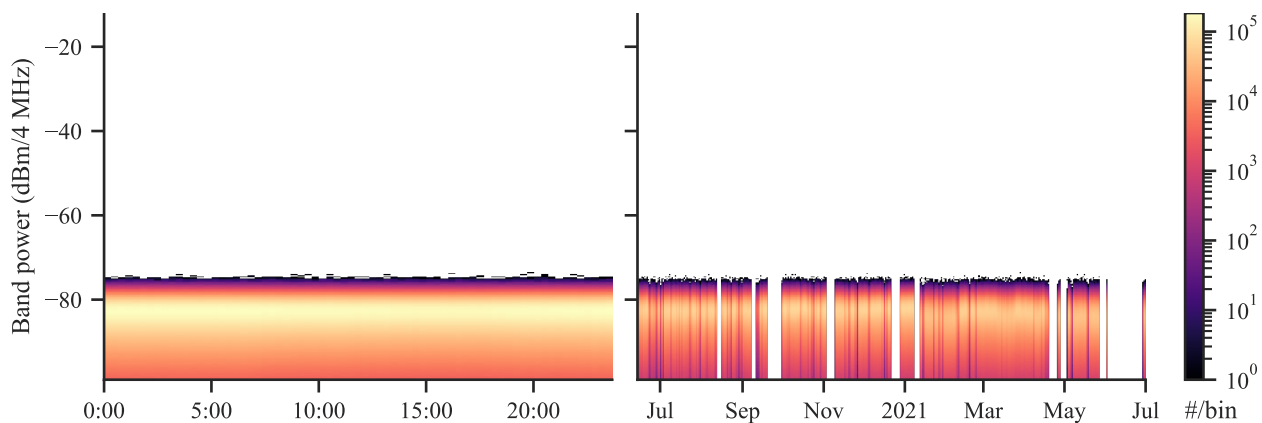


Figure 4.23: Histogram heat maps of band power at 2695.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

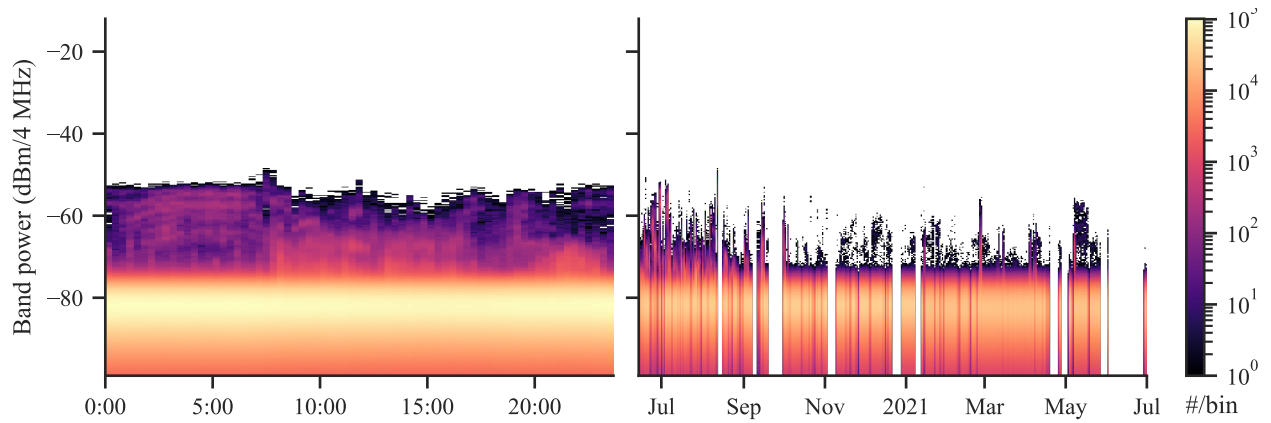


Figure 4.24: Histogram heat maps of band power at 5170.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

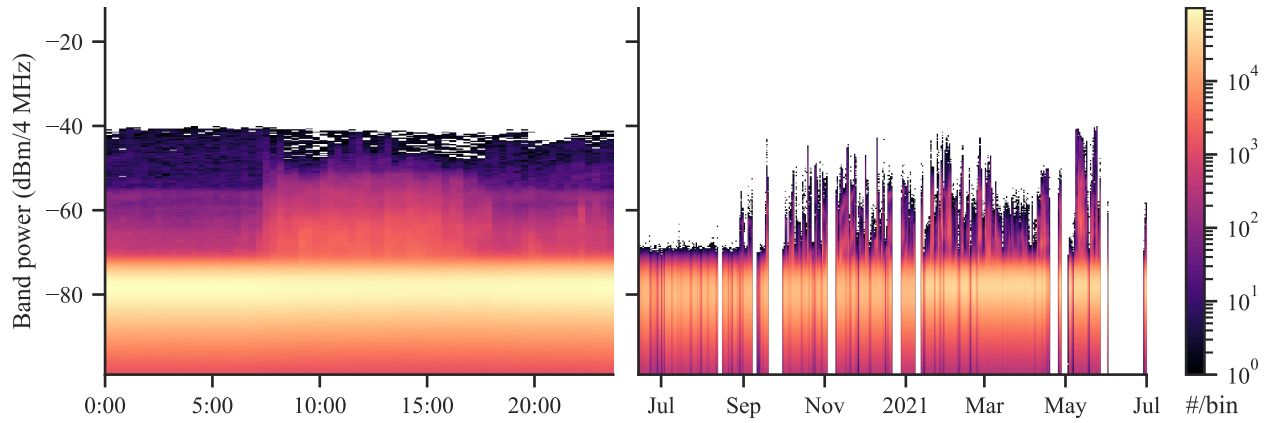


Figure 4.25: Histogram heat maps of band power at 5775.0 MHz from site 1 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

The slow change in channel selection resembles the behavior of the ISM band, as discussed in Subsection 4.3.3. However, the peak reading across U-NII channels, near -38 dBm/4 MHz , was nearly 15 dB weaker than that in the ISM band.

The survival function aggregated across all time is illustrated by Figure 4.26 for each U-NII channel. Power readings at the two upper frequencies (5775 MHz and 5795 MHz) share nearly the same power distribution, suggesting that an AP occupied both as part of a single 40- or 80- MHz channel. The same is true for the pair 5210 MHz and 5230 MHz.

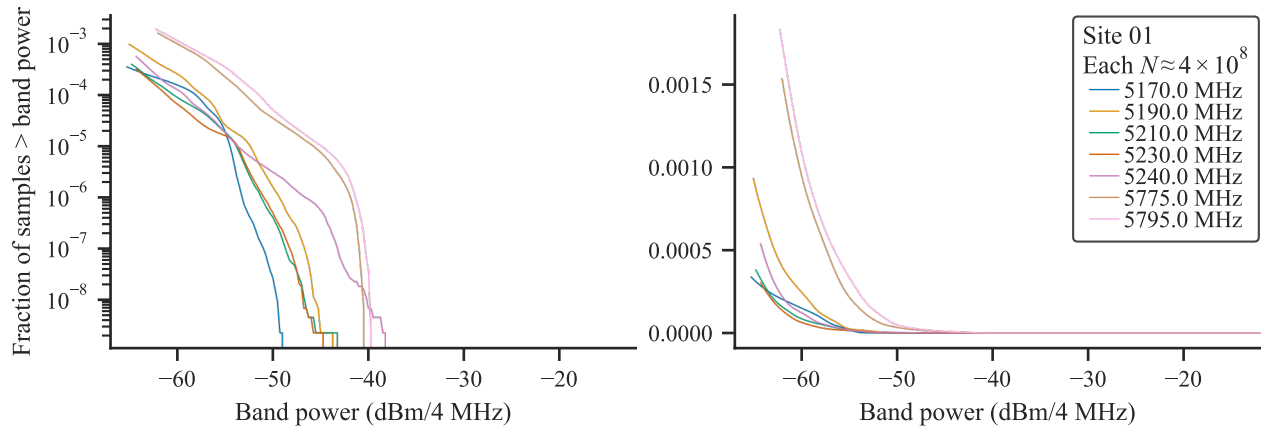


Figure 4.26: Empirical survival functions of band power in U-NII bands at site 1, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.

Chapter 5

Network Profiling Data

Diagnostic network profiling data was collected with commercial wireless analyzer instrument. That data was collected to augment the more extensive swept-frequency power measurements that were presented in Chapter 4. The results are included in the public data release [1].

Limited data captures were collected at the hospital site, as well as residential sites 7 and 11. Network profiling data were collected for both cellular and WLAN networks.

The sections of this chapter outline the collection of this data, and together with example plots of empirical distributions. More extensive plots of these distributions are given in Appendix E.

5.1 Summary of Cellular Data

The wireless analyzer is capable of monitoring LTE and 5G downlinks. By decoding the downlink broadcasts, the instrument also provides information about the resource blocks that were allocated to uplink users in the band. The instrument did not decode any user data.

Configuration of the instrument required input of the downlink center frequency and channel bandwidth, and receive gain. At each test site, we attempted to observe at each of the LTE downlink frequencies listed by Table 2.1. The channel bandwidth and receive gain needed to be tuned in order to properly decode broadcasts from the base station. A first guess for the channel bandwidth was found in some cases through sources on the internet, and the gain was adjusted depending on a signal strength indicated by the instrument. However, in some cases, the instrument could not decode the base station broadcast, even at maximum gain. Therefore, data is not available at every combination of test site and frequency.

Data are provided at the time resolution of the cellular TTI, which is 1 ms. At each time step, we collected:

1. Downlink bands: number of users, number of occupied resource blocks (RBs), and average modulation coding scheme (MCS); and,
2. Uplink bands: number of users, total channel data rate, number of occupied RBs according to the resource indication value (RIV) from the downlink, and average MCS.

These are each present as columns in the public data release.

Figure 5.1 and Figure 5.2 show first examples of this data in a matched pair of uplink and downlink bands. These were collected at the hospital site. In what turned out to be typical in all of these data, resource blocks were most often allocated to only 1 user at a time. The number of allocated resource blocks was often very large in the downlink (48 of the 50 available), but rarely exceeded 10 in the uplink. Meanwhile, the average MCS was spread out more evenly in downlink than the uplink, which was had more limited spread.

As a further example pair, Figure 5.3 and Figure 5.4 show the empirical distributions of the same parameters collected

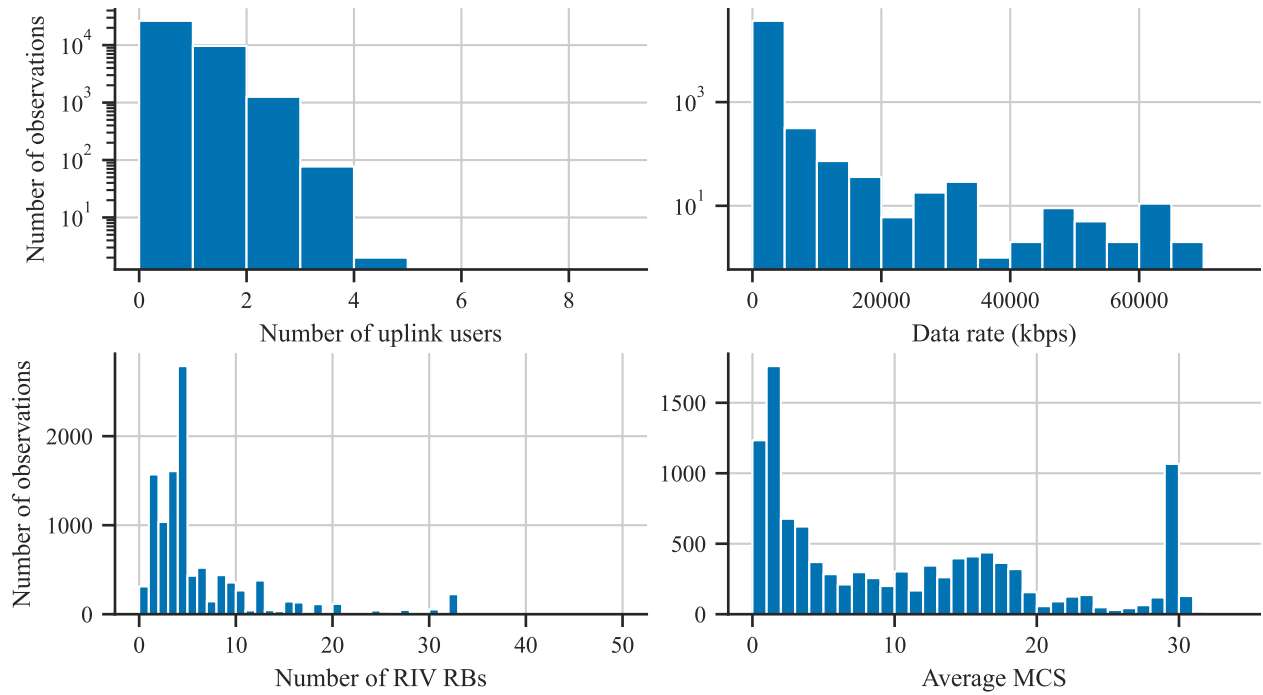


Figure 5.1: Histograms of LTE uplink resource grants from the hospital site on 2020-12-07 observed at 739.0 MHz

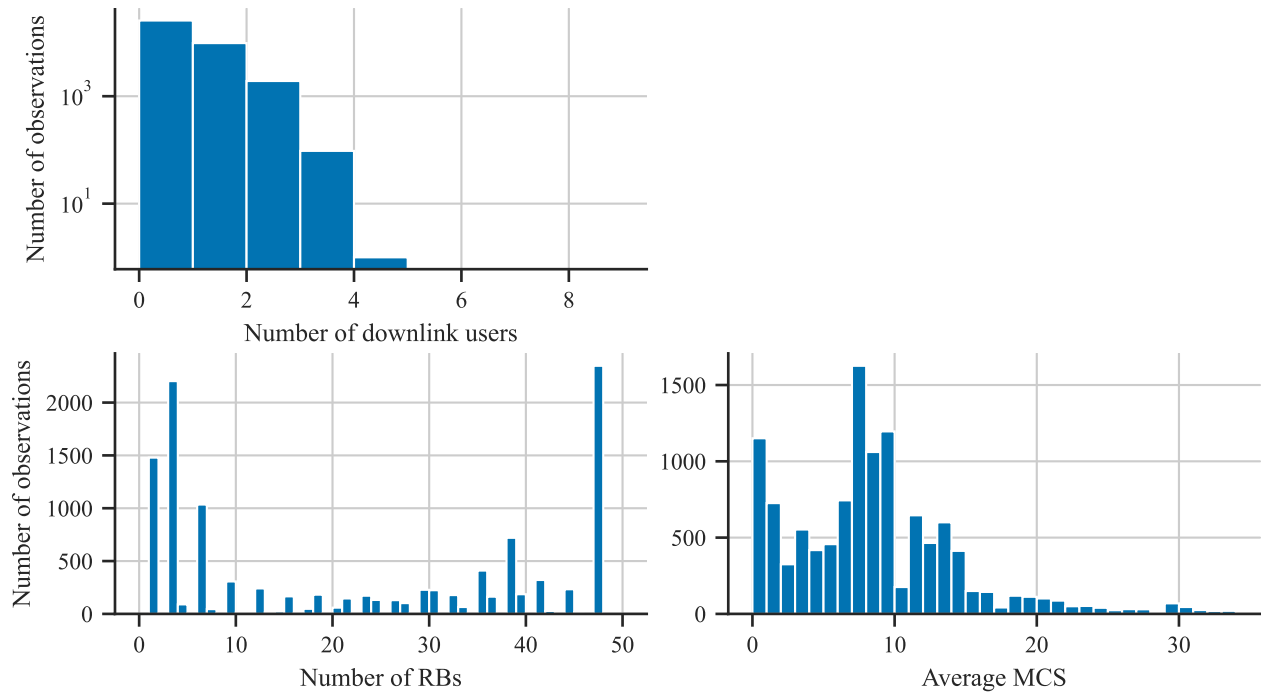


Figure 5.2: Histograms of LTE downlink resource grants from the hospital site on 2020-12-07 observed at 739.0 MHz

at residential site 7 in a different LTE band. The distributions of allocated RB and number of users per TTI remained broadly similar to those in the hospital. However, the MCS distributions included large peaks at different frequencies. This difference may be a result of a combination of different base station configuration or traffic loading in these

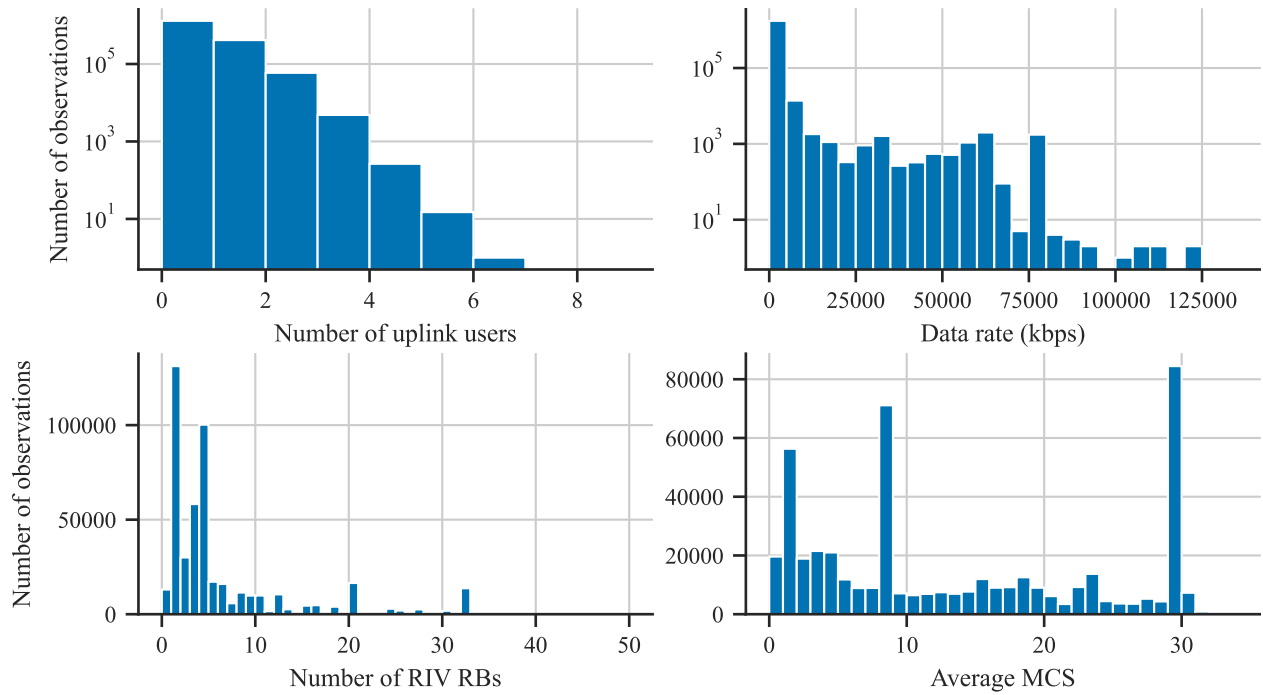


Figure 5.3: Histograms of LTE uplink resource grants from site 07 observed at 739.0 MHz

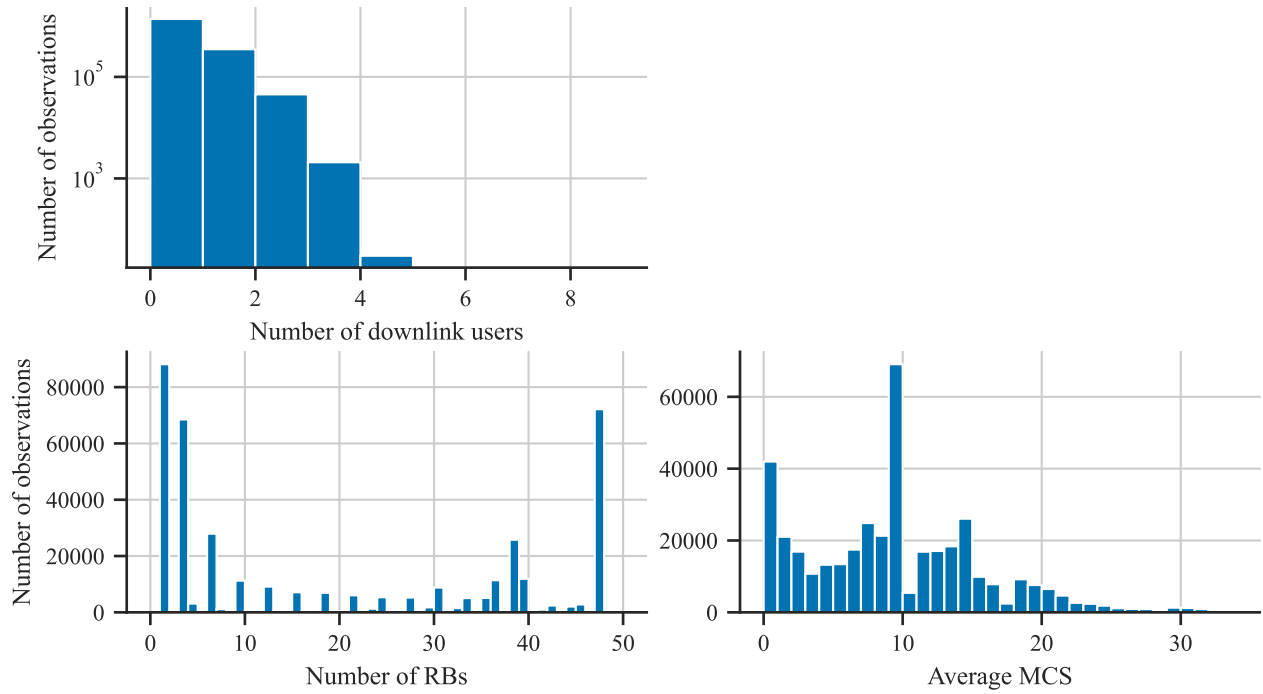


Figure 5.4: Histograms of LTE downlink resource grants from site 07 observed at 739.0 MHz

different cells.

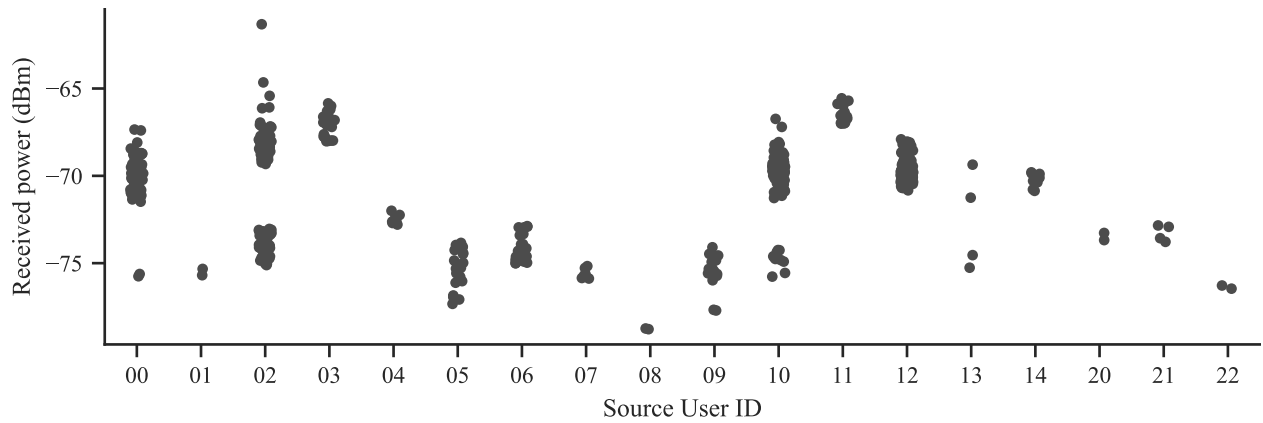


Figure 5.5: Received power levels by transmission source in WLAN measured from the hospital site on 2021-09-24 data at 2412.0 MHz

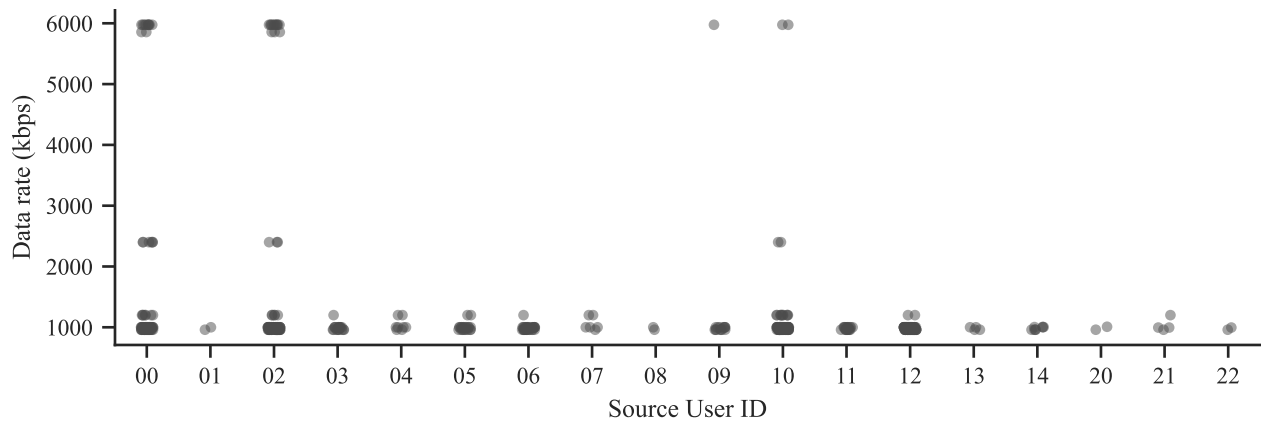


Figure 5.6: Data rate by transmission source in WLAN measured from the hospital site on 2021-09-24 data at 2412.0 MHz

5.2 Summary of WLAN Data

We used the wireless analyzer to monitor WLAN activity in ISM center frequencies near 2.4 GHz that are listed in Table 2.1. The instrument can only monitor one band at a time, so we stepped through each frequency. The WLAN bandwidth was set to 20 MHz, so transmissions with other bandwidths were likely not captured in the data. The data acquisition duration was approximately 5 seconds; due to the large size of raw waveform data that the instrument collected for processing, it was not practical to collect longer data captures.

The data stream output by the analyzer is a sequence of bursts tagged with the same timestamp. Each burst corresponds with 1 or more 802.11 WLAN packets. The record for each packet is composed of a start timestamp, end timestamp, packet type label, the MCS, power level, number of bytes, EVM, MAC address of the sender, and MAC address of the destination. In order to anonymize the data, we 1) replaced each MAC address (which are personally-identifiable information) with an arbitrary integer index, and 2) replaced end timestamps with packet transmission duration.

Data capture recordings of WLAN network profiling characteristics was performed once, at the hospital site on 24 September, 2021. The frequency at which the greatest number of packets was decoded was 2412 MHz. Some summary distributions at this frequency are illustrated by Figures 5.7 – 5.8.

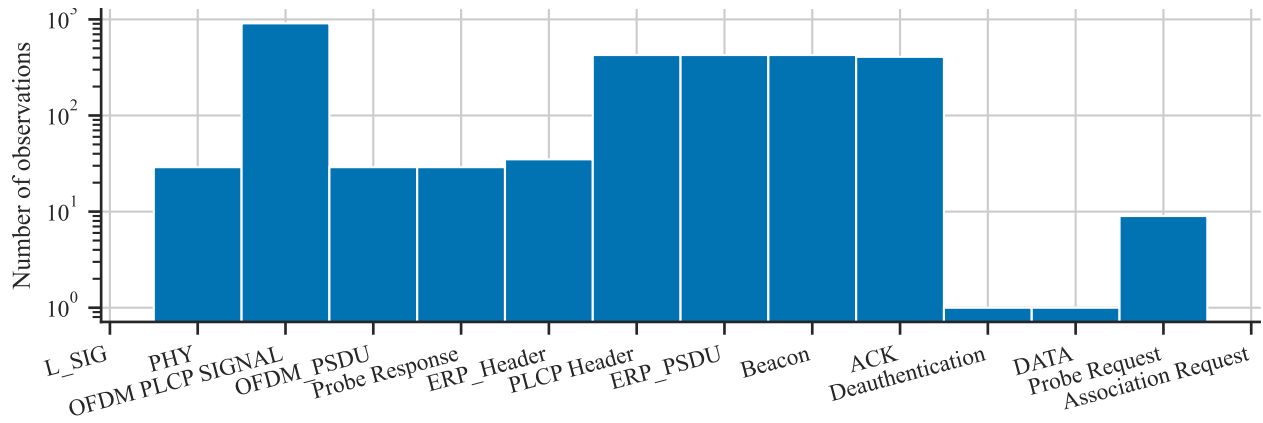


Figure 5.7: Histogram of packet types observed in WLAN measured from the hospital site on 2021-09-24 data at 2412.0 MHz

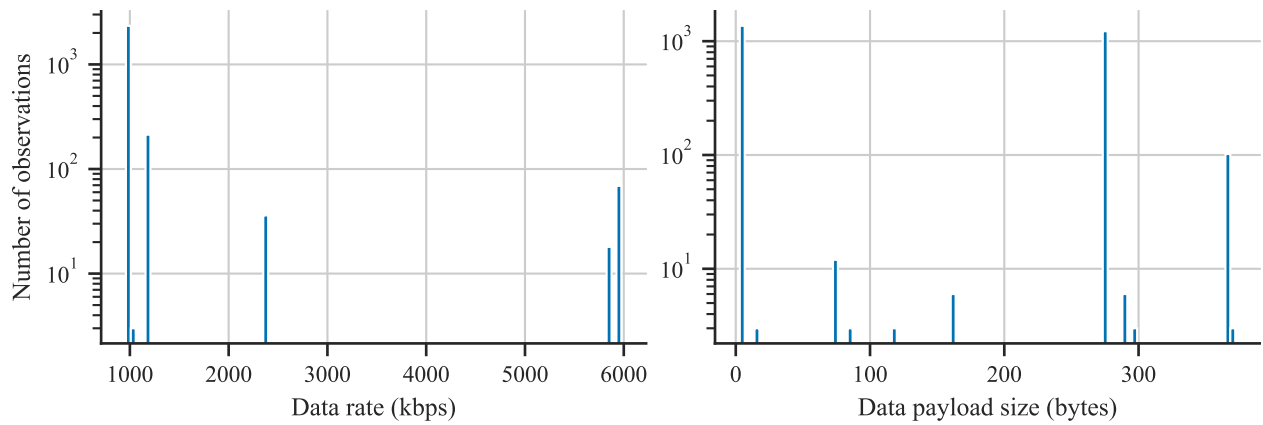


Figure 5.8: Histograms of WLAN data rate and payload sizes from the hospital site on 2021-09-24 observed at 2412.0 MHz

A total of 23 different MAC addresses were observed; 5 of these were destination addresses that did not transmit any packets that were decoded during the data capture. Scatter plots of received power and data rate are shown by unique MAC address in Figure 5.6 and Figure 5.7, respectively. The range of power levels was observed from each user was narrow during this short time span. Further, the data rate observed from over the course of each packet was most often 1 Mbps, which likely reflects the packet structure. Further, 12 different packet types were observed; 5 of them were most common. The number of bytes sent per packet was also heavily quantized, likely determined by the type of packet sent.

Chapter 6

Conclusion

6.1 Findings

The characteristics observed in each type of band were discussed in detail by Subsection 4.1.3. Some key features of each band were observed consistently across all sites:

- Cellular downlink channels:
Broadcasts continued almost unstopped at all sites at which the power level was strong enough to be detected. The center 50% of band power levels within each combination of site and frequency varied across a range of approximately 10 dB, between minimum and maximum levels (Figure 4.4). These bands also exhibited a slight diurnal pattern: power readings were typically 5 dB lower at night (Figure 4.7).
The most powerful band power readings in the cellular downlink bands were lower than those in any cellular uplink, ISM, or U-NII channels. However, the median energy level of the downlinks were the greatest of any of the channel types. This is due to the substantially higher occupancy rate.
- Cellular uplink channels:
The LTE uplinks were received in short bursts, shorter than 4.5 ms in 90% of all cases (Figure 4.10). The bursts tended to maintain consistent power levels within 20-minute time spans – 90% fell within ± 1 dB of the median during these time windows using a -75 dBm threshold level (Figure 4.6). The mobility of uplink devices resulted in a very wide range of power readings which spanned the full dynamic range of the sensors and at a rate of 1 in 10^6 , likely driving sensors into saturation (Figure 4.3).
- ISM and U-NII bands:
In 90% of all samples, the duration of occupancy events stronger than -75 dBm/4 MHz were 4.5 ms or shorter in 2.4 GHz ISM channels, and 2 ms in 5 GHz U-NII channels (figures 4.11 and 4.12). However, in the ISM bands, these durations varied significantly by site. Similar to the cellular uplink channels, the mobility of transmitters in these bands resulted in a wide range of observed power levels (Figure 4.3), though for U-NII channels these observations were limited by the reduced dynamic range of the sensor at 5 GHz.

Further analysis on this large dataset could yield more conclusions. With this in mind, the underlying data is available to the public in its entirety [1].

6.2 Application to Resilience Testing

6.2.1 Existing Test Standards

6.2.1.1 Tests for Medical Equipment

Standard IEC 60601-1-2 [18] specifies susceptibility test standards for medical equipment. The frequencies under test in that test between 700 MHz and 5800 MHz overlap closely with those studied here. The susceptibility test in each band is specifically designed to assess impacts of the radio access technologies listed here by Table 2.1. Thanks to the shared test frequency, the data published here has implications for IEC 60601-1-2.

Consider first the field strength levels under test. The test conditions in the standard correspond with published sensor power readings in this document above +15 dBm (by way of [27]). All power readings in our study were 10s of decibels below this power level, so the present study gives no evidence to suggest changing it.

The standard also prescribes specific waveforms for the testing. Each band is to be tested with square wave modulation at either 217 Hz or 18 Hz, with duty cycle 50%.

6.2.1.2 Tests for Household Products

Standard CISPR 14-2 [19] specifies immunity requirements for household products. The electromagnetic disturbance conditions are inherited from environmental conditions for immunity defined by IEC 61000-4-3. Field testing is prescribed for VHF frequencies up to 1 GHz. The incident field condition across this frequency range is modulated with a rectangular waveform at 80% duty cycle, at a field strength that would excite a sensor response in this report at approximately 0 dBm.

6.2.2 Implications of the Test Data

Based on the testing in this report, and in particular the findings summarized by Section 6.1, the following changes would help to ensure representative conditions for the immunity tests:

1. To emulate representative electromagnetic disturbances from cellular uplink traffic:
 - The duration of these bursts could be set to 2 ms, the median observed in testing. Typical separation between the bursts should not be longer than 4.5 ms, which was the 90th percentile.
 - The duty cycle for testing cellular uplink bursts could be between 10^{-3} and 10^{-6} . Occupancy rate of 10^{-6} was more represented of the largest power levels, but may result in impractically long immunity test times.
 - While modulation in each burst should be noise-like, the power in each burst can be left constant.Testing against cellular uplink is notably important because close-proximity mobile transmitters made these the most powerful observations in our testing.
2. To emulate representative electromagnetic disturbances from cellular downlink traffic:
 - The disturbance should be a continuous broadcast (100% duty cycle)
 - The modulation should be noise-like with a CCDF shape similar to that of Figure 4.4Some caution should be used in interpreting the range of power levels observed in the cellular downlink data. Because the locations of the sensors and cellular base stations were fixed, there was very little sampling in space - effectively only 1 for each test site. As a result, a more representative sampling across space may yield some significantly higher power levels.
3. To emulate representative electromagnetic disturbances from ISM and U-NII activity:
 - The duration of these bursts could be set to 2 ms, the median observed in testing. It should not be longer than 4.5 ms, which was the 90th percentile.
 - Application of these disturbances to susceptibility testing above 2 GHz would be justified from the data, which include band power levels nearly as high as the 700 MHz - 900 MHz cellular uplinks.

Several other details of the bursts could be refined using data from further measurements collected in the future. For example, measurements at greater resolution would be necessary to measure typical duration and occupancy rate of bursts in ISM bands.

Power spectral density measurements would also be necessary to estimate a representative distribution of occupied bandwidths. This would augment resource block distribution data that can be produced by the network traffic profiling instrument in (Chapter 5, Appendix E).

6.3 Challenges and Future Direction

The work done for this report points to potential benefits from a variety of potential follow-on efforts in the future.

6.3.1 Analysis of Averaged Band Power

The technique of reporting time-averaged power was simple enough to make real-time processing possible in the background of office laptops. These band power time series were recorded and are the lowest-level data released in the dataset [1]. This power integration was a compressive sensing technique: the recorded data discarded magnitude and correlation relationships on scales shorter than 0.5 ms, and all phase information.

A significant body of prior work is concerned with the related but different parameter, the amplitude probability distribution. This is the survival function on instantaneous measurements of baseband voltage amplitude. Publications discussed this type of approach as far back as the 1930s [28], and were expanded with some Rayleigh distribution transformations for atmospheric noise measurement applications at the National Bureau of Standards in the 1950s [29]. Variations of this approach began to appear in various widespread application to spectrum monitoring in the 1990s [30]. However, some detailed statistical analyses still build on the approach of the 1950s in the context of digitally modulated wireless communications [31].

This report differs from the above, because post-analyses were based on the average band power. Because fewer analyses have been performed on the basis of average band power, further developments in post-analysis could unlock insights into more features in the radio environment, such as the number of users. The fruits of this work might be able to enrich results from the released data, refine test methods in future experiments, and identify complimentary streams of real-time spectrum data.

6.3.2 Sensor Noise De-embedding

Because the goal of the spectrum measurements is to assess the radio environment *outside* the sensor, it would be useful to de-embed the contributions of the sensor from both time series and empirical distributions of measured band power.

In practice, the empirical distribution functions of additive noise power varied from one sensor to the next. This was observed both in terms of the calibration and in monitoring the passive radio band at 2695 MHz. As a result, techniques for de-embedding thermal noise from the measured power distributions would require a calibration procedure and accompanying statistical method for de-embedding.

6.3.3 Sensor Performance and Calibration

The design and test of low-cost sensor nodes is a key problem in producing trustworthy data with spectrum sensing networks. The low cost of the sensors is vital to scaling the size of the distributed network, but brings poorer performance that introduces technical challenges which need to be addressed to ensure trustworthy data.

One such challenge is in the variability of radio performance between sensors. Response of different sensor nodes can easily vary by several decibels, even when among sensor nodes that share the same list of part numbers. This can be corrected through calibration, but this adds extra cost. Calibration of each sensor and quantifiable uncertainty in the corrected sensor data are tractable problems. Significant improvements to sensor trustworthiness could be realized by developing calibration measurements designed to minimize added time and cost. Co-design with computationally efficient real-time corrections

Another limitation to the trustworthiness of sensor data is its limited frequency selectivity. The risk is contamination created by spectral regrowth when powerful carriers are received at frequencies outside band under test. Prior work has pointed to some of these challenges [32] and characterization methods to assess relevant sensor performance [21].

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Appendix A

Sensor Tuning and Performance

A.1 Tuning the Settling Time Delay

The dwell windows collected in the passive services band are shown aggregated in Figure A.1, takes the full body of field data at 2695 MHz, where which the readings are presumed closest to thermal noise in all of the tested bands. Because the timing of interference received in this band is uncorrelated with the start time of each dwell window, we can see trends in settling time transients. It is clear that the transients last up to 195 ms in the test data set.

In order to reject these spurious readings, sensors were configured to reject the first 195 ms of each dwell window. The result was a reduction in spurious readings by more than 10^2 . While applying this in post-processing reduced the valid data acquisition time per dwell window to 105 ms, it significantly improves the ability to resolve survival function curves.

A.2 Dead Time Performance

The fraction of measurement time not spent acquiring valid data is referred to as the dead time,

$$\text{Dead time} = 100\% \times \left(1 - \frac{T_{\text{acq}}}{\Delta t}\right). \quad (\text{A.1})$$

Here T_{acq} is the duration of valid data in each dwell window (fixed at 105 ms in this campaign), and Δt is the difference between the start time of neighboring dwell windows.

Figure A.2 shows the distribution of Δt taken from all nodes during the test campaign. Energy is widely distributed here because the frequency list is shuffled before each sweep. The time delay increased for this hardware when the frequency steps were greater than at least 1 GHz.

The dead time averaged over the entire measurement data set was 77%.

A.3 Noise performance

The noise performance of the SDR largely determines the detection limit of the receiver. The ability to detect the signal is somewhat a statistical quantity, since the internal noise is determined through calibration with measurement uncertainty. The ability deteriorates significantly as the signal level approaches the internal noise level of the SDR. Figure A.3 shows an example of a SDR with 40 dB gain and 5 dB NF. The detection bandwidth is set to 10 MHz. The receiver has high ability to resolve the signal power when the signal is much higher than the internal noise (about -100 dBm). As the signal level becomes comparable to the noise level, the detection ability reduces. As the signal level further reduces, the 95th quantile reaches a plateau. In other words, the receiver no longer has high confidence in determining the signal power level lower than the SDR internal noise.

From the calibration aspect, the internal noise level also implies that at least one of the reference input signals P_{in}^{cold} and P_{in}^{hot} has to be much stronger than the internal noise power level. Otherwise the calibration equation may likely be

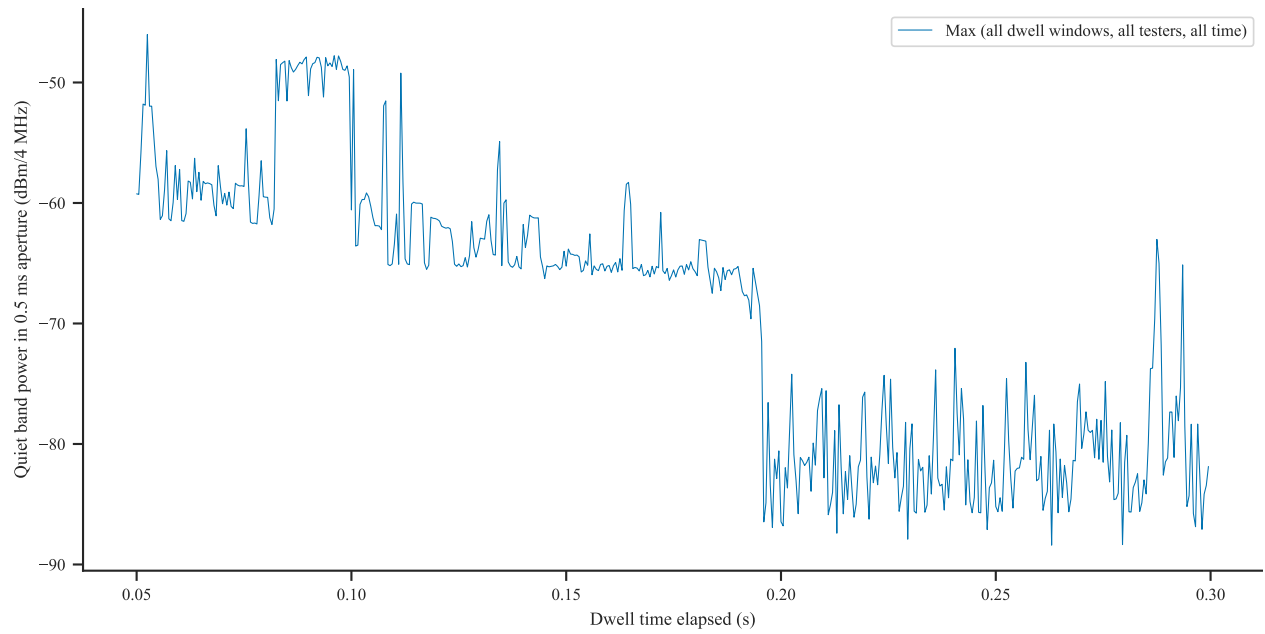


Figure A.1: Maximum power at 2695 MHz in all readings through November 2020, by time elapsed in the dwell window. Holdoff time was set to 195 ms to remove the noise plateau from published data.

ill-conditioned. As a consequence, the gain and noise calibration cannot be solved accurately.

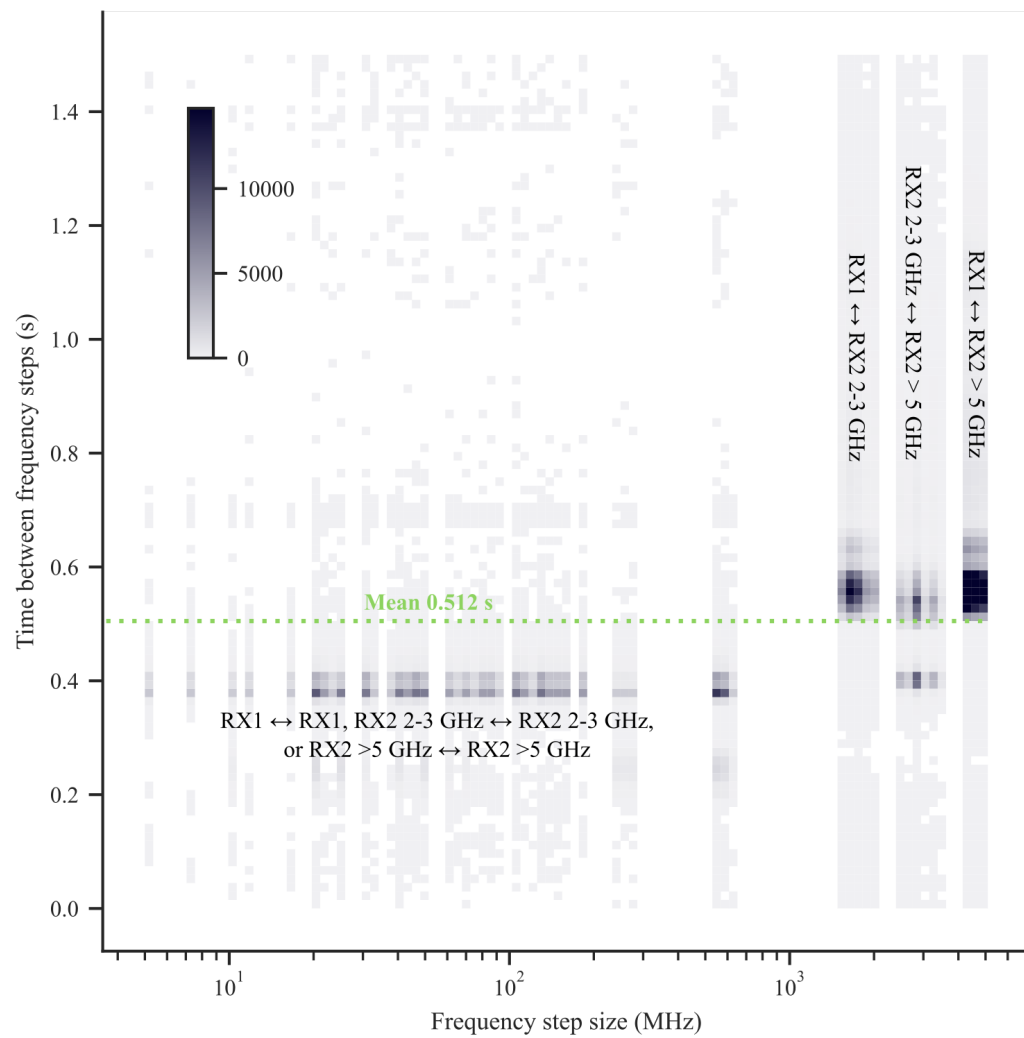


Figure A.2: Distribution of the time duration between frequency steps, including acquisition time and settling holdoff time for transients.

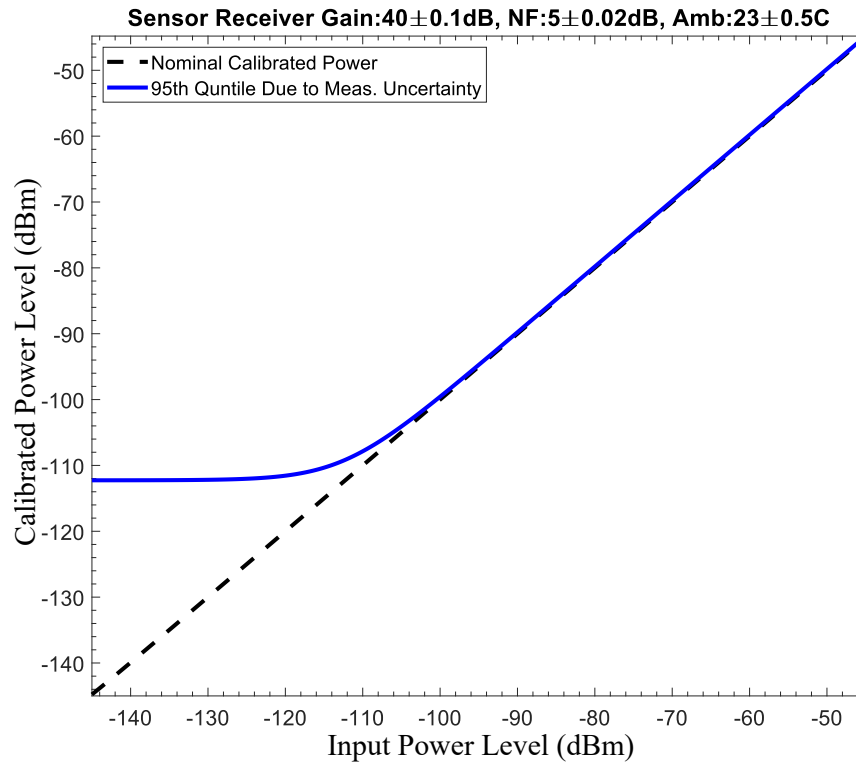


Figure A.3: Simulation results of a SDR with 40 dB gain and 5 dB NF. The detection bandwidth is set to 10 MHz. The 95th quantile indicates the confidence level of the receiver to determine the input singal level.

Appendix B

Calibration and Uncertainty

The software-defined radio (SDR) is essentially a reconfigurable transceiver that combines transmitter and receiver functions into one compact package. For this project, we are solely concerned about SDR's receiver part. The highly integrable configuration has a advantage in commercialization and dissemination although it also brings challenges in testing and qualification. Metrologists are left with limited access to the SDR. There are no connectorized points aside from the coaxial input ports and the digital output ports. As such, diagnosis cannot be made on the component level as all components are integrated permanently on a circuit board. We detail our receiver calibration approach in this appendix.

B.1 Microwave Network Model of the SDR

We consider the SDR a two-port network that is terminated by a detector, as shown in Fig. B.1. Such detector can be regarded as a closely-matched load ($\Gamma_{load} = 0$). The goal is to establish a relation between the output wave b_2 and the input wave a_0 . For radiometric measurements, we are more concerned about the ensemble average of the products of the wave and its conjugate. More specifically, $\langle |b_2|^2 \rangle$ indicates the noise power measured by the SDR and $\langle |a_0|^2 \rangle$ is the noise power presented by the noise source. Note that $\langle |a_0|^2 \rangle$ correspond to the power delivered to a matched load or a matched receiver, which is not the desired available power. More on this topic is shown below in Section B.1.1.

Typical wave analysis can be applied here, namely

$$\mathbf{b} = \mathbf{S}\mathbf{a} + \mathbf{x}, \quad (\text{B.1})$$

where $\mathbf{b}$ and $\mathbf{a}$ are the scattered and incident wave vectors, respectively, $\mathbf{S}$ is the scattering matrix, and $\mathbf{x}$ is a noise vector. Each is complex-valued.

In addition, we also have the wave relationship governed by the port reflection at Port 1 and 2.

$$a_1 = \Gamma_s b_1 + a_0, \quad (\text{B.2a})$$

$$a_2 = \Gamma_{load} b_2. \quad (\text{B.2b})$$

Γ_s and Γ_{load} are the reflection coefficients of the source and the load, respectively. Substitution of (B.2) in (B.1) leads to

$$b_1 = S_{11}(\Gamma_s b_1 + a_0) + x_1, \quad (\text{B.3a})$$

$$b_2 = S_{21}(\Gamma_s b_1 + a_0) + x_2, . \quad (\text{B.3b})$$

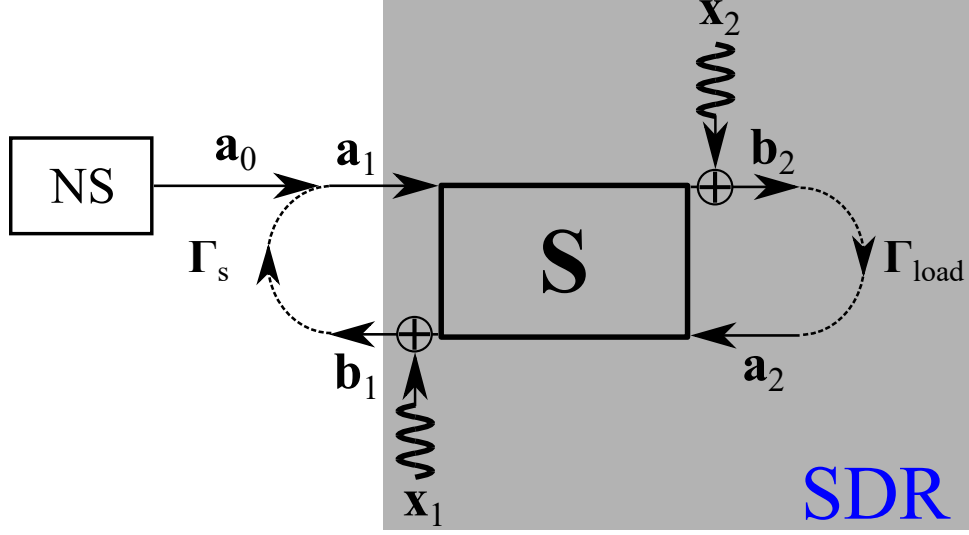


Figure B.1: The scattering parameter model of noise waves at the sensor input, used as the basis for the sensor calibration. The shaded region indicates the SDR receiver.

Solving b_1 from (B.3a) and feed the expression into (B.3b), we obtain

$$b_2 = \frac{S_{21}}{1 - S_{11}\Gamma_s} a_0 + \frac{S_{21}\Gamma_s}{1 - S_{11}\Gamma_s} x_1 + x_2. \quad (\text{B.4})$$

We then can derive the ensemble average of the wave products; i.e. $\langle b_2 b_2^* \rangle$ or $\langle |b_2|^2 \rangle$. Note that a_0 does NOT correlate with either x_1 or x_2 waves. However, correlation exists between x_1 and x_2 waves.

$$\langle |b_2|^2 \rangle = \frac{|S_{21}|^2}{|1 - S_{11}\Gamma_s|^2} \langle |a_0|^2 \rangle + \frac{|S_{21}\Gamma_s|^2}{|1 - S_{11}\Gamma_s|^2} \langle |x_1|^2 \rangle + \langle |x_2|^2 \rangle + 2\Re \left\{ \frac{S_{21}\Gamma_s}{1 - S_{11}\Gamma_s} \langle x_1 x_2^* \rangle \right\}. \quad (\text{B.5})$$

B.1.1 Available Power (Wave)

We also need to clarify one subtle yet important point. The ensemble average $\langle |a_0|^2 \rangle$ is not equivalent to the available noise power of the source, which is a physical quantity of general interest. Referring to Fig. B.2, the a and b waves are governed by

$$a = \Gamma_s b + a_0, \quad (\text{B.6a})$$

$$b = \Gamma_{load} a. \quad (\text{B.6b})$$

From the above equations, we can solve a as

$$a = \frac{1}{1 - \Gamma_s \Gamma_{load}} a_0. \quad (\text{B.7})$$

Furthermore, the power delivered to the load is simply

$$P_{del} = |a|^2 - |b|^2 = (1 - |\Gamma_{load}|^2) |a|^2 = \frac{1 - |\Gamma_{load}|^2}{|1 - \Gamma_s \Gamma_{load}|^2} |a_0|^2. \quad (\text{B.8})$$

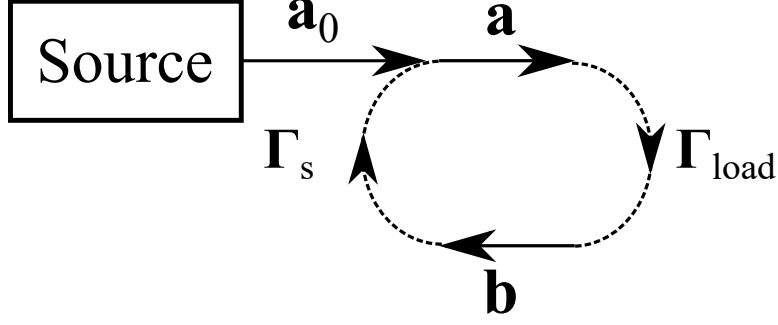


Figure B.2: Waves generated by a source being delivered to a load. Both source and load present reflections, which are non-idealities that must be accounted for through calibration.

The available power is the maximum power that can be delivered to a load. It occurs when the impedance of the load is conjugate matched to the impedance of the source.

$$P_{av} = P_{del}|_{\Gamma_{load}=\Gamma_s^*} = \frac{1}{1-|\Gamma_s|^2}|a_0|^2. \quad (\text{B.9})$$

As we can see, the available power is greater than $|a_0|^2$ except when the source is reflectionless. Here, we abuse terminology slightly, and introduce the available wave a_{av} .

$$a_{av} = \frac{1}{\sqrt{1-|\Gamma_s|^2}}a_0. \quad (\text{B.10})$$

B.2 Calibration with Known Input Signals

We solve a_0 in (B.10) and plug its expression in (B.5).

$$\begin{aligned} \langle |b_2|^2 \rangle &= \frac{|S_{21}|^2(1-|\Gamma_s|^2)}{|1-S_{11}\Gamma_s|^2} \langle |a_{av}|^2 \rangle + \frac{|S_{21}\Gamma_s|^2}{|1-S_{11}\Gamma_s|^2} \langle |x_1|^2 \rangle + \langle |x_2|^2 \rangle + 2\Re \left\{ \frac{S_{21}\Gamma_s}{1-S_{11}\Gamma_s} \langle x_1 x_2^* \rangle \right\} \\ &= \frac{|S_{21}|^2}{1-|S_{11}|^2} \frac{(1-|\Gamma_s|^2)(1-|S_{11}|^2)}{|1-S_{11}\Gamma_s|^2} \langle |a_{av}|^2 \rangle + \langle |x_2|^2 \rangle \\ &\quad + \frac{|S_{21}\Gamma_s|^2}{|1-S_{11}\Gamma_s|^2} \langle |x_1|^2 \rangle + 2\Re \left\{ \frac{S_{21}\Gamma_s}{1-S_{11}\Gamma_s} \langle x_1 x_2^* \rangle \right\} \\ &= GM \langle |a_{av}|^2 \rangle + \langle |x_2|^2 \rangle + \frac{|S_{21}\Gamma_s|^2}{|1-S_{11}\Gamma_s|^2} \langle |x_1|^2 \rangle + 2\Re \left\{ \frac{S_{21}\Gamma_s}{1-S_{11}\Gamma_s} \langle x_1 x_2^* \rangle \right\} \end{aligned} \quad (\text{B.11})$$

Here, the gain of the receiver G and the mismatch factor M at the interface follow the convention.

$$G = \frac{|S_{21}|^2}{1-|S_{11}|^2}, \quad (\text{B.12a})$$

$$M = \frac{(1-|\Gamma_s|^2)(1-|S_{11}|^2)}{|1-S_{11}\Gamma_s|^2}. \quad (\text{B.12b})$$

Note that S_{11} is approximately the reflection seen at the input of the SDR Γ_{in} , which is directly obtainable from measurements.

We reach the following more familiar radiometer equation for ordinary receiver ($x_1 \ll x_2$) or for a reflectionless noise input ($\Gamma_s = 0$).

$$P_{meas} = GM P_{in} + P_{eqn}, \quad (\text{B.13})$$

where input noise power $P_{in} = \langle |a_{av}|^2 \rangle$ and equivalent noise added by the SDR $P_{eqn} = \langle |x_2|^2 \rangle$.

Calibration of the SDR entails connecting two dissimilar devices (e.g. hot and cold) with known P_{in} 's, so that any other DUT measured by the SDR can be quantitatively determined. Three radiometer equations can be formulated below.

$$P_{meas}^{\text{hot}} = GM^{\text{hot}} P_{in}^{\text{hot}} + P_{eqn}, \quad (\text{B.14a})$$

$$P_{meas}^{\text{cold}} = GM^{\text{cold}} P_{in}^{\text{cold}} + P_{eqn}, \quad (\text{B.14b})$$

$$P_{meas}^{\text{DUT}} = GM^{\text{DUT}} P_{in}^{\text{DUT}} + P_{eqn}, \quad (\text{B.14c})$$

The two unknowns associated with the SDR can be obtained as follows.

$$G = \frac{P_{meas}^{\text{hot}} - P_{meas}^{\text{cold}}}{M^{\text{hot}} P_{in}^{\text{hot}} - M^{\text{cold}} P_{in}^{\text{cold}}}, \quad (\text{B.15a})$$

$$P_{eqn} = \frac{M^{\text{hot}} P_{in}^{\text{hot}} P_{meas}^{\text{cold}} - M^{\text{cold}} P_{in}^{\text{cold}} P_{meas}^{\text{hot}}}{M^{\text{hot}} P_{in}^{\text{hot}} - M^{\text{cold}} P_{in}^{\text{cold}}}, \quad (\text{B.15b})$$

With G and P_{eqn} at our disposal, the unknown DUT input power can be solved in straightforward manner from (B.14c).

B.3 Uncertainty

B.3.1 Uncertainty Due to S-parameter Measurements

The mismatch factors in (B.12b) contains a number of scattering parameters that is typically made on a vector network analyzer (VNA). Like other scientific instruments, a VNA needs to be calibrated to account for systematic errors. The calibration of the VNA involves a number of man-made standards. These standards possess specified tolerances of mechanical and electric characteristics, which in turn determine the calibration models.

The mechanical and electric tolerances are expressed in uncertainties, which propagate through the measurement path to the end parameters. To systematically track the uncertainty propagation, we rely on the NIST microwave uncertainty framework. A number of post-processor modules were developed to represent measurement steps. Uncertainties of intermediate parameters along with the correlations among them are preserved in this systematic approach. For example, uncertainties in M^{hot} and M^{cold} in (B.15) are correlated to some extent since both of them are derived from the S-parameters measured on the same VNA. Although the correlation may not be significant to impact the uncertainty of the end parameter, this rigorous approach eliminates all the guesswork and warrants a valid result.

B.3.2 Uncertainty Due to Unknown x_1

Evidently, the approximation made in (B.13) represents the ideal case. For metrology purpose, we need to take into account the residual terms in (B.11) for measurements of hot, cold and DUT devices. They are

$$\delta P^{\text{hot}} = \frac{|S_{21}\Gamma_s^{\text{hot}}|^2}{|1 - S_{11}\Gamma_s^{\text{hot}}|^2} \langle |x_1|^2 \rangle + 2\Re \left\{ \frac{S_{21}\Gamma_s^{\text{hot}}}{1 - S_{11}\Gamma_s^{\text{hot}}} \langle x_1 x_2^* \rangle \right\}, \quad (\text{B.16a})$$

$$\delta P^{\text{cold}} = \frac{|S_{21}\Gamma_s^{\text{cold}}|^2}{|1 - S_{11}\Gamma_s^{\text{cold}}|^2} \langle |x_1|^2 \rangle + 2\Re \left\{ \frac{S_{21}\Gamma_s^{\text{cold}}}{1 - S_{11}\Gamma_s^{\text{cold}}} \langle x_1 x_2^* \rangle \right\}, \quad (\text{B.16b})$$

$$\delta P^{\text{DUT}} = \frac{|S_{21}\Gamma_s^{\text{DUT}}|^2}{|1 - S_{11}\Gamma_s^{\text{DUT}}|^2} \langle |x_1|^2 \rangle + 2\Re \left\{ \frac{S_{21}\Gamma_s^{\text{DUT}}}{1 - S_{11}\Gamma_s^{\text{DUT}}} \langle x_1 x_2^* \rangle \right\}, \quad (\text{B.16c})$$

From our experience, the intrinsic noise power emanating from the input ($\langle |x_1|^2 \rangle$) is smaller than the intrinsic noise power at the output divided by the gain ($\langle |x_2|^2 \rangle / G$). This knowledge allows us to model the x_1 and x_2 with three random variables; α , θ_1 and θ_2 .

$$x_1 = \alpha e^{j\theta_1}, \quad (\text{B.17a})$$

$$x_2 = \sqrt{P_{eqn}} e^{j\theta_2}, \quad (\text{B.17b})$$

where α is uniformly distributed in the range $[0, \sqrt{P_{eqn}/G}]$ and both θ_1 and θ_2 are uniformly distributed in the range $[-\pi, \pi]$.

This manipulation allows us to update (B.16) as follows.

$$\delta P^{\text{hot}} = \frac{|\Gamma_s^{\text{hot}}|^2(1 - |S_{11}|^2)}{|1 - S_{11}\Gamma_s^{\text{hot}}|^2} G\alpha^2 + 2\Re \left\{ \frac{\sqrt{G(1 - |S_{11}|^2)}\Gamma_s^{\text{hot}}}{1 - S_{11}\Gamma_s^{\text{hot}}} \alpha e^{j(\theta_1 + \text{Arg}\{S_{21}\} - \theta_2)} \right\}, \quad (\text{B.18a})$$

$$\delta P^{\text{cold}} = \frac{|\Gamma_s^{\text{cold}}|^2(1 - |S_{11}|^2)}{|1 - S_{11}\Gamma_s^{\text{cold}}|^2} G\alpha^2 + 2\Re \left\{ \frac{\sqrt{G(1 - |S_{11}|^2)}\Gamma_s^{\text{cold}}}{1 - S_{11}\Gamma_s^{\text{cold}}} \alpha e^{j(\theta_1 + \text{Arg}\{S_{21}\} - \theta_2)} \right\}, \quad (\text{B.18b})$$

$$\delta P^{\text{DUT}} = \frac{|\Gamma_s^{\text{DUT}}|^2(1 - |S_{11}|^2)}{|1 - S_{11}\Gamma_s^{\text{DUT}}|^2} G\alpha^2 + 2\Re \left\{ \frac{\sqrt{G(1 - |S_{11}|^2)}\Gamma_s^{\text{DUT}}}{1 - S_{11}\Gamma_s^{\text{DUT}}} \alpha e^{j(\theta_1 + \text{Arg}\{S_{21}\} - \theta_2)} \right\}, \quad (\text{B.18c})$$

Here S_{21} is also modeled as random variable with a deterministic magnitude $\sqrt{G(1 - |S_{11}|^2)}$. Its phase $\text{Arg}\{S_{21}\}$ is uniformly distributed in the range of $[-\pi, \pi]$. Note the linear superposition of the uniformly distributed phase remains uniformly distributed. As such, we can reduce the sum $\theta_1 + \text{Arg}\{S_{21}\} - \theta_2$ to one random angle θ . In the end, (B.18) can be simplified as

$$\delta P^{\text{hot}} = \frac{|\Gamma_s^{\text{hot}}|^2(1 - |S_{11}|^2)}{|1 - S_{11}\Gamma_s^{\text{hot}}|^2} G\alpha^2 + 2\Re \left\{ \frac{\Gamma_s^{\text{hot}} e^{j\theta}}{1 - S_{11}\Gamma_s^{\text{hot}}} \right\} \alpha \sqrt{G(1 - |S_{11}|^2)}, \quad (\text{B.19a})$$

$$\delta P^{\text{cold}} = \frac{|\Gamma_s^{\text{cold}}|^2(1 - |S_{11}|^2)}{|1 - S_{11}\Gamma_s^{\text{cold}}|^2} G\alpha^2 + 2\Re \left\{ \frac{\Gamma_s^{\text{cold}} e^{j\theta}}{1 - S_{11}\Gamma_s^{\text{cold}}} \right\} \alpha \sqrt{G(1 - |S_{11}|^2)}, \quad (\text{B.19b})$$

$$\delta P^{\text{DUT}} = \frac{|\Gamma_s^{\text{DUT}}|^2(1 - |S_{11}|^2)}{|1 - S_{11}\Gamma_s^{\text{DUT}}|^2} G\alpha^2 + 2\Re \left\{ \frac{\Gamma_s^{\text{DUT}} e^{j\theta}}{1 - S_{11}\Gamma_s^{\text{DUT}}} \right\} \alpha \sqrt{G(1 - |S_{11}|^2)}. \quad (\text{B.19c})$$

Using the Monte Carlo simulation of α and θ , we can generate a large number of samples $\check{P}^{\text{hot}}$, $\check{P}^{\text{cold}}$ and $\check{P}^{\text{DUT}}$. As a consequence, statistical analysis can be conducted on simulated samples calculated from (B.14c).

B.3.3 Uncertainty Due to Power Measurements

The two probing signals generated by an arbitrary waveform generator were band-limited noise signal. They were measured by a commercial power meter in order to calculate values P_{in}^{hot} and P_{in}^{cold} for calibration. Note that both of the quantities are available power. However, the direct readings of the power sensor are usually the net power delivered to it.

There are two related calibration coefficients associated with a power sensor. One is the effective efficiency and the other is the calibration factor. They differ by their reference; whether it's referred to the delivered power (P_{del}) to the sensor or it's referred to the incident power ($|a_0|^2$) to the sensor. Since we use the mismatch factor to relate the delivered power with the available power, the effective efficiency is directly applicable in this work. The effective efficiency is simply a ratio between the sensor substituted power (P_{sub}) and the delivered power (P_{del}).

$$\eta = \frac{P_{sub}}{P_{del}} \quad (\text{B.20})$$

The frequency-dependent effective efficiency and its uncertainty of the power sensor can be obtained from the manufacturer.

Aside from the aforementioned uncertainty sources, the sensor inhomogeneity may also warrant consideration. During this campaign, a number of SDRs were deployed at various teleworking sites, labs and offices. We have limited time and resources to calibrate all the sensors individually.

Appendix C

Sample Data Verification in the 2695 MHz Passive Service Band

Data collected in the passive services allocation at 2695 MHz helps to validate field data from the deployed sensors.

C.1 Spurious Readings

To illustrate how this is done, consider for comparison the ideal behavior of the sensor in a quiet electromagnetic environment. The band power in this case follows a distribution in the Gamma family. Both its value and derivative decrease monotonically with input power level.

When the distribution of power readings in the field does not match this ideal, then either interference is present in the band, or the sensor is producing spurious data. While we can't be sure which of these is true based on data alone, we can interpret the spurious part of the distribution as an upper bound on spurious power reading performance of the sensor.

With this in mind, consider the survival functions observed at 2695 MHz, beginning with the left side of Figure C.1. This shows the empirical number of power readings aggregated as the sum of all readings across all sites. The rate of decrease has a knee near -77 dBm/4 MHz. This is non-monotonic in the slope of survival function (SF) with respect to power, indicating anomaly relative to thermal noise. As a result, we assign an upper limit to the aggregate rate of spurious occupancy detection across all sensors as power increases from the threshold knee. For example, the bound at -70 dBm/4 MHz is about 10^{-6} , decreasing to 10^{-8} at -55 dBm/4 MHz.

The SF of power readings in the quiet band is split by site in Figure C.1. They are shown here in absolute numbers rather than by fraction in order to emphasize their weight in the aggregate plot on the left. The dramatic majority of spurious readings originated from site 1, and the reason for this is not clear. At the other extreme, 7 sensors exhibited no detectable spurious readings across up to 8 orders of magnitude.

Figures C.2 and C.3 give two views of the joint distributions between time and power. Spurious readings (from site 1) were concentrated during daylight hours during Sept. to Nov. in 2020.

In future work, this type of diagnostic approach could be an effective way to identify problems in deployed sensors. This was not undertaken in the work presented here, because data analysis was mostly performed after these interference events had occurred.

C.2 Time Stability of Power Readings

The time average of readings offer some insights into the time stability of the sensor hardware. This is important because environmental changes (including temperature and sunlight exposure) have impacts on the RF performance of the hardware.

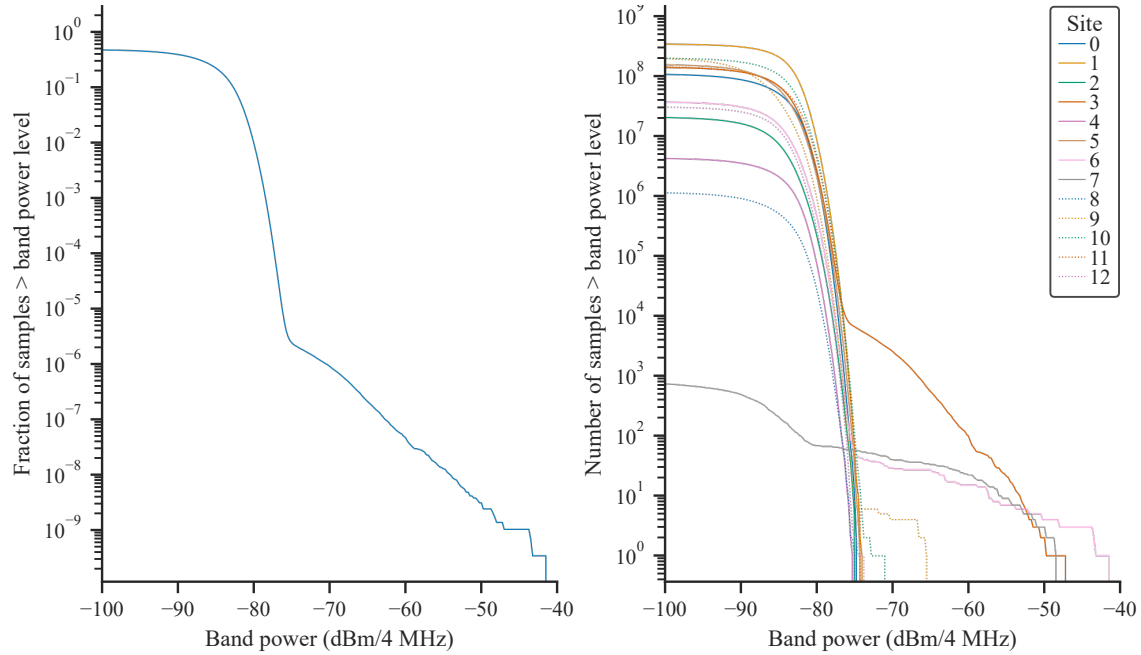


Figure C.1: Empirical survival functions of band power in the passive services band at 2695 MHz, both across all sites (left) and categorized by site (right). To illustrate rare events, plots average of the SF from each site (left) are shown on a logarithmic vertical axis. The SF of all samples received, shown with linear scale (right), emphasizes the most frequent power levels. Dotted lines indicate expected distortion of the power level by 1 dB due to noise or compression inside the sensor.

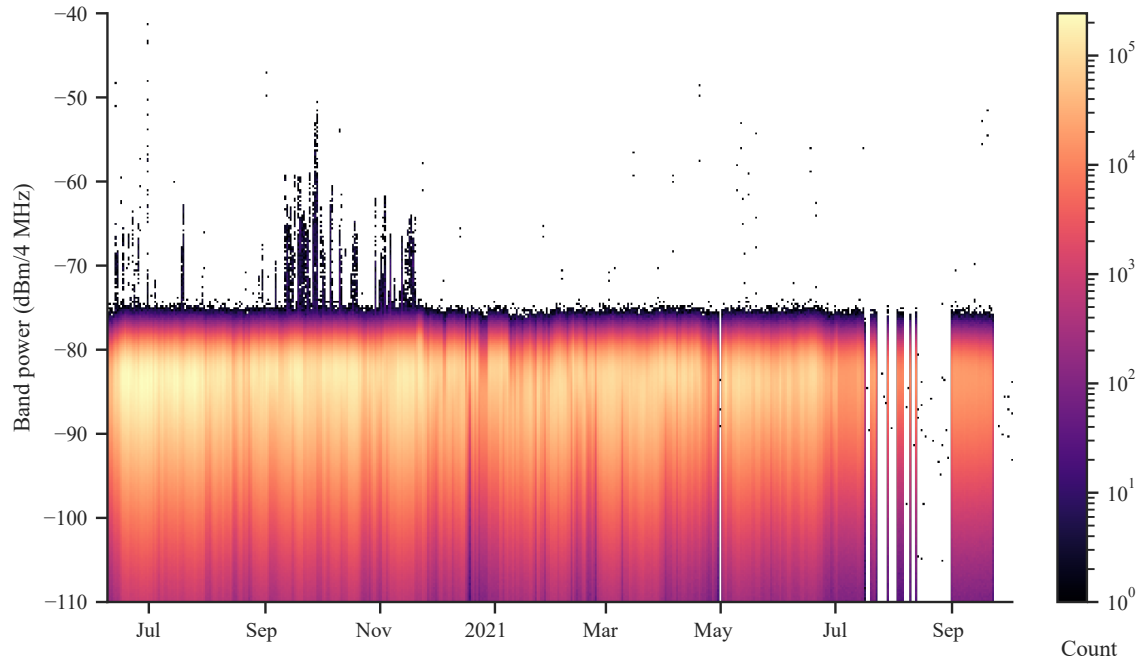


Figure C.2: Histogram heat map of all band power samples in the passive services band at 2695 MHz, summed across all sites on each calendar day. Spurious high readings (around 1 part in 10^6) were acquired mostly in September through November of 2020.

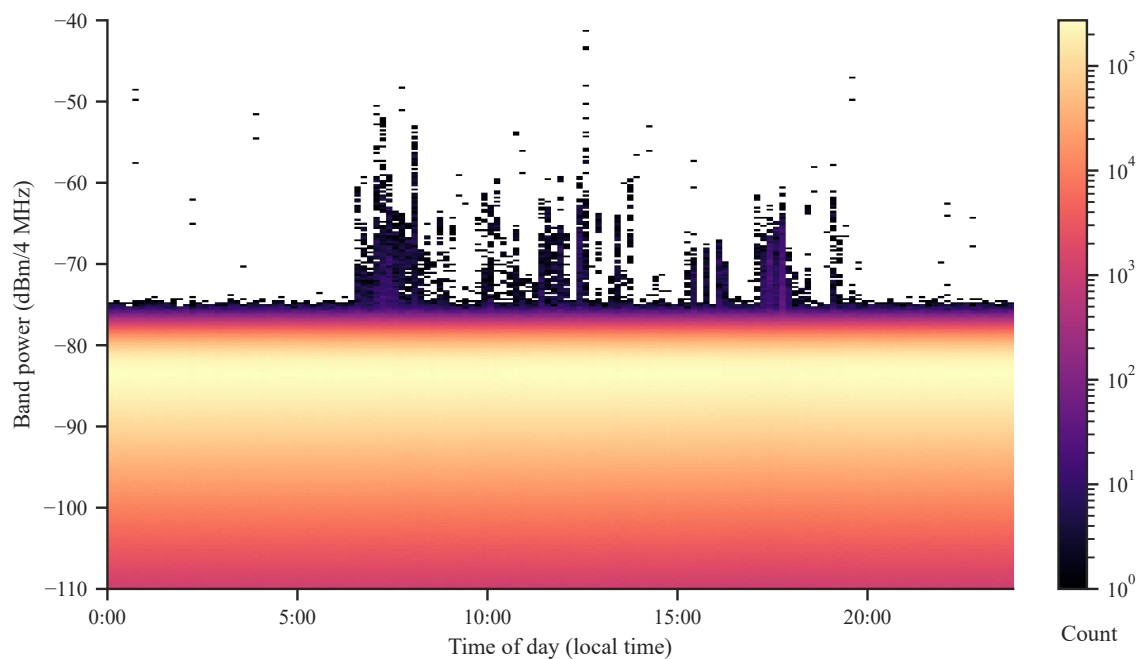


Figure C.3: Histogram heat map of all band power samples in the passive services band at 2695 MHz, summed across all sites by time of day with bin size 10 minutes. Spurious high power samples (around 1 part in 10^6) were acquired mostly during daylight and early evening hours.

The data are plotted in Figure C.4. In most cases, the time-average trend at each site was stable to within approximately 1 dB.

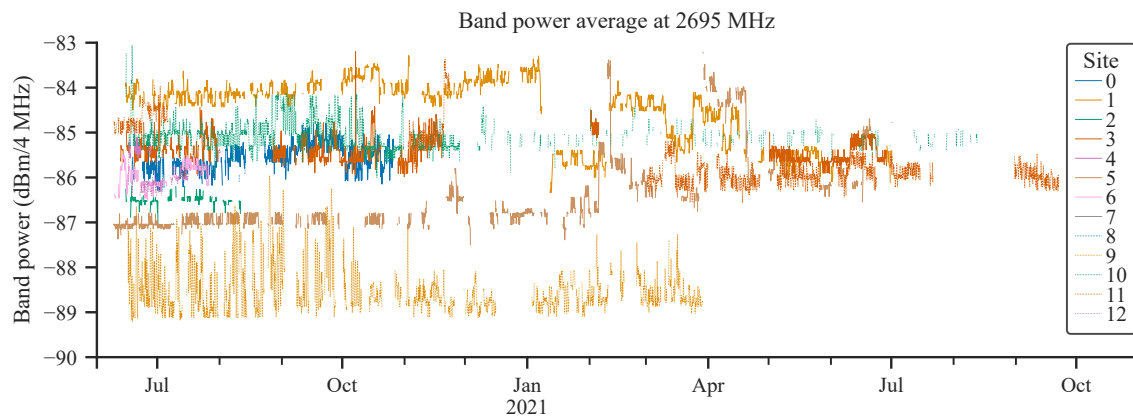


Figure C.4: Long-term stability in band power sensed at 2695 MHz. To improve clarity on this time scale, averaging was applied to reduce variance. The mean was computed on the center 2 quartiles of each dwell window, and the traces are a 1 hour moving mean of this dwell average. The result here encapsulates the full data set, categorized by site.

Appendix D

Sample Power Distributions by Site

Residential Site 0

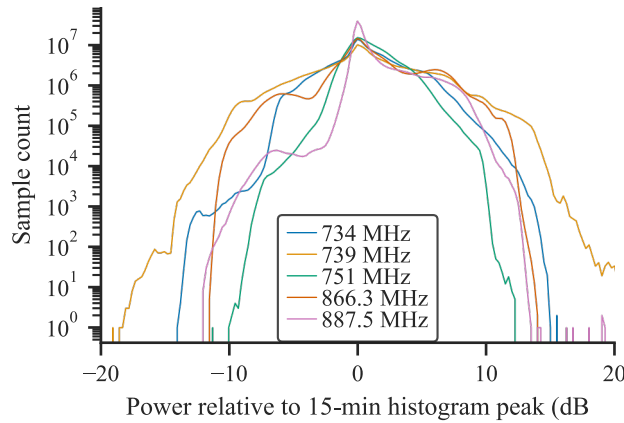


Figure D.1: Histogram of band power samples in downlink channels in LTE downlink bands relative to the site noise and interference level at site 0, as gauged by the peak histogram level in each dwell window.

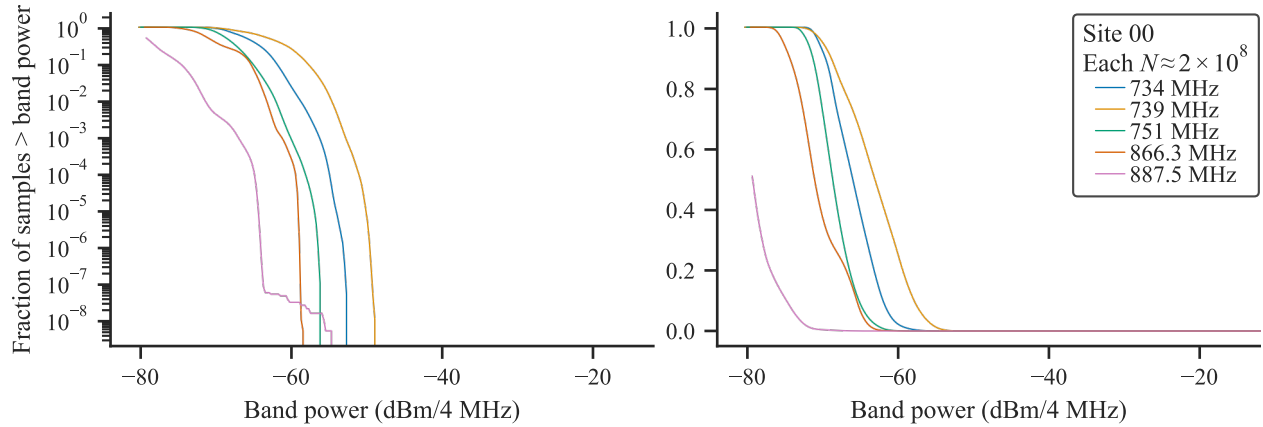


Figure D.2: Plots of empirical survival functions offband power in downlink channels in LTE downlink bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

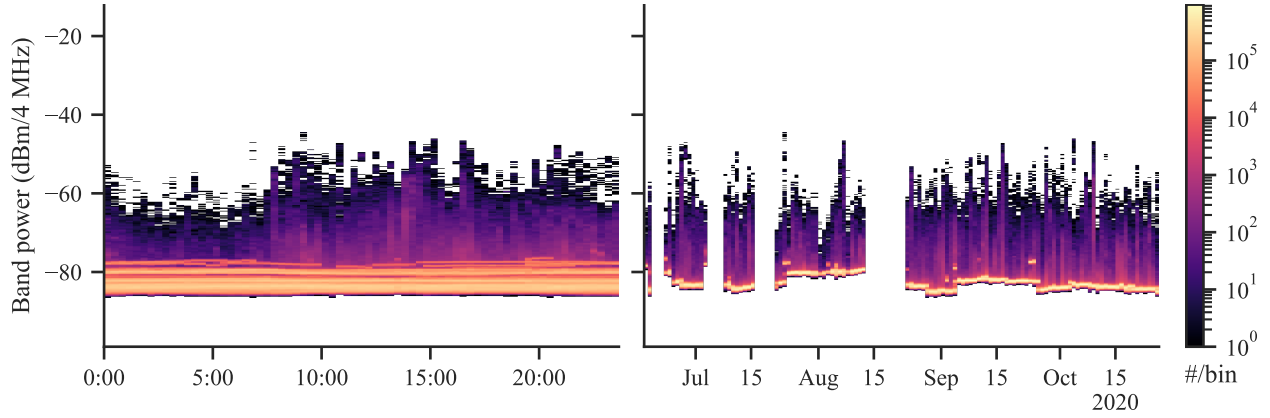


Figure D.3: Histogram heat maps of band power at 821.3 MHz from site 0 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

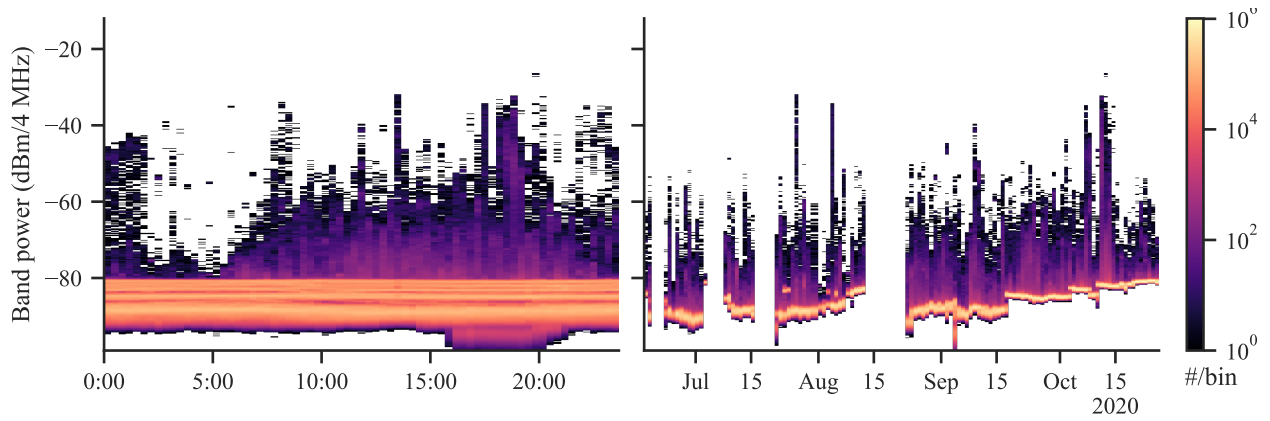


Figure D.4: Histogram heat maps of band power at 782.0 MHz from site 0 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

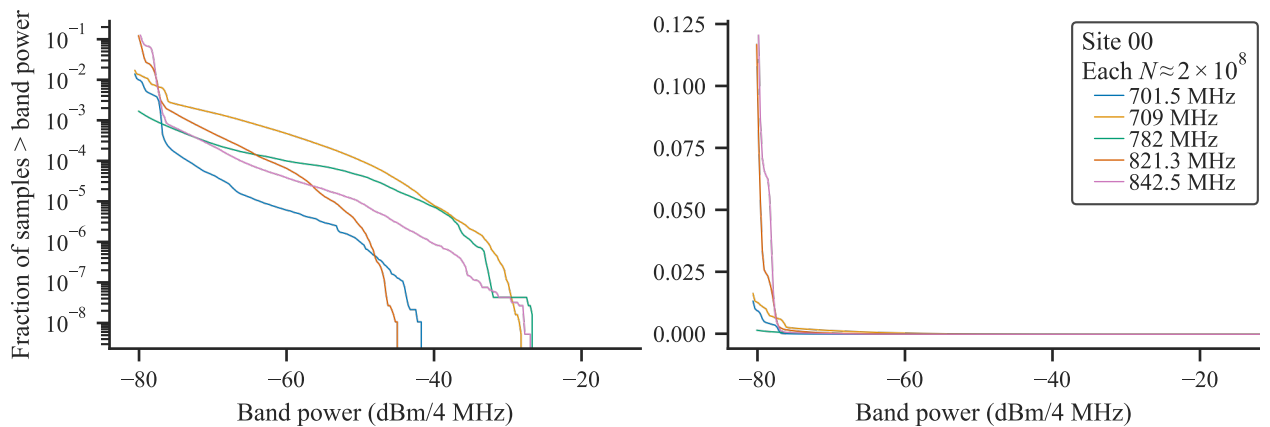


Figure D.5: Plots of empirical survival functions of band power in uplink channels in LTE bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

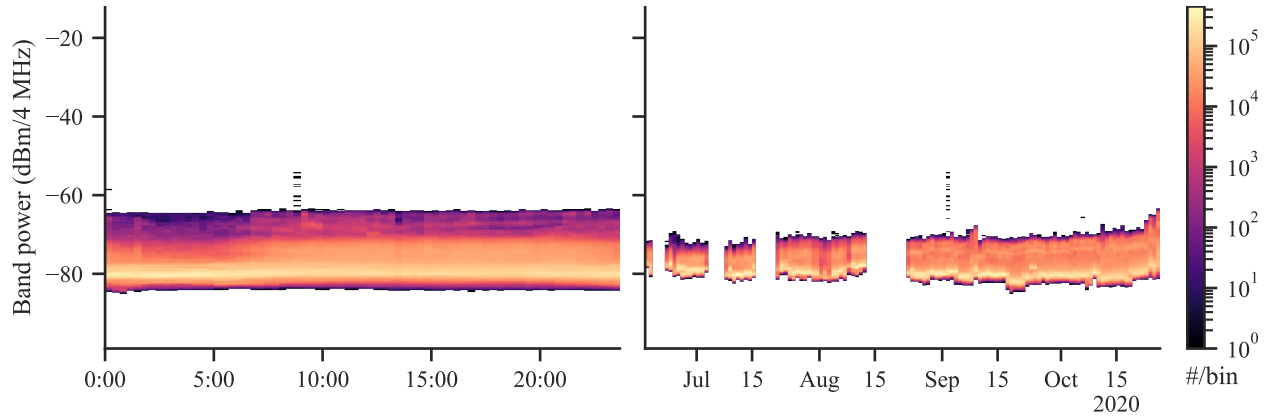


Figure D.6: Histogram heat maps of band power at 887.5 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

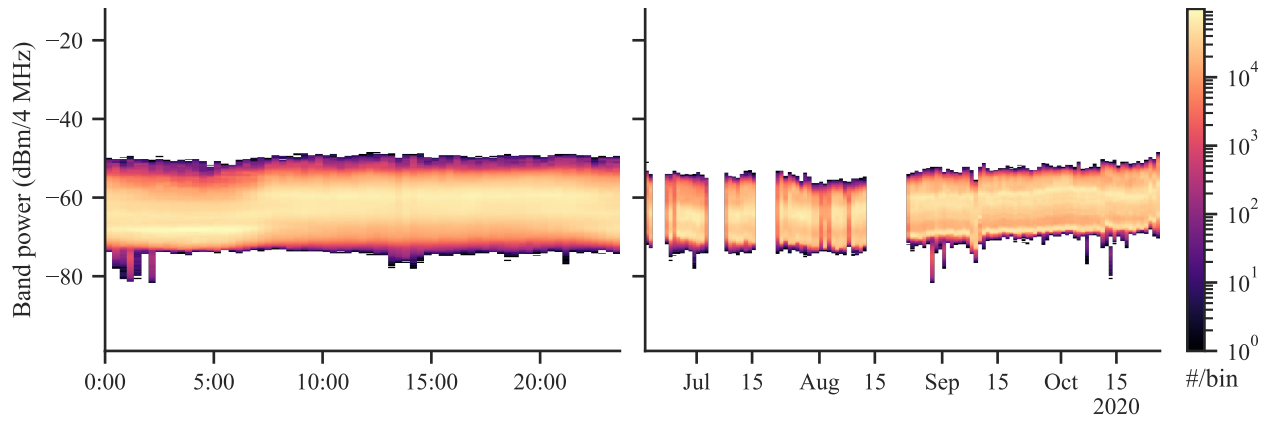


Figure D.7: Histogram heat maps of band power at 739.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

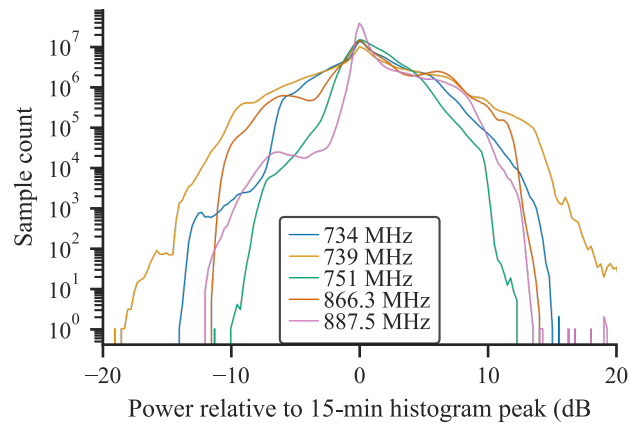


Figure D.8: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 0, as gauged by the peak histogram level in each dwell window.

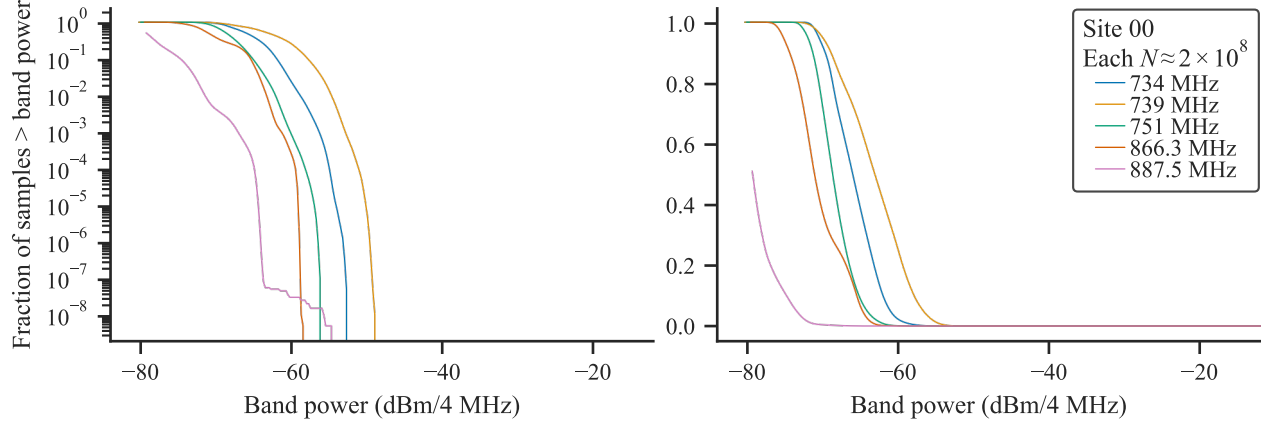


Figure D.9: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

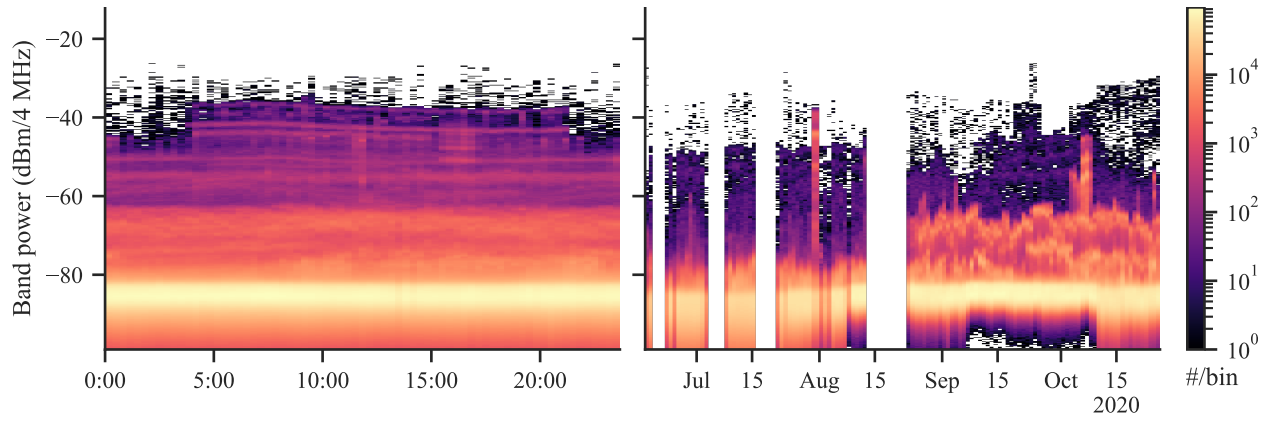


Figure D.10: Histogram heat maps of band power at 2412.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

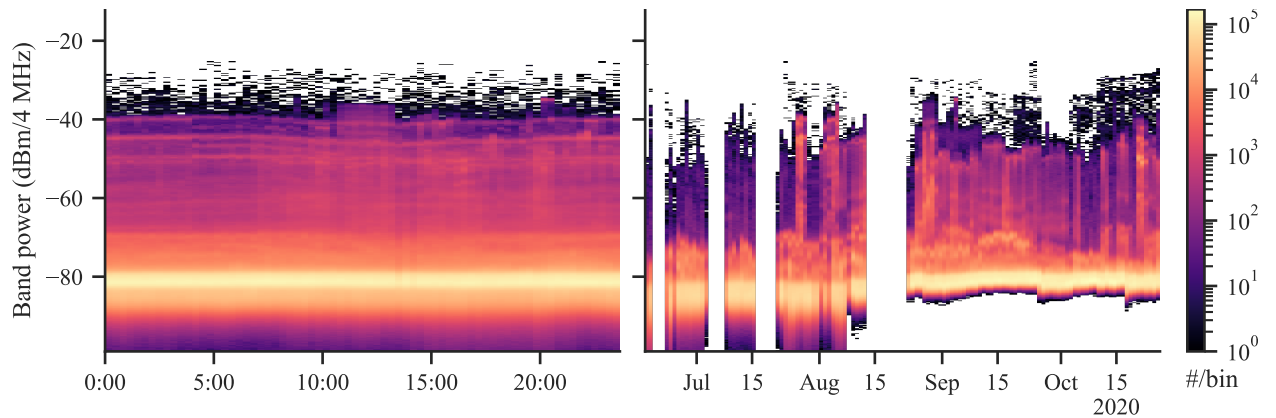


Figure D.11: Histogram heat maps of band power at 2462.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

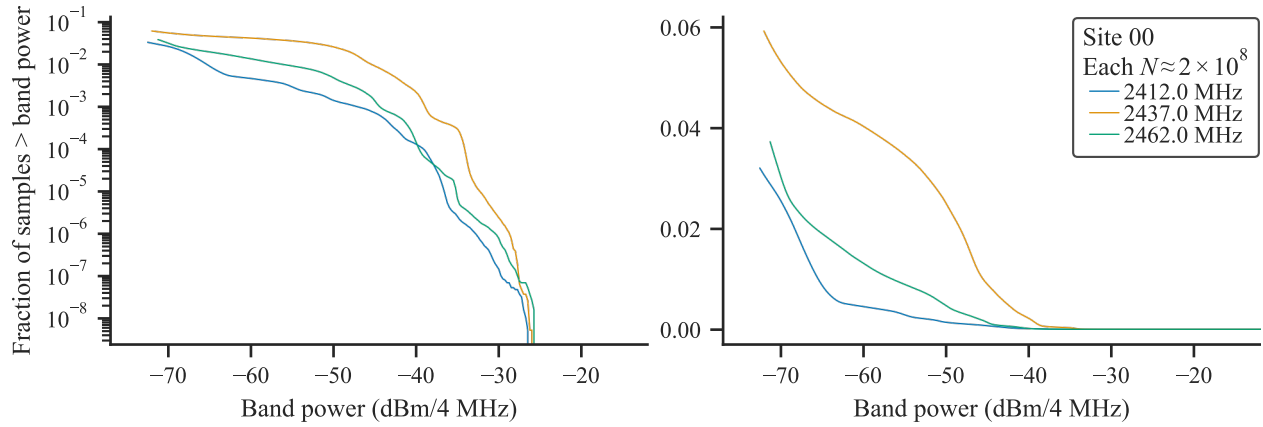


Figure D.12: Plots of empirical survival functions offband power in ISM bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

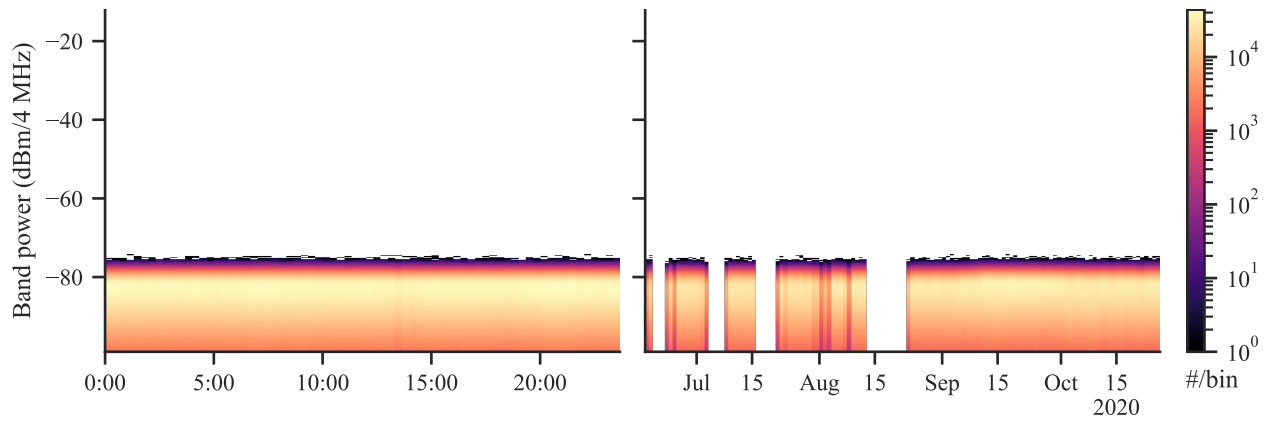


Figure D.13: Histogram heat maps of band power at 2695.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

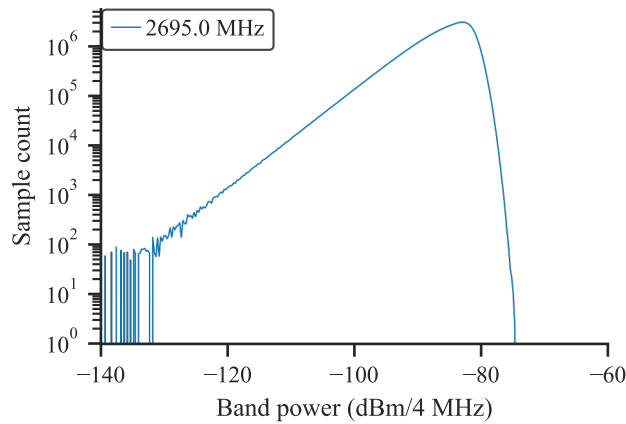


Figure D.14: Histogram of band power measured in the 2695 MHz passive service band at site 0.

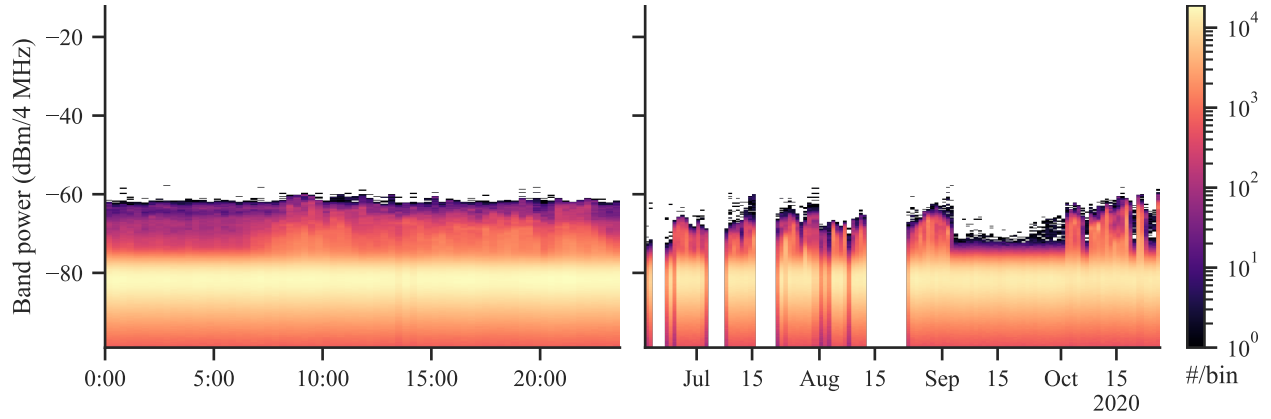


Figure D.15: Histogram heat maps of band power at 5210.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

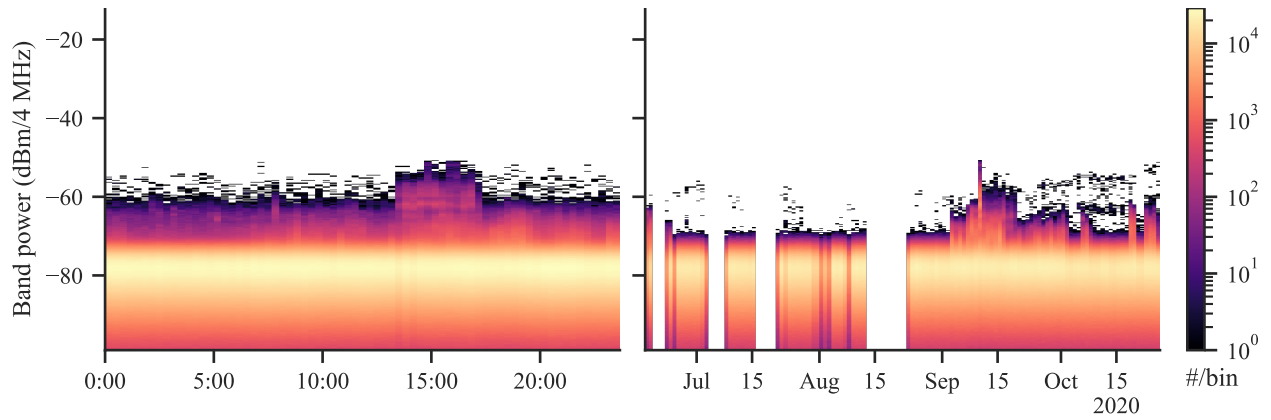


Figure D.16: Histogram heat maps of band power at 5775.0 MHz from site 0 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

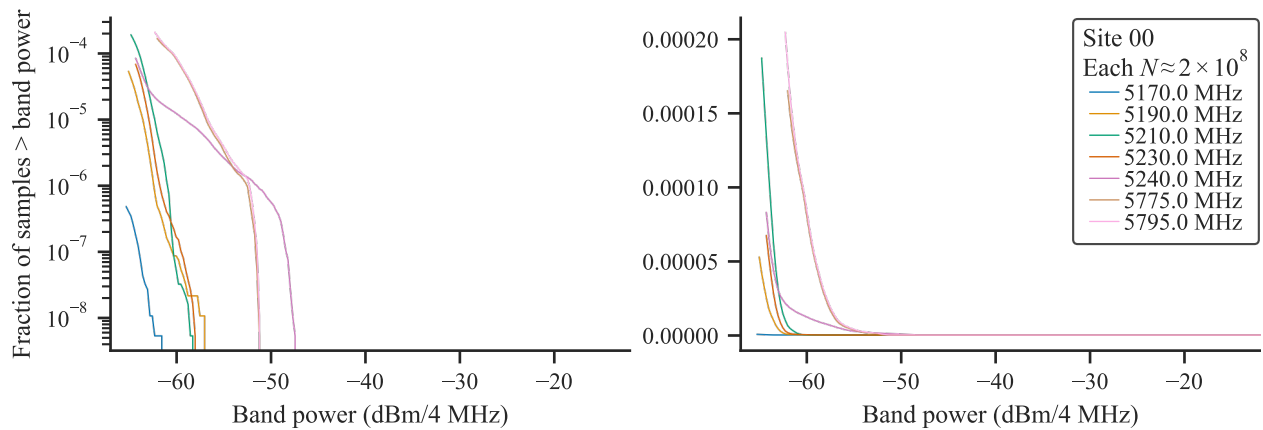


Figure D.17: Plots of empirical survival functions of band power in U-NII bands at site 0, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

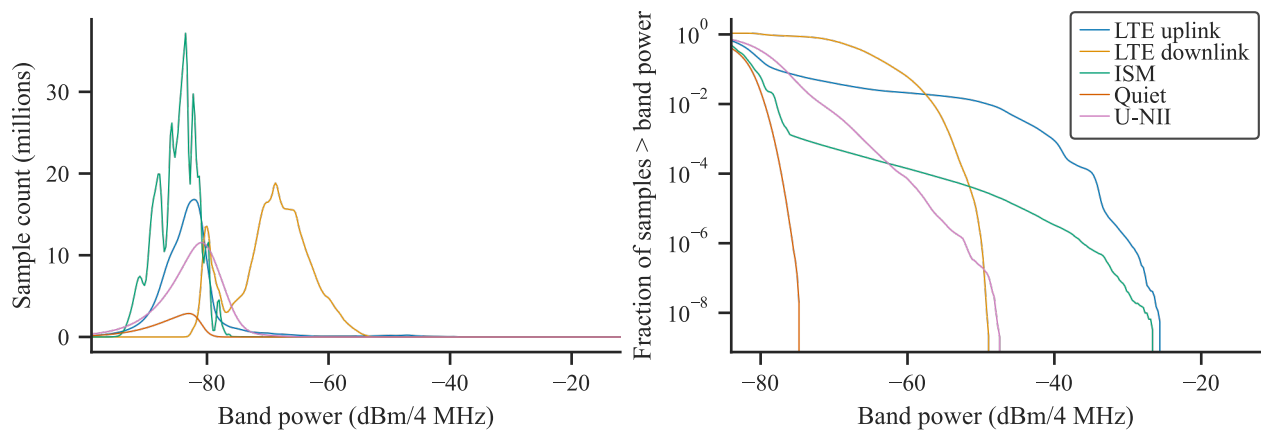


Figure D.18: Histograms (left) and empirical survival functions (right) of all samples received in site 0 in each type of band under test.

Residential Site 1

These data are presented in the case study of Section 4.3.

Residential Site 2

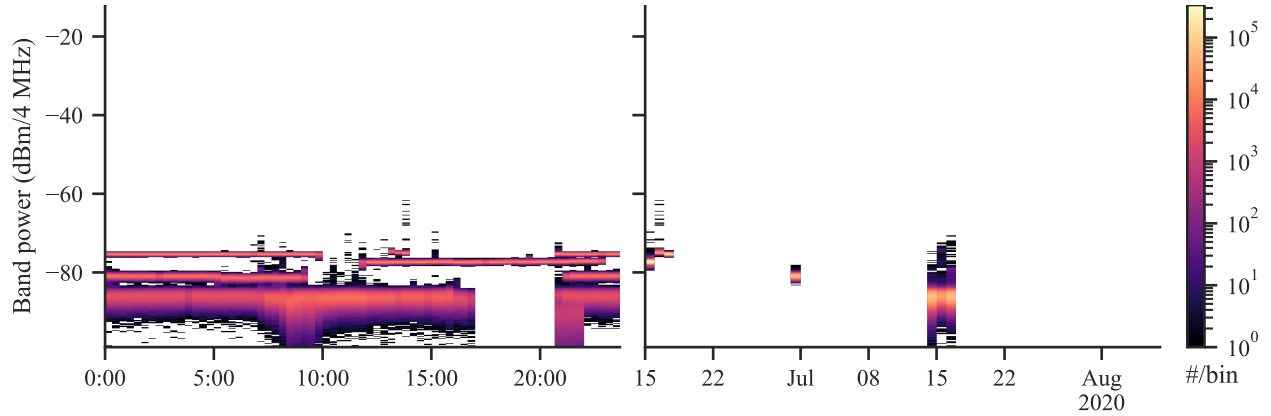


Figure D.19: Histogram heat maps of band power at 842.5 MHz from site 2 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

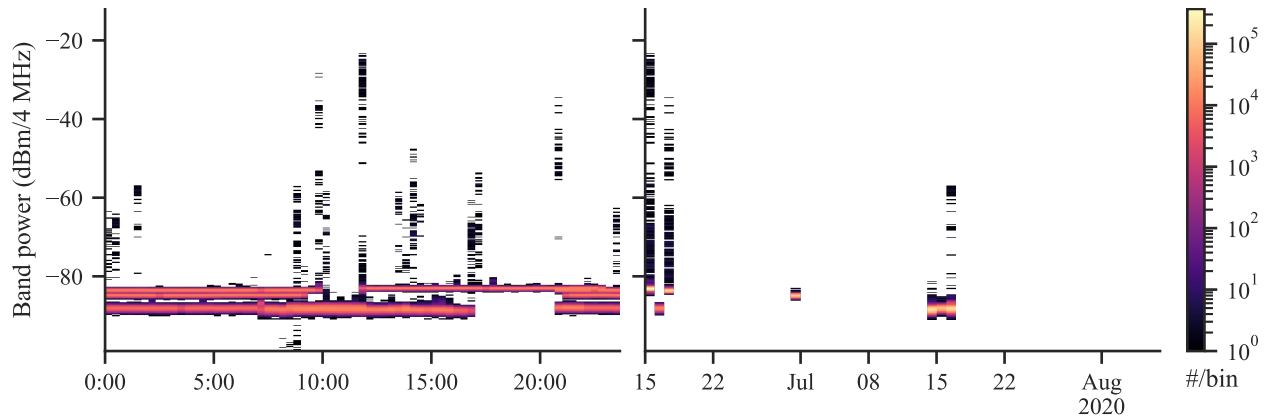


Figure D.20: Histogram heat maps of band power at 701.5 MHz from site 2 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

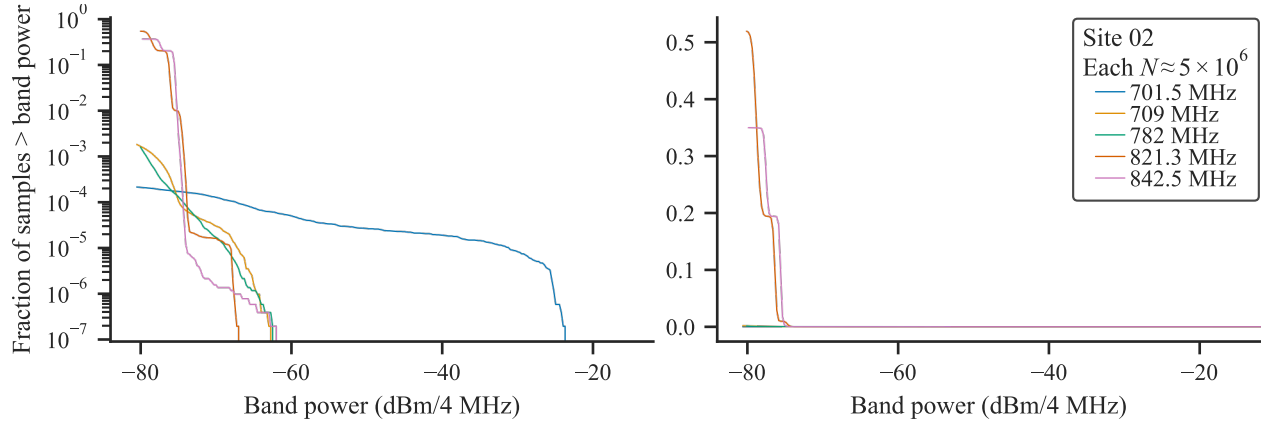


Figure D.21: Plots of empirical survival functions offband power in uplink channels in LTE bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

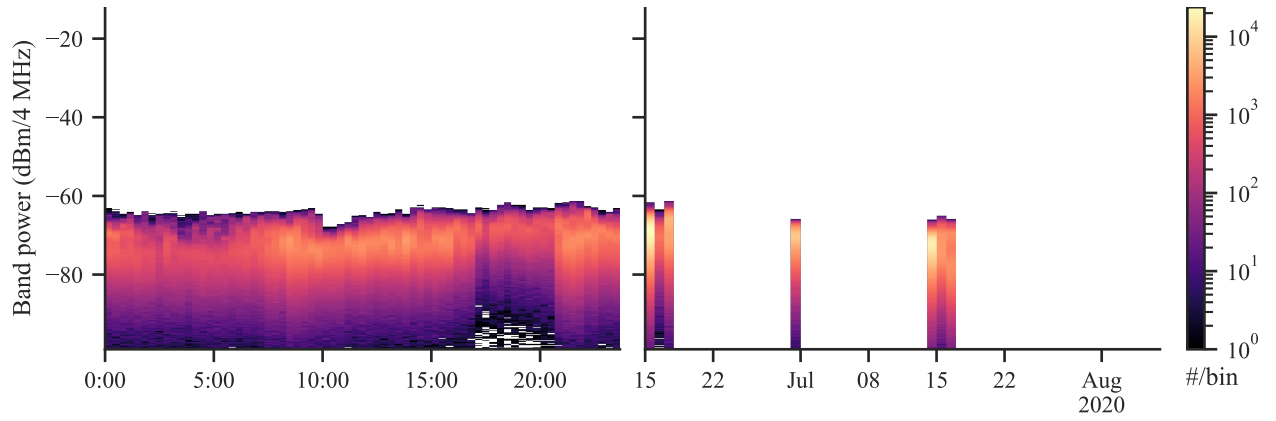


Figure D.22: Histogram heat maps of band power at 739.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

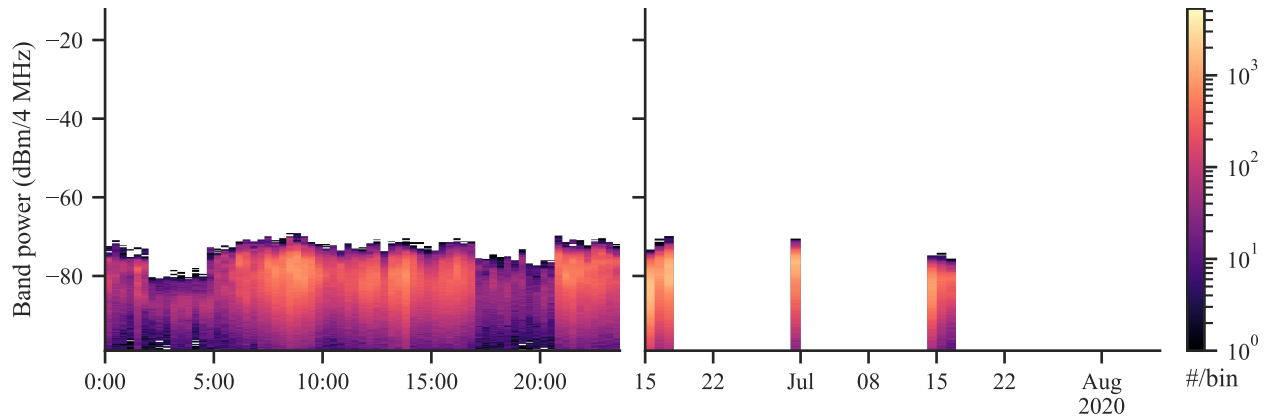


Figure D.23: Histogram heat maps of band power at 887.5 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

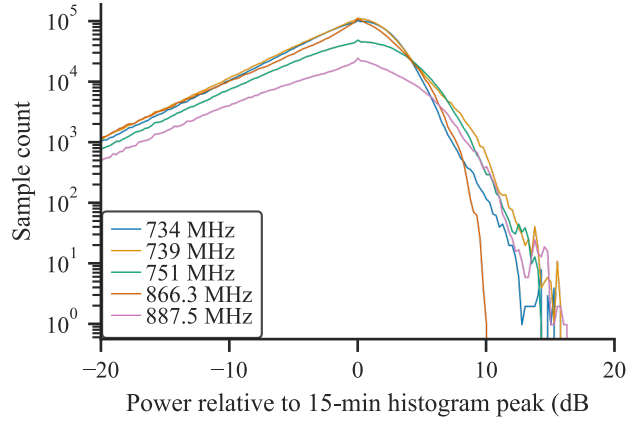


Figure D.24: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 2, as gauged by the peak histogram level in each dwell window.

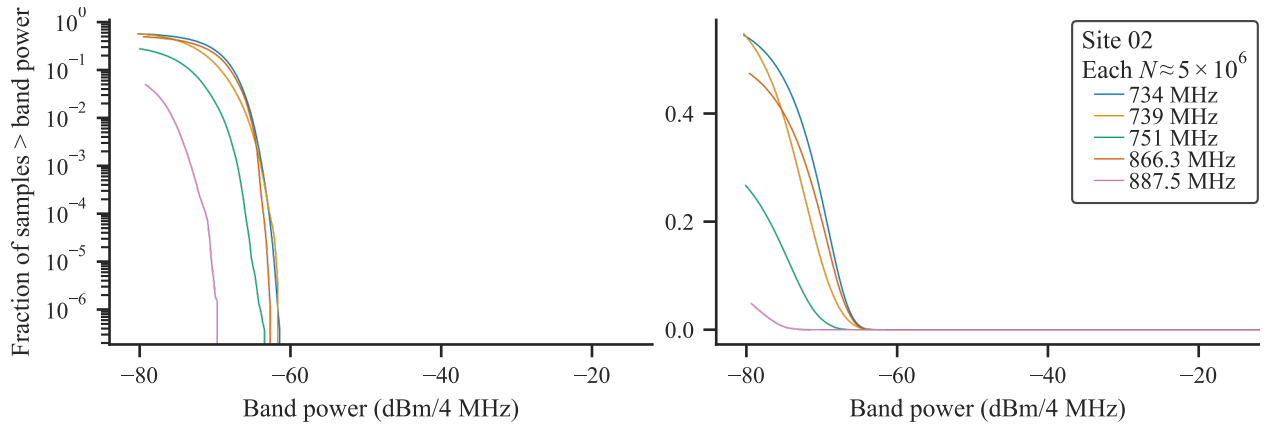


Figure D.25: Plots of empirical survival functions ofband power in downlink channels in LTE bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

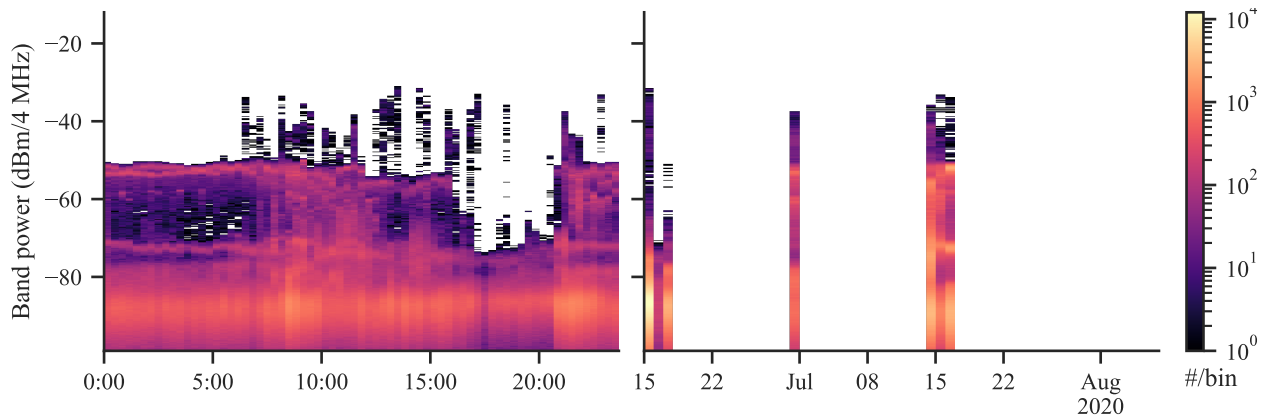


Figure D.26: Histogram heat maps of band power at 2462.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

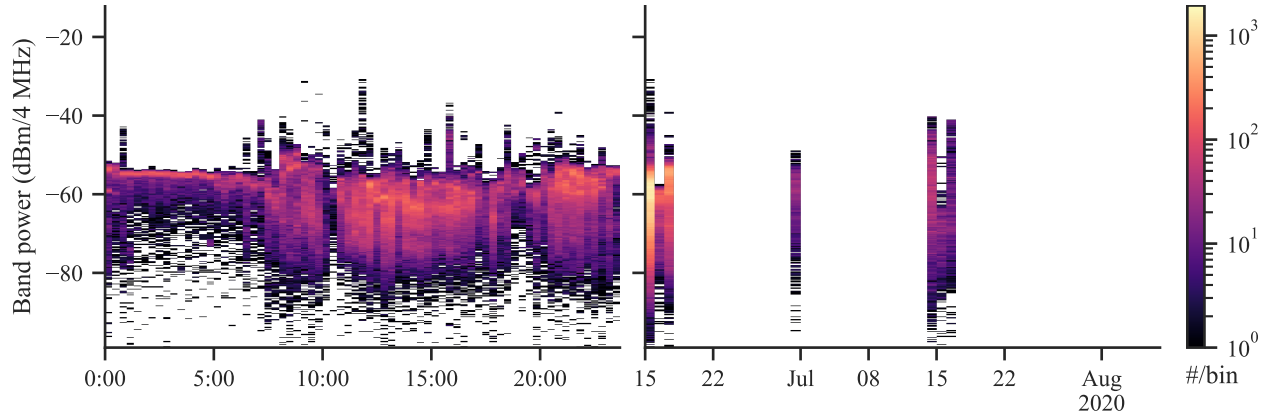


Figure D.27: Histogram heat maps of band power at 2437.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

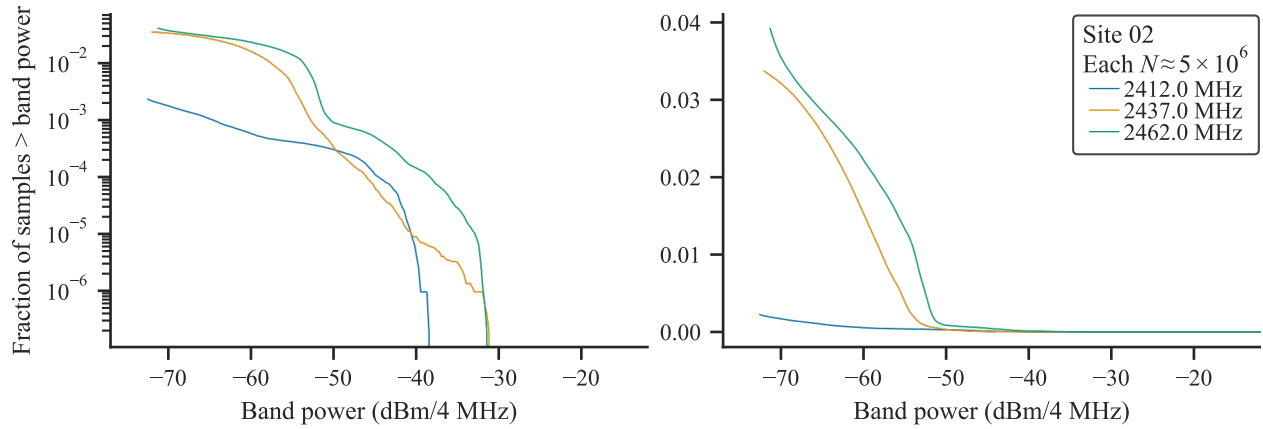


Figure D.28: Plots of empirical survival functions of band power in ISM bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

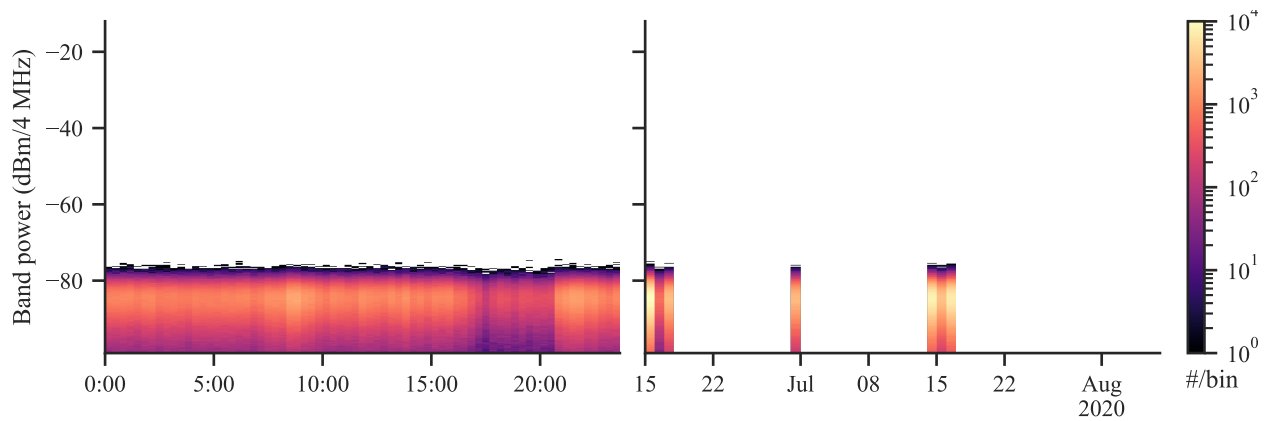


Figure D.29: Histogram heat maps of band power at 2695.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

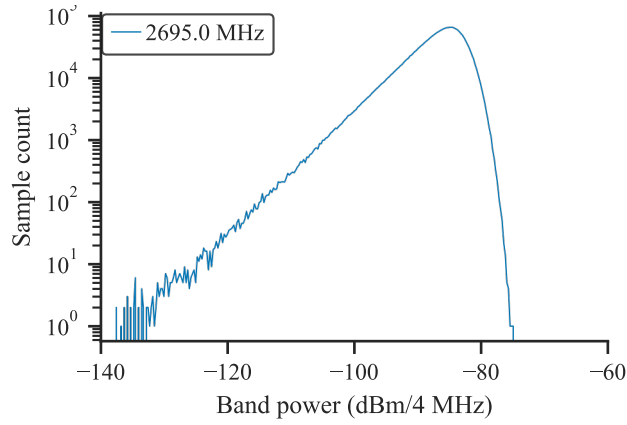


Figure D.30: Histogram of band power measured in the 2695 MHz passive service band at site 2.

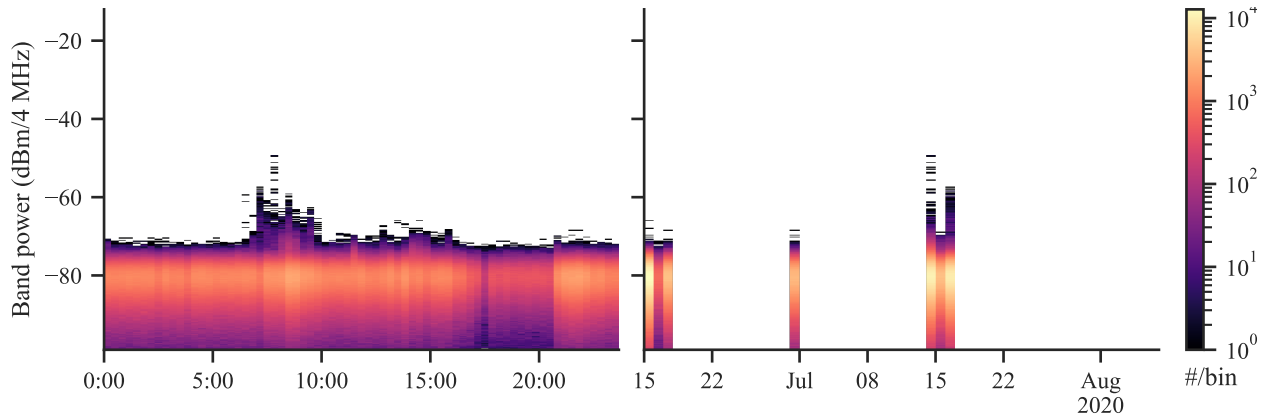


Figure D.31: Histogram heat maps of band power at 5240.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

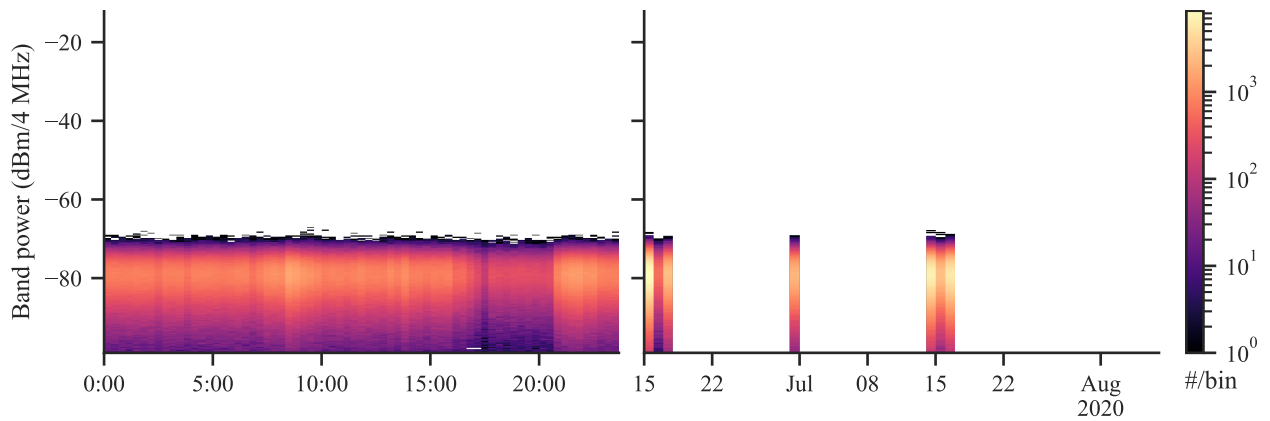


Figure D.32: Histogram heat maps of band power at 5795.0 MHz from site 2 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

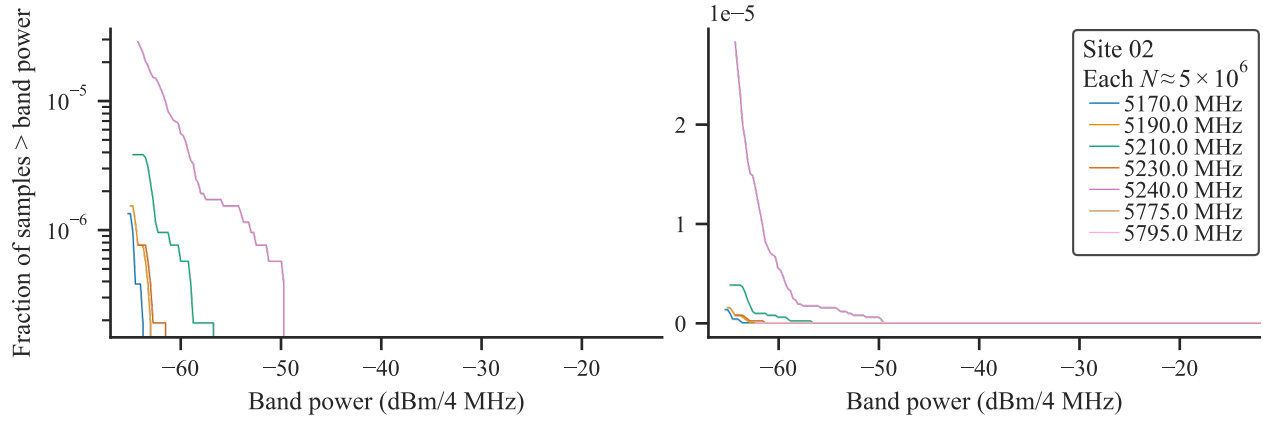


Figure D.33: Plots of empirical survival functions of band power in U-NII bands at site 2, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

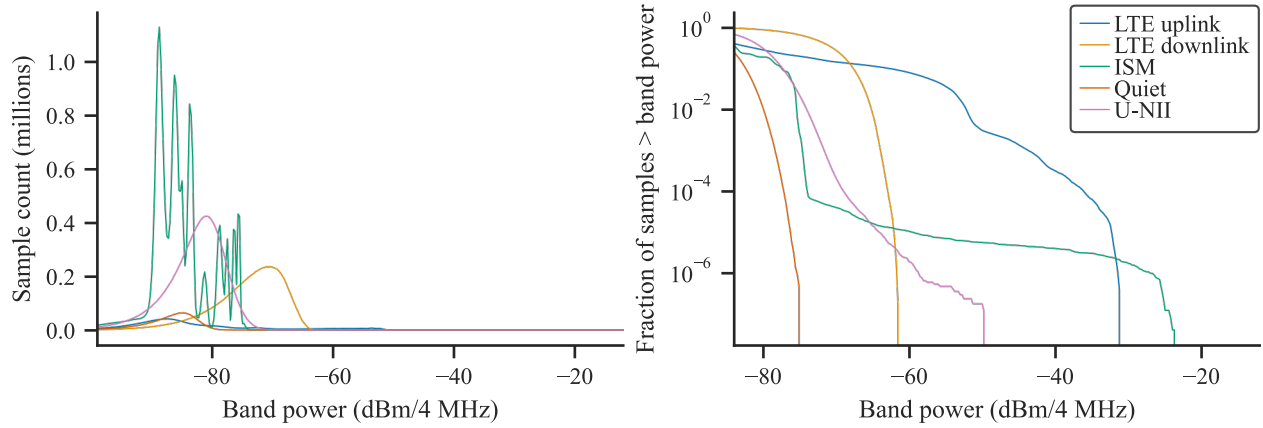


Figure D.34: Histograms (left) and empirical survival functions (right) of all samples received in site 2 in each type of band under test.

Residential Site 3

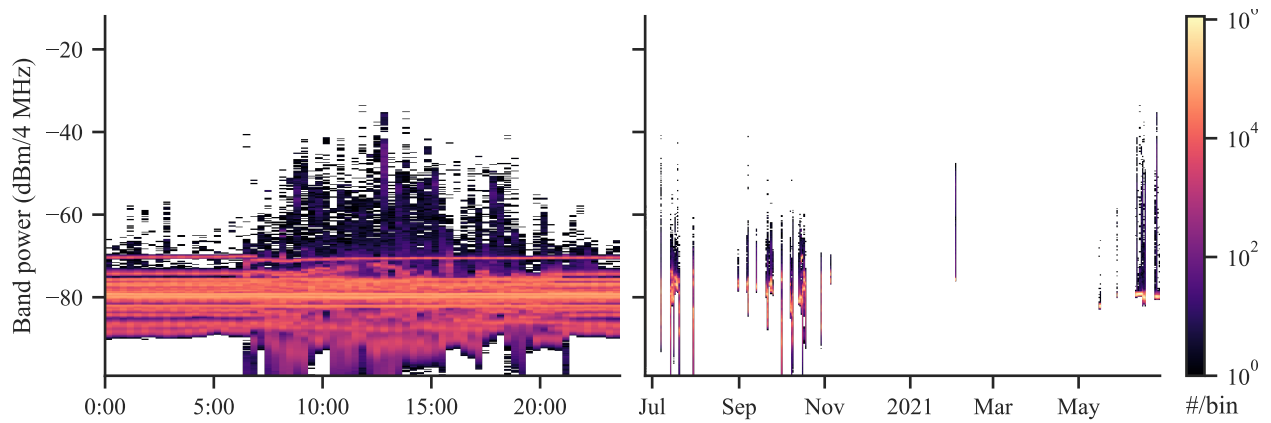


Figure D.35: Histogram heat maps of band power at 782.0 MHz from site 3 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

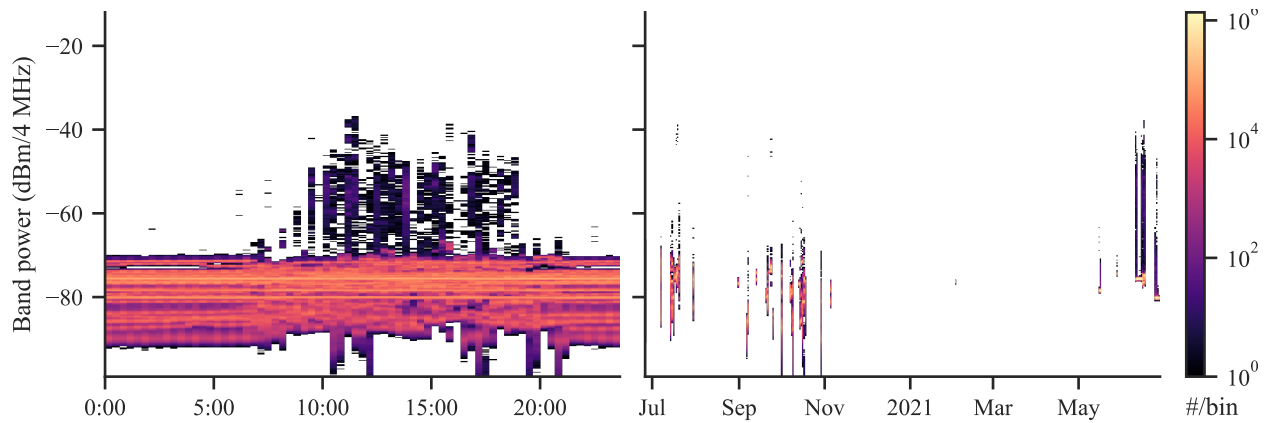


Figure D.36: Histogram heat maps of band power at 821.3 MHz from site 3 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

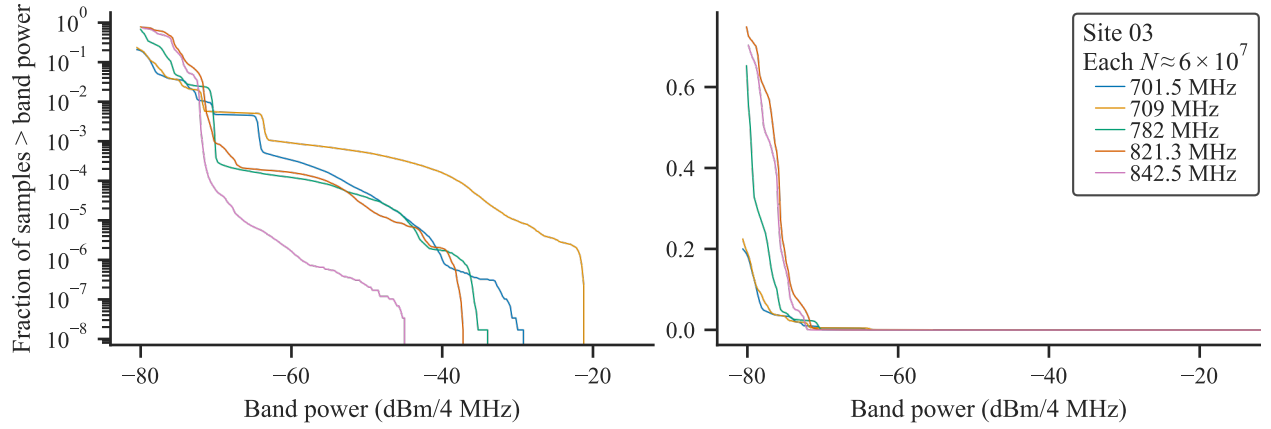


Figure D.37: Plots of empirical survival functions offband power in uplink channels in LTE bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

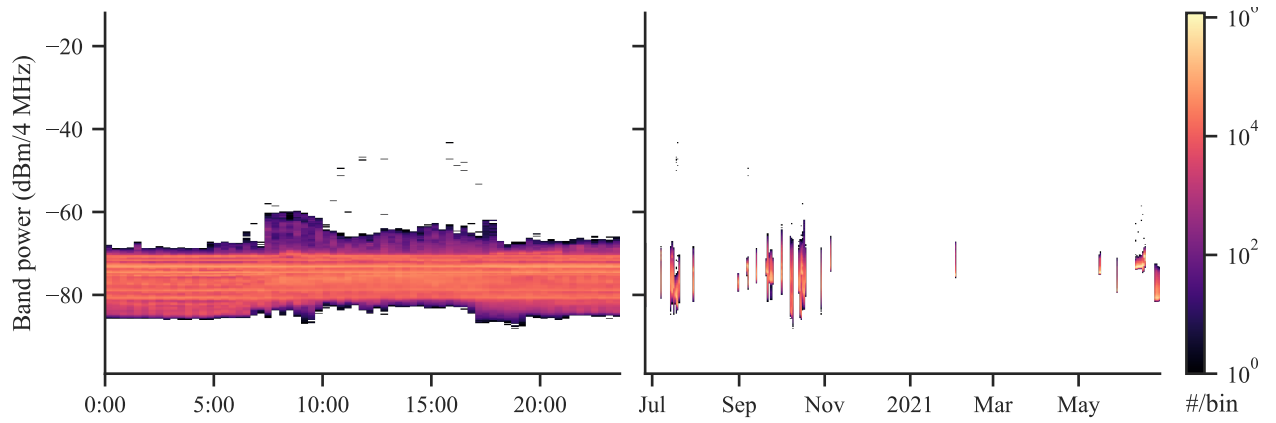


Figure D.38: Histogram heat maps of band power at 887.5 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

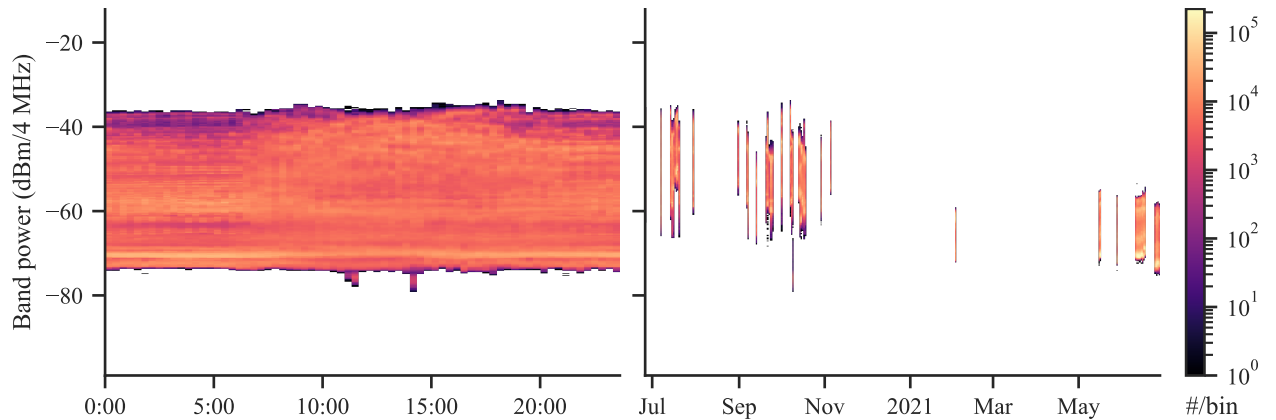


Figure D.39: Histogram heat maps of band power at 866.3 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

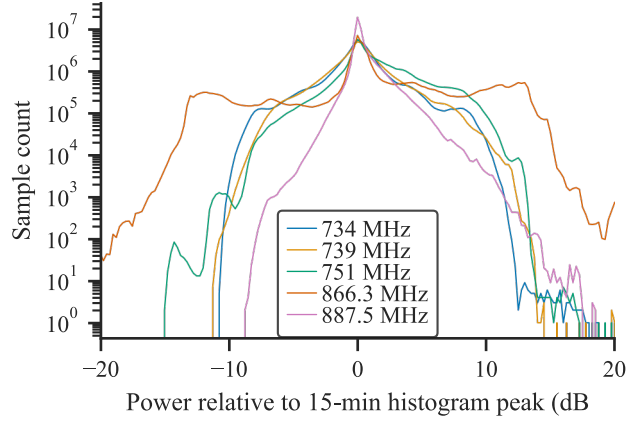


Figure D.40: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 3, as gauged by the peak histogram level in each dwell window.

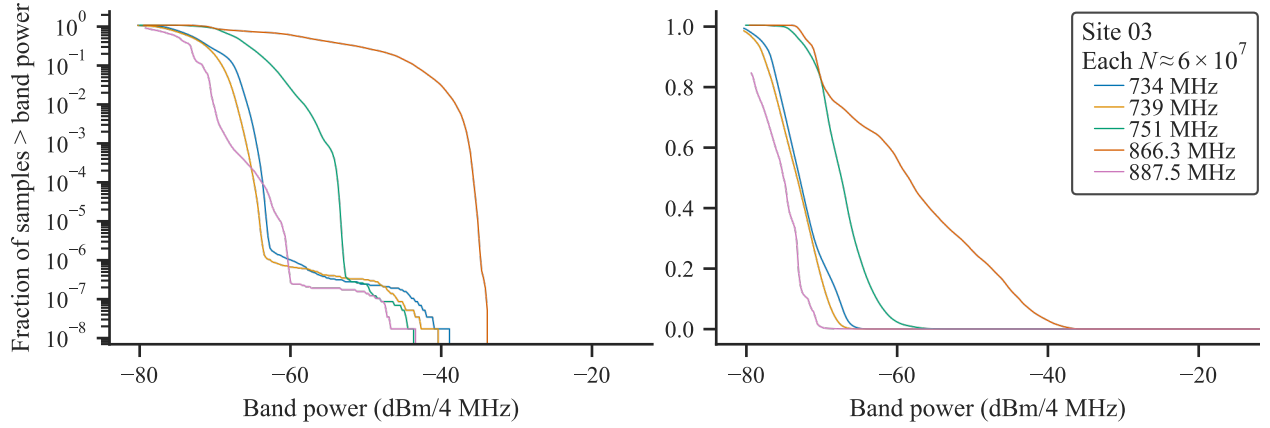


Figure D.41: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

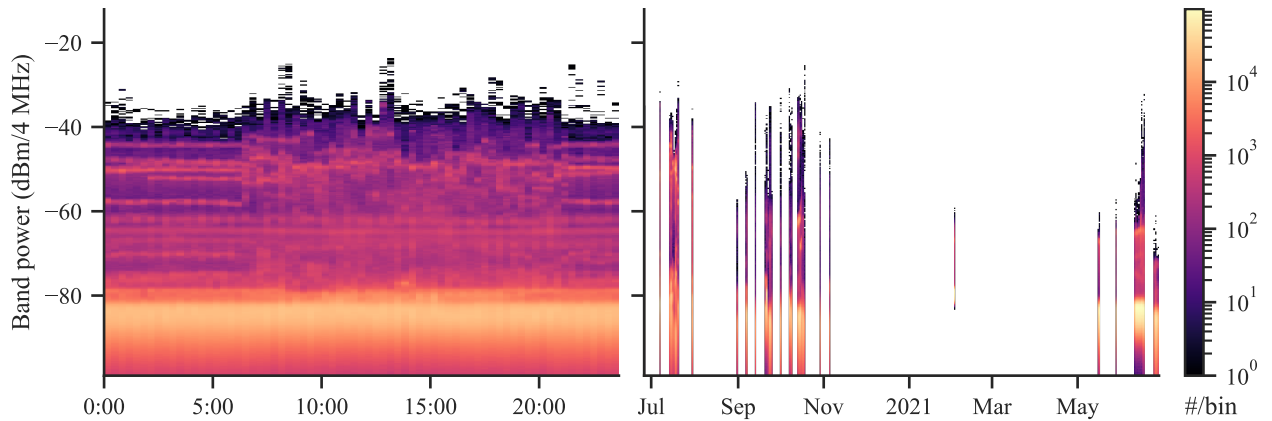


Figure D.42: Histogram heat maps of band power at 2437.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

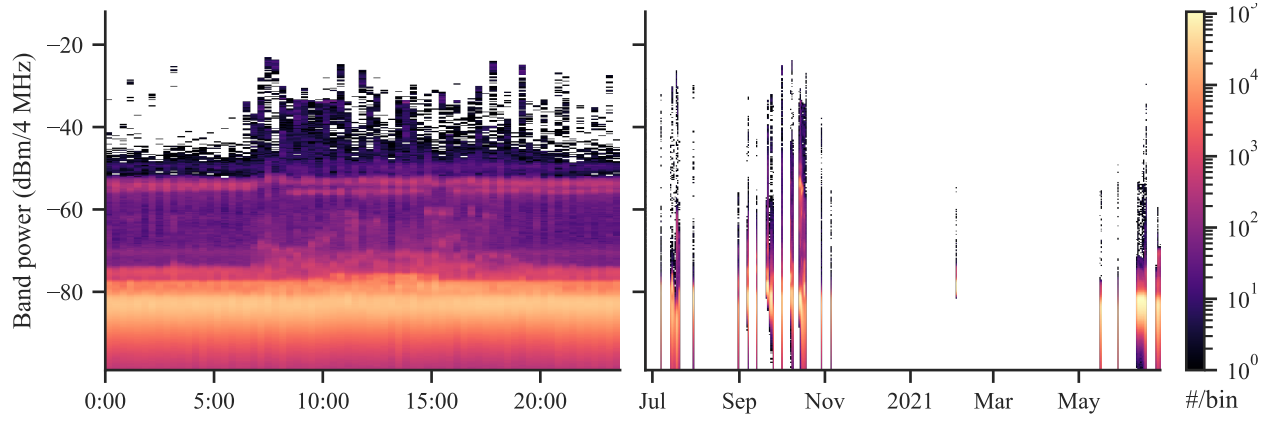


Figure D.43: Histogram heat maps of band power at 2462.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

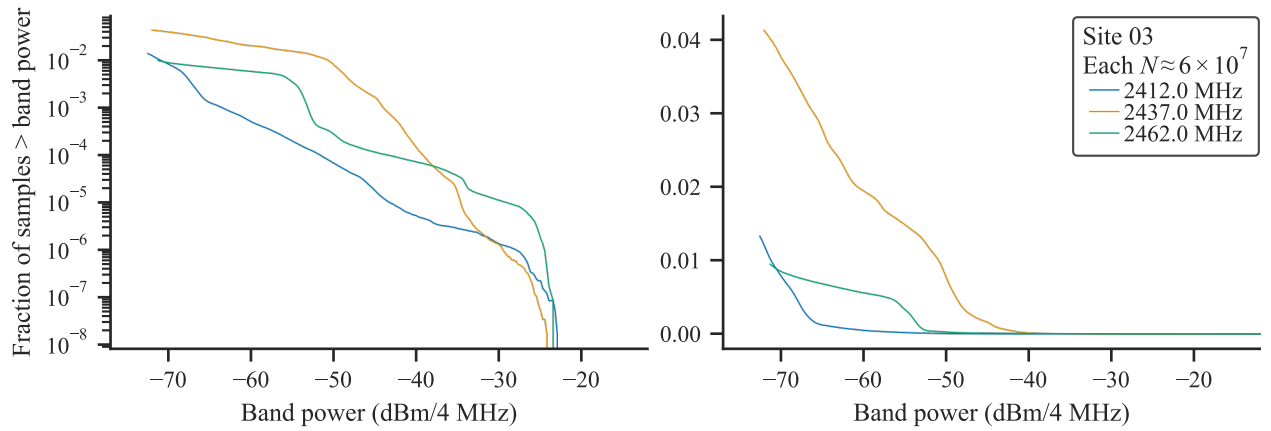


Figure D.44: Plots of empirical survival functions of band power in ISM bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

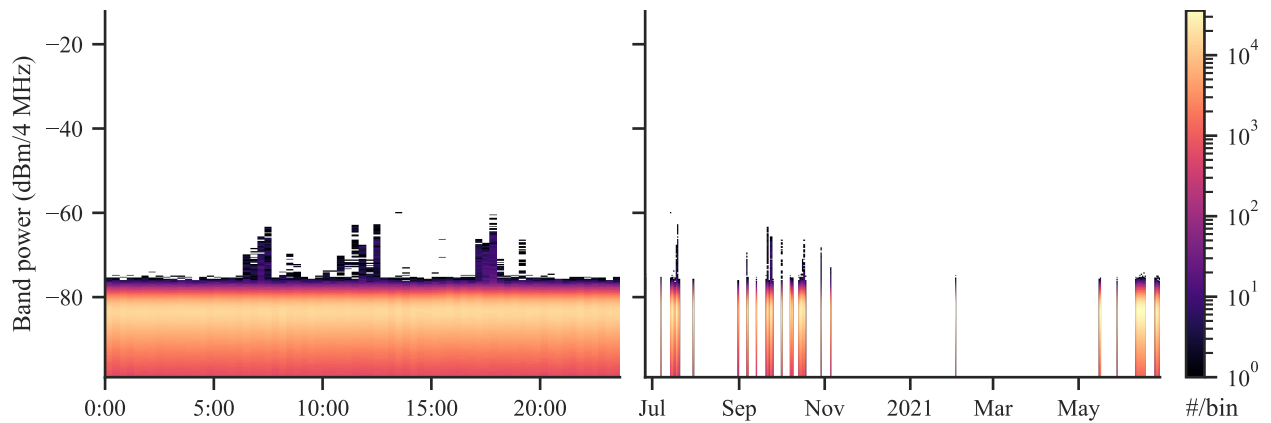


Figure D.45: Histogram heat maps of band power at 2695.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

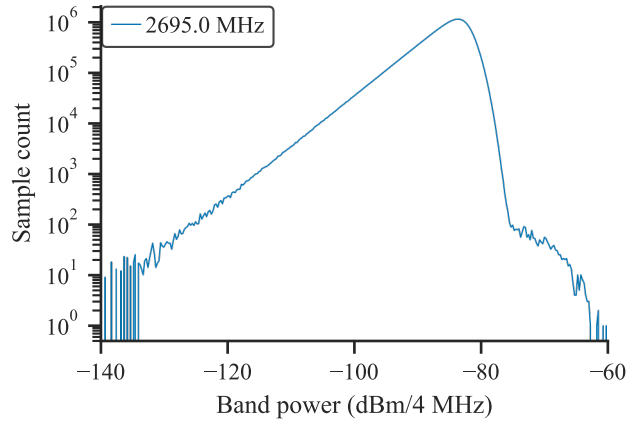


Figure D.46: Histogram of band power measured in the 2695 MHz passive service band at site 3.

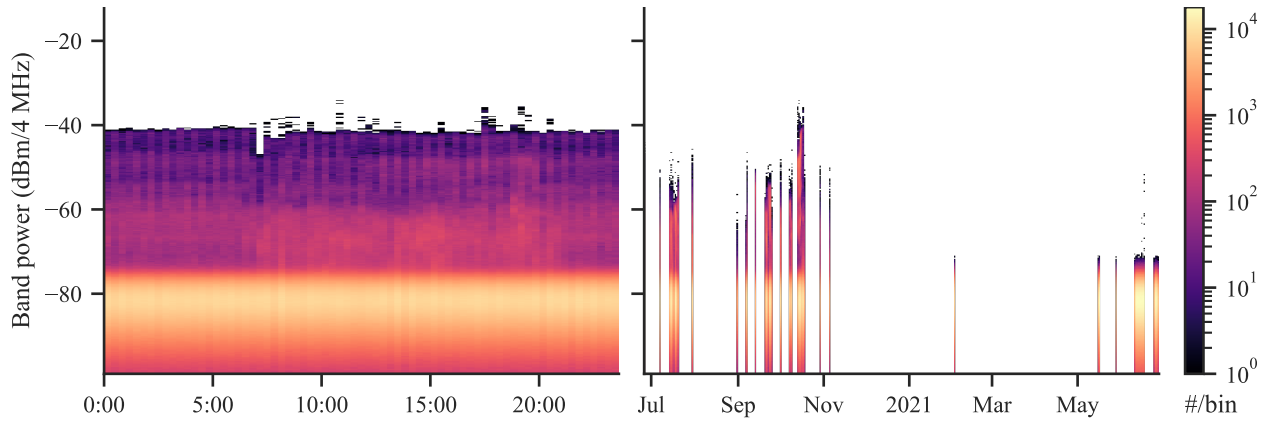


Figure D.47: Histogram heat maps of band power at 5230.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

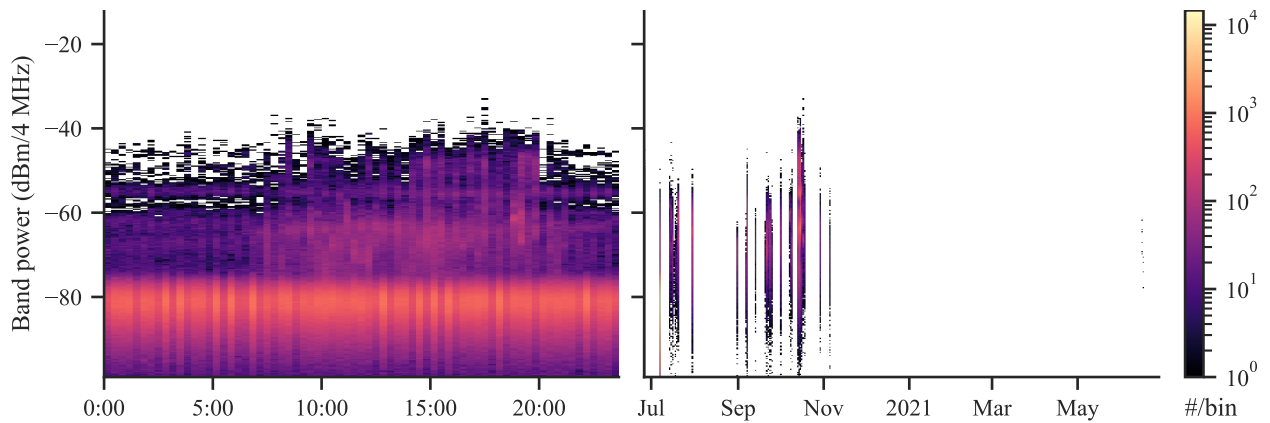


Figure D.48: Histogram heat maps of band power at 5190.0 MHz from site 3 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

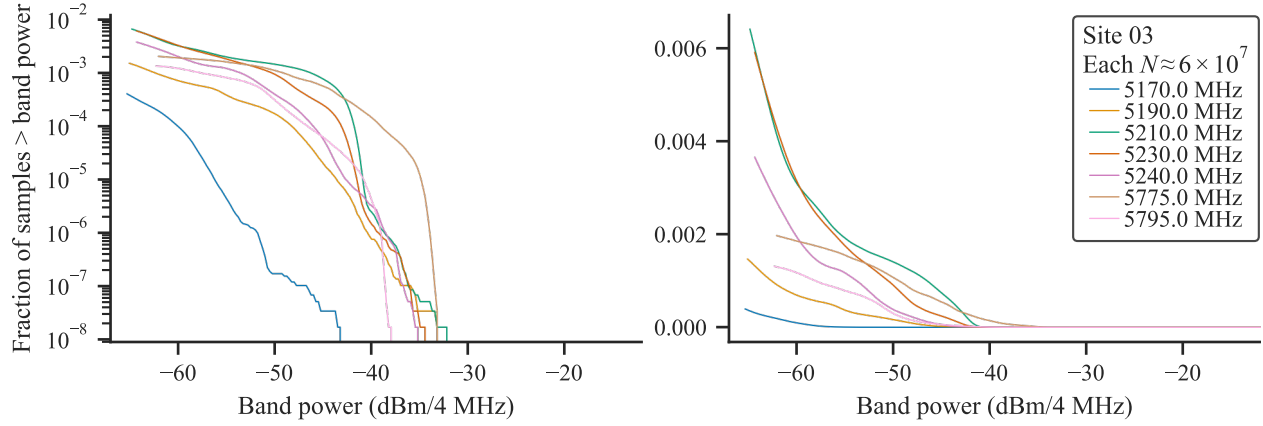


Figure D.49: Plots of empirical survival functions of band power in U-NII bands at site 3, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

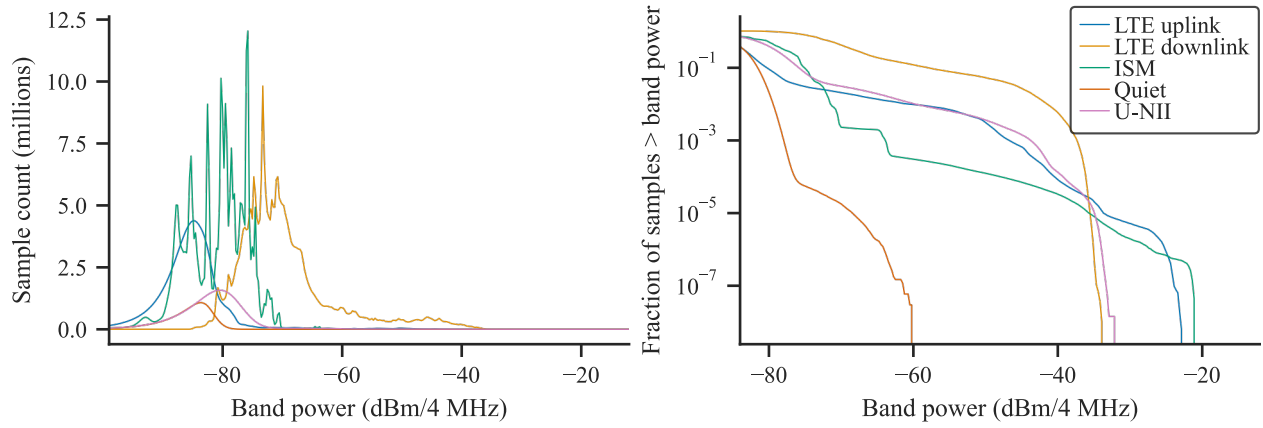


Figure D.50: Histograms (left) and empirical survival functions (right) of all samples received in site 3 in each type of band under test.

Empirical survival functions of

Residential Site 4

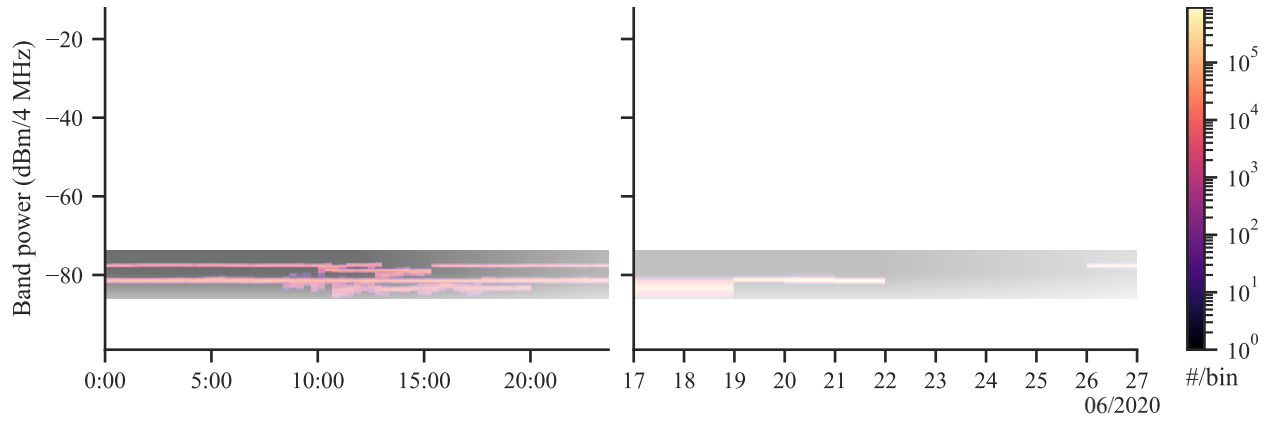


Figure D.51: Histogram heat maps of band power at 842.5 MHz from site 4 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

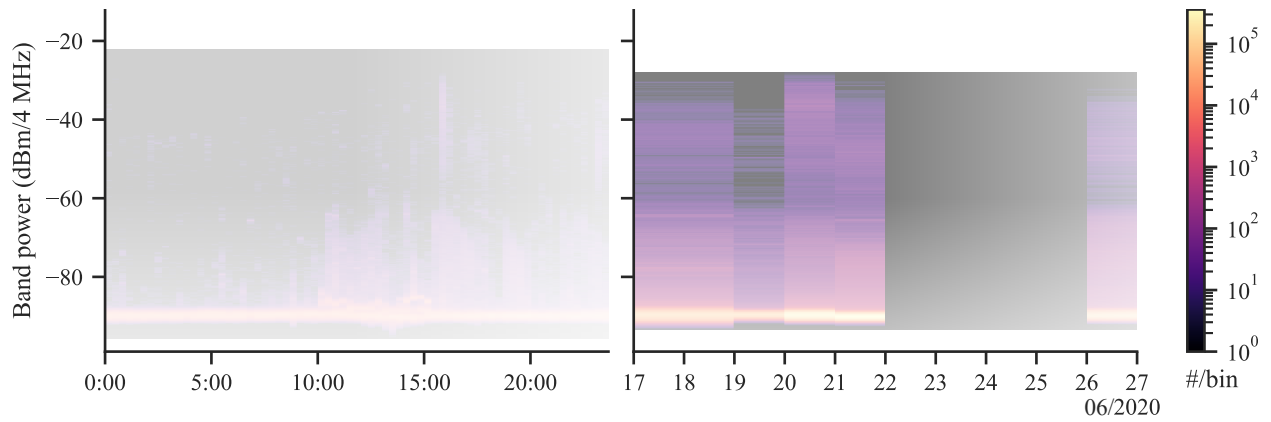


Figure D.52: Histogram heat maps of band power at 709.0 MHz from site 4 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

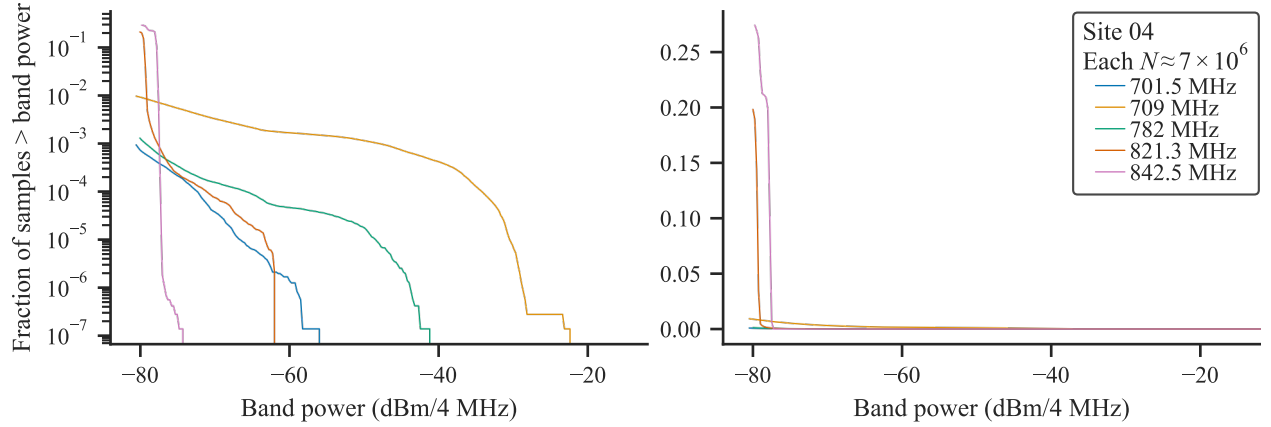


Figure D.53: Plots of empirical survival functions offband power in uplink channels in LTE bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

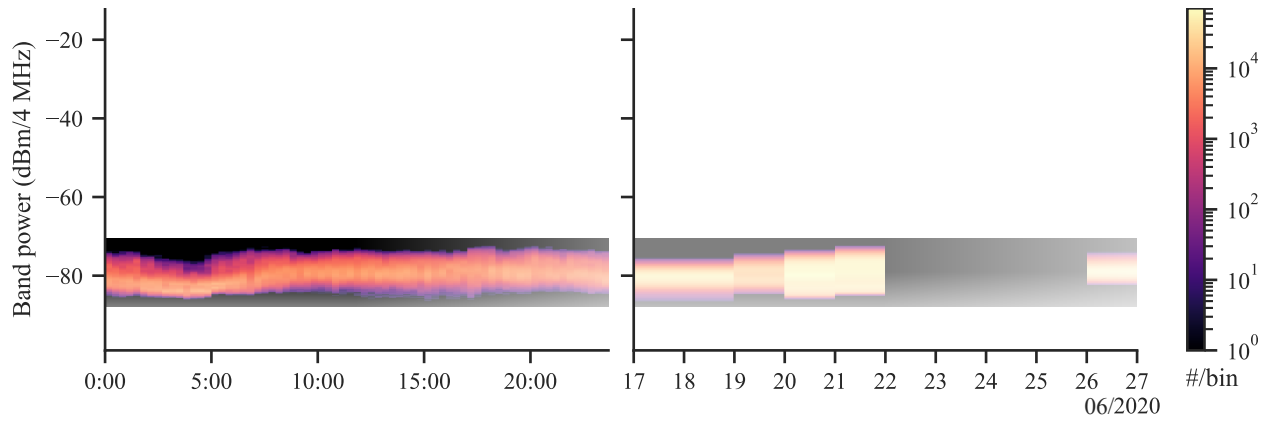


Figure D.54: Histogram heat maps of band power at 887.5 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

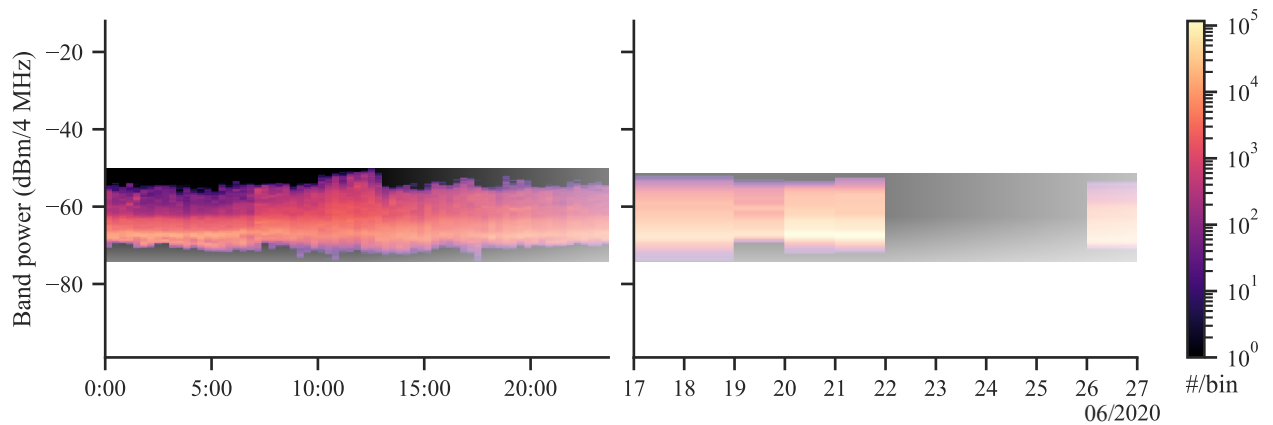


Figure D.55: Histogram heat maps of band power at 751.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

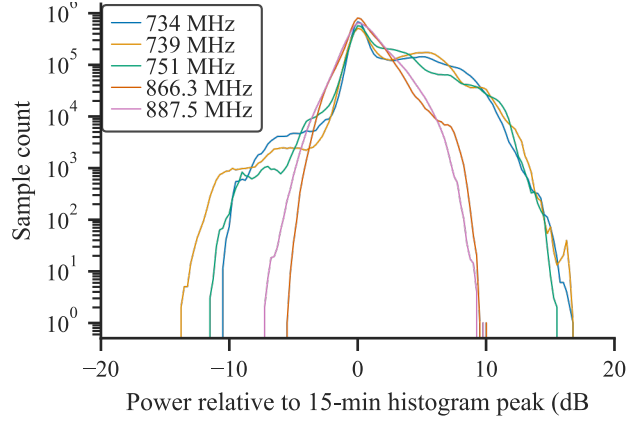


Figure D.56: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 4, as gauged by the peak histogram level in each dwell window.

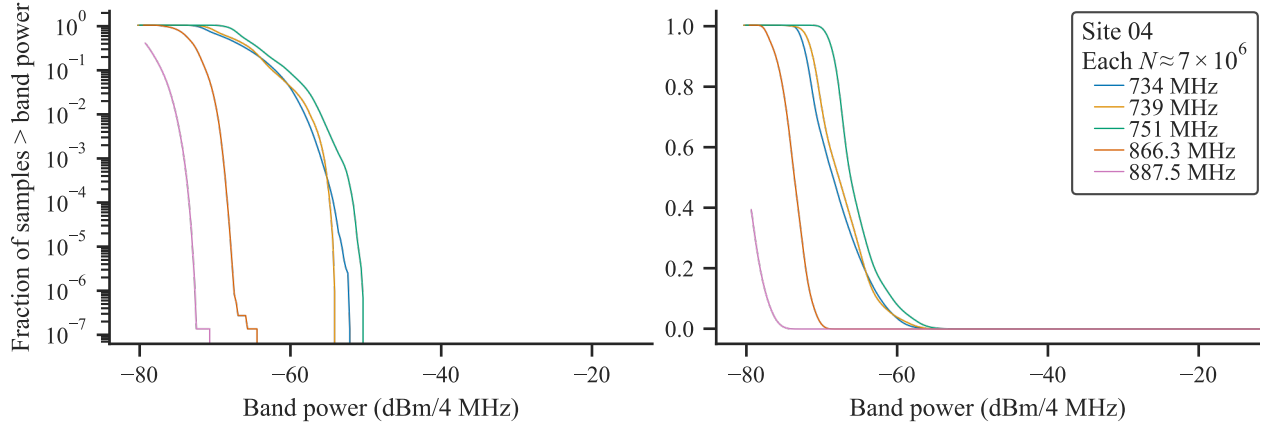


Figure D.57: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

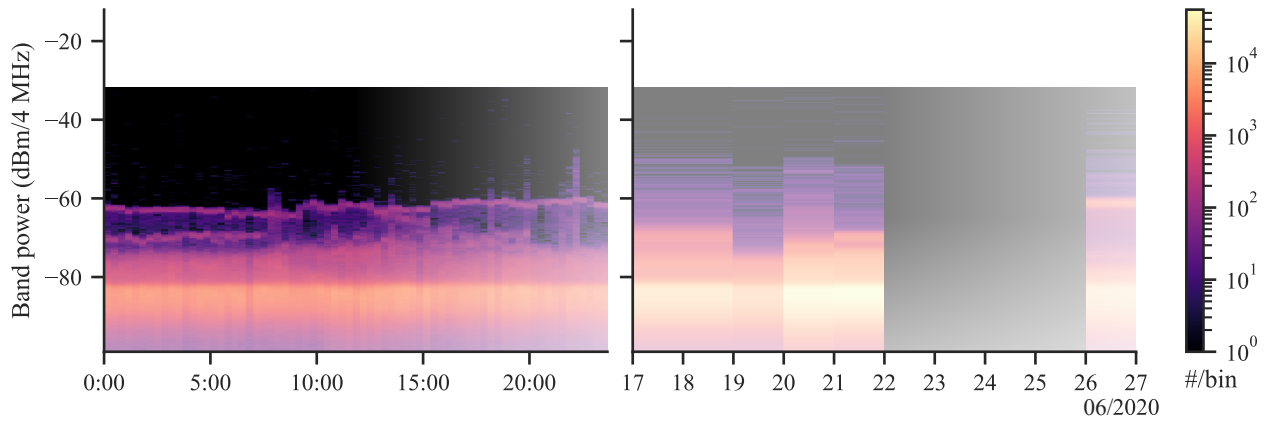


Figure D.58: Histogram heat maps of band power at 2437.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

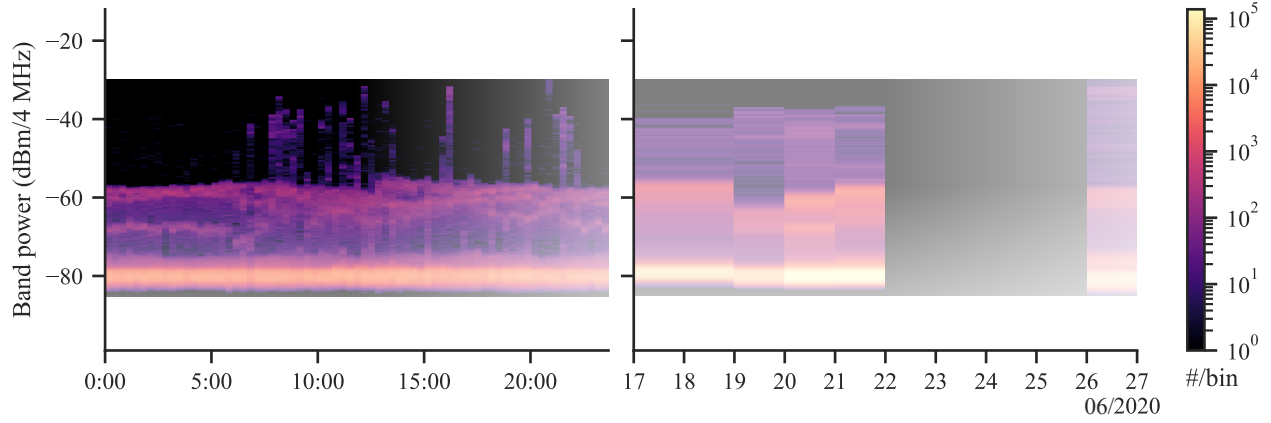


Figure D.59: Histogram heat maps of band power at 2462.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

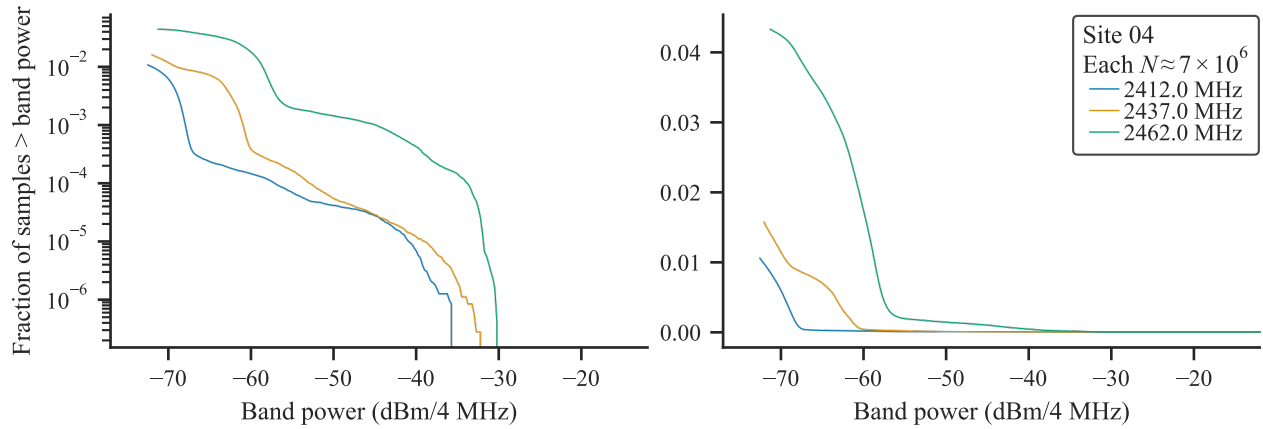


Figure D.60: Plots of empirical survival functions of band power in ISM bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

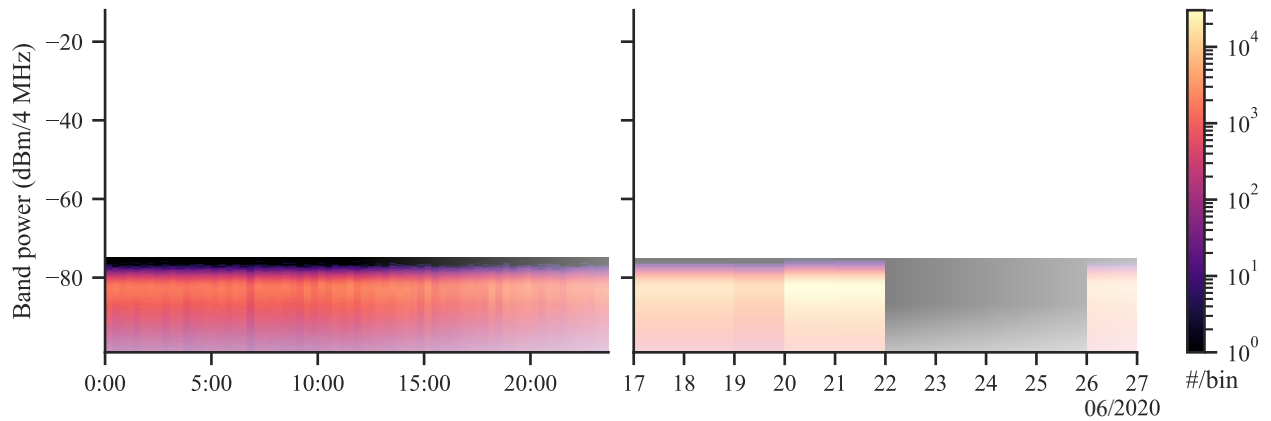


Figure D.61: Histogram heat maps of band power at 2695.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

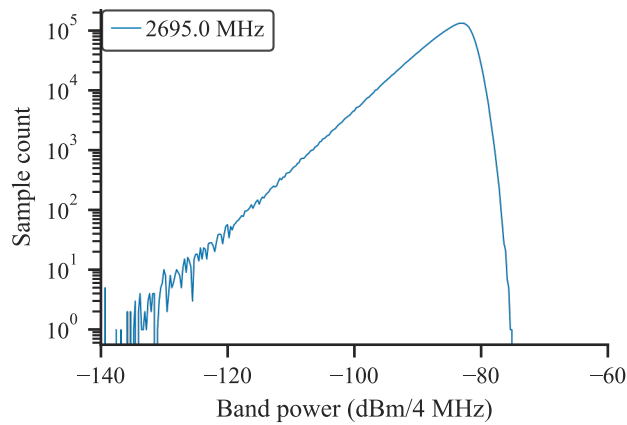


Figure D.62: Histogram of band power measured in the 2695 MHz passive service band at site 4.

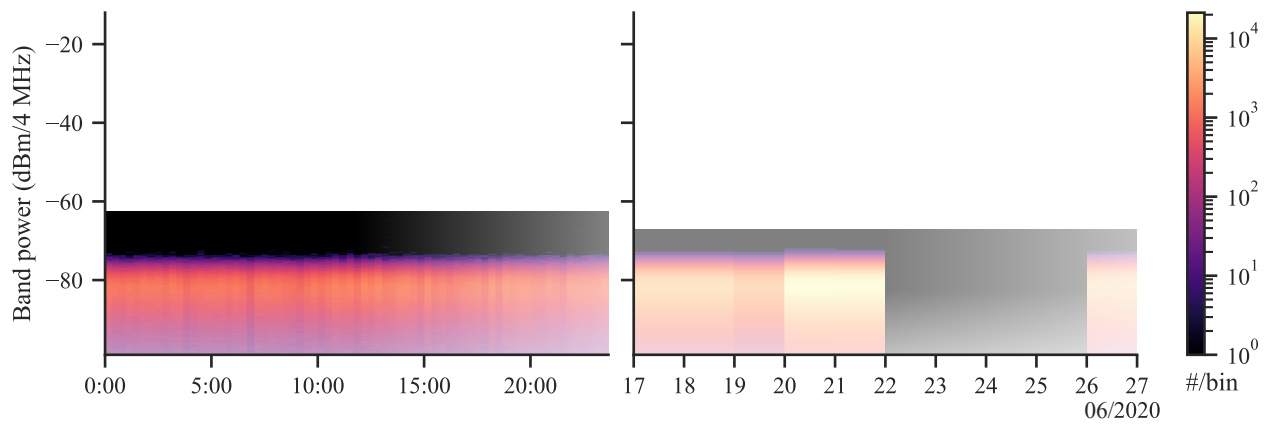


Figure D.63: Histogram heat maps of band power at 5190.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

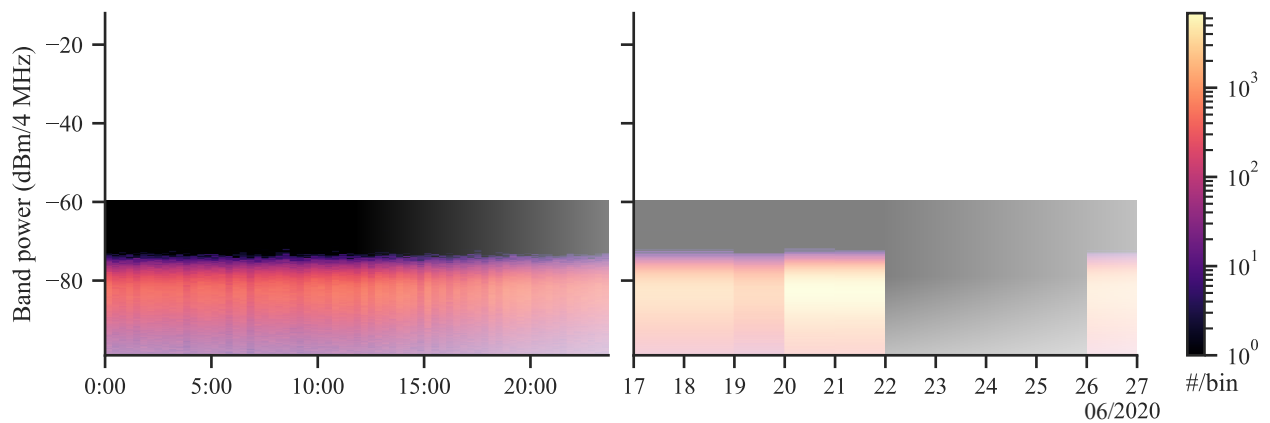


Figure D.64: Histogram heat maps of band power at 5230.0 MHz from site 4 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

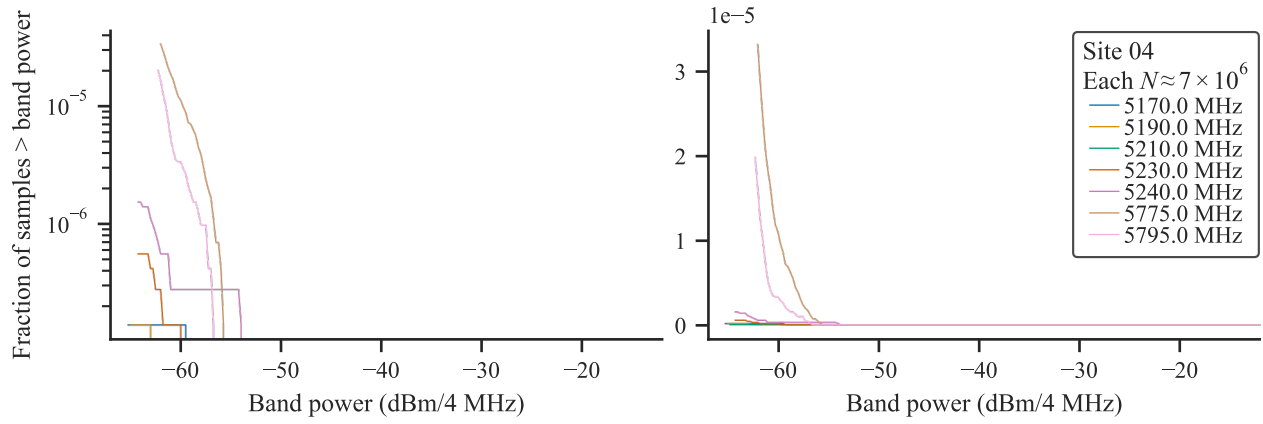


Figure D.65: Plots of empirical survival functions of band power in U-NII bands at site 4, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

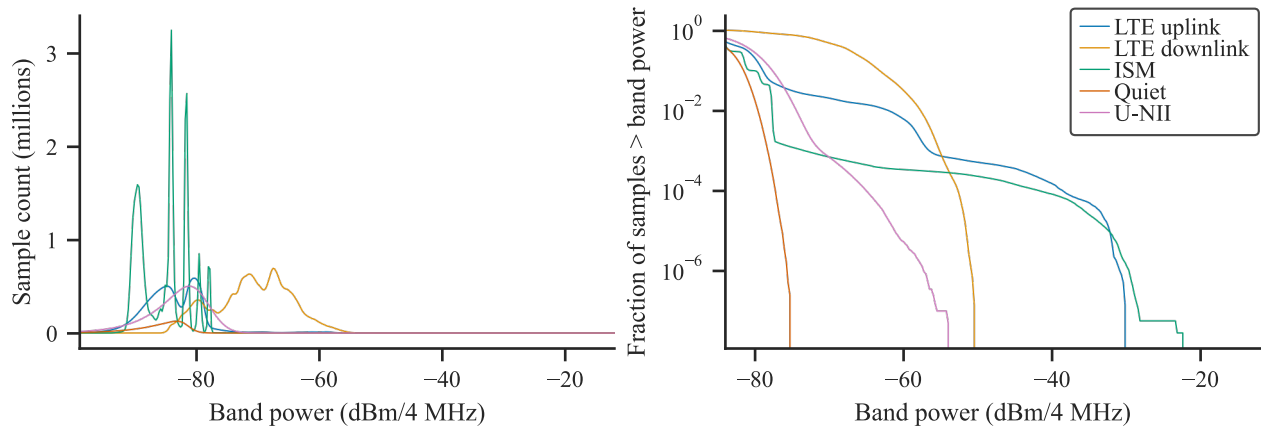


Figure D.66: Histograms (left) and empirical survival functions (right) of all samples received in site 4 in each type of band under test.

Residential Site 5

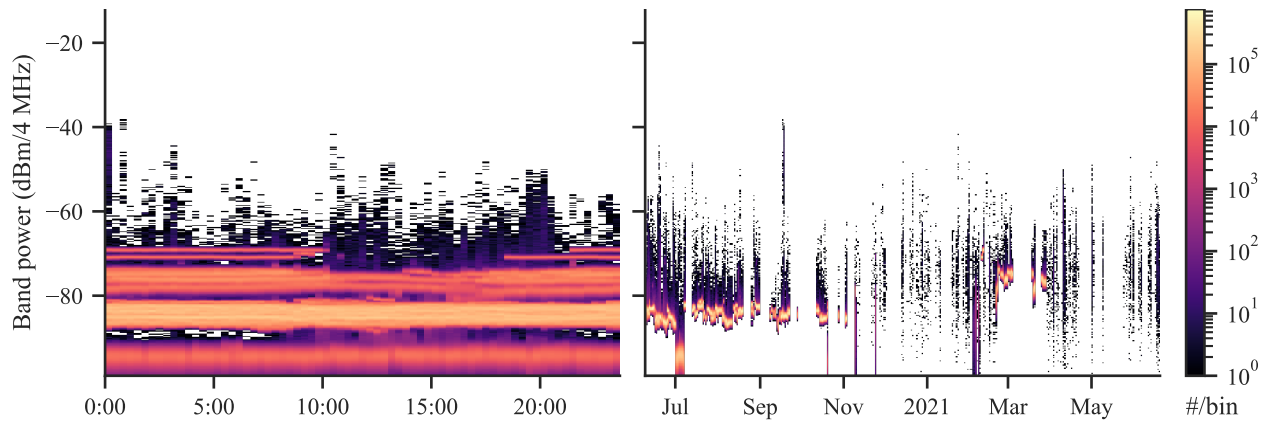


Figure D.67: Histogram heat maps of band power at 782.0 MHz from site 5 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

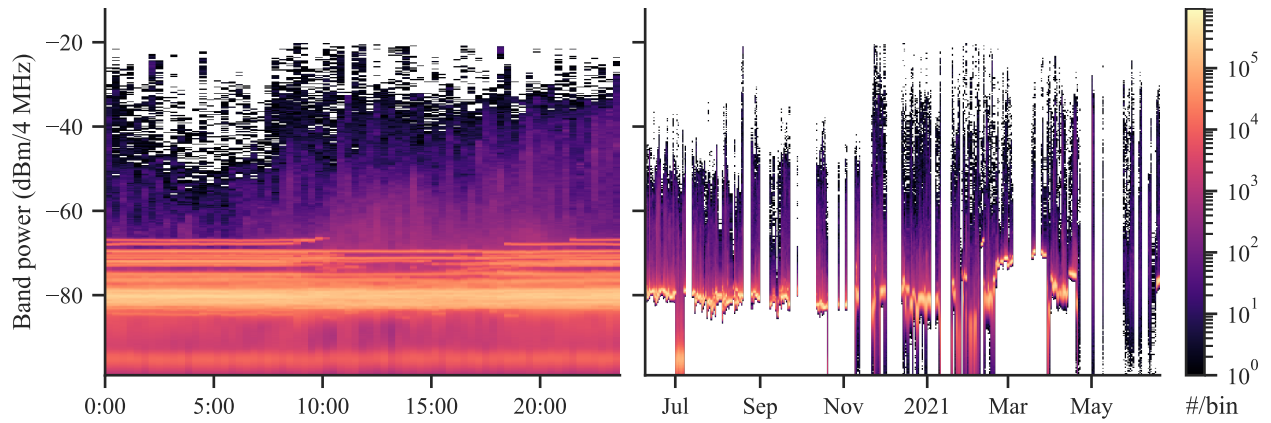


Figure D.68: Histogram heat maps of band power at 821.3 MHz from site 5 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

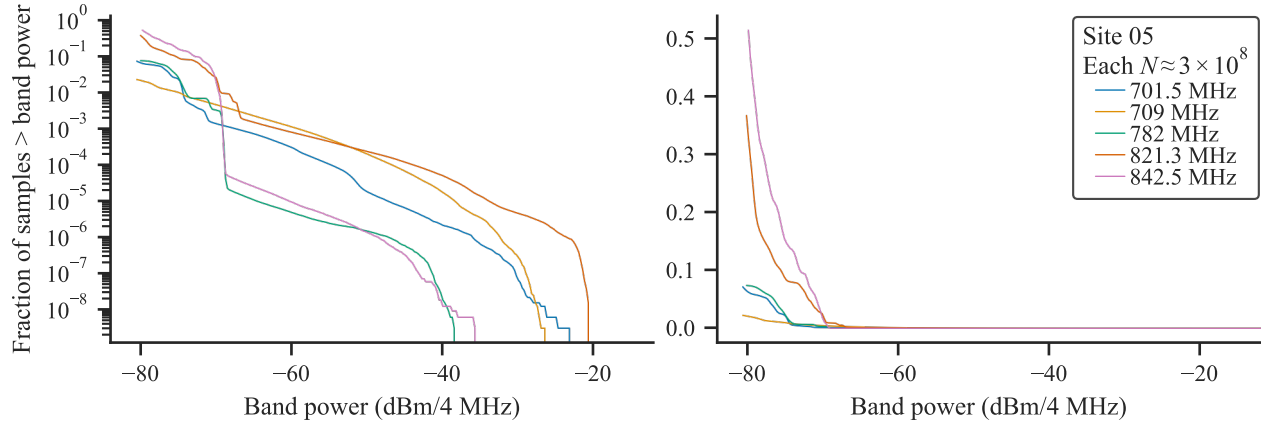


Figure D.69: Plots of empirical survival functions offband power in uplink channels in LTE bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

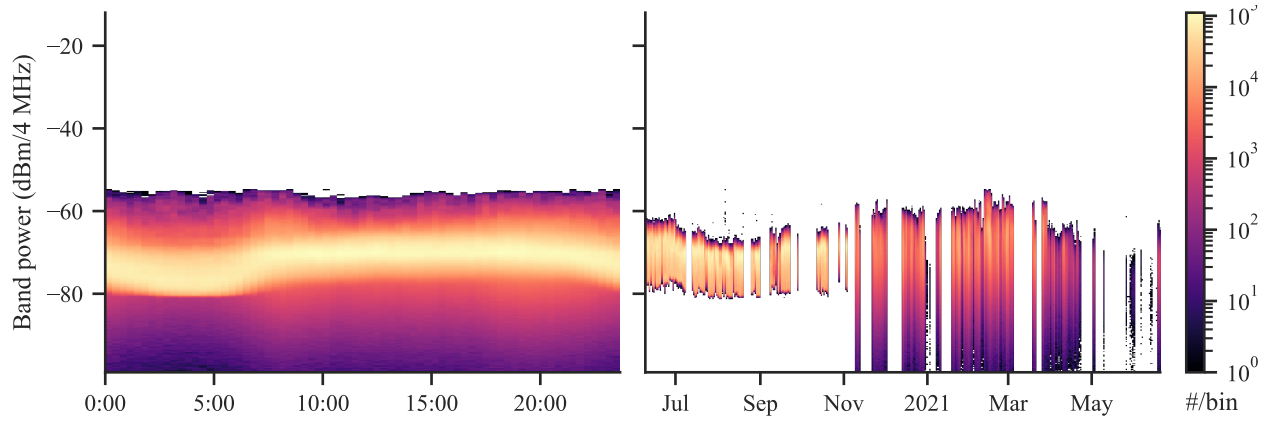


Figure D.70: Histogram heat maps of band power at 739.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

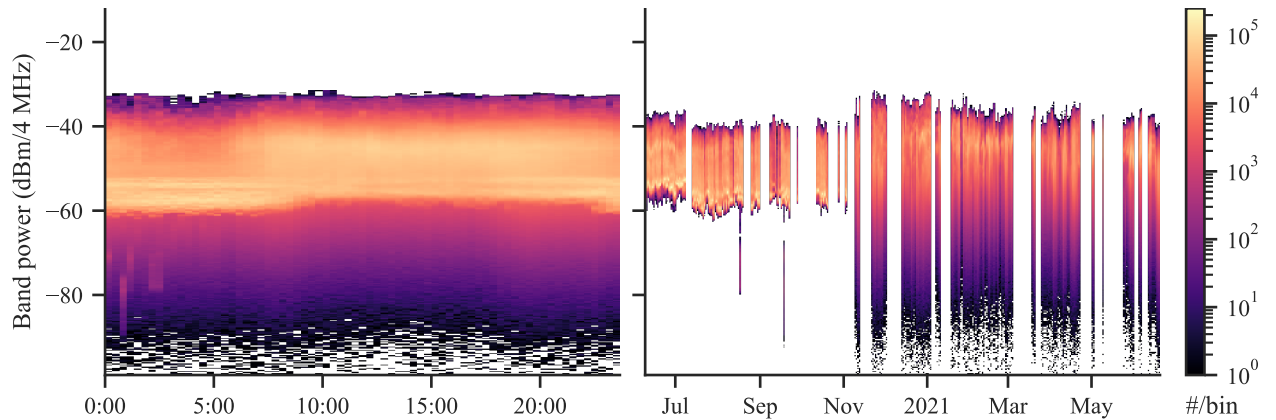


Figure D.71: Histogram heat maps of band power at 751.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

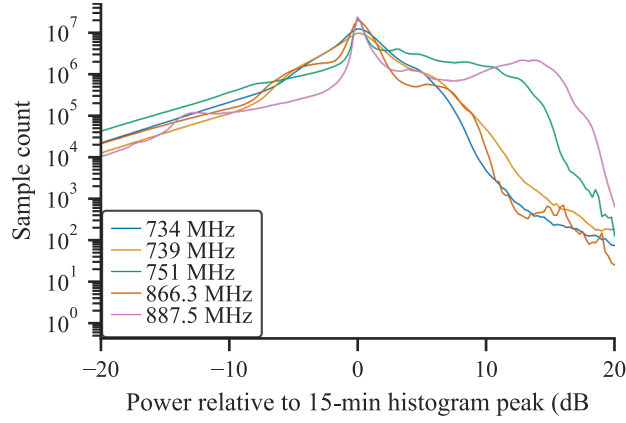


Figure D.72: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 5, as gauged by the peak histogram level in each dwell window.

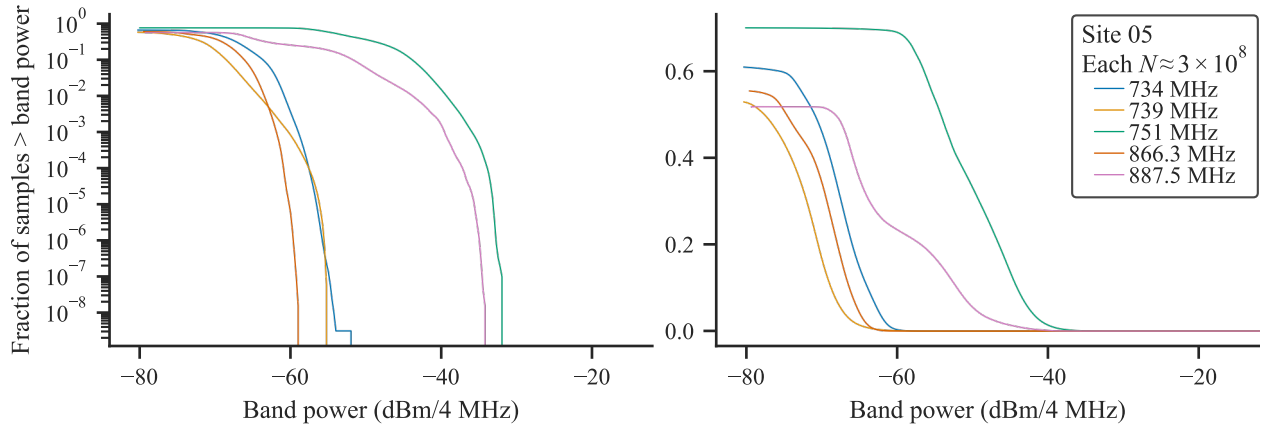


Figure D.73: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

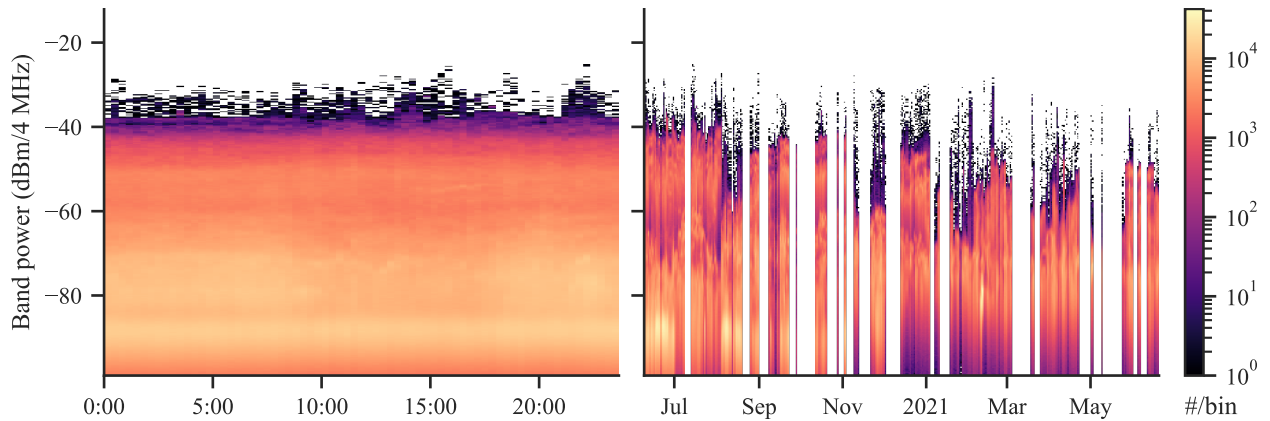


Figure D.74: Histogram heat maps of band power at 2412.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

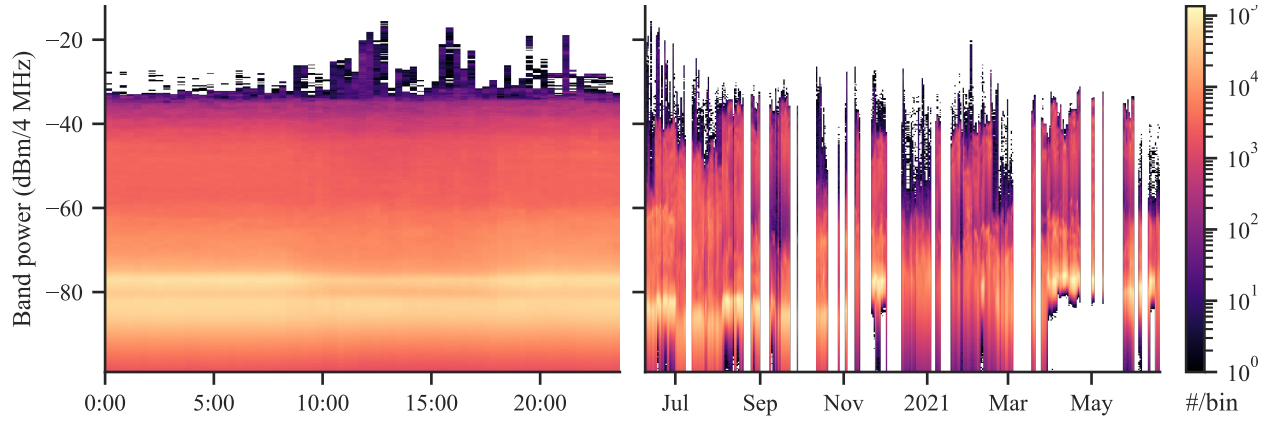


Figure D.75: Histogram heat maps of band power at 2462.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

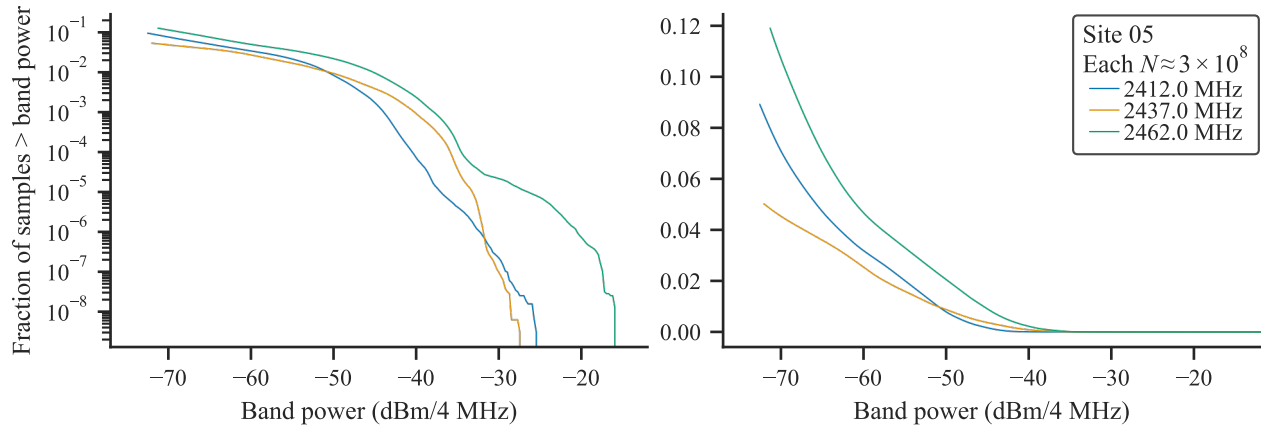


Figure D.76: Plots of empirical survival functions of band power in ISM bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

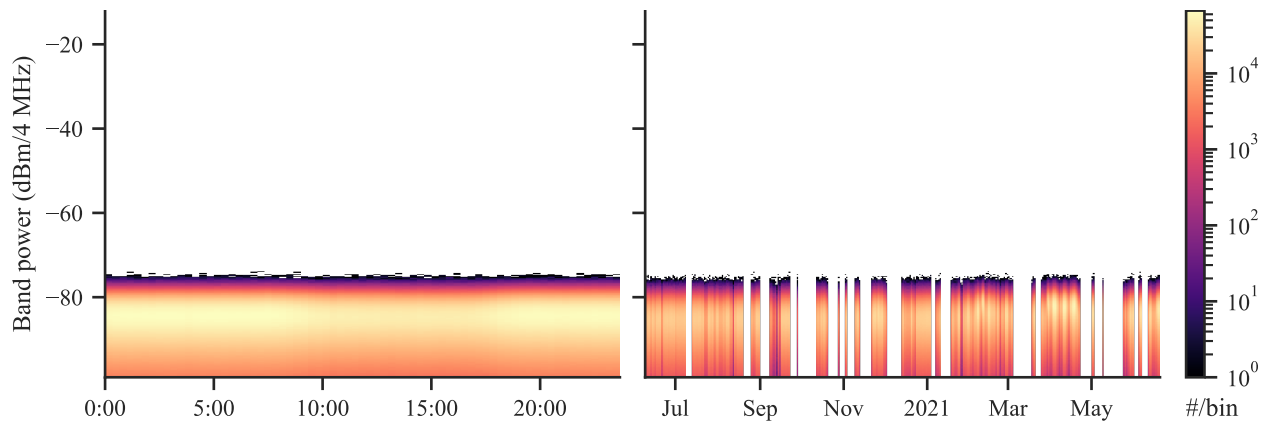


Figure D.77: Histogram heat maps of band power at 2695.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

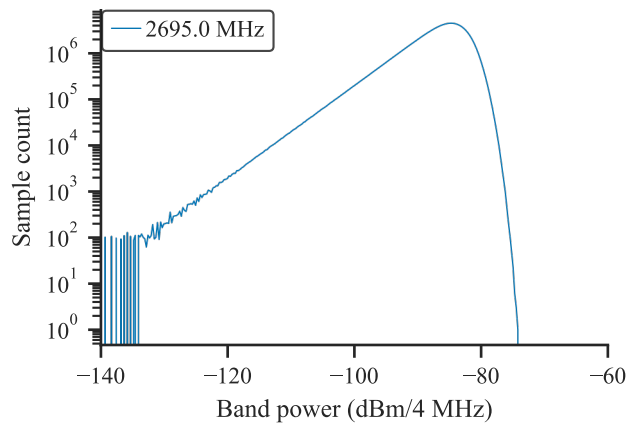


Figure D.78: Histogram of band power measured in the 2695 MHz passive service band at site 5.

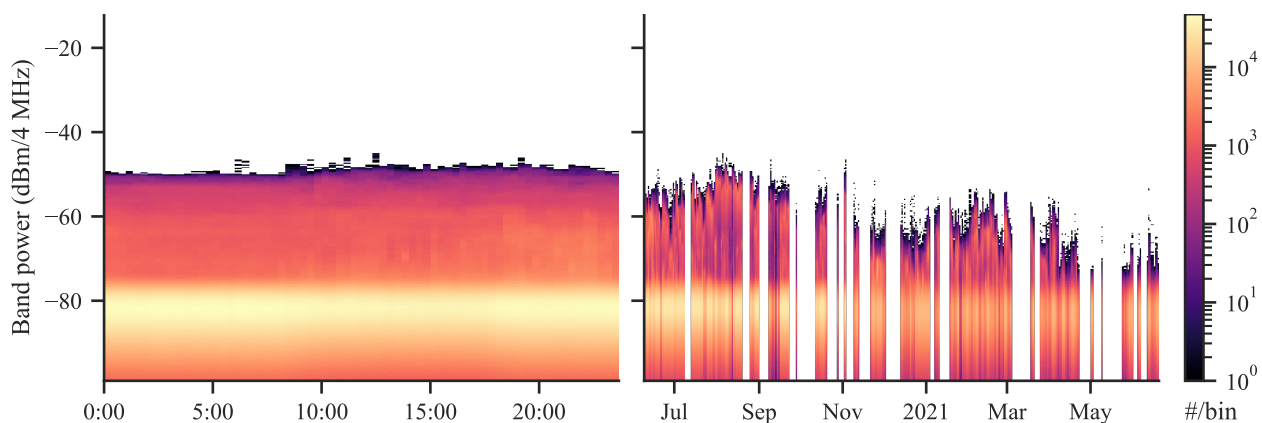


Figure D.79: Histogram heat maps of band power at 5170.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

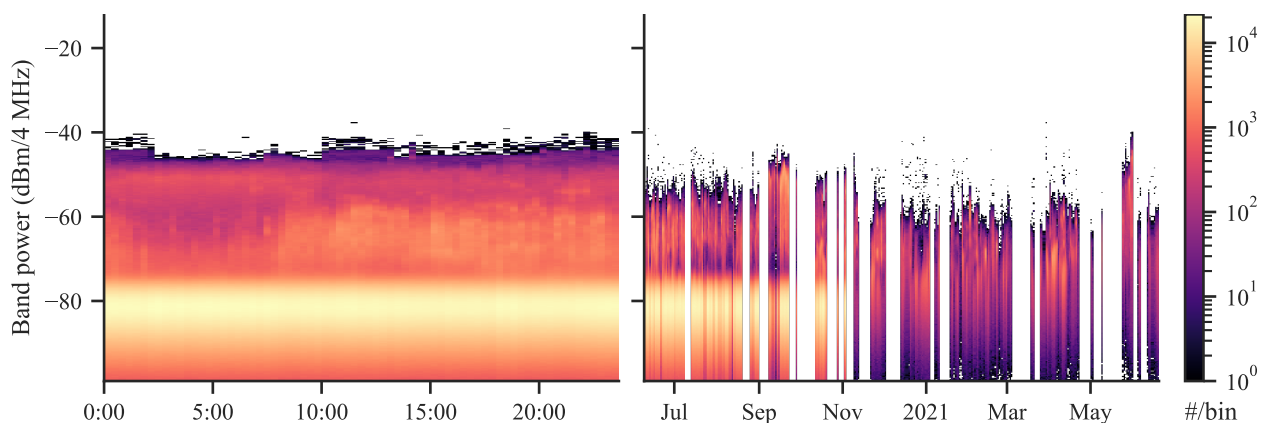


Figure D.80: Histogram heat maps of band power at 5240.0 MHz from site 5 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

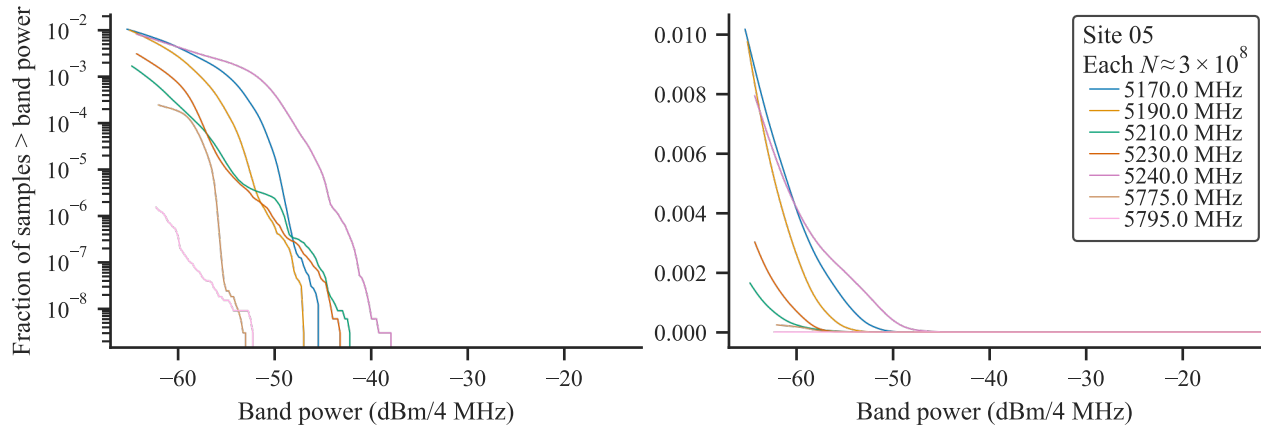


Figure D.81: Plots of empirical survival functions of band power in U-NII bands at site 5, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

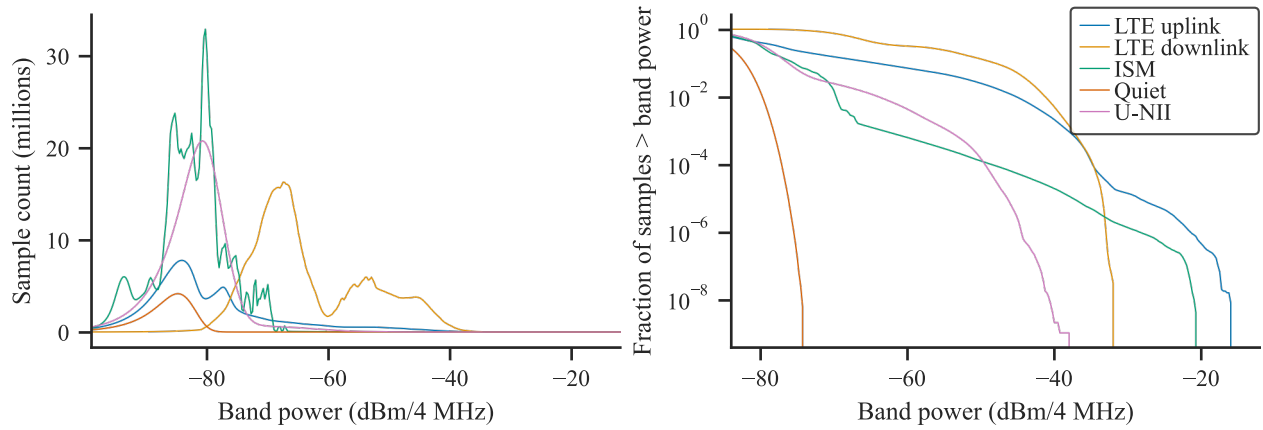


Figure D.82: Histograms (left) and empirical survival functions (right) of all samples received in site 5 in each type of band under test.

Residential Site 6

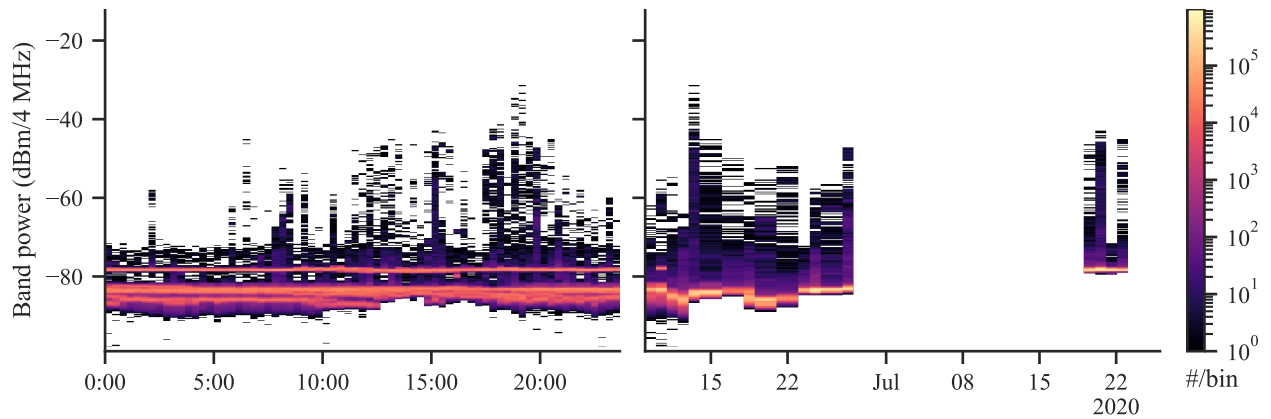


Figure D.83: Histogram heat maps of band power at 701.5 MHz from site 6 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

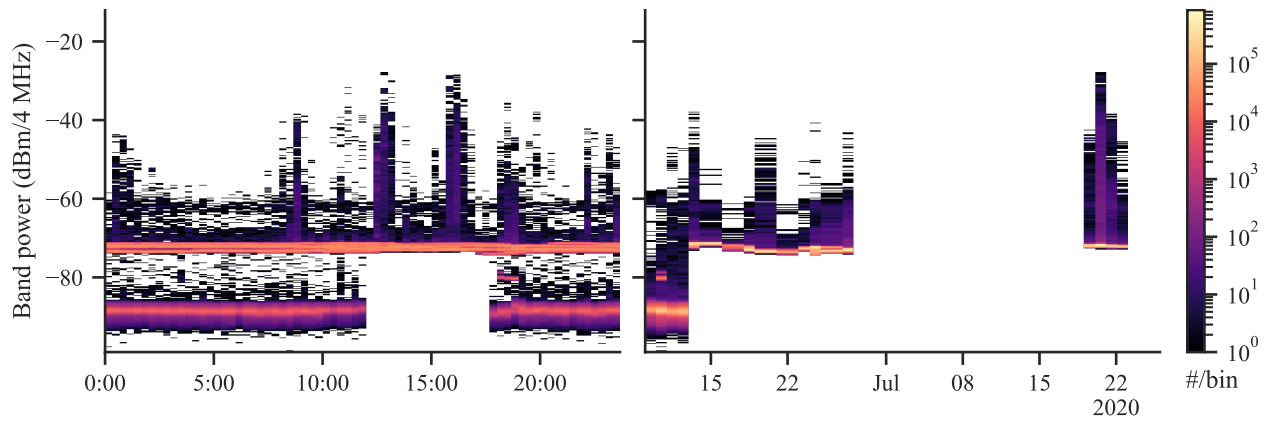


Figure D.84: Histogram heat maps of band power at 842.5 MHz from site 6 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

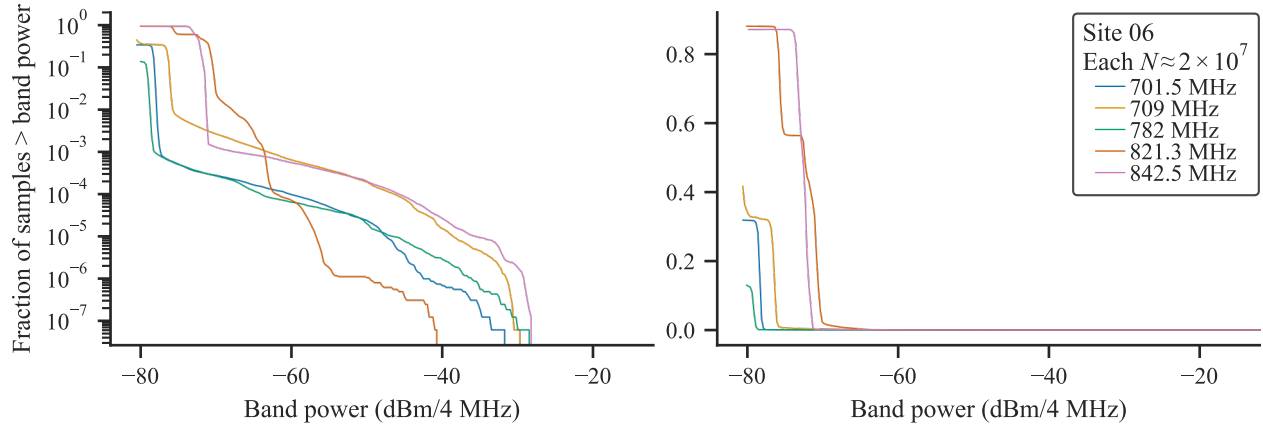


Figure D.85: Plots of empirical survival functions offband power in uplink channels in LTE bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

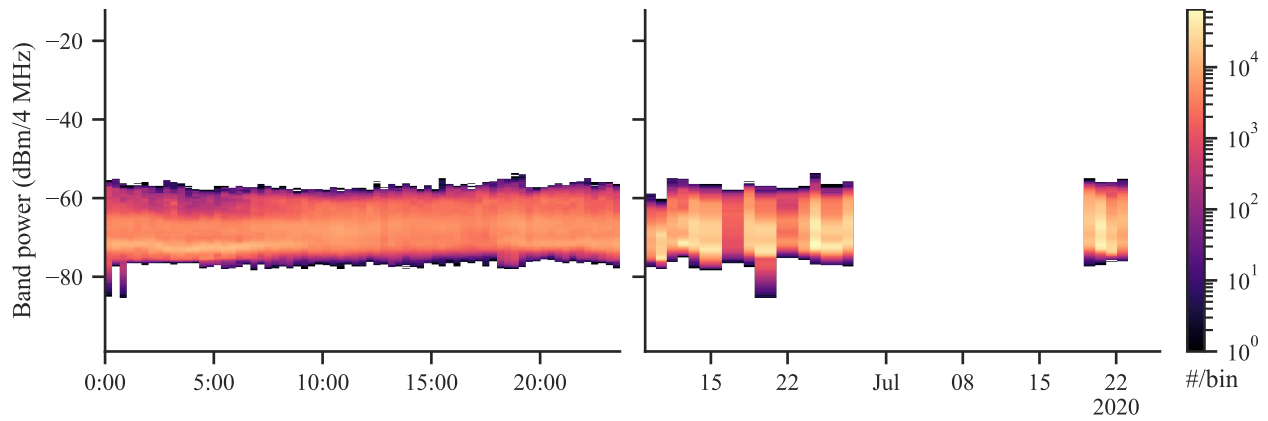


Figure D.86: Histogram heat maps of band power at 739.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

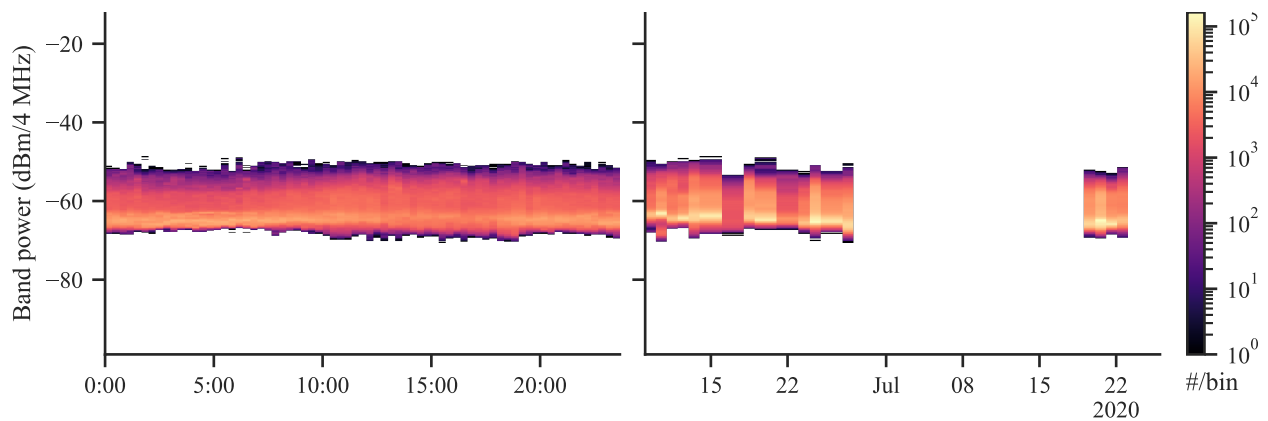


Figure D.87: Histogram heat maps of band power at 751.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

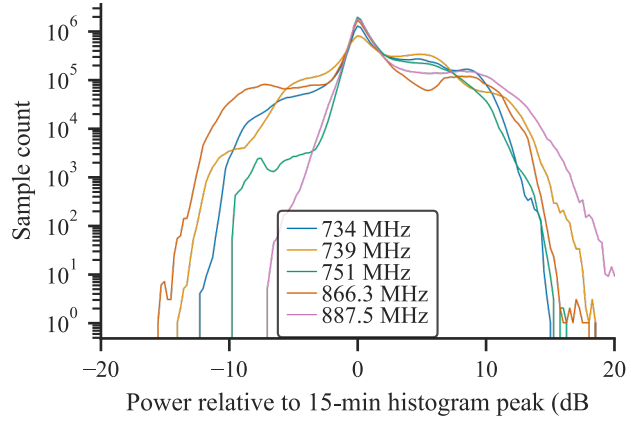


Figure D.88: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 6, as gauged by the peak histogram level in each dwell window.

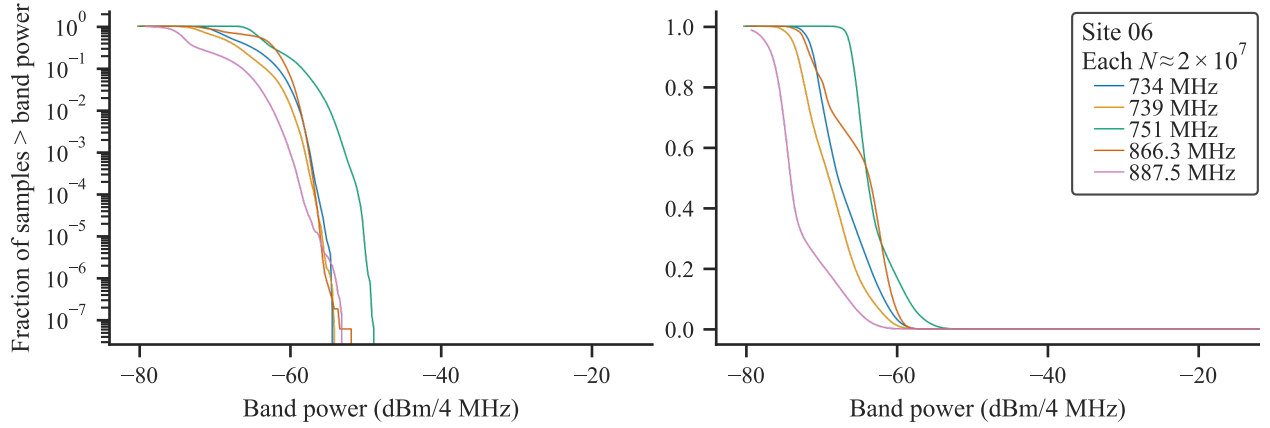


Figure D.89: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

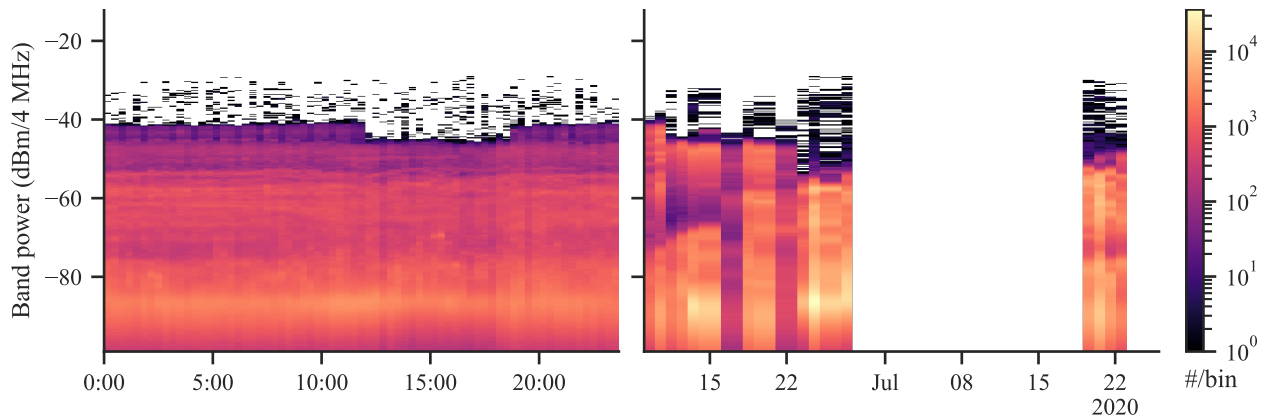


Figure D.90: Histogram heat maps of band power at 2412.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

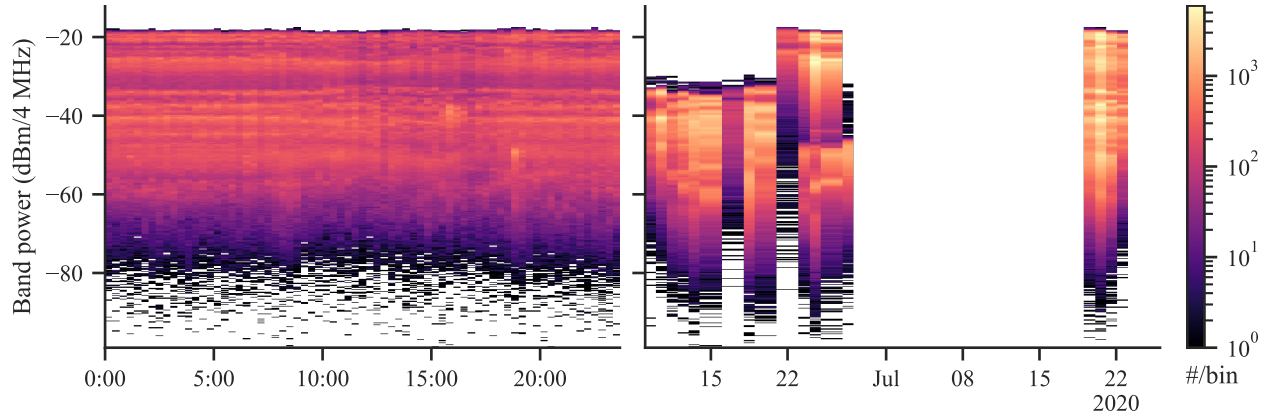


Figure D.91: Histogram heat maps of band power at 2437.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

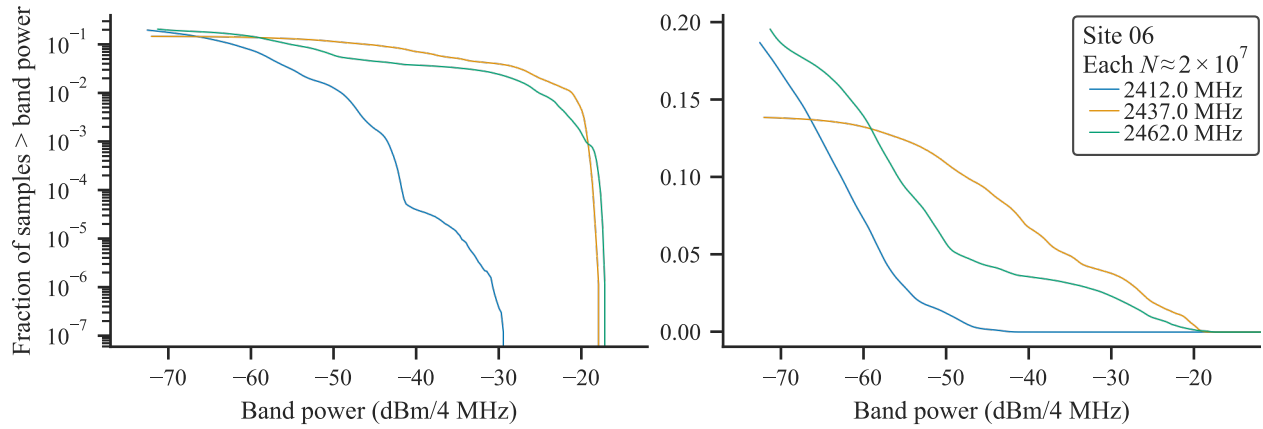


Figure D.92: Plots of empirical survival functions ofband power in ISM bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

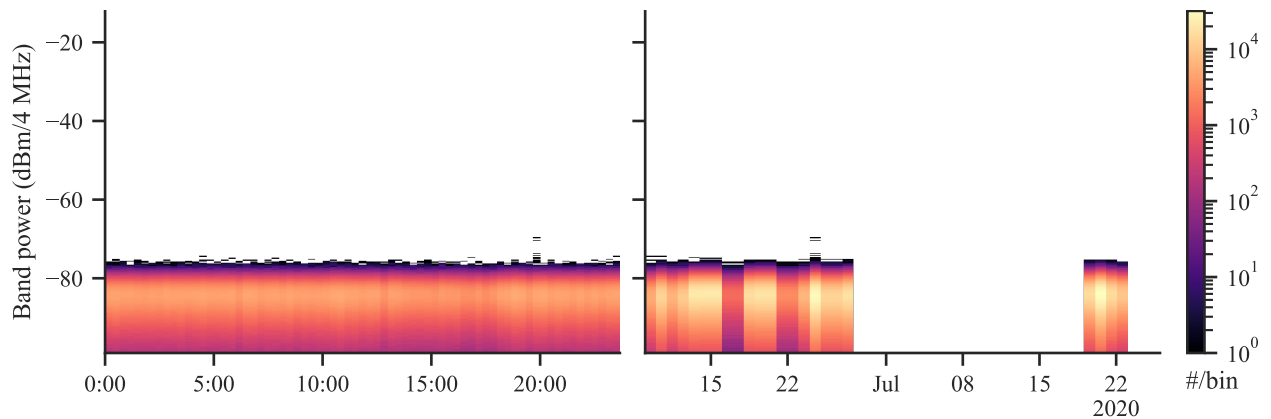


Figure D.93: Histogram heat maps of band power at 2695.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

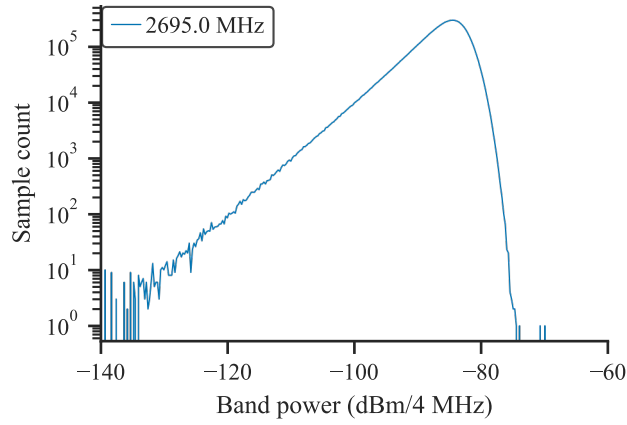


Figure D.94: Histogram of band power measured in the 2695 MHz passive service band at site 6.

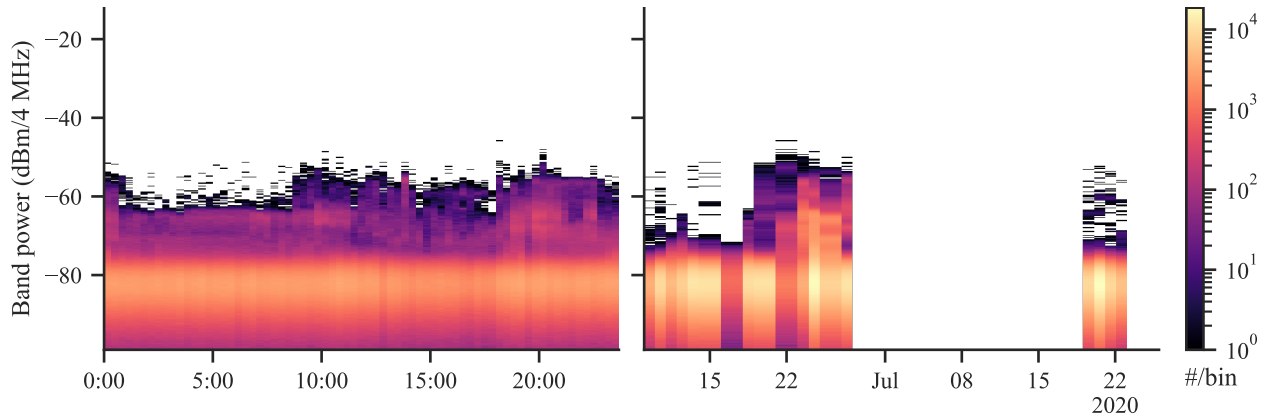


Figure D.95: Histogram heat maps of band power at 5170.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

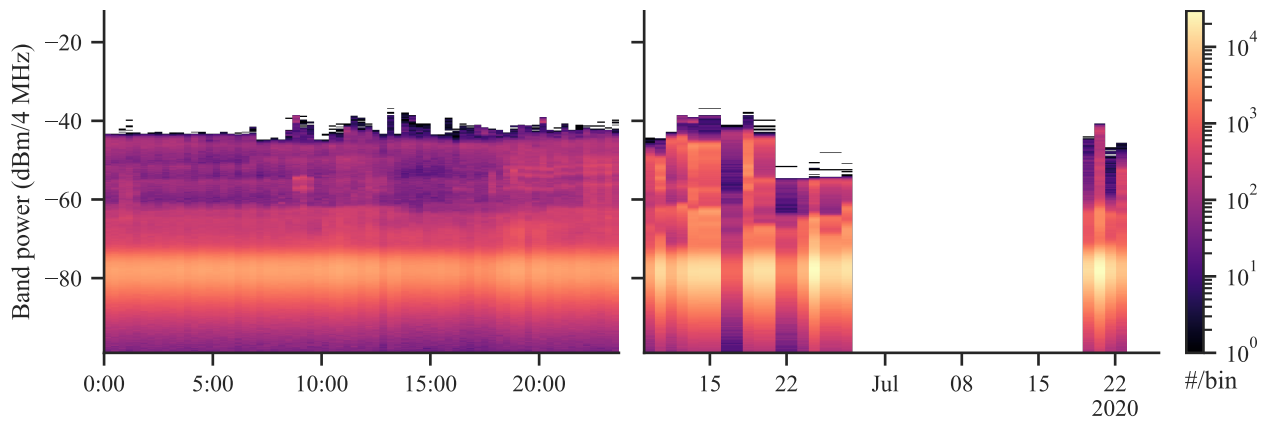


Figure D.96: Histogram heat maps of band power at 5775.0 MHz from site 6 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

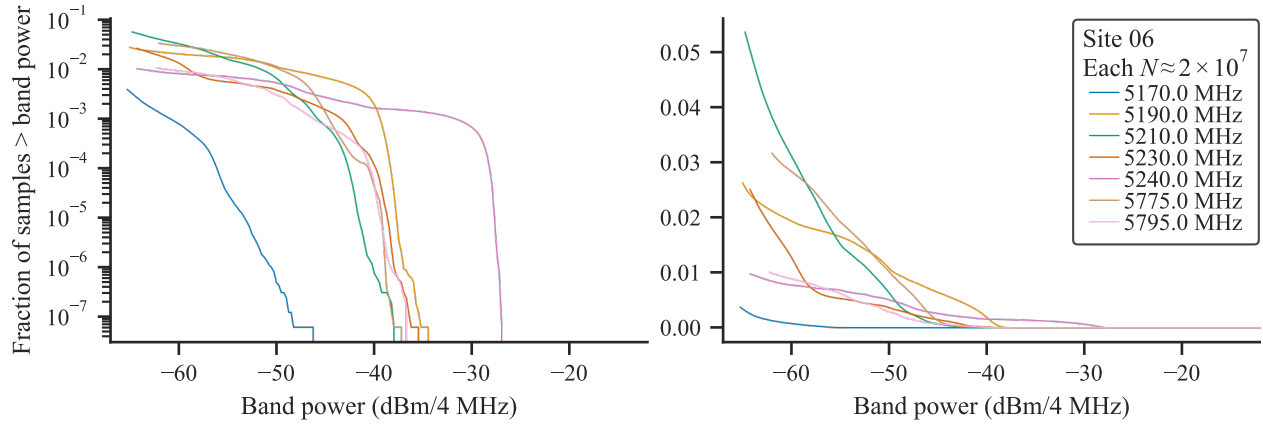


Figure D.97: Plots of empirical survival functions of band power in U-NII bands at site 6, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

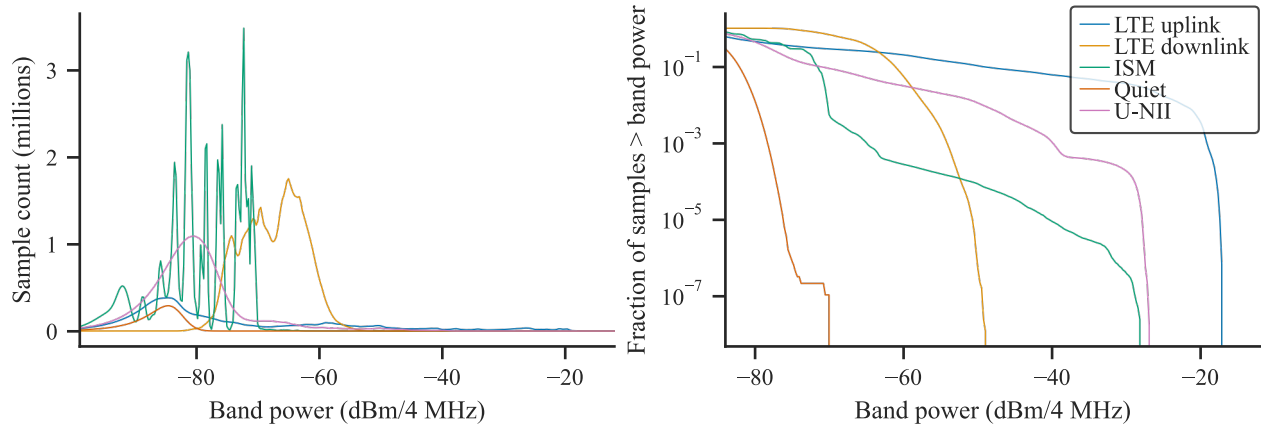


Figure D.98: Histograms (left) and empirical survival functions (right) of all samples received in site 6 in each type of band under test.

Residential Site 7

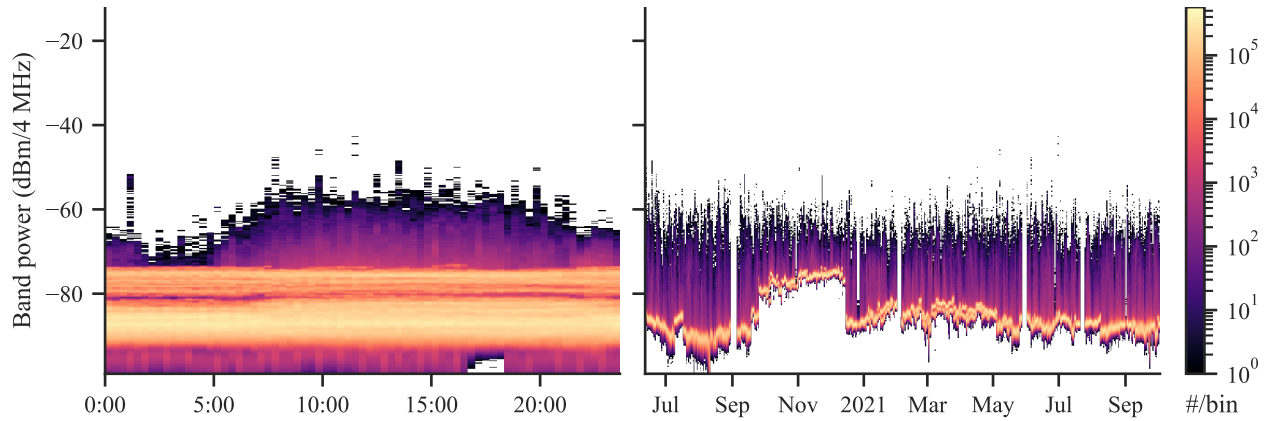


Figure D.99: Histogram heat maps of band power at 782.0 MHz from site 7 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

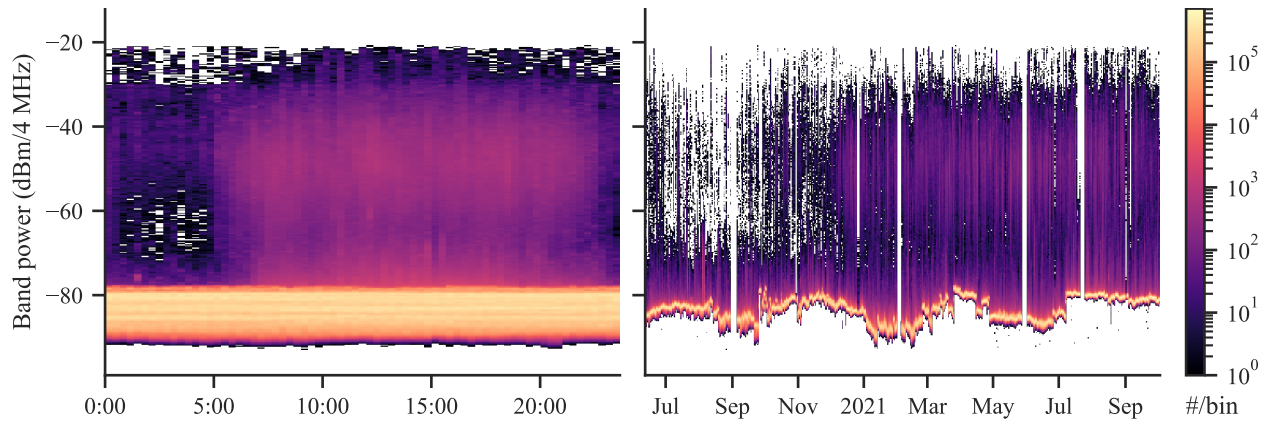


Figure D.100: Histogram heat maps of band power at 701.5 MHz from site 7 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

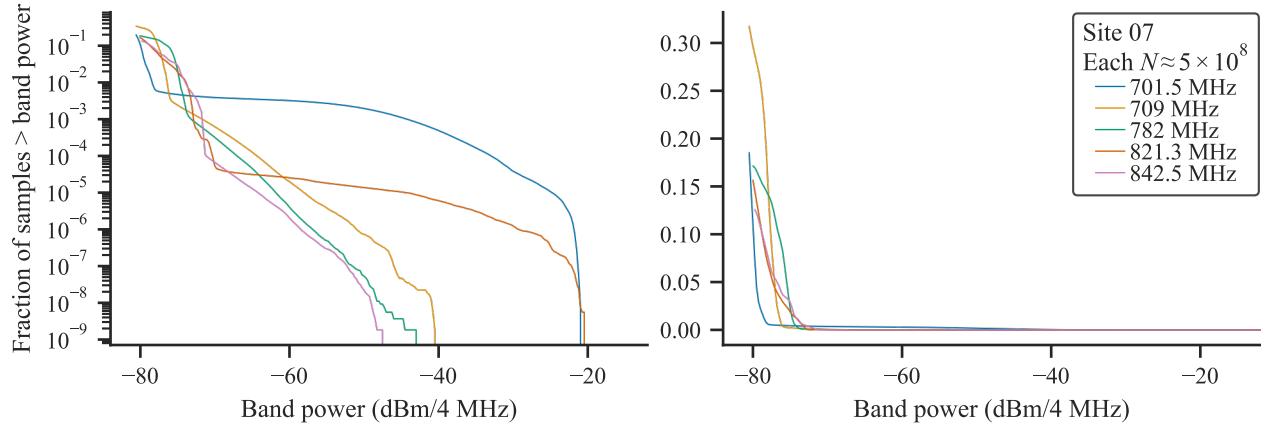


Figure D.101: Plots of empirical survival functions of band power in uplink channels in LTE bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

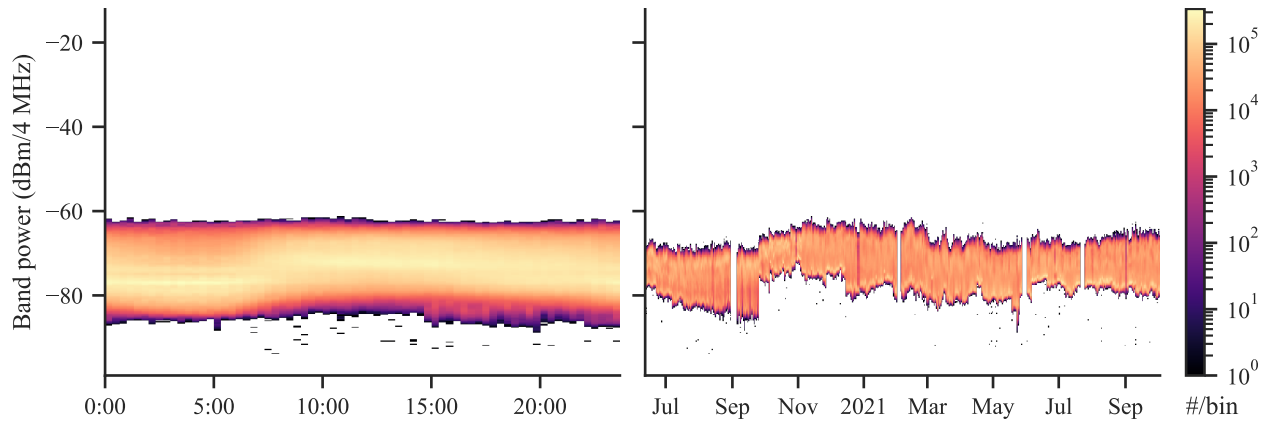


Figure D.102: Histogram heat maps of band power at 866.3 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

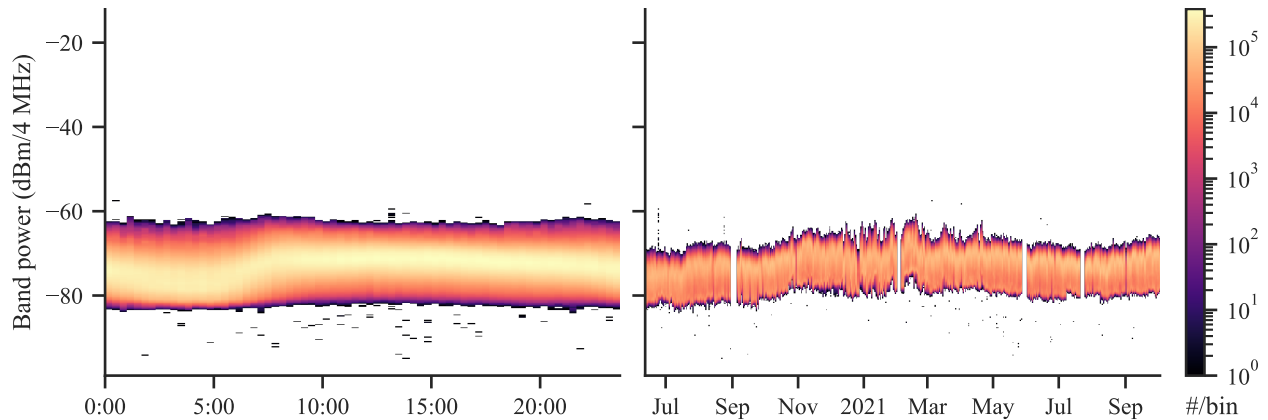


Figure D.103: Histogram heat maps of band power at 734.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

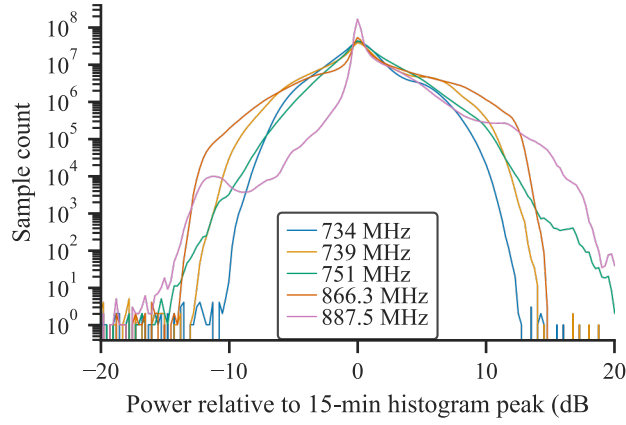


Figure D.104: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 7, as gauged by the peak histogram level in each dwell window.

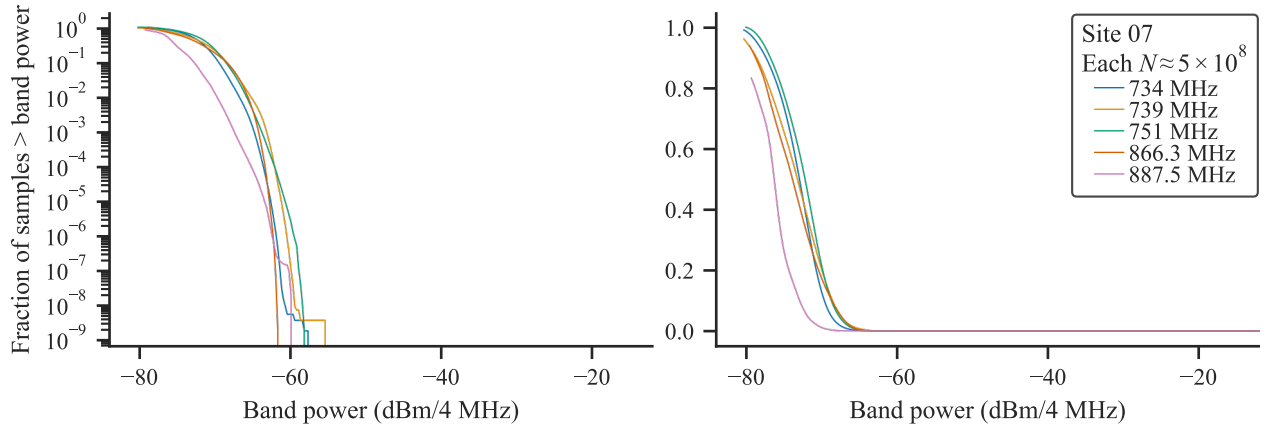


Figure D.105: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

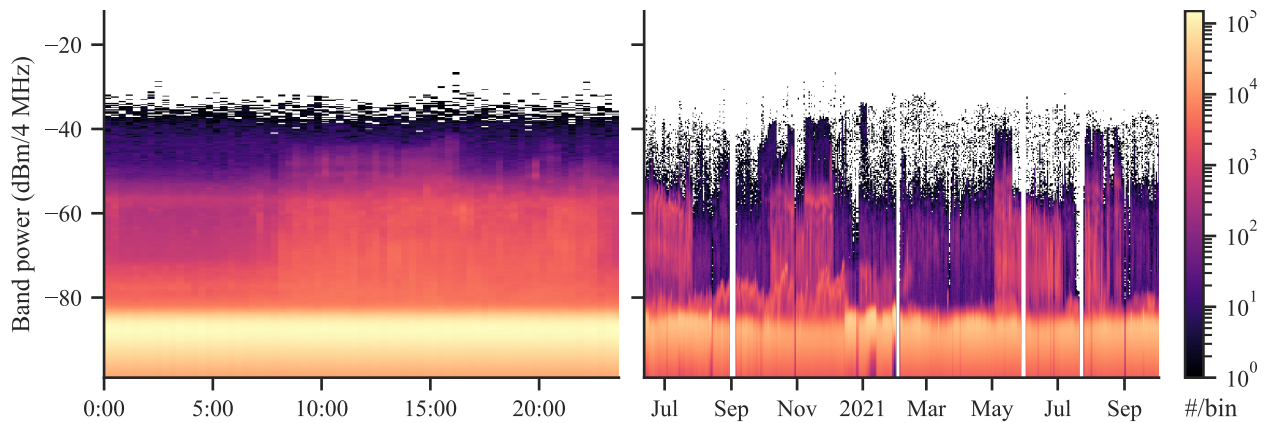


Figure D.106: Histogram heat maps of band power at 2412.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

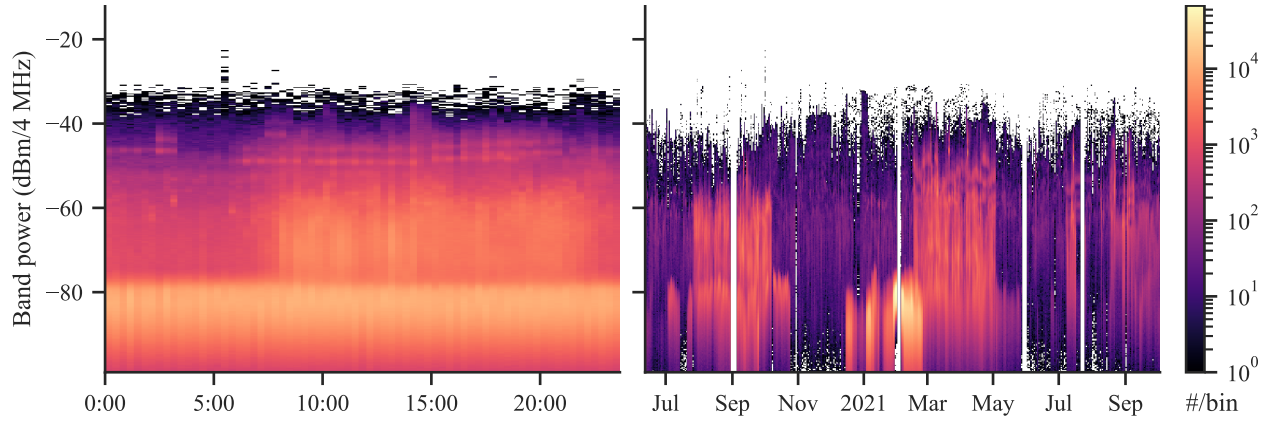


Figure D.107: Histogram heat maps of band power at 2462.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

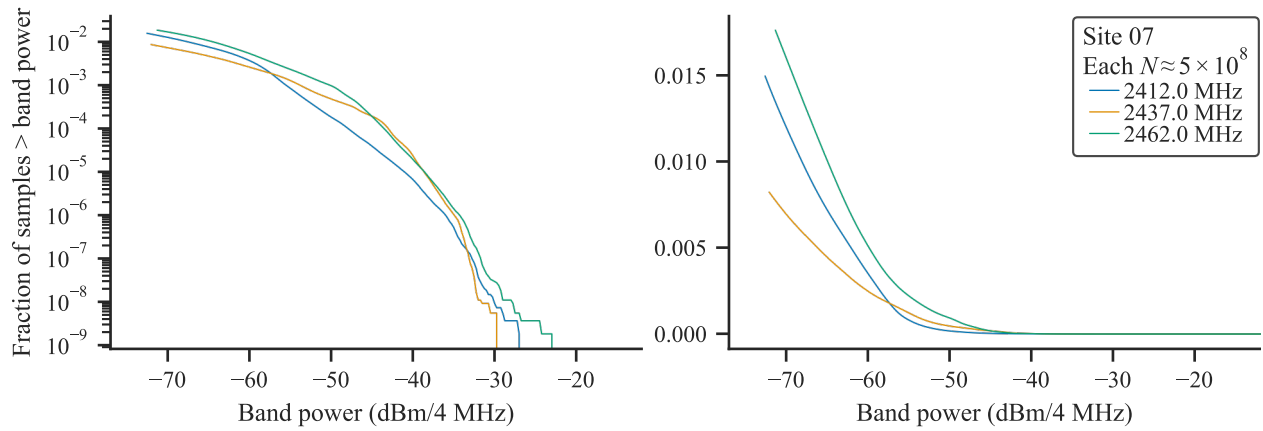


Figure D.108: Plots of empirical survival functions of band power in ISM bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

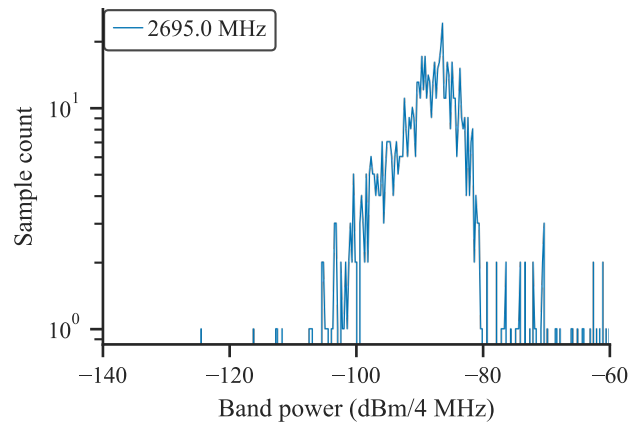


Figure D.109: Histogram of band power measured in the 2695 MHz passive service band at site 7.

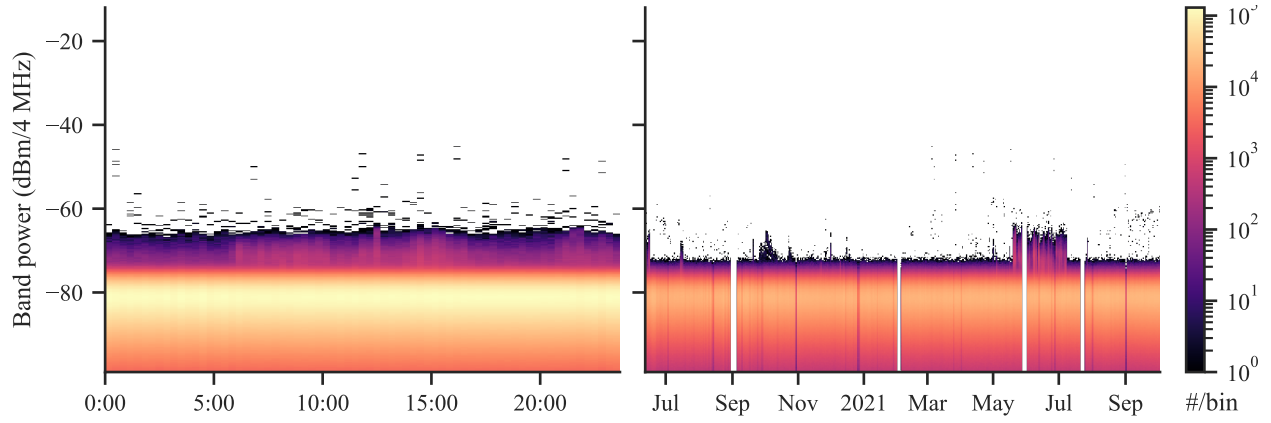


Figure D.110: Histogram heat maps of band power at 5170.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

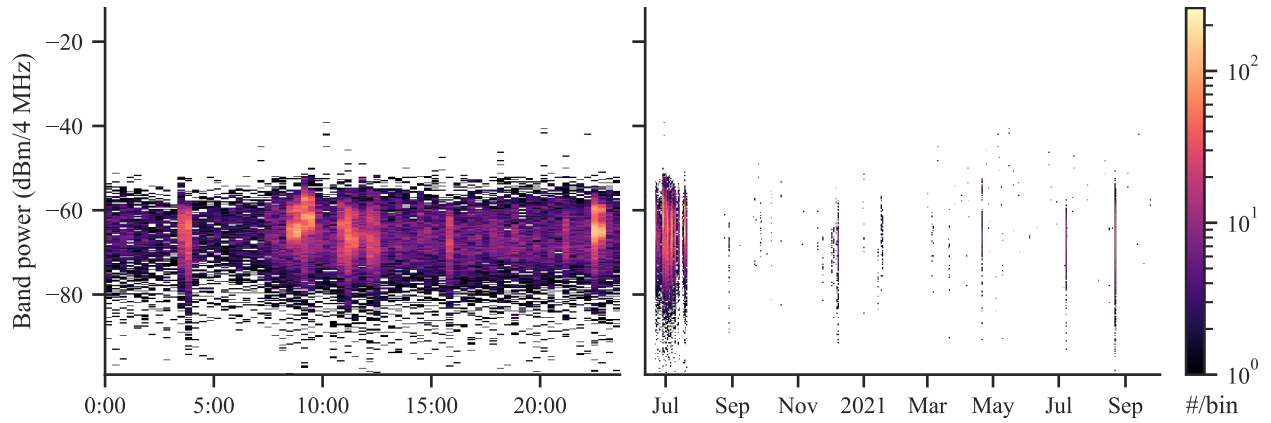


Figure D.111: Histogram heat maps of band power at 5775.0 MHz from site 7 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

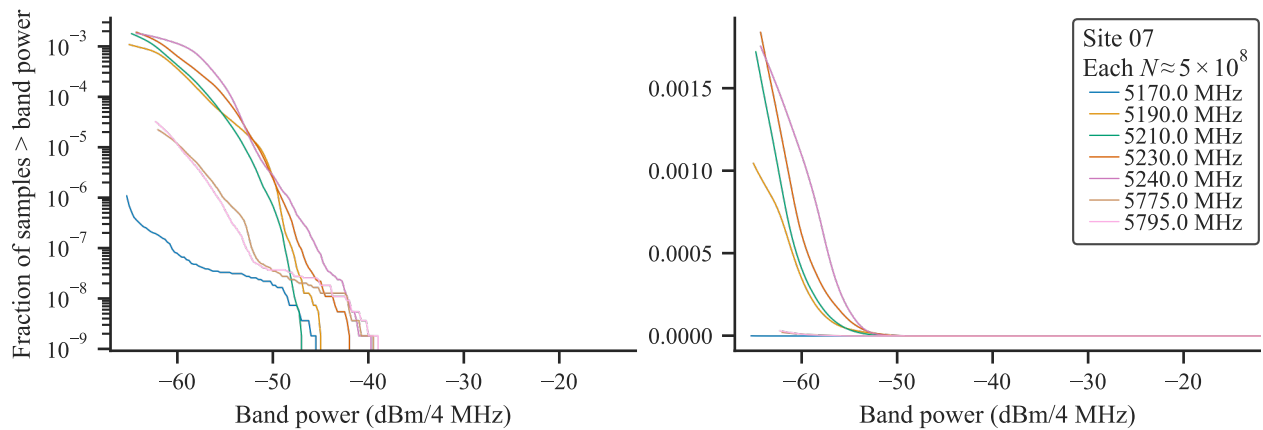


Figure D.112: Plots of empirical survival functions of band power in U-NII bands at site 7, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

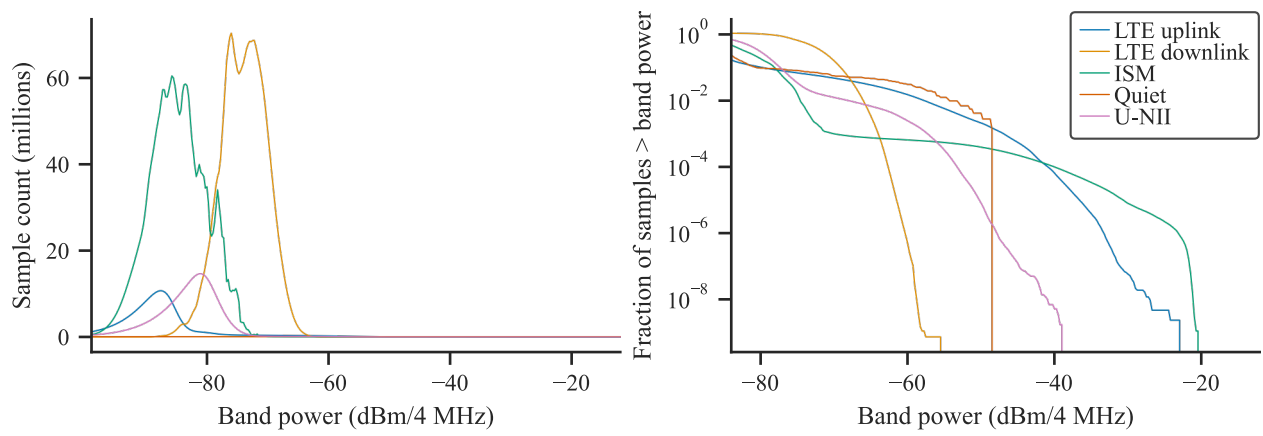


Figure D.113: Histograms (left) and empirical survival functions (right) of all samples received in site 7 in each type of band under test.

Residential Site 8

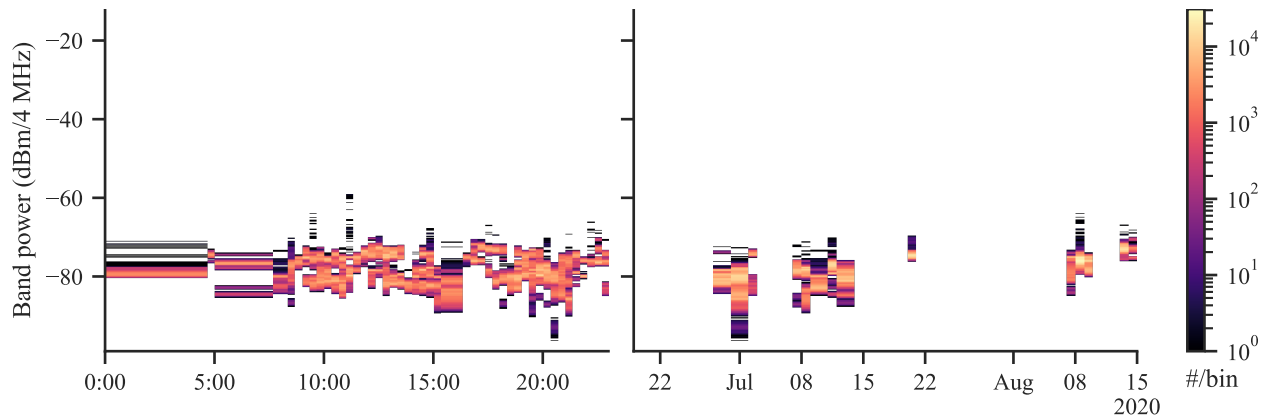


Figure D.114: Histogram heat maps of band power at 821.3 MHz from site 8 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

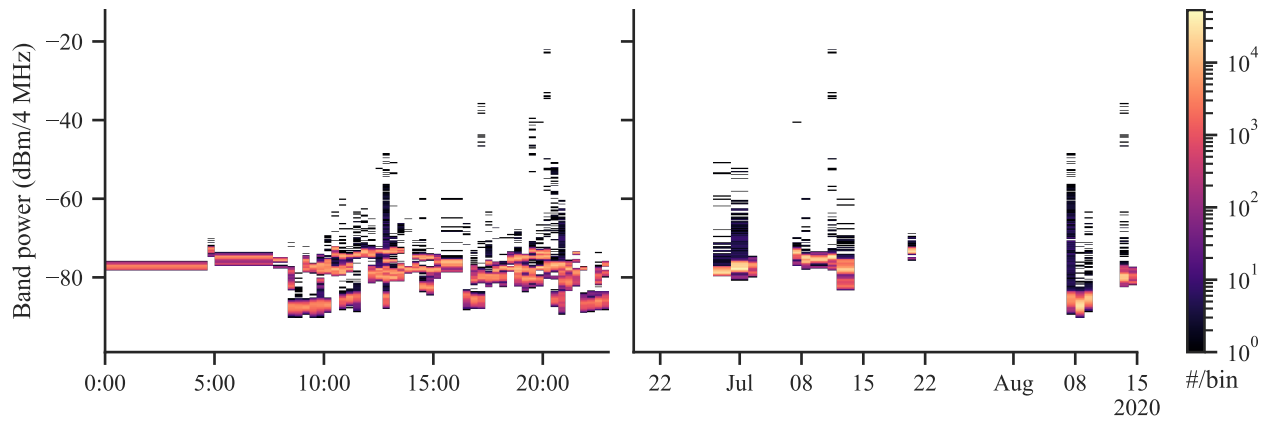


Figure D.115: Histogram heat maps of band power at 709.0 MHz from site 8 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

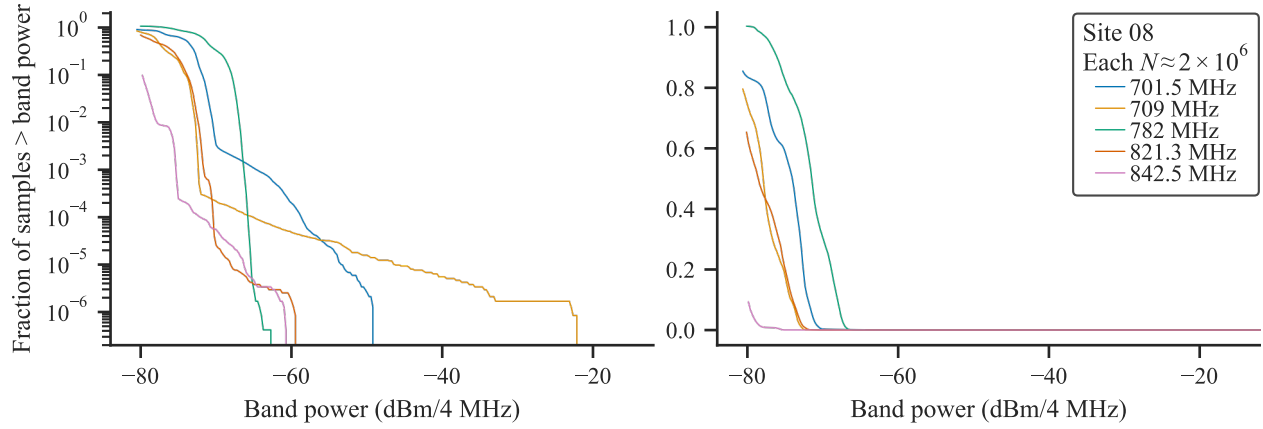


Figure D.116: Plots of empirical survival functions of band power in uplink channels in LTE bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

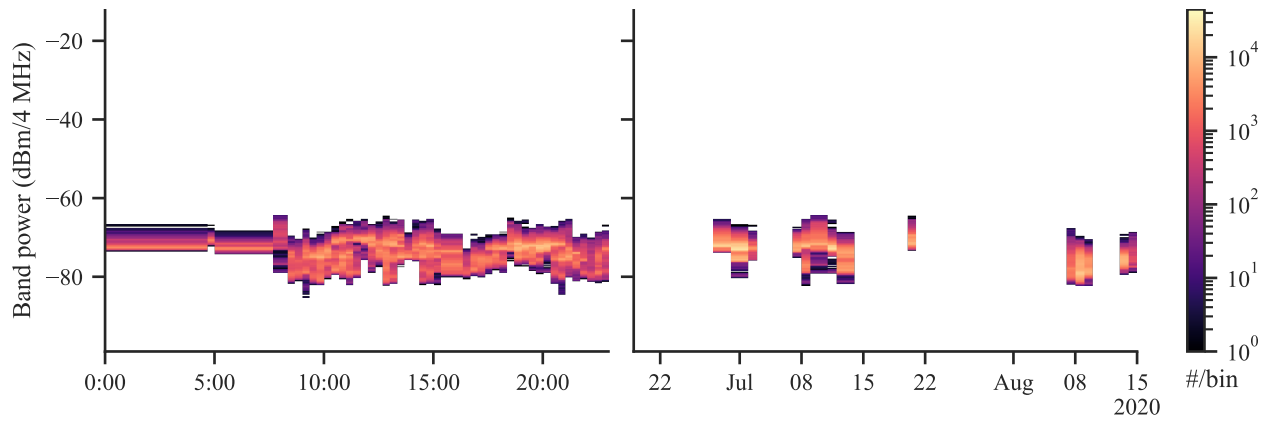


Figure D.117: Histogram heat maps of band power at 887.5 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

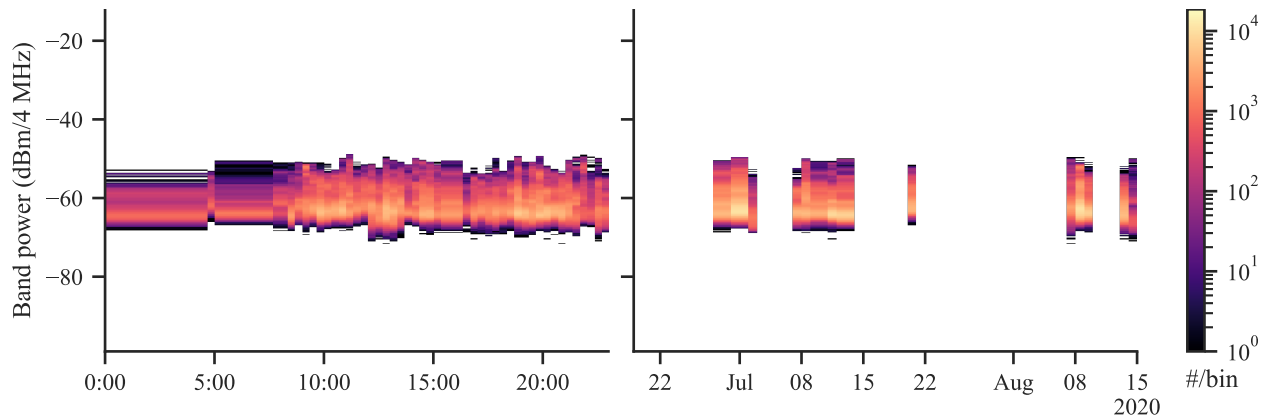


Figure D.118: Histogram heat maps of band power at 751.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

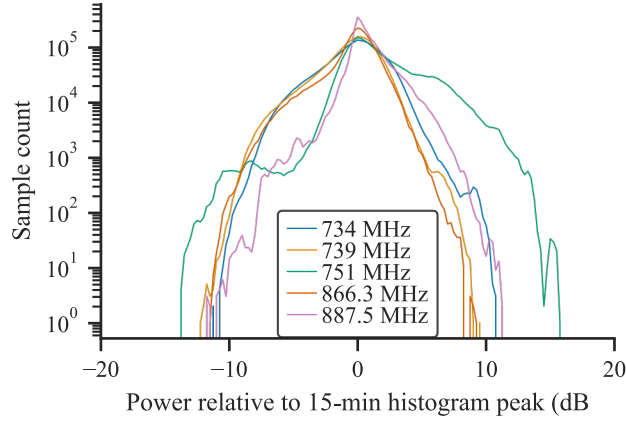


Figure D.119: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 8, as gauged by the peak histogram level in each dwell window.

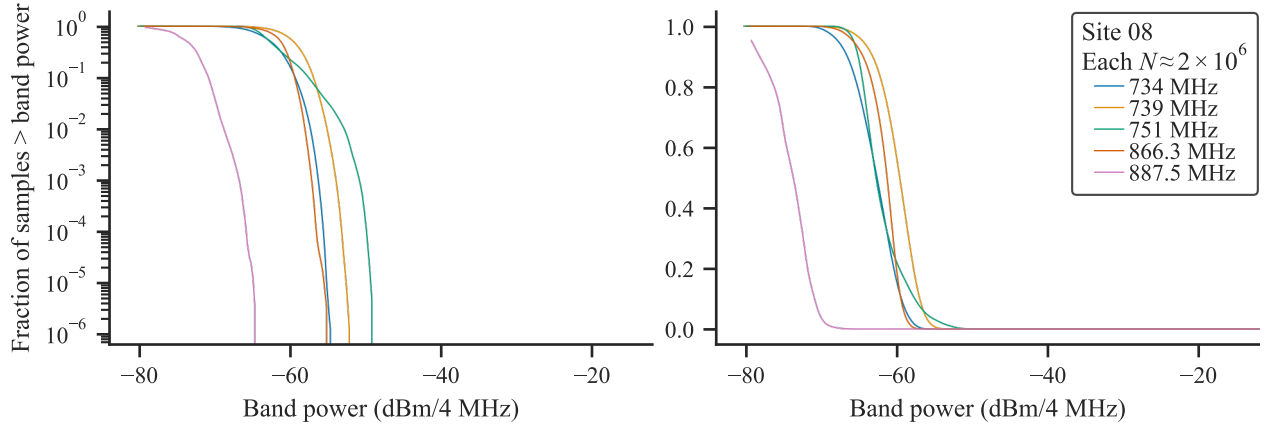


Figure D.120: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

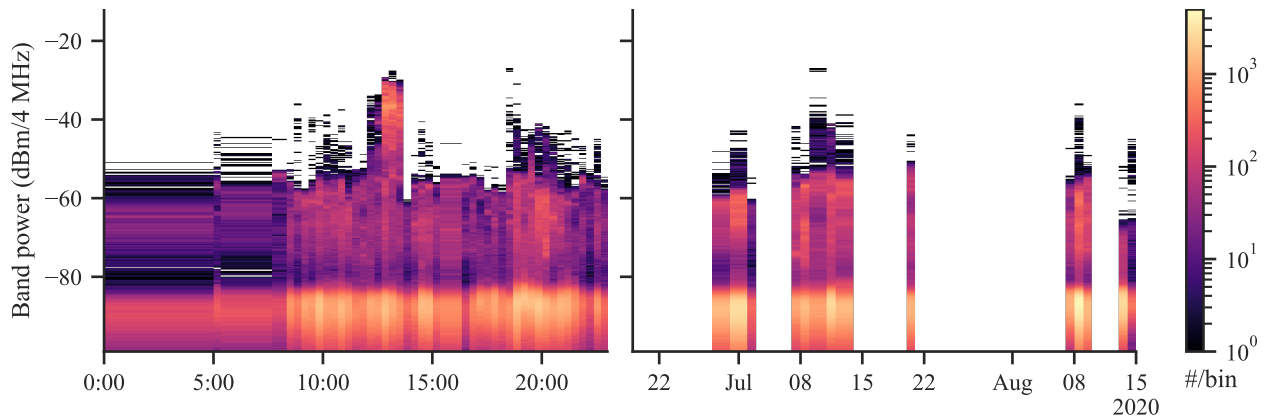


Figure D.121: Histogram heat maps of band power at 2412.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

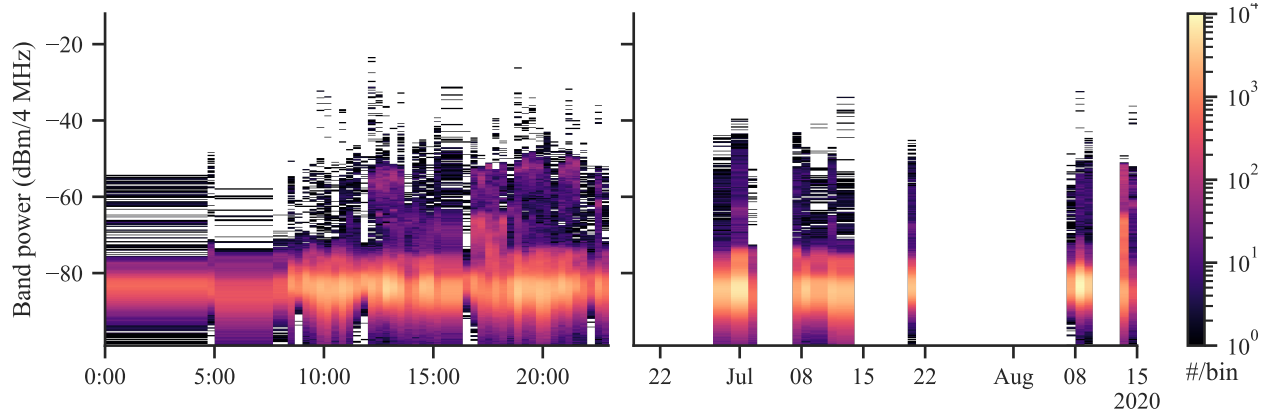


Figure D.122: Histogram heat maps of band power at 2462.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

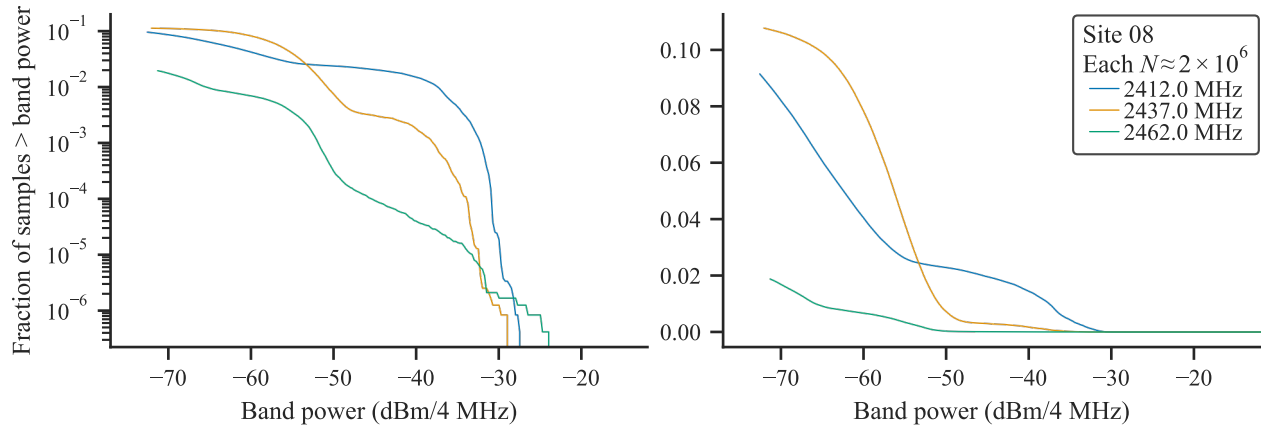


Figure D.123: Plots of empirical survival functions of band power in ISM bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

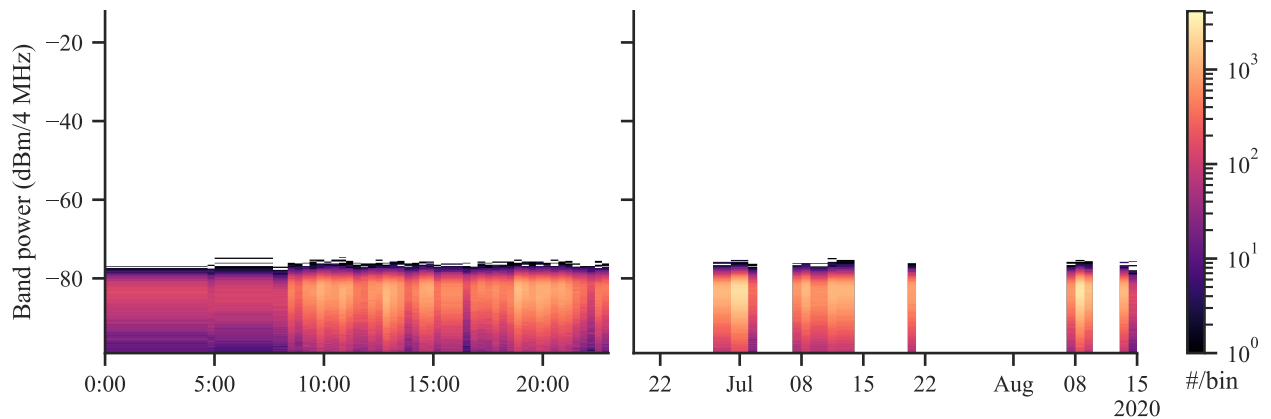


Figure D.124: Histogram heat maps of band power at 2695.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

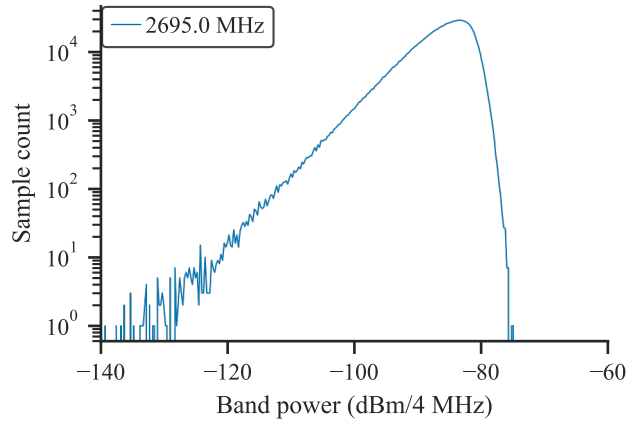


Figure D.125: Histogram of band power measured in the 2695 MHz passive service band at site 8.

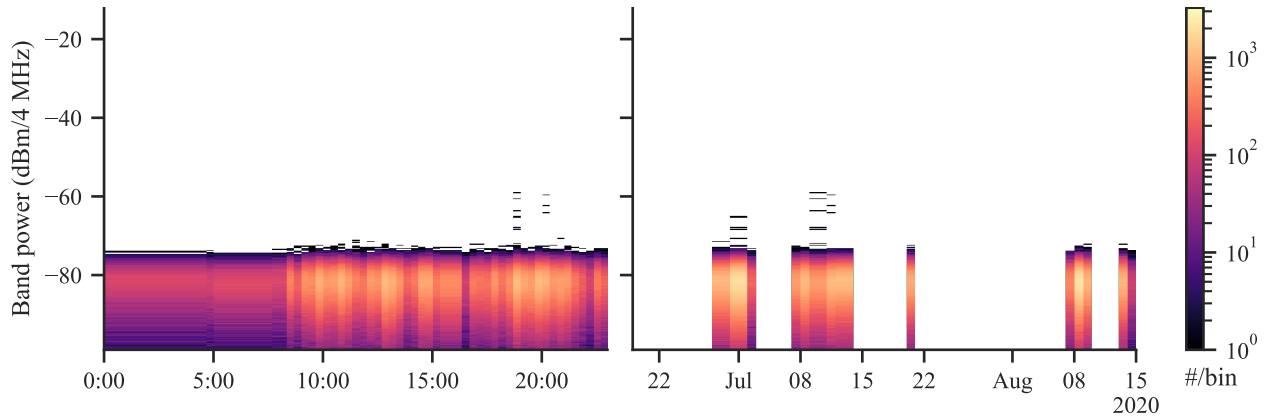


Figure D.126: Histogram heat maps of band power at 5170.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

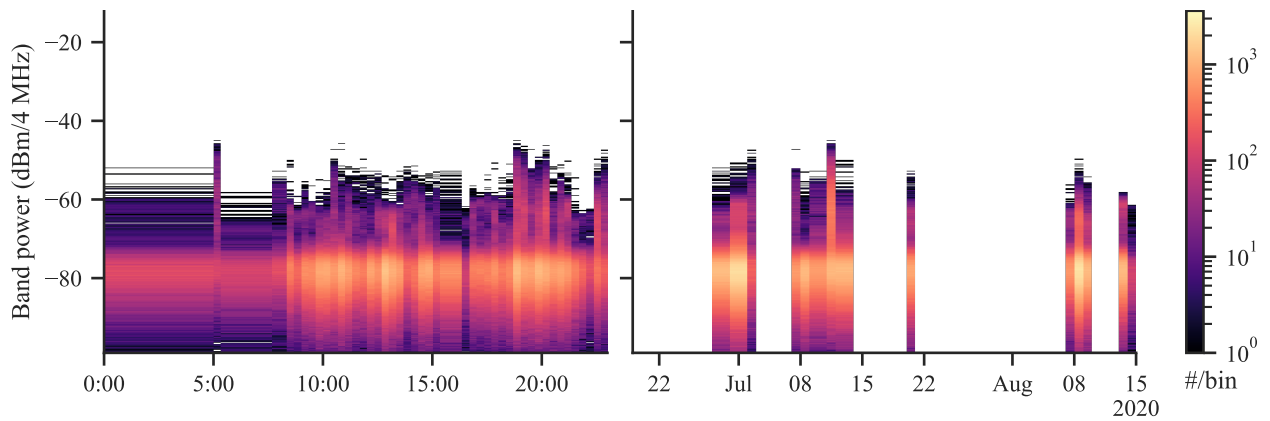


Figure D.127: Histogram heat maps of band power at 5795.0 MHz from site 8 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

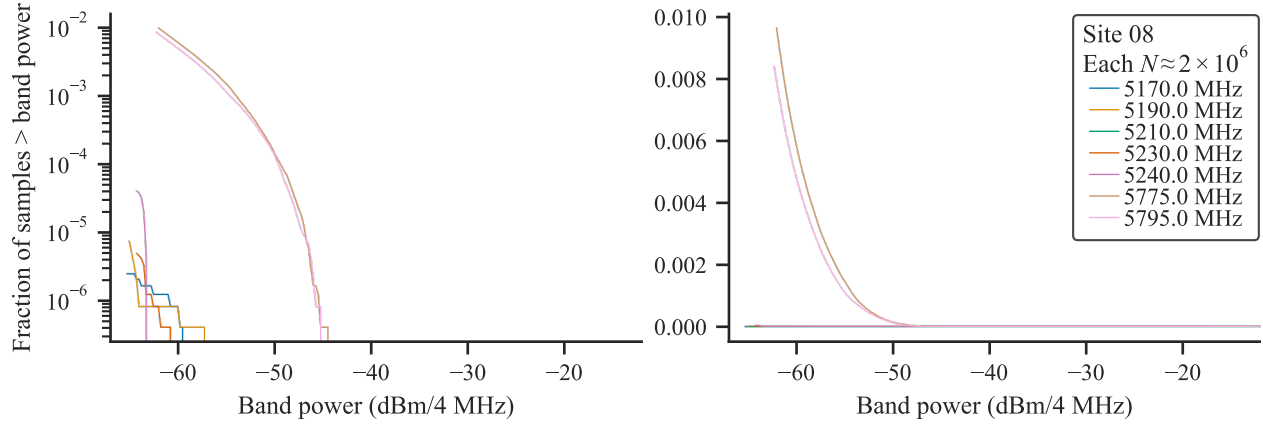


Figure D.128: Plots of empirical survival functions offband power in U-NII bands at site 8, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

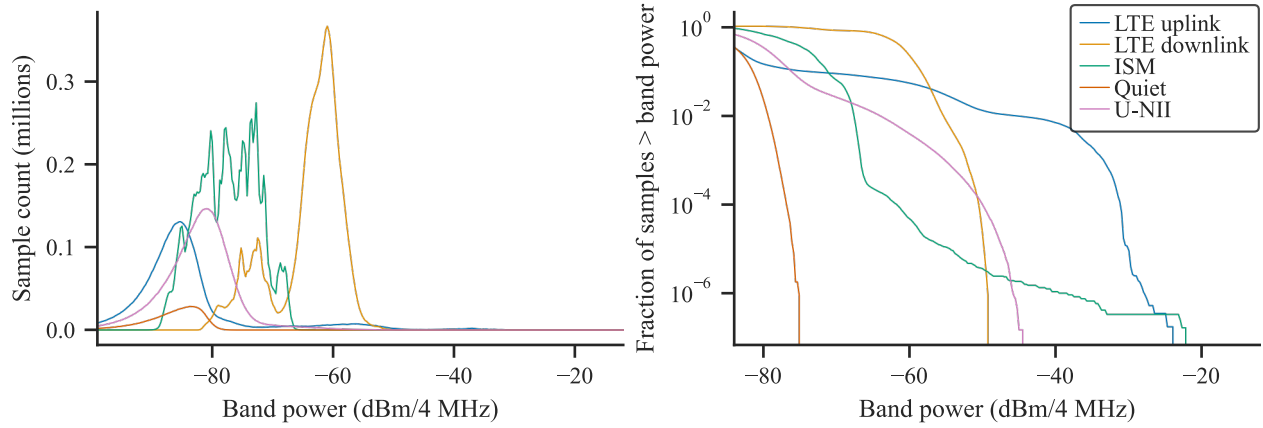


Figure D.129: Histograms (left) and empirical survival functions (right) of all samples received in site 8 in each type of band under test.

Residential Site 9

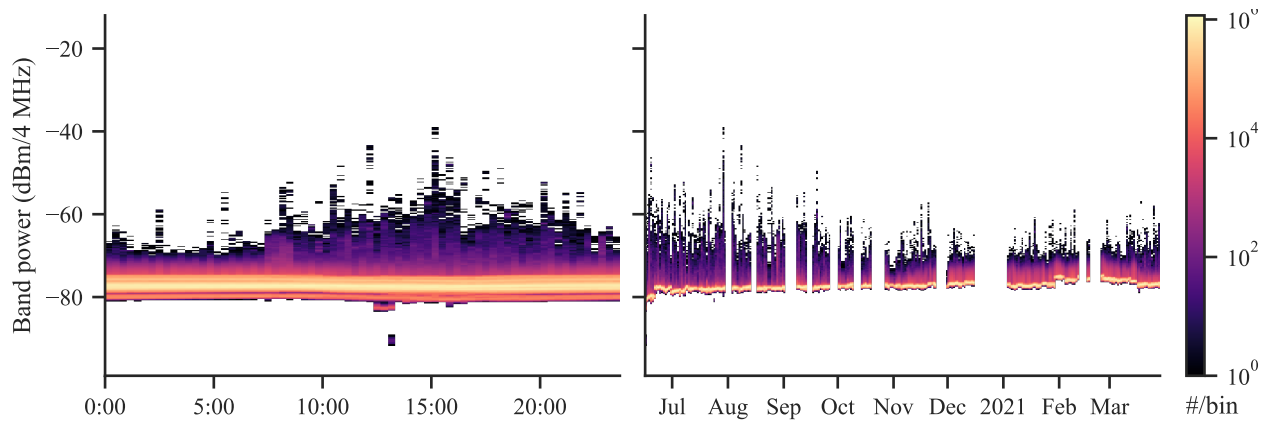


Figure D.130: Histogram heat maps of band power at 701.5 MHz from site 9 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

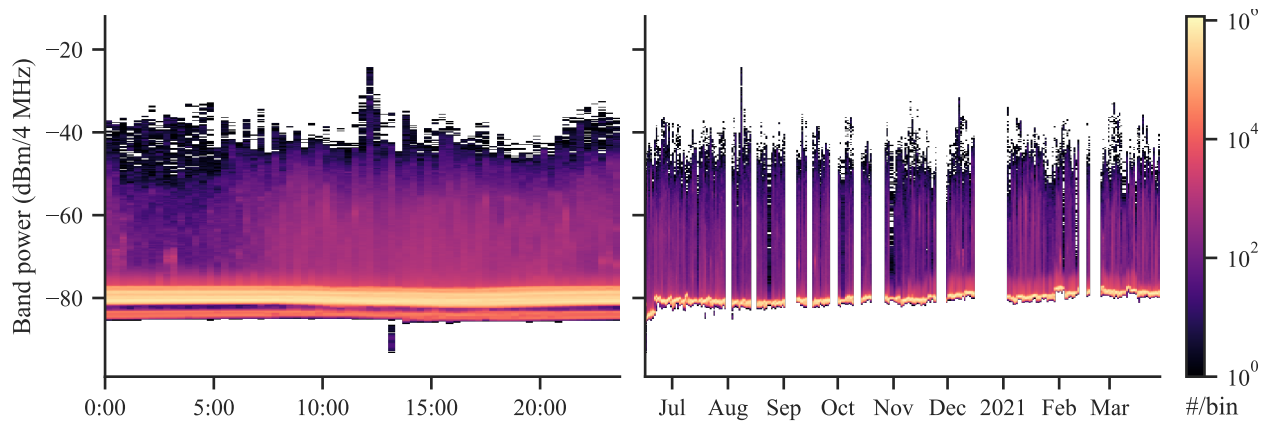


Figure D.131: Histogram heat maps of band power at 709.0 MHz from site 9 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

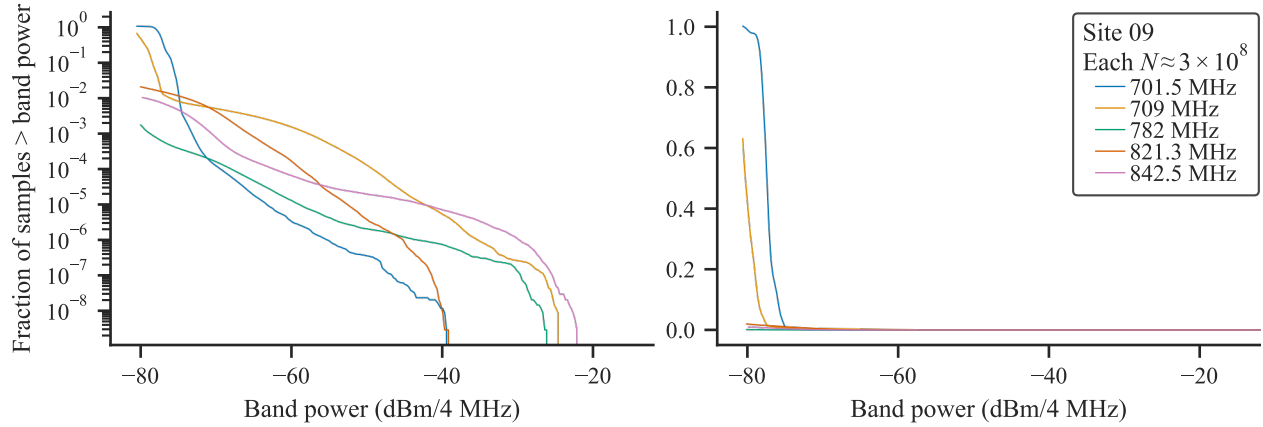


Figure D.132: Plots of empirical survival functions of band power in uplink channels in LTE bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

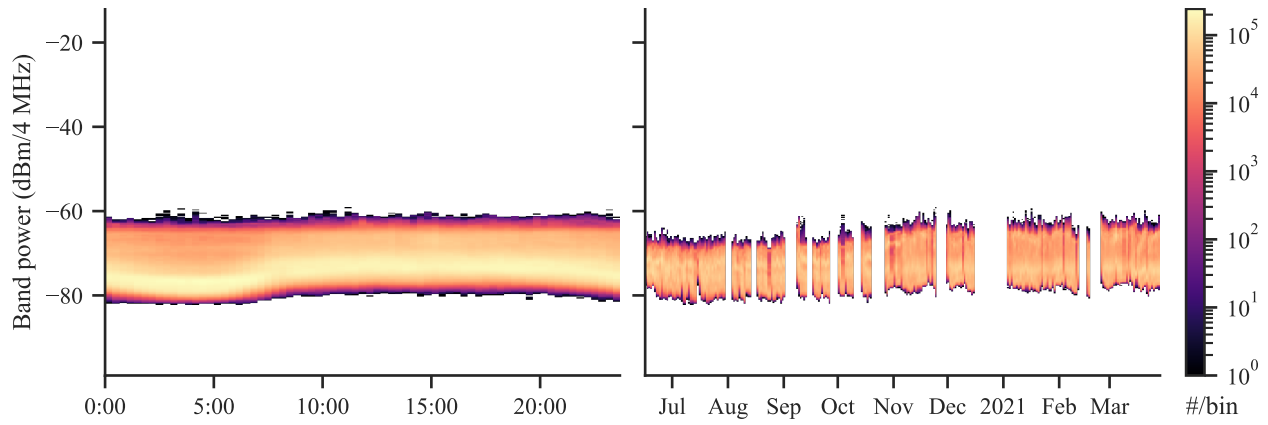


Figure D.133: Histogram heat maps of band power at 866.3 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

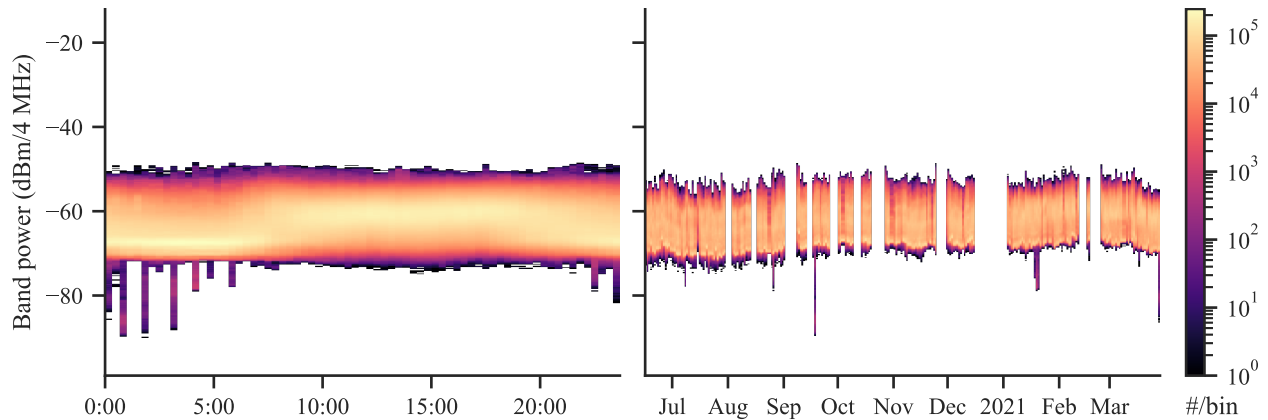


Figure D.134: Histogram heat maps of band power at 751.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

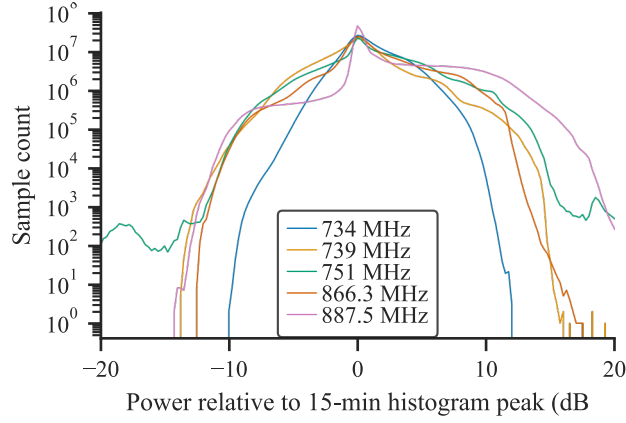


Figure D.135: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 9, as gauged by the peak histogram level in each dwell window.

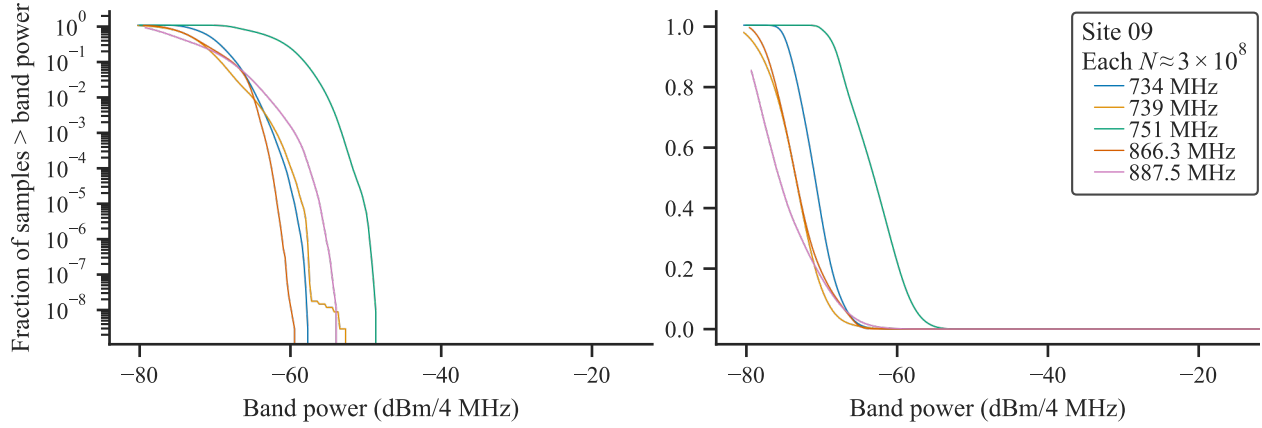


Figure D.136: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

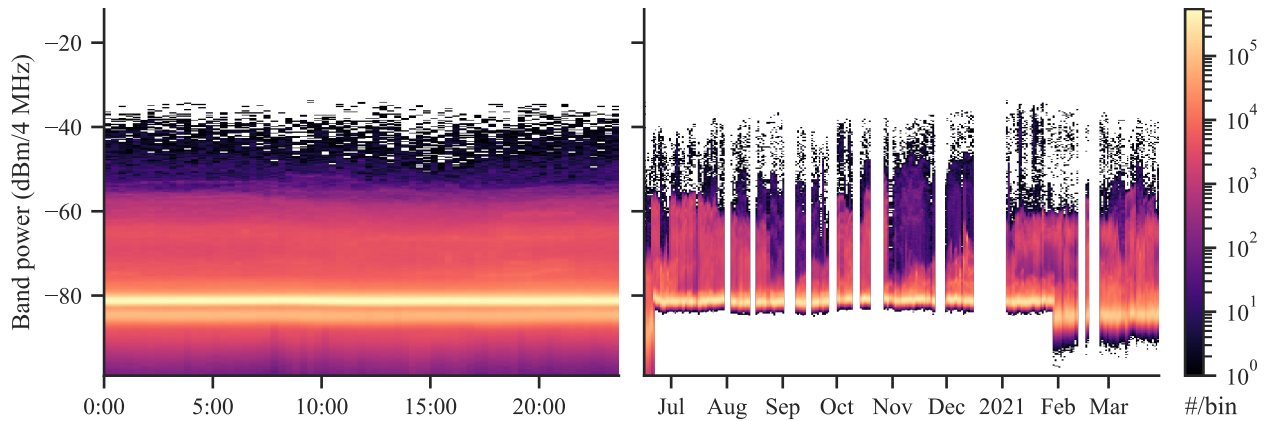


Figure D.137: Histogram heat maps of band power at 2437.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

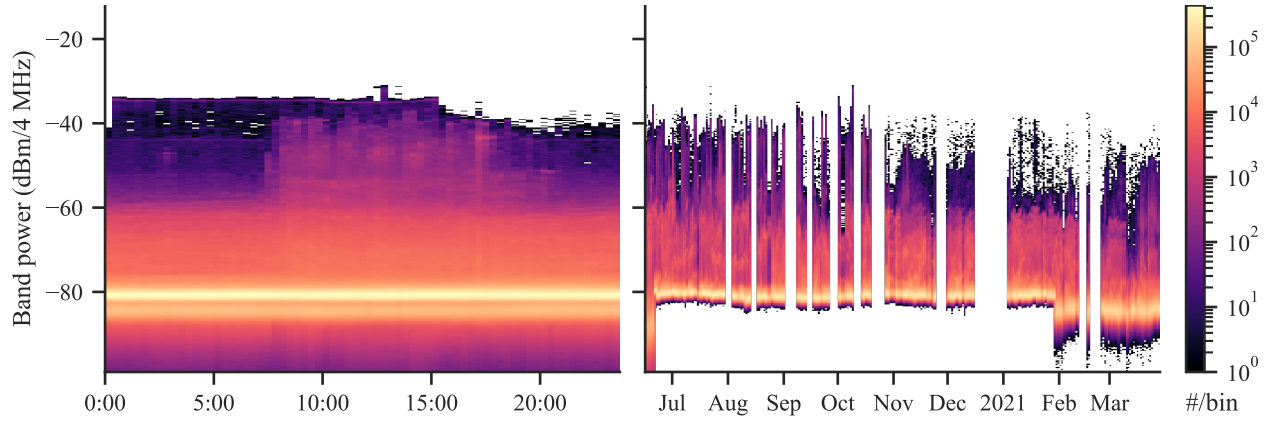


Figure D.138: Histogram heat maps of band power at 2462.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

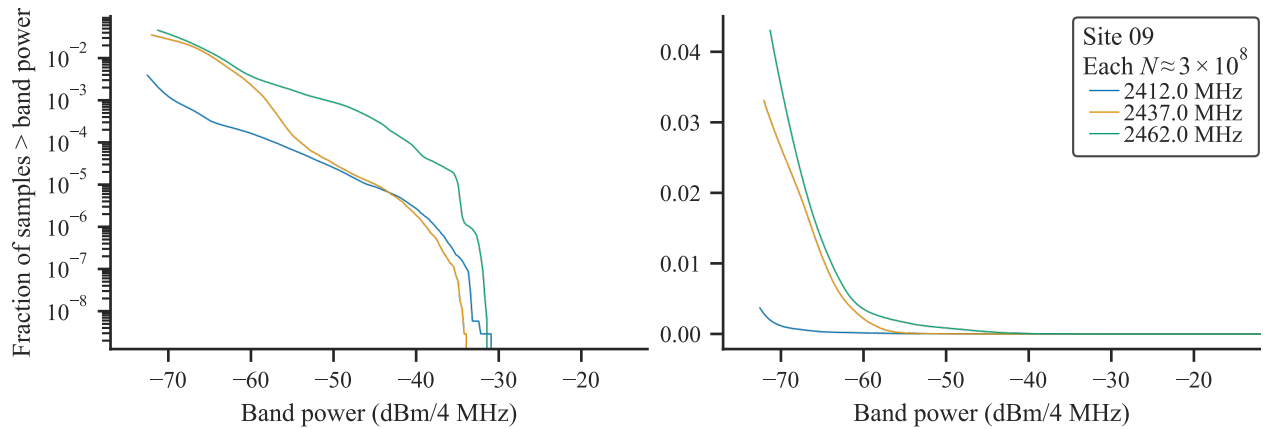


Figure D.139: Plots of empirical survival functions of band power in ISM bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

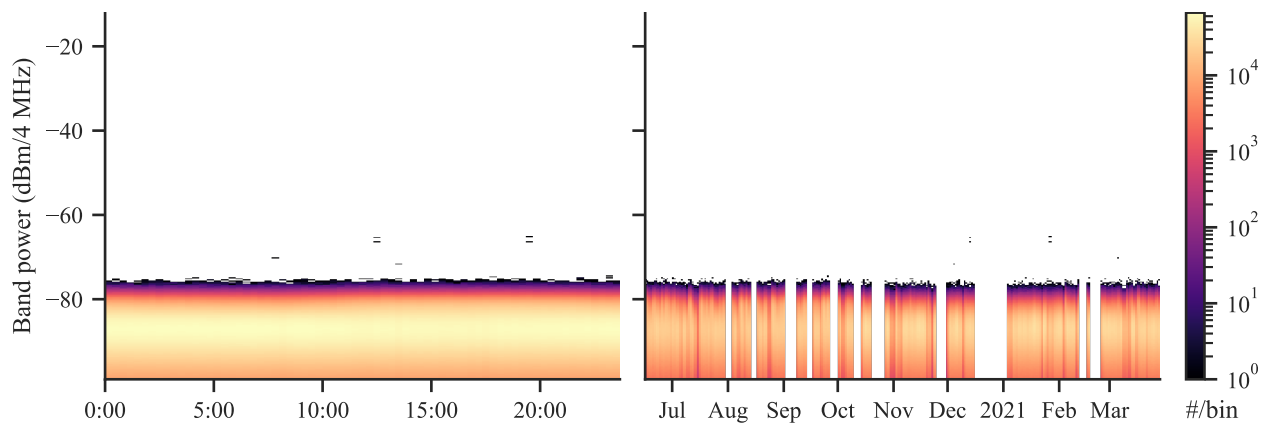


Figure D.140: Histogram heat maps of band power at 2695.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

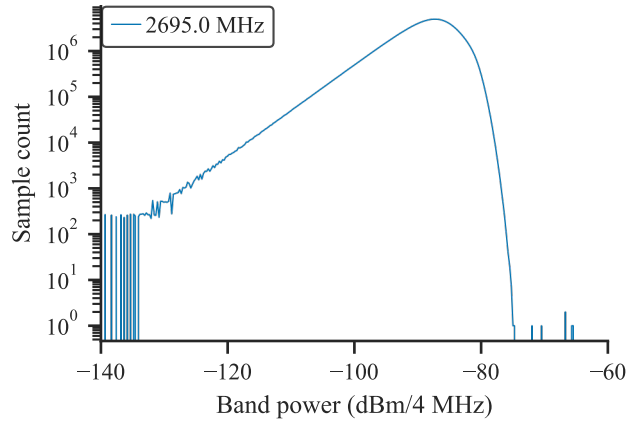


Figure D.141: Histogram of band power measured in the 2695 MHz passive service band at site 9.

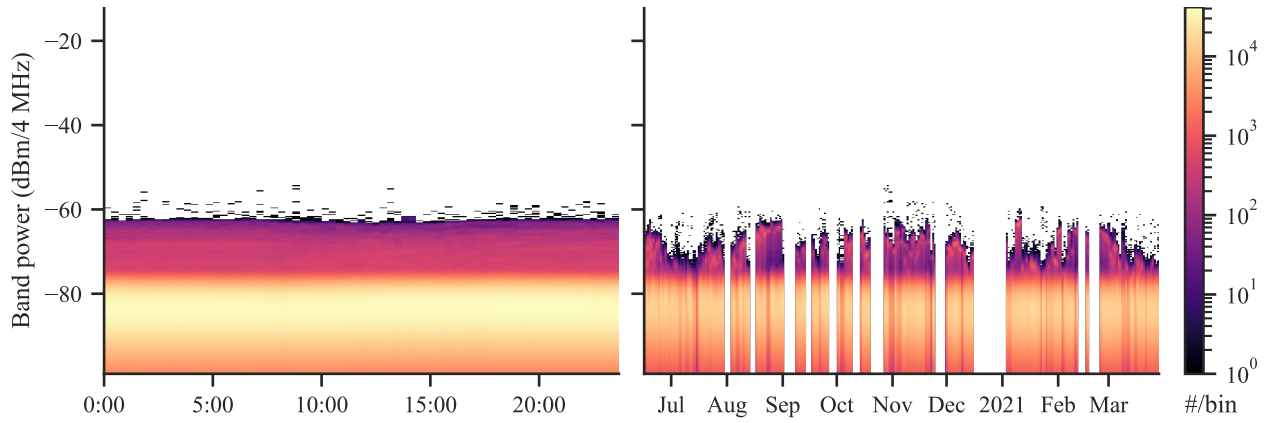


Figure D.142: Histogram heat maps of band power at 5190.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

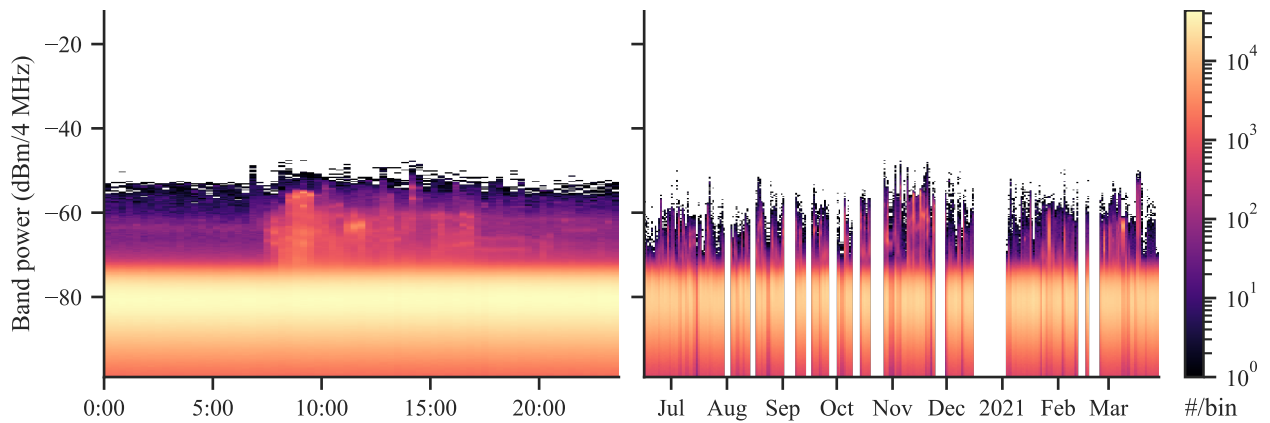


Figure D.143: Histogram heat maps of band power at 5795.0 MHz from site 9 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

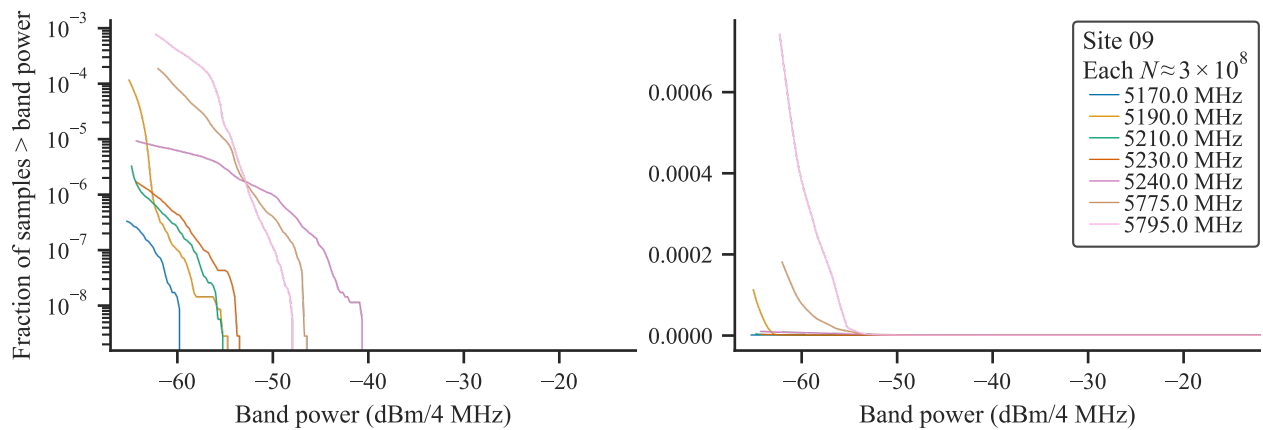


Figure D.144: Plots of empirical survival functions offband power in U-NII bands at site 9, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

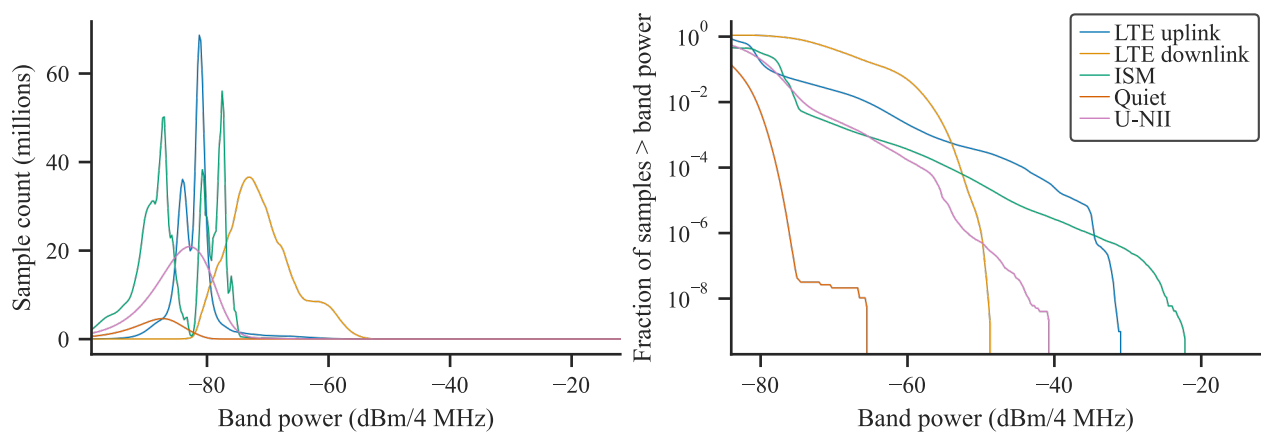


Figure D.145: Histograms (left) and empirical survival functions (right) of all samples received in site 9 in each type of band under test.

Residential Site 10

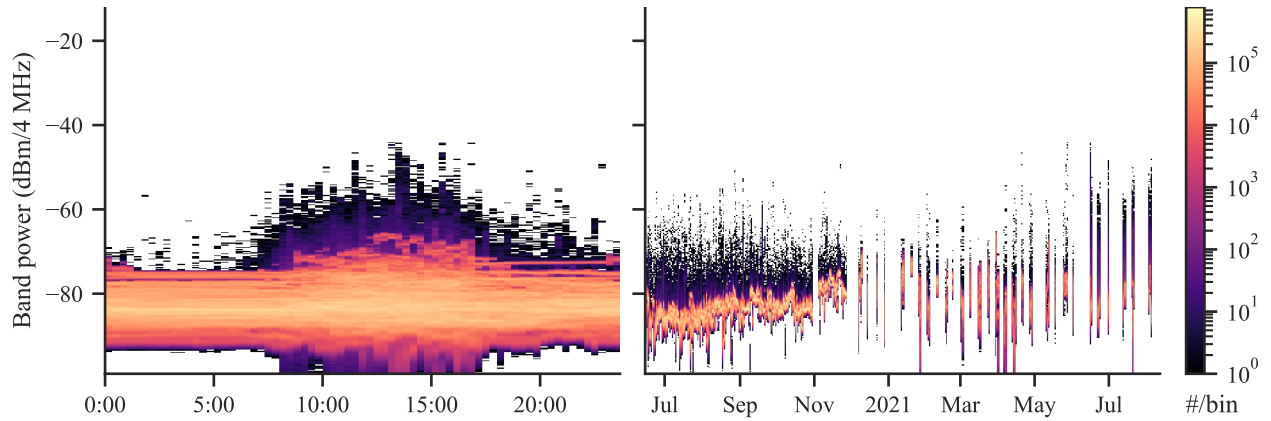


Figure D.146: Histogram heat maps of band power at 709.0 MHz from site 10 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

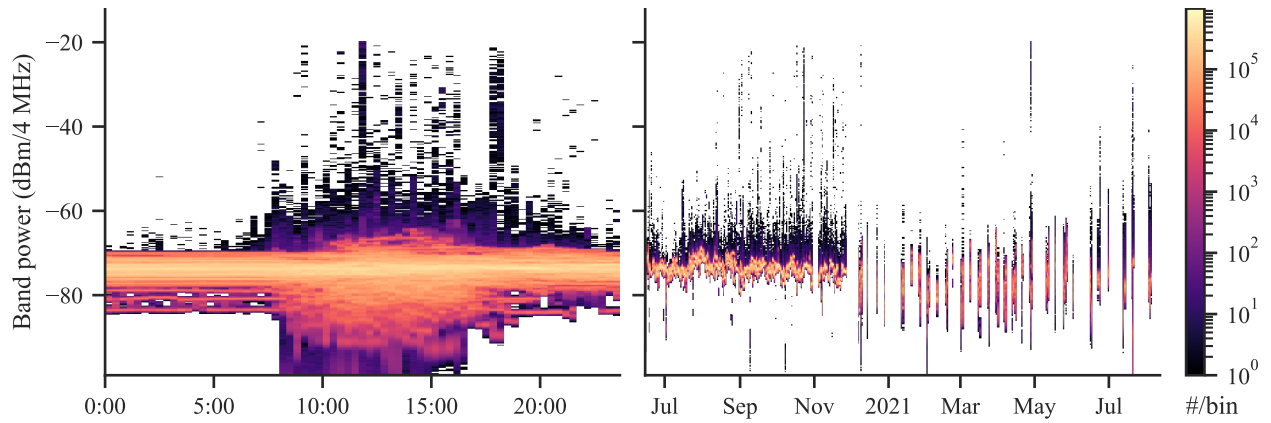


Figure D.147: Histogram heat maps of band power at 842.5 MHz from site 10 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

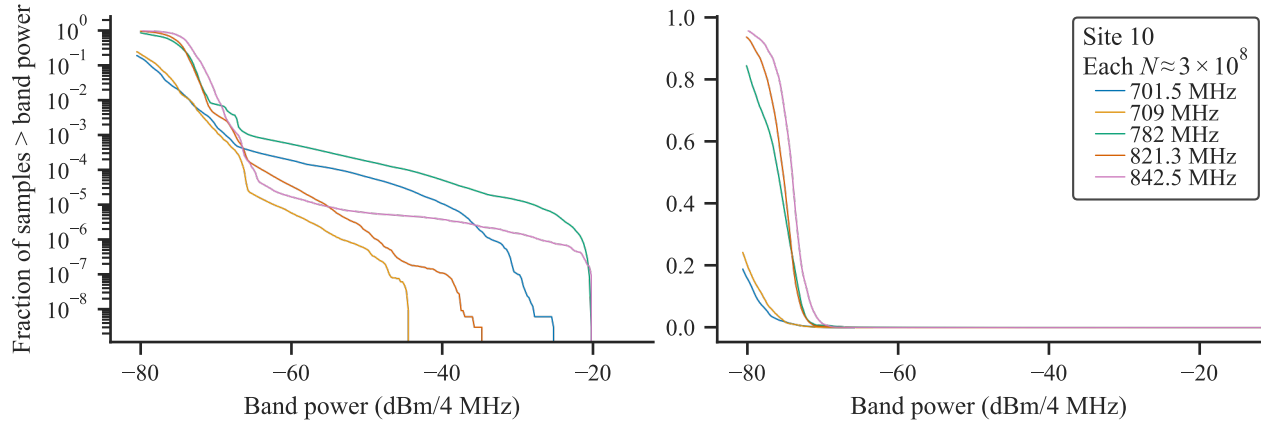


Figure D.148: Plots of empirical survival functions of band power in uplink channels in LTE bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

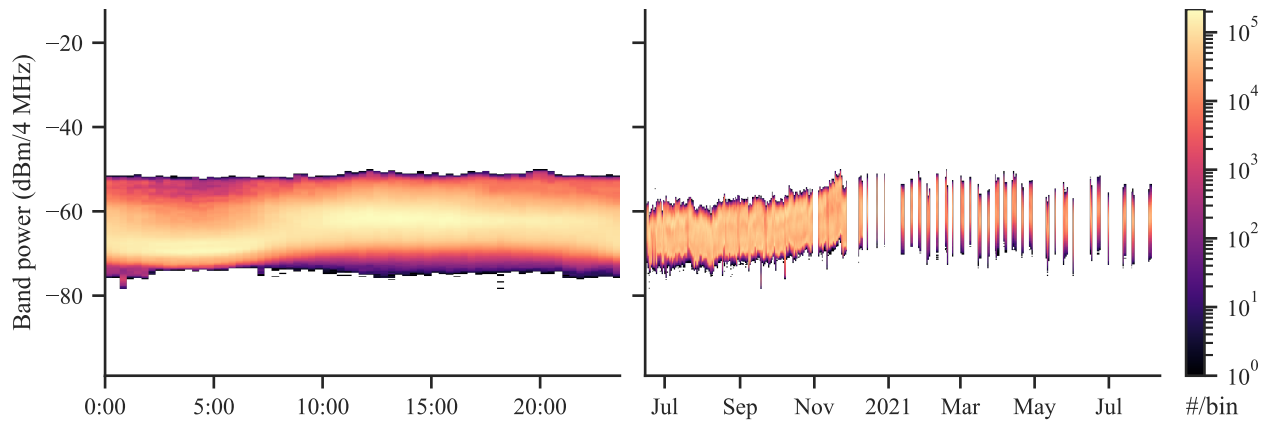


Figure D.149: Histogram heat maps of band power at 751.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

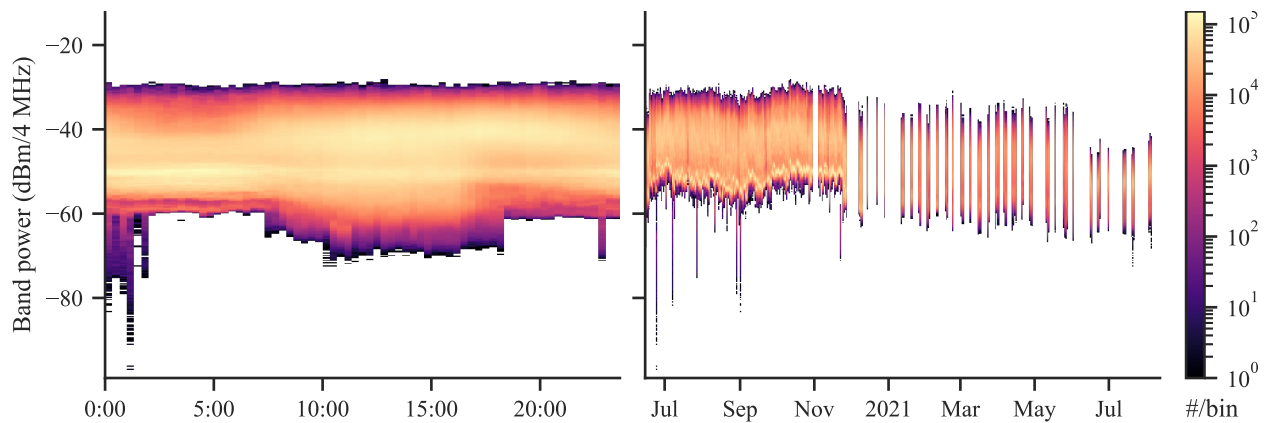


Figure D.150: Histogram heat maps of band power at 739.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

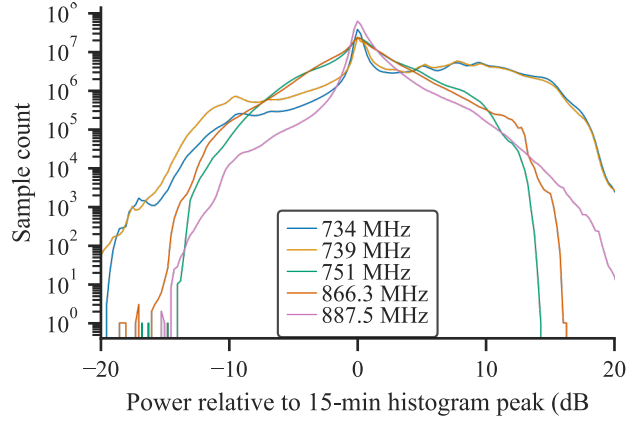


Figure D.151: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 10, as gauged by the peak histogram level in each dwell window.

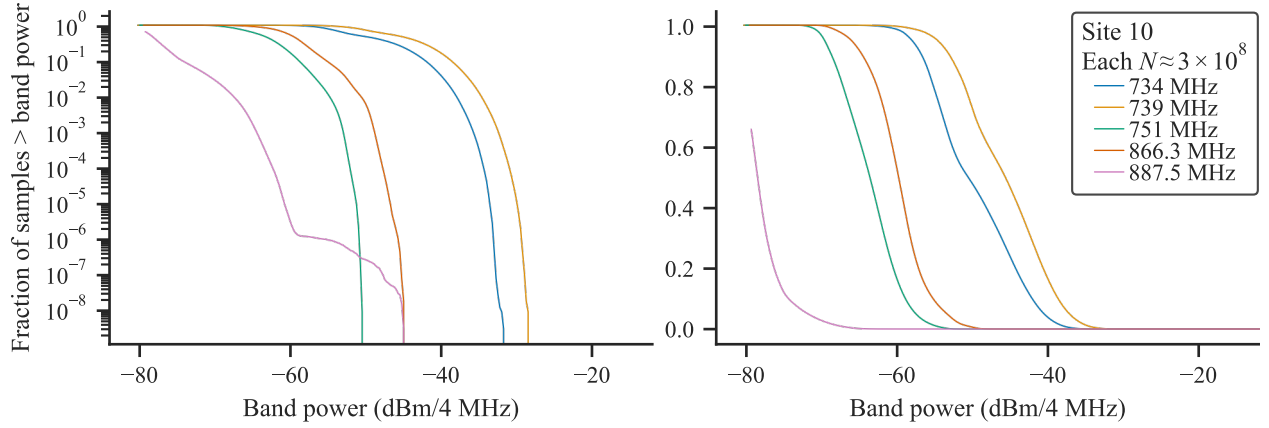


Figure D.152: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

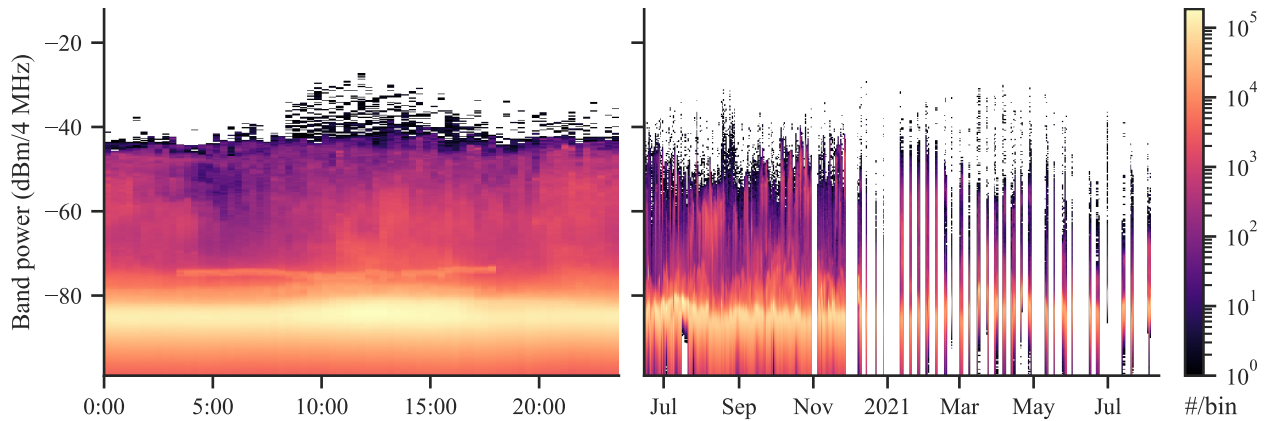


Figure D.153: Histogram heat maps of band power at 2412.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

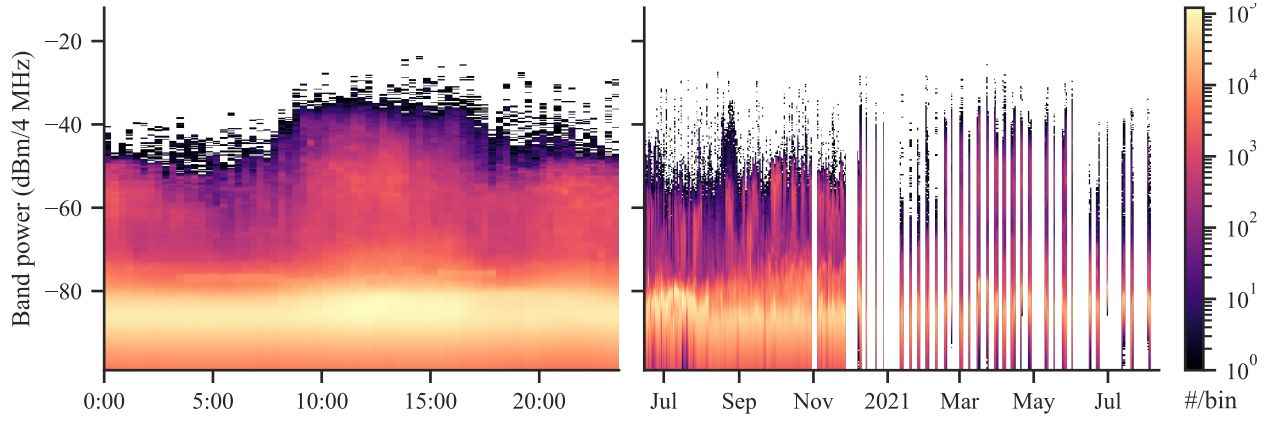


Figure D.154: Histogram heat maps of band power at 2437.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

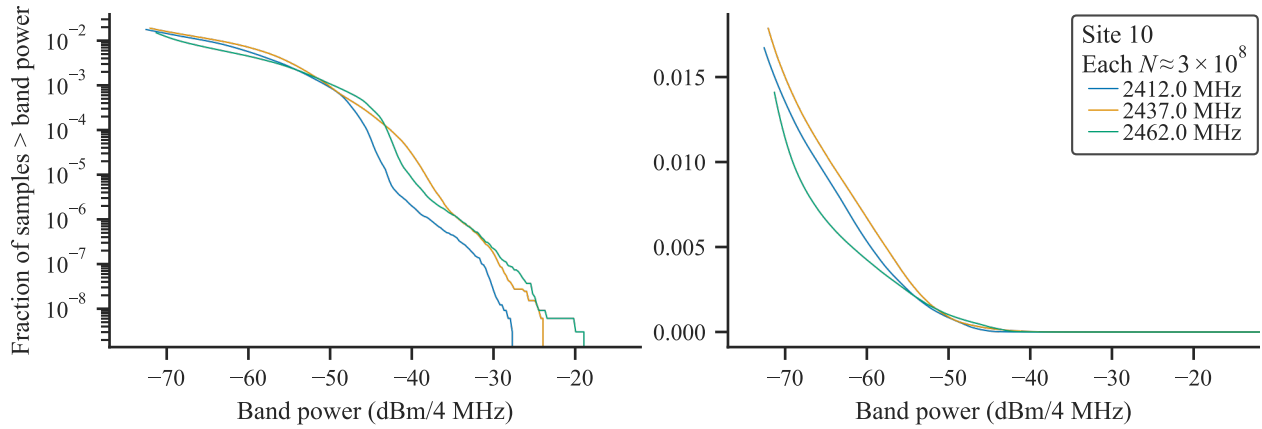


Figure D.155: Plots of empirical survival functions of band power in ISM bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

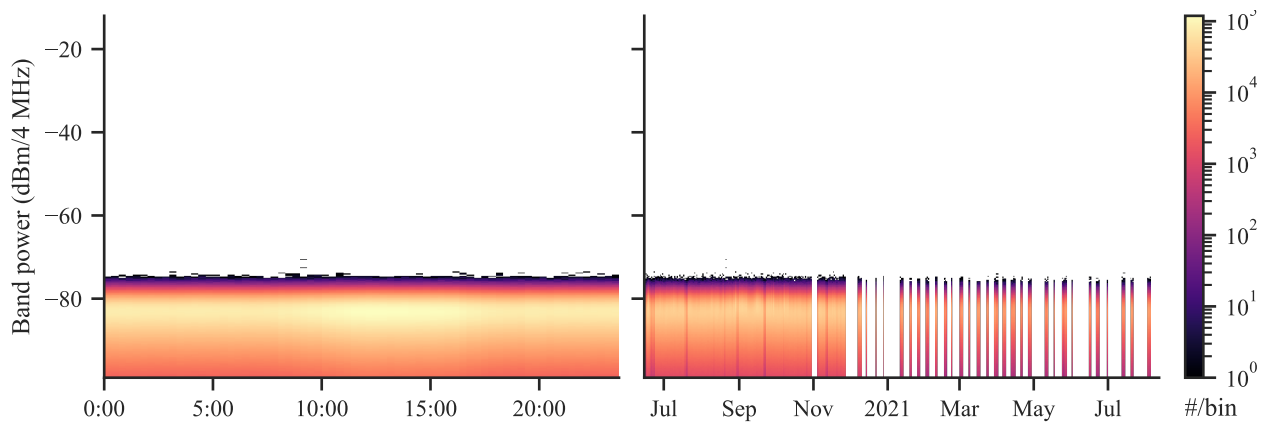


Figure D.156: Histogram heat maps of band power at 2695.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

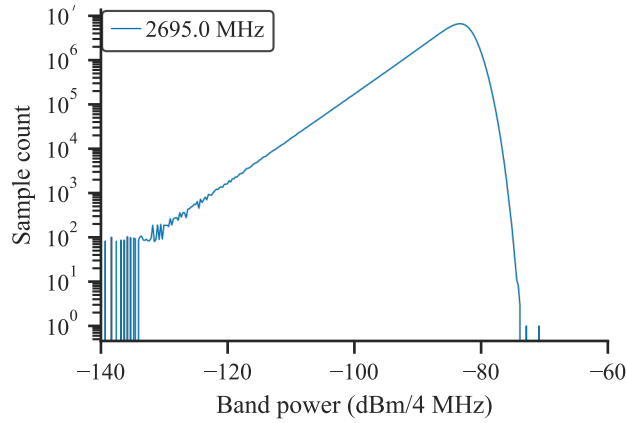


Figure D.157: Histogram of band power measured in the 2695 MHz passive service band at site 10.

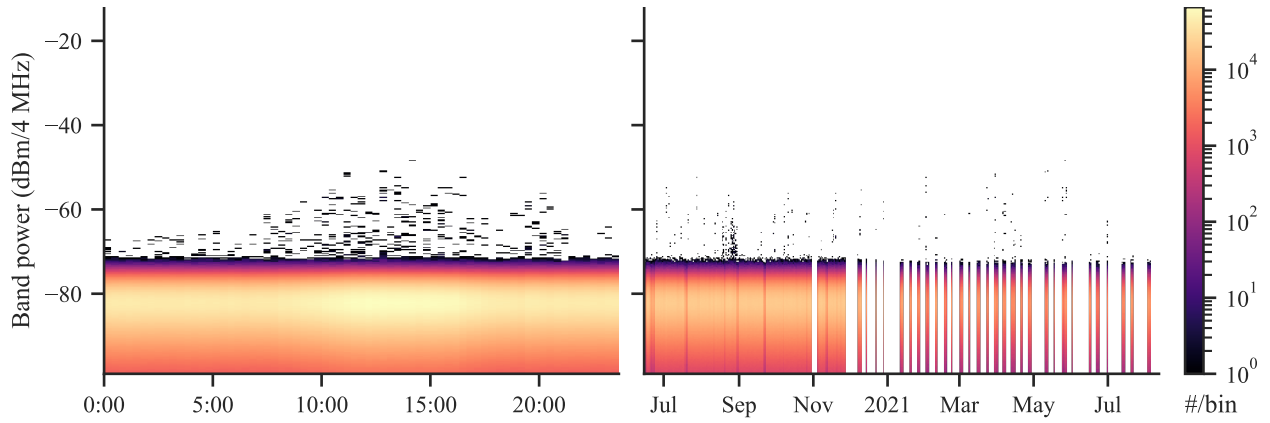


Figure D.158: Histogram heat maps of band power at 5170.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

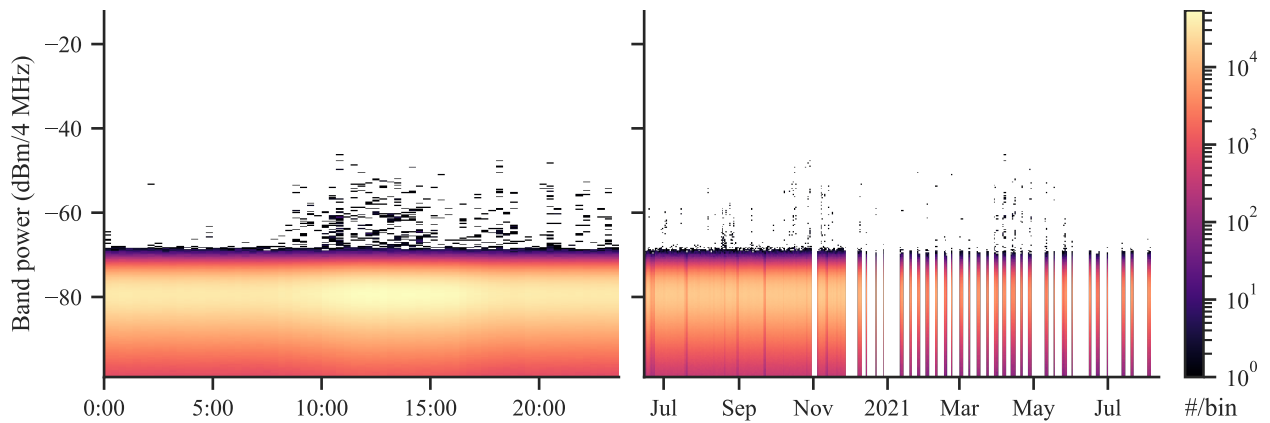


Figure D.159: Histogram heat maps of band power at 5795.0 MHz from site 10 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

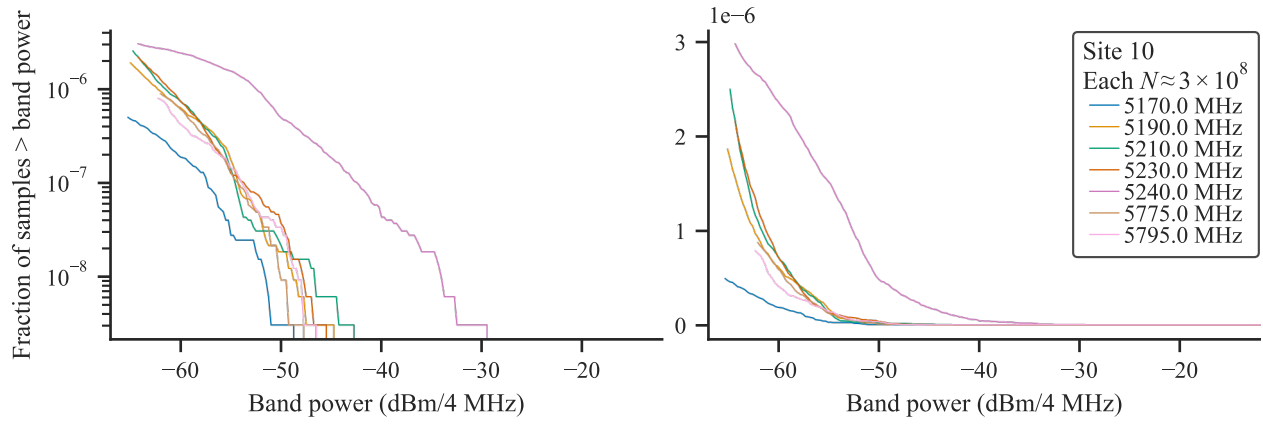


Figure D.160: Plots of empirical survival functions of band power in U-NII bands at site 10, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

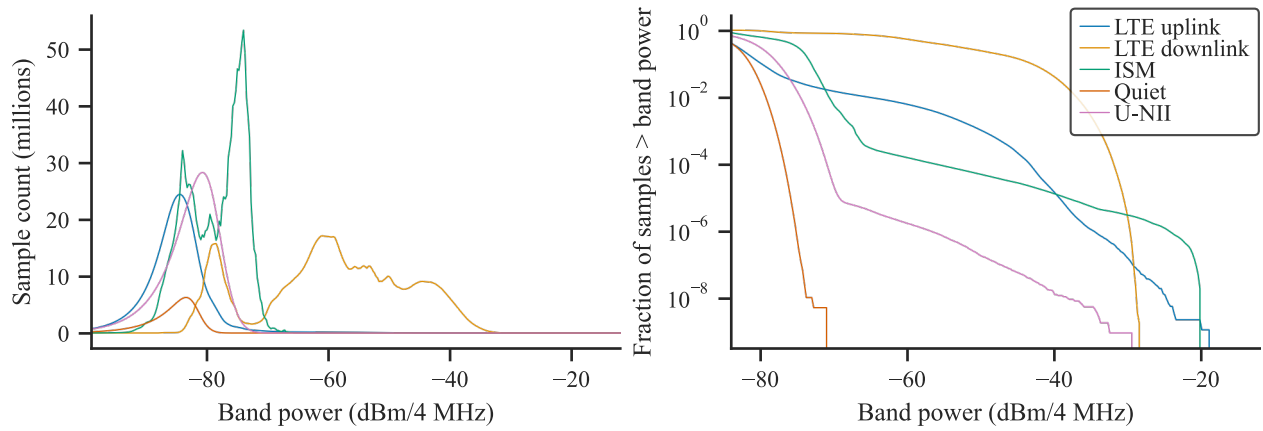


Figure D.161: Histograms (left) and empirical survival functions (right) of all samples received in site 10 in each type of band under test.

Residential Site 11

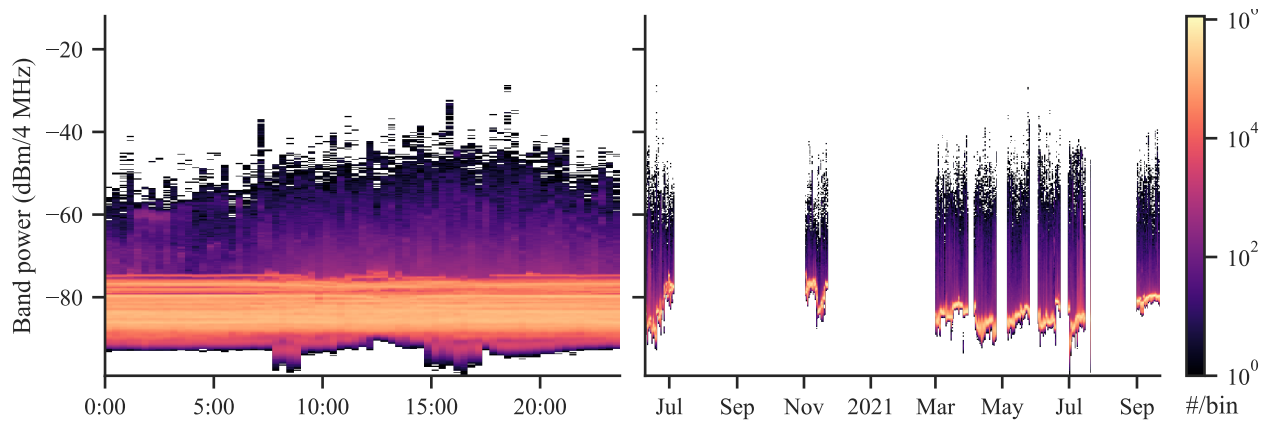


Figure D.162: Histogram heat maps of band power at 709.0 MHz from site 11 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

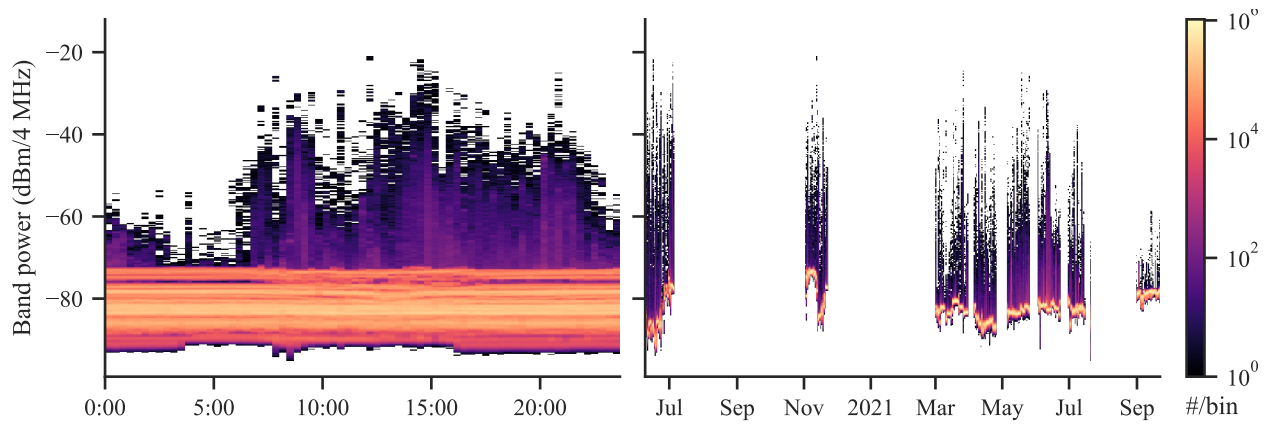


Figure D.163: Histogram heat maps of band power at 701.5 MHz from site 11 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

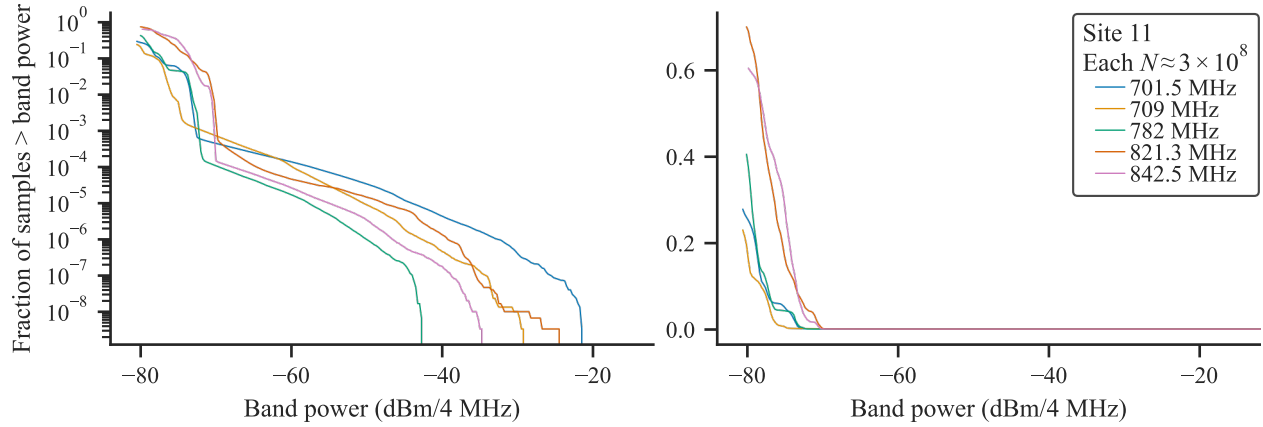


Figure D.164: Plots of empirical survival functions of band power in uplink channels in LTE bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

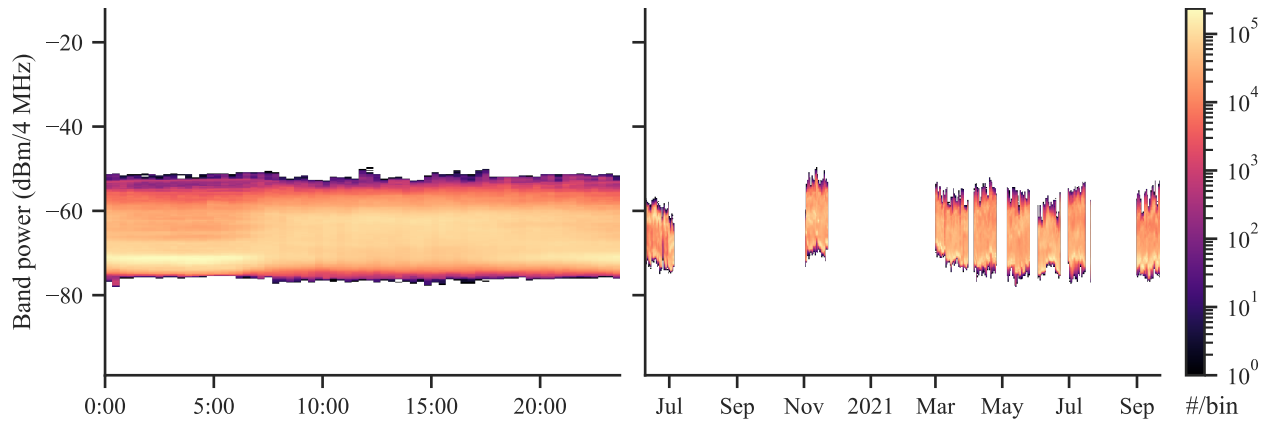


Figure D.165: Histogram heat maps of band power at 866.3 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

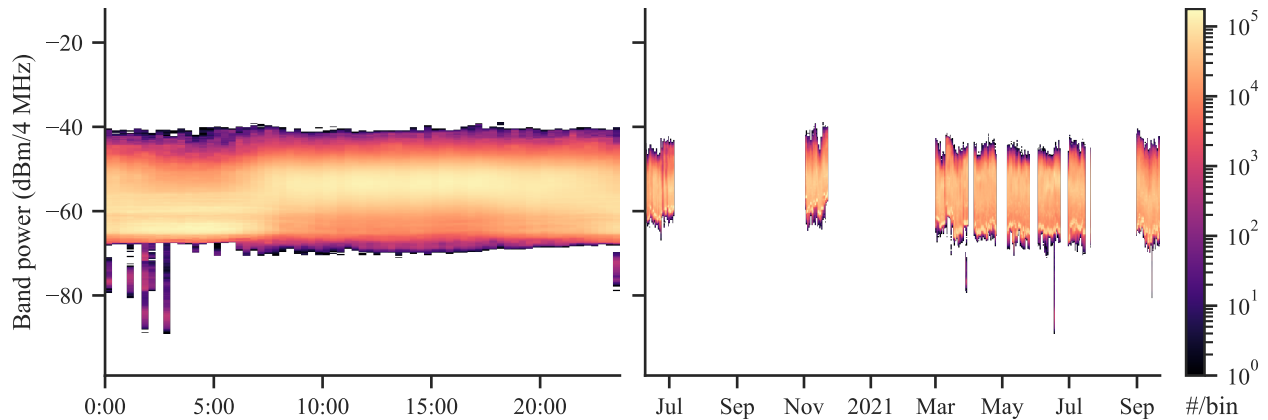


Figure D.166: Histogram heat maps of band power at 751.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

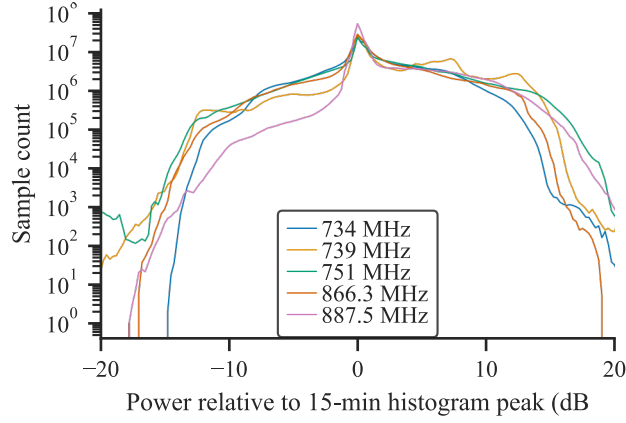


Figure D.167: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 11, as gauged by the peak histogram level in each dwell window.

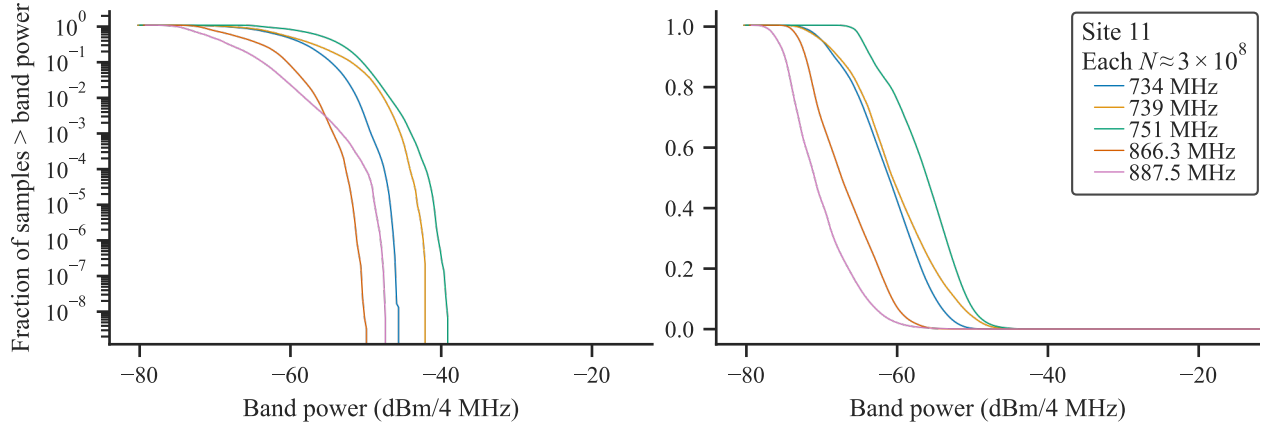


Figure D.168: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

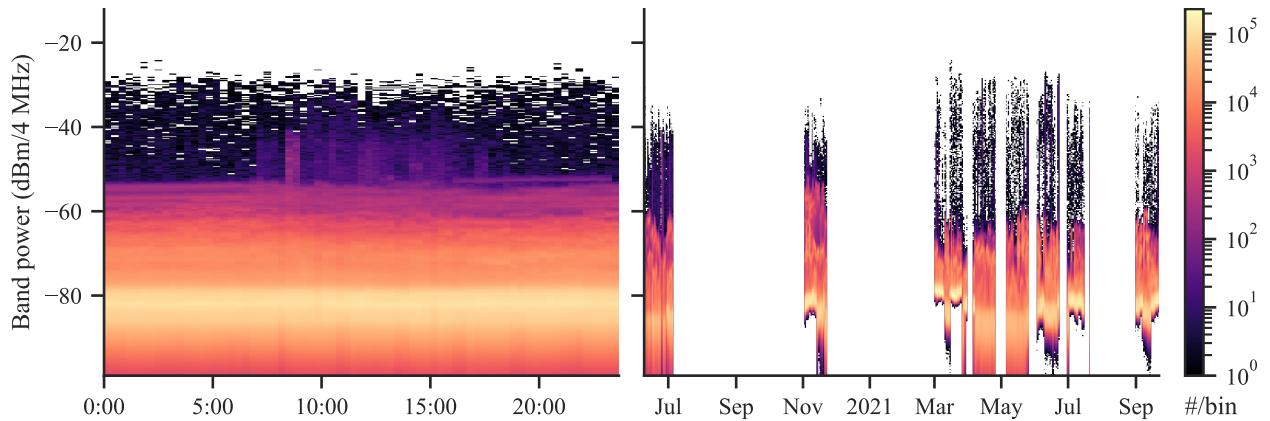


Figure D.169: Histogram heat maps of band power at 2412.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

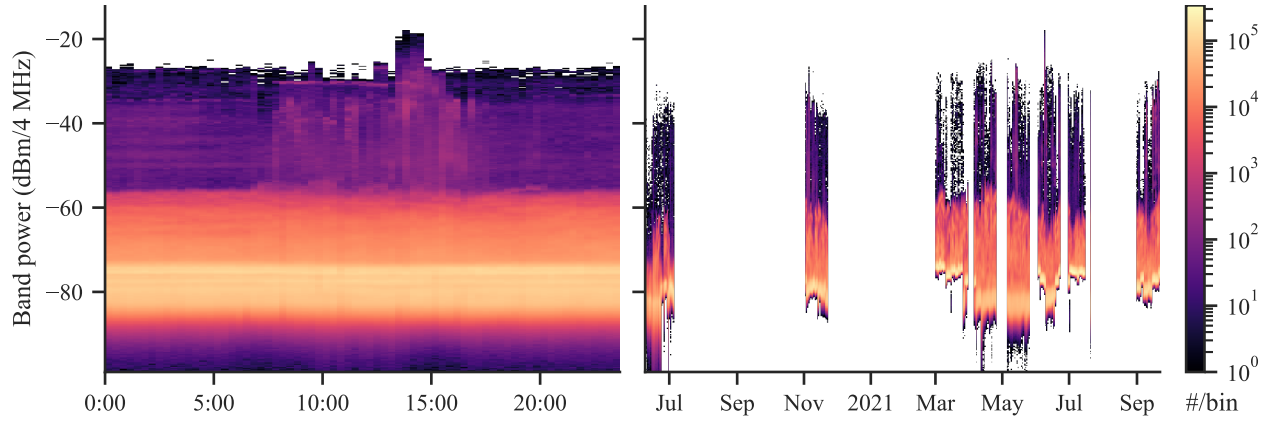


Figure D.170: Histogram heat maps of band power at 2462.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

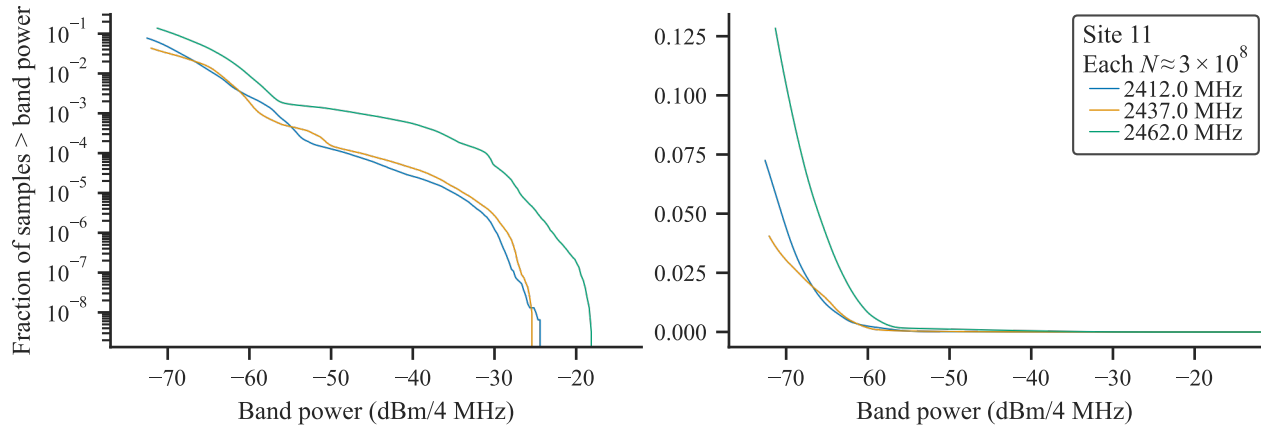


Figure D.171: Plots of empirical survival functions of band power in ISM bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

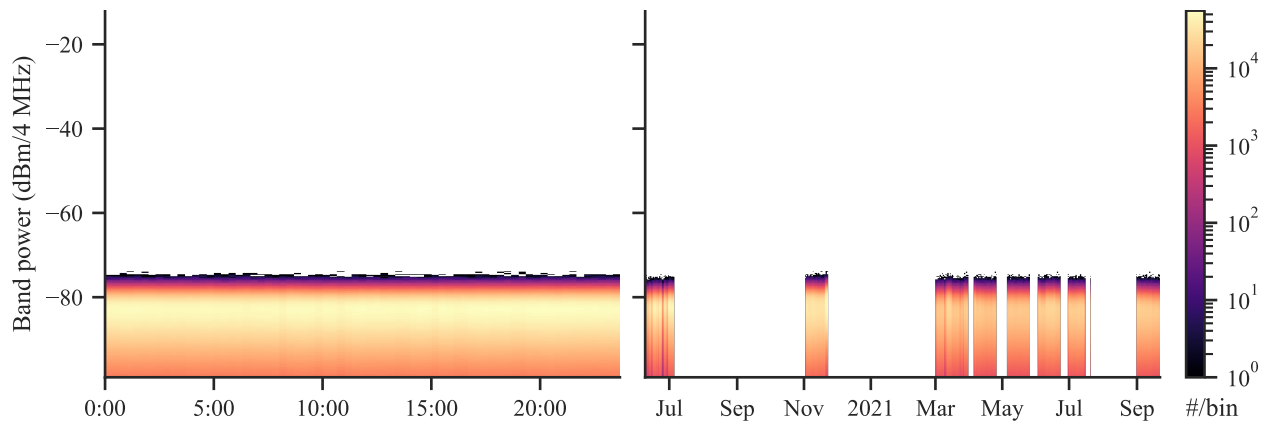


Figure D.172: Histogram heat maps of band power at 2695.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

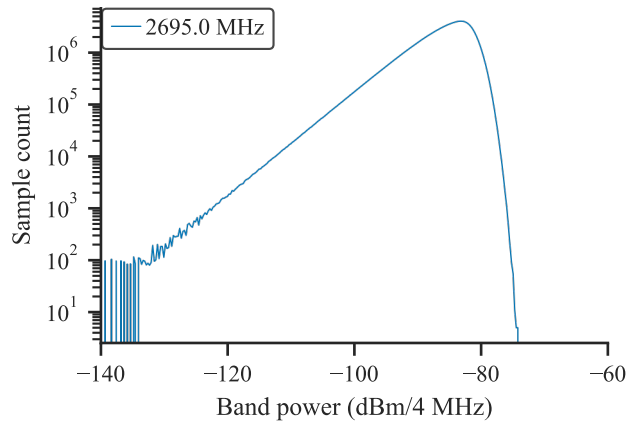


Figure D.173: Histogram of band power measured in the 2695 MHz passive service band at site 11.

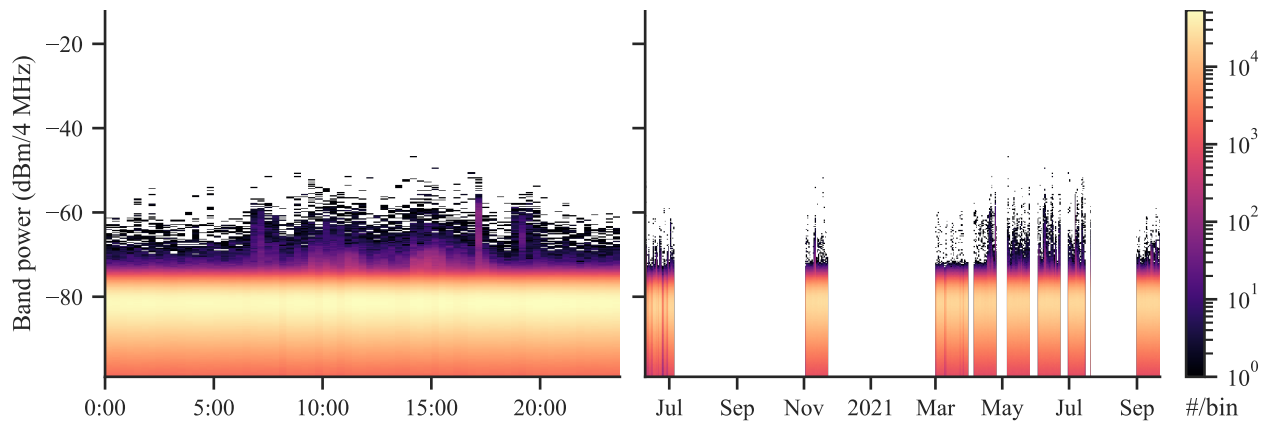


Figure D.174: Histogram heat maps of band power at 5170.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

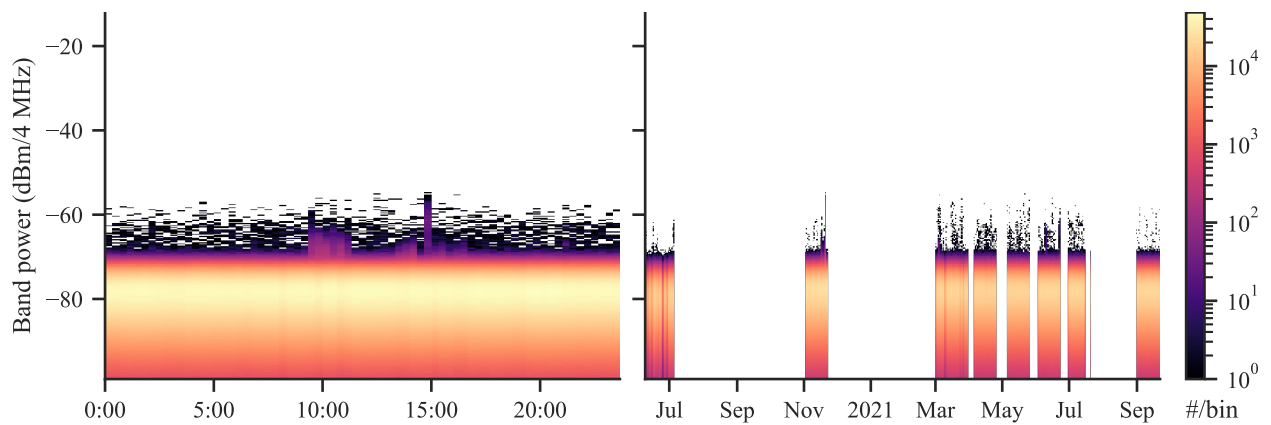


Figure D.175: Histogram heat maps of band power at 5775.0 MHz from site 11 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

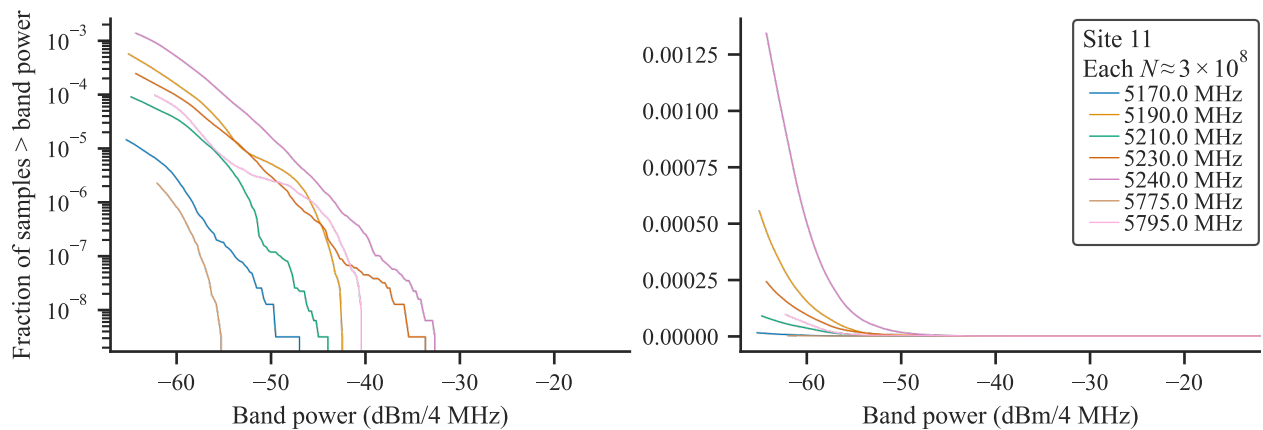


Figure D.176: Plots of empirical survival functions of band power in U-NII bands at site 11, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

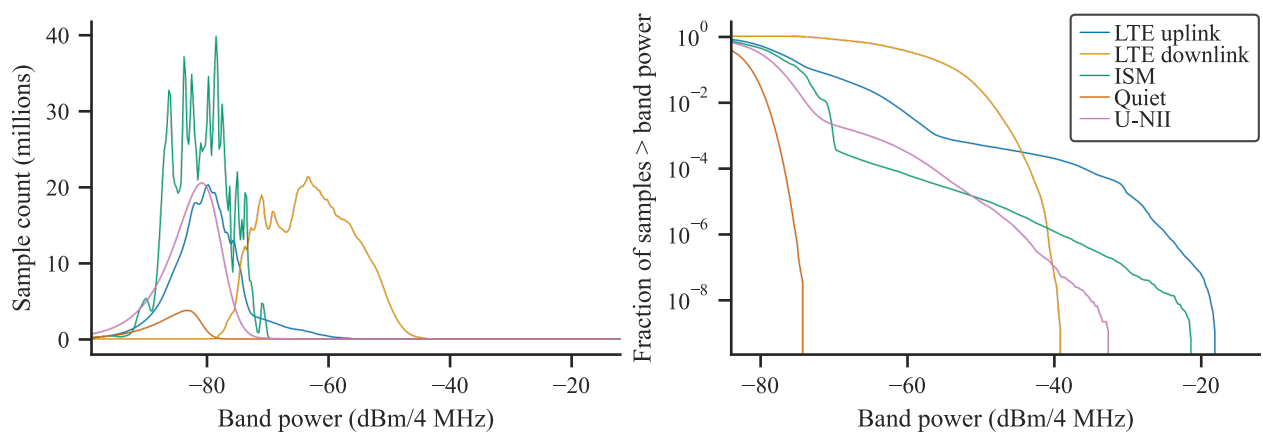


Figure D.177: Histograms (left) and empirical survival functions (right) of all samples received in site 11 in each type of band under test.

Residential Site 12

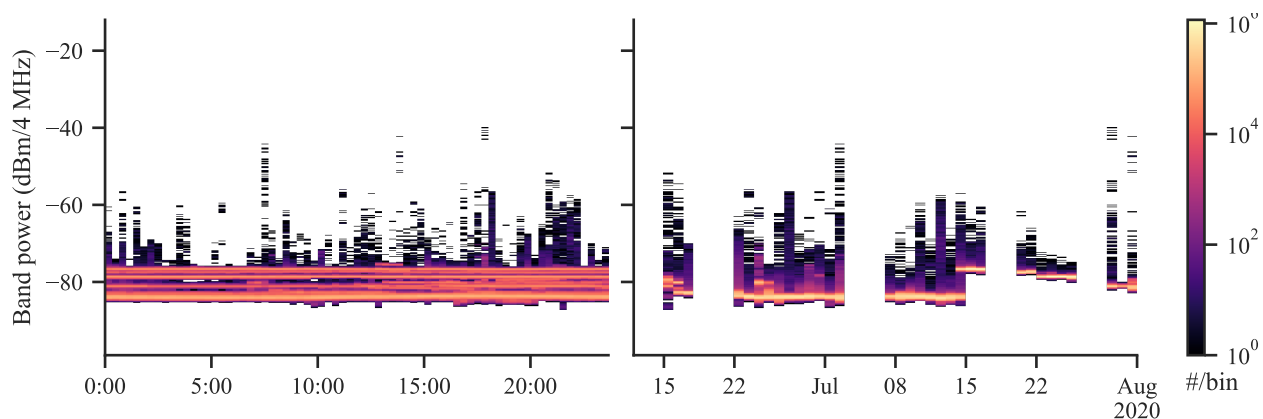


Figure D.178: Histogram heat maps of band power at 701.5 MHz from site 12 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the smallest among uplink channels in LTE bands at this site.

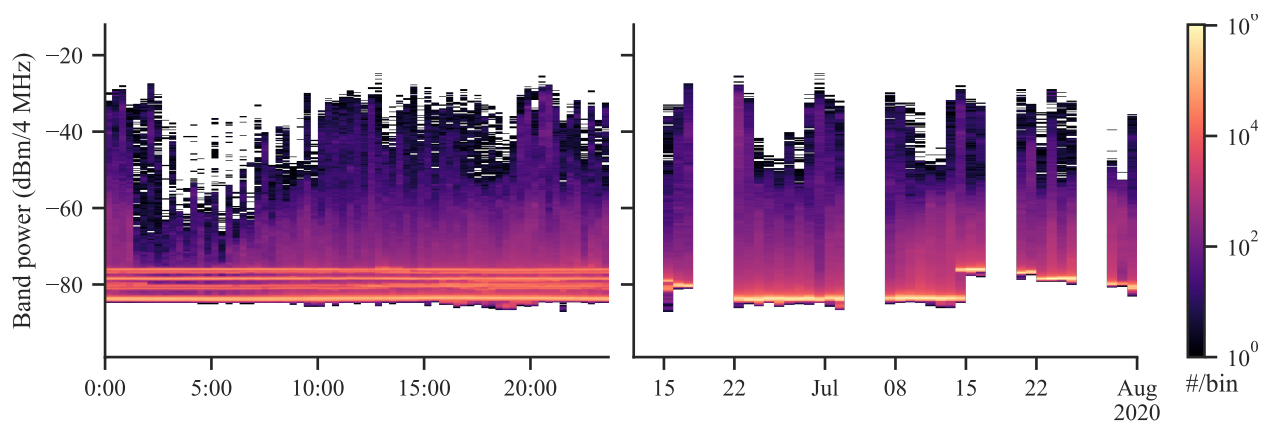


Figure D.179: Histogram heat maps of band power at 709.0 MHz from site 12 across the full data time span, by time of day (20 min. bin, left) and date (1 day bin, right). The peak band power at this frequency was the greatest among uplink channels in LTE bands at this site.

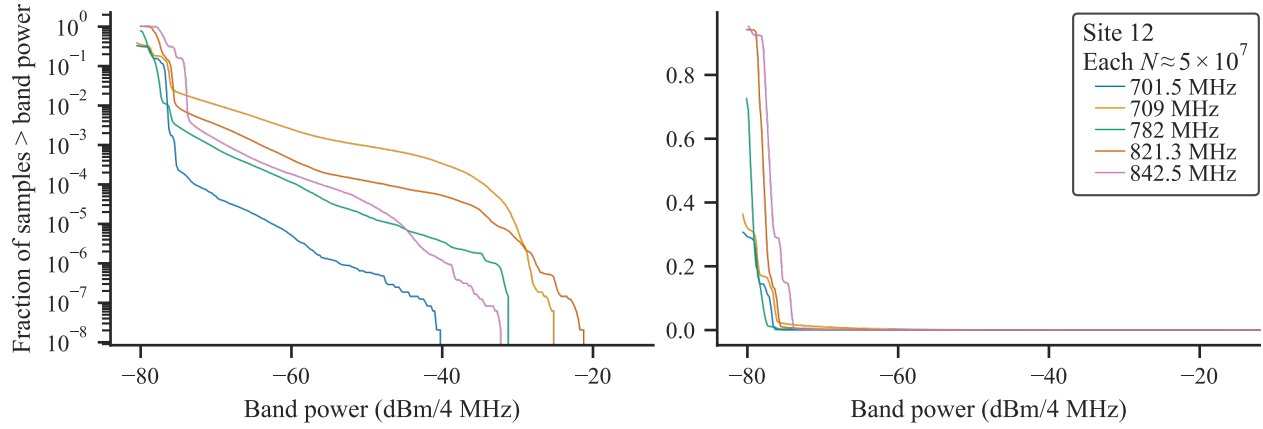


Figure D.180: Plots of empirical survival functions of band power in uplink channels in LTE bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

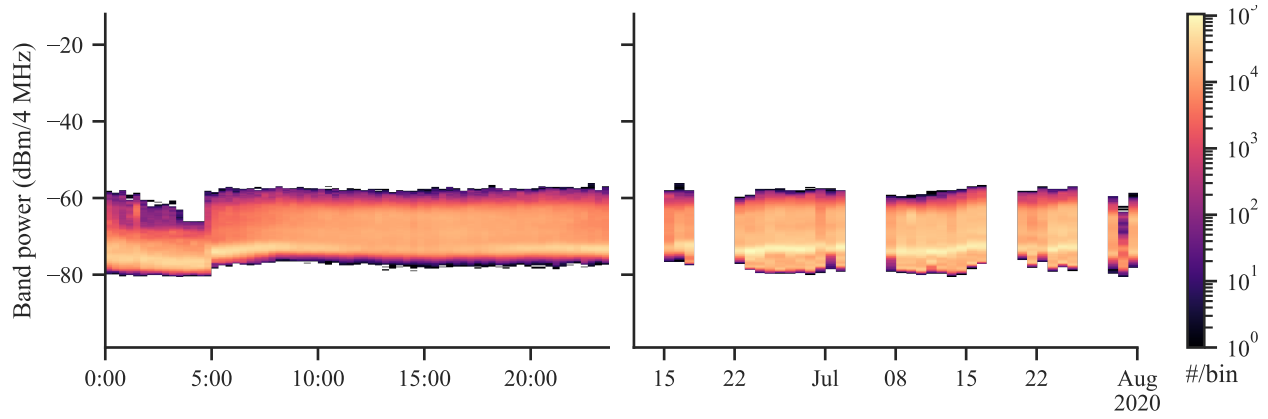


Figure D.181: Histogram heat maps of band power at 887.5 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among downlink channels in LTE bands at this site.

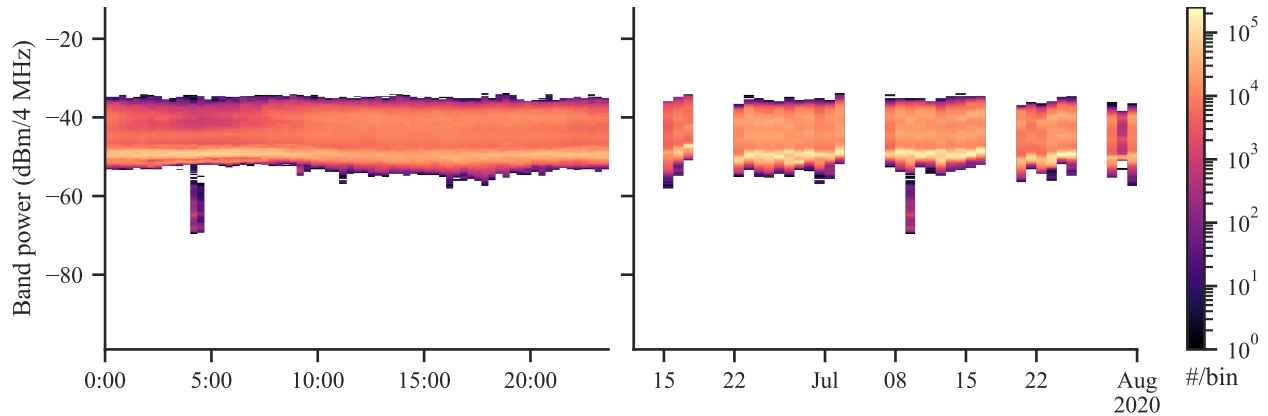


Figure D.182: Histogram heat maps of band power at 734.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among downlink channels in LTE bands at this site.

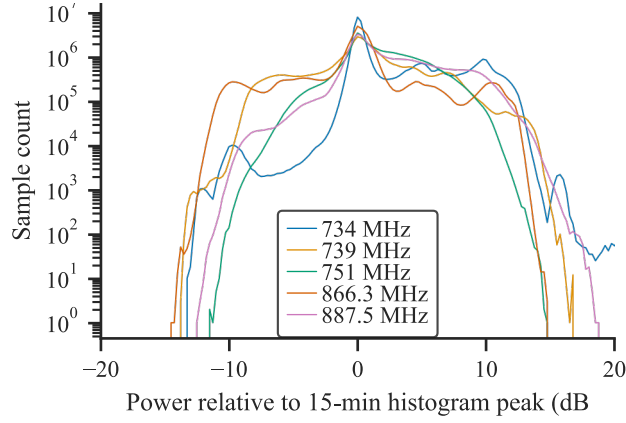


Figure D.183: Histogram of band power samples in downlink channels in LTE bands relative to the site noise and interference level at site 12, as gauged by the peak histogram level in each dwell window.

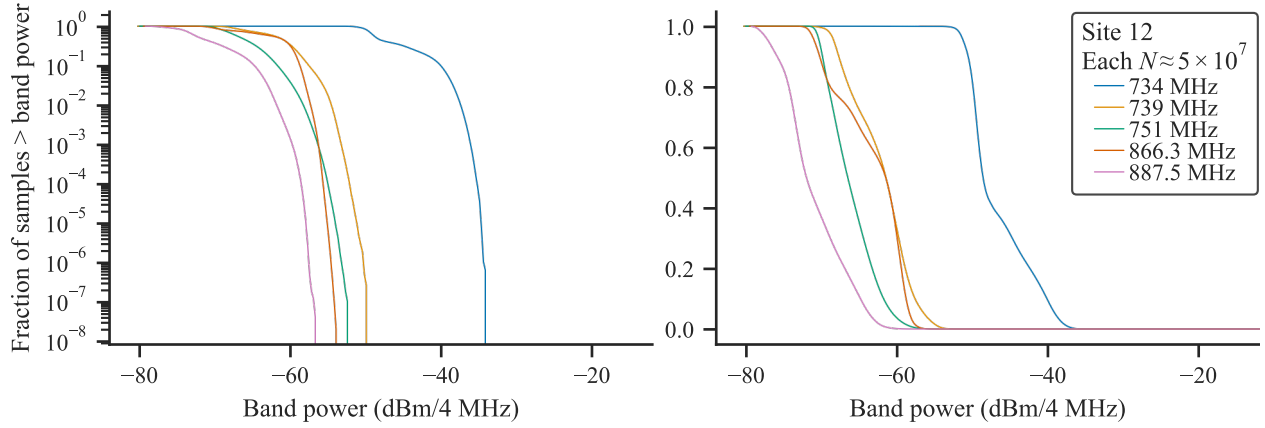


Figure D.184: Plots of empirical survival functions of band power in downlink channels in LTE bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

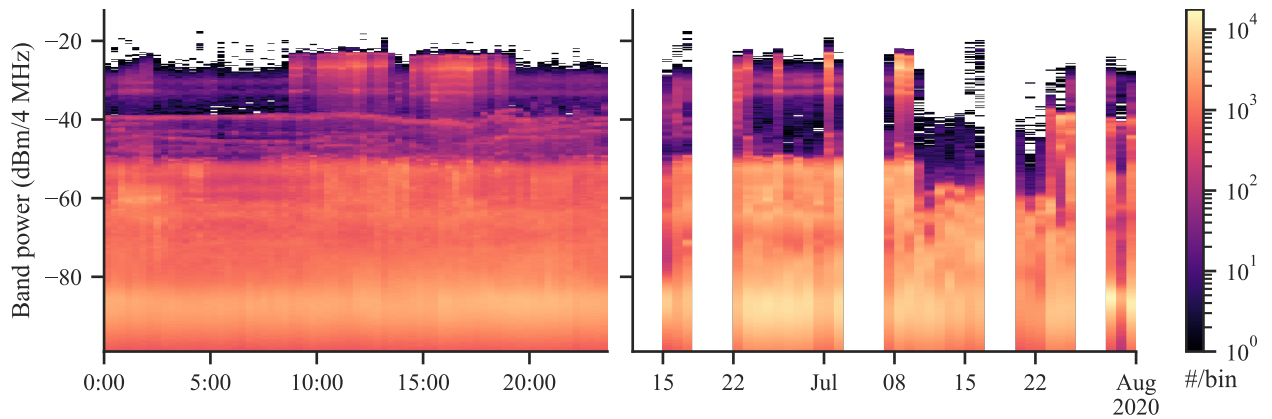


Figure D.185: Histogram heat maps of band power at 2462.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among ISM bands at this site.

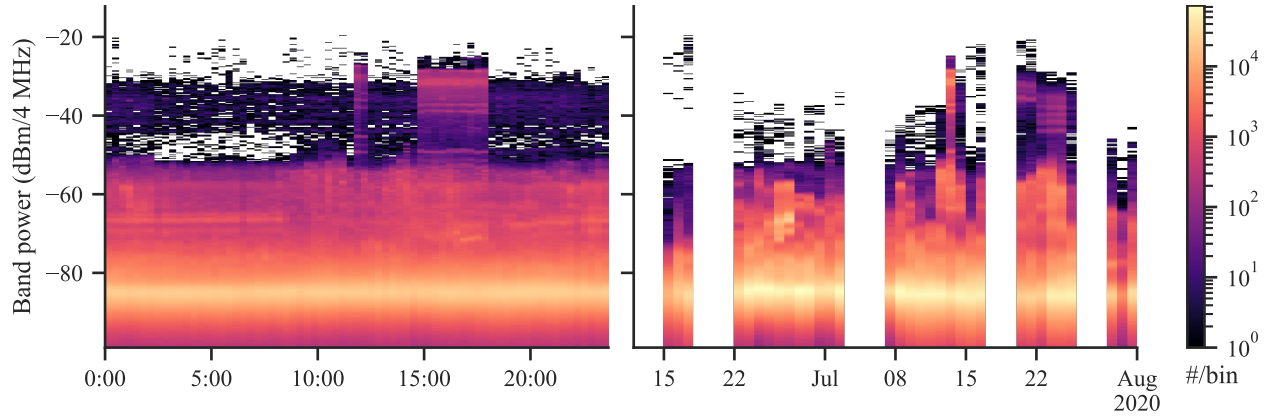


Figure D.186: Histogram heat maps of band power at 2412.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

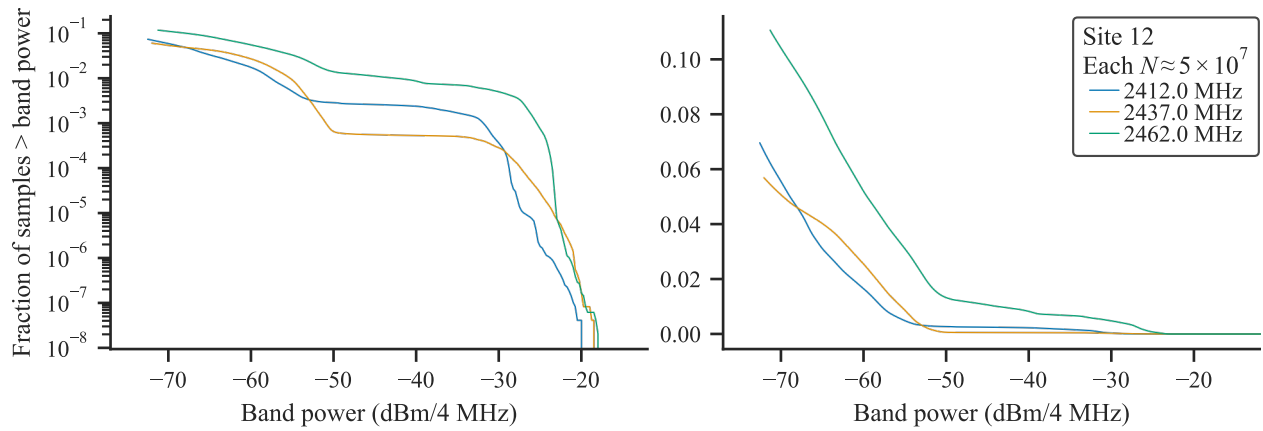


Figure D.187: Plots of empirical survival functions of band power in ISM bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

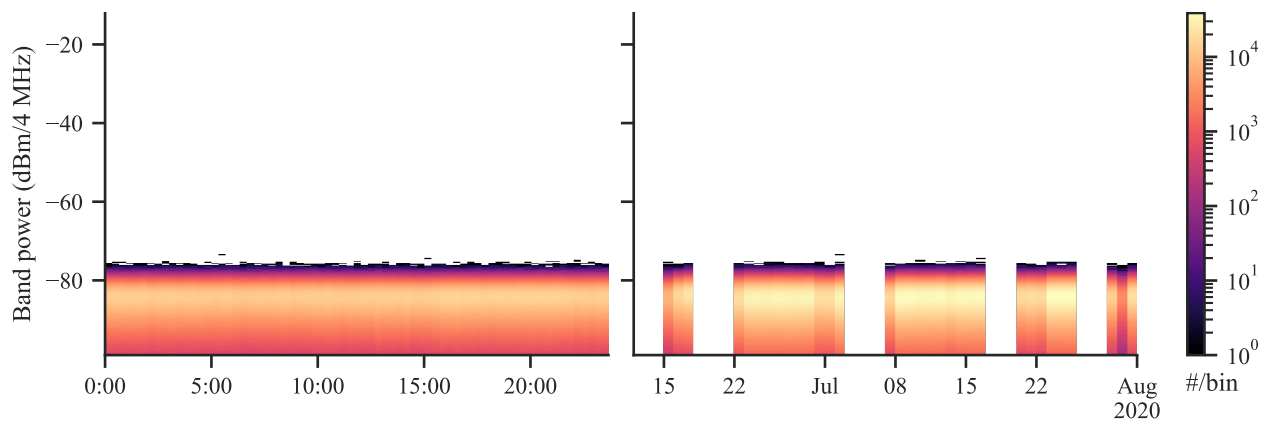


Figure D.188: Histogram heat maps of band power at 2695.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among ISM bands at this site.

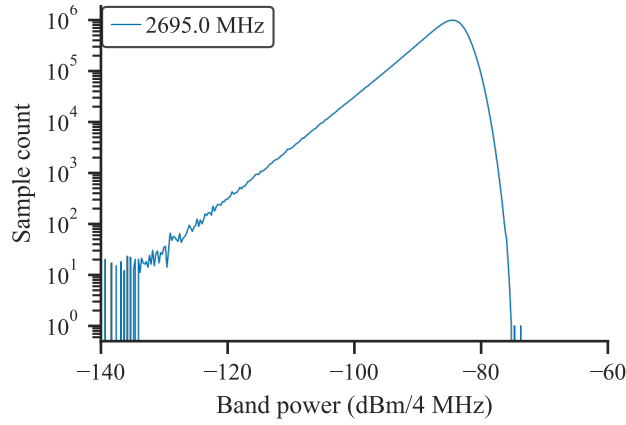


Figure D.189: Histogram of band power measured in the 2695 MHz passive service band at site 12.

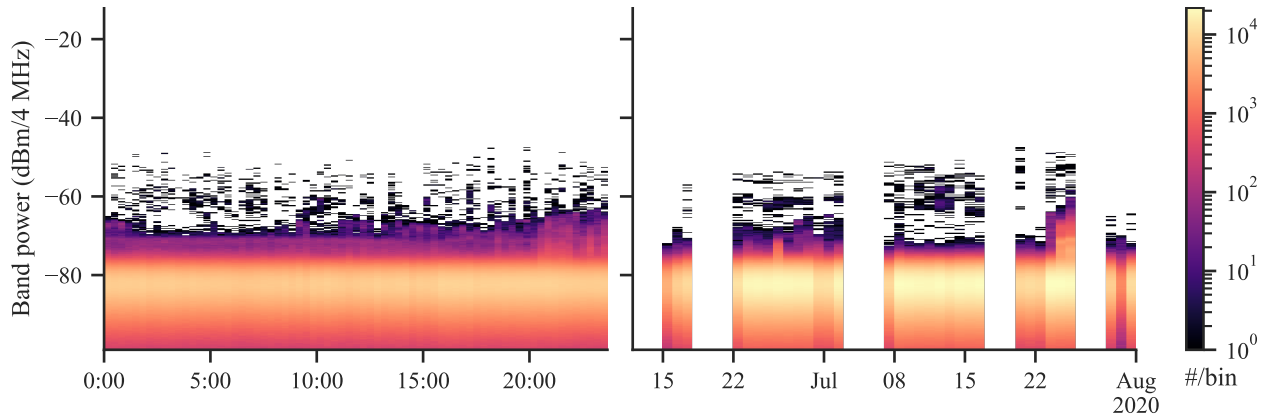


Figure D.190: Histogram heat maps of band power at 5190.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the smallest among U-NII bands at this site.

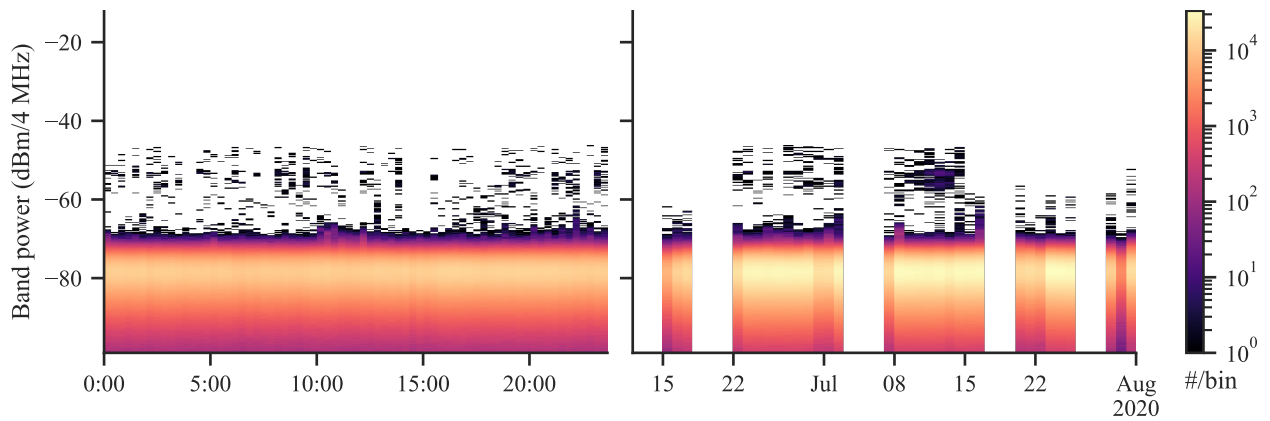


Figure D.191: Histogram heat maps of band power at 5775.0 MHz from site 12 across the full data time span, binned by time of day (20 min. bin, left) and and date (1 day bin, right). The peak band power at this frequency was the greatest among U-NII bands at this site.

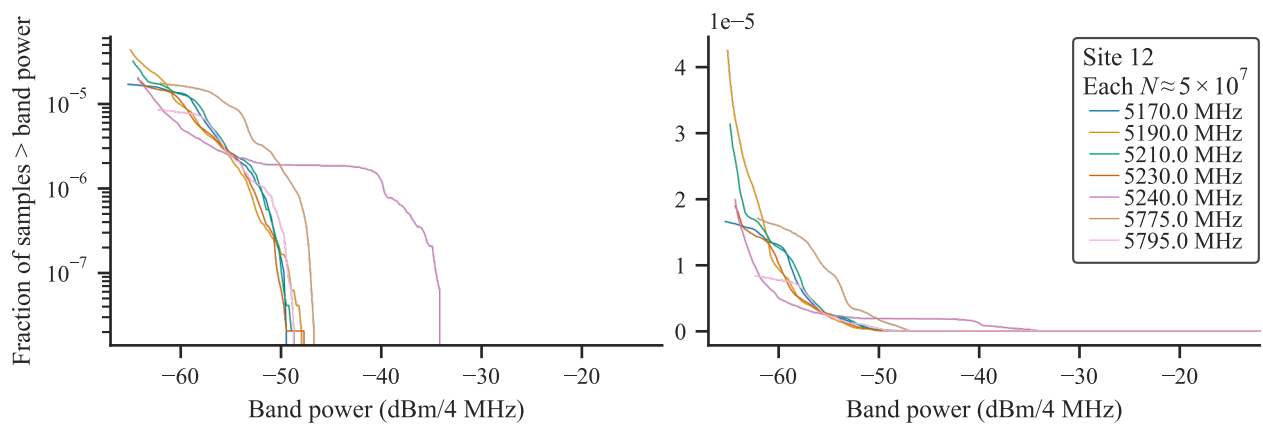


Figure D.192: Plots of empirical survival functions of band power in U-NII bands at site 12, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

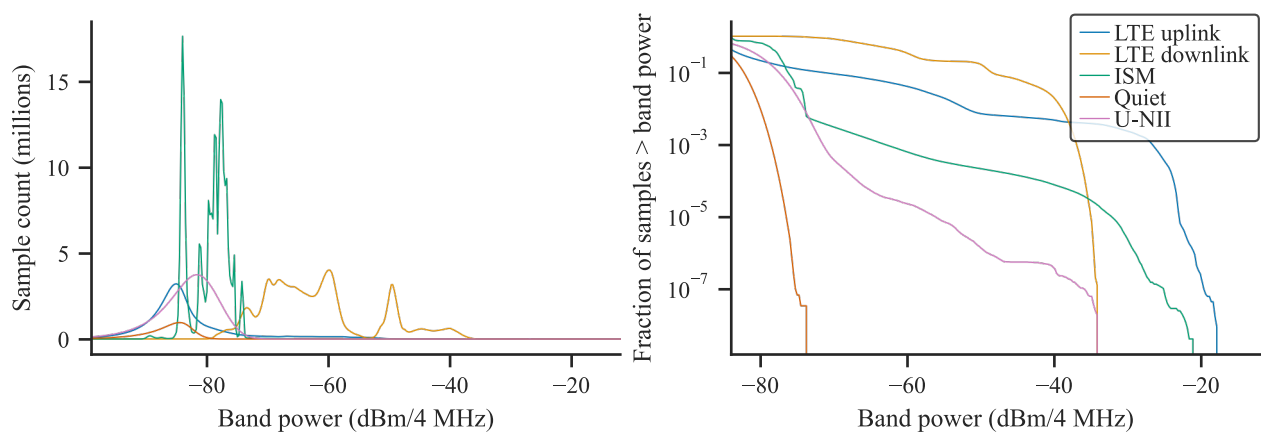


Figure D.193: Histograms (left) and empirical survival functions (right) of all samples received in site 12 in each type of band under test.

Hospital Site

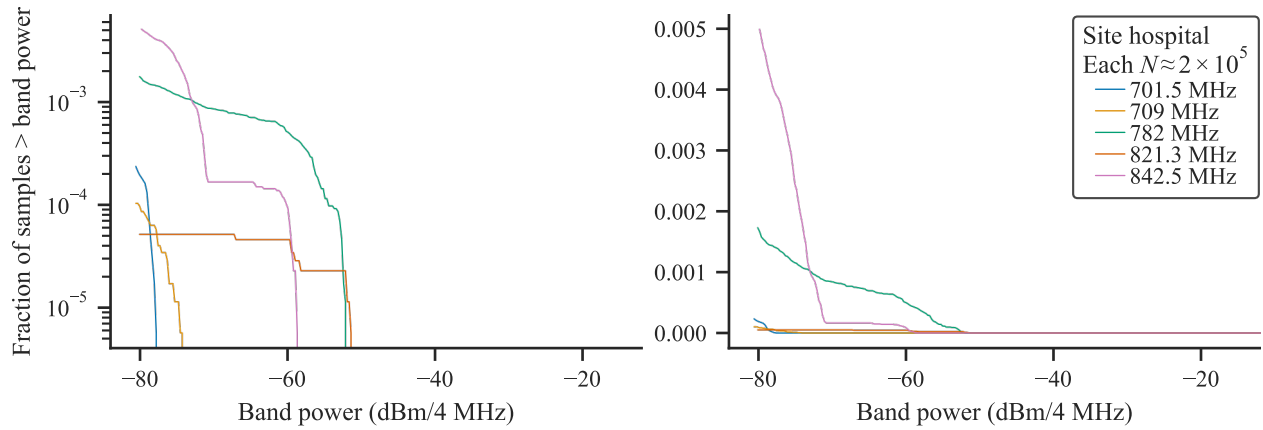


Figure D.194: Empirical survival functions of band power in uplink channels in LTE bands at site hospital, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

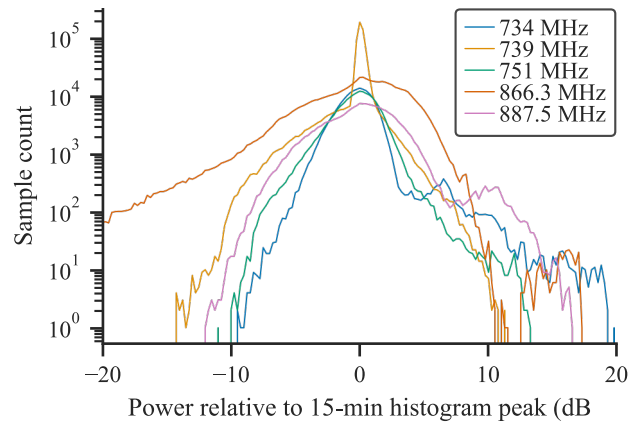


Figure D.195: Band power samples in downlink channels in LTE bands relative to the site noise and interference level at site hospital, as gauged by the peak histogram level in each dwell window.

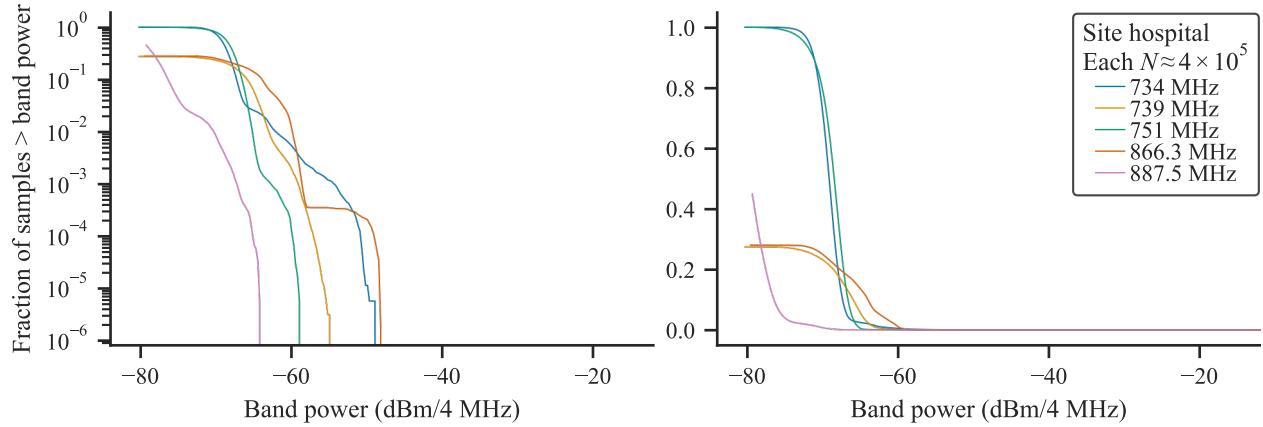


Figure D.196: Empirical survival functions of band power in downlink channels in LTE bands at site hospital, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

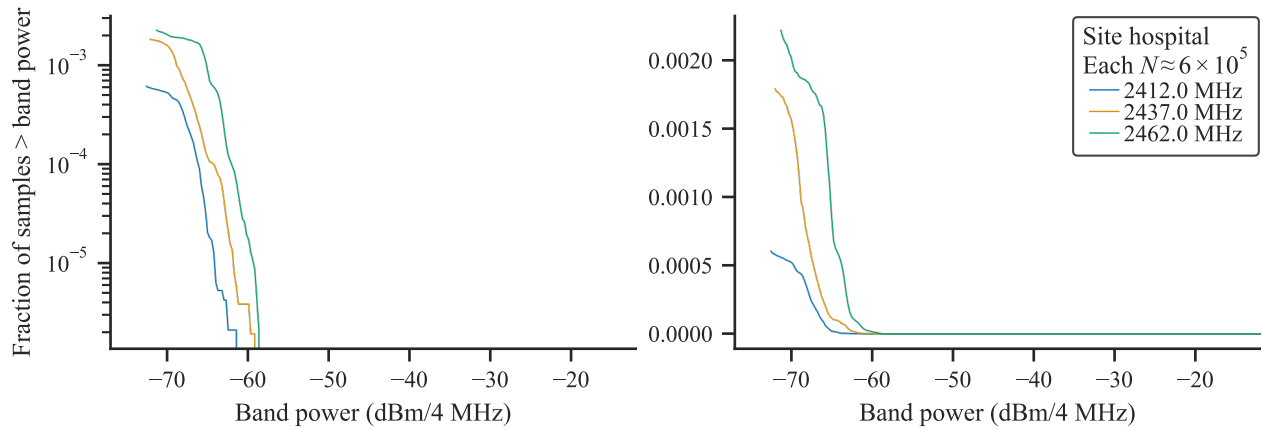


Figure D.197: Empirical survival functions of band power in ISM bands at site hospital, shown first on log scale to illustrate rare events (left) and then on a linear scale (right) to emphasize the most frequent power levels.

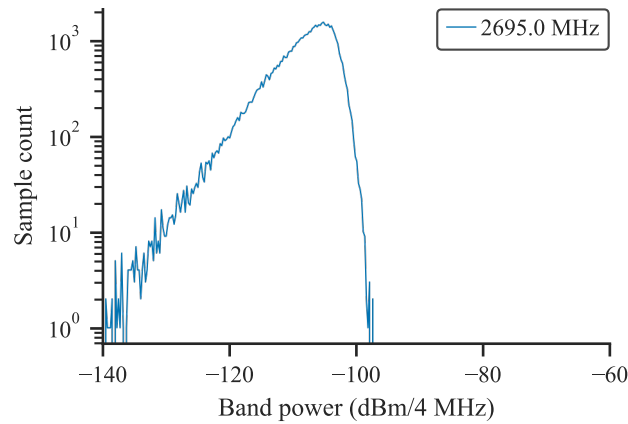


Figure D.198: Histogram of band power measured in the 2695 MHz passive service band at site hospital.

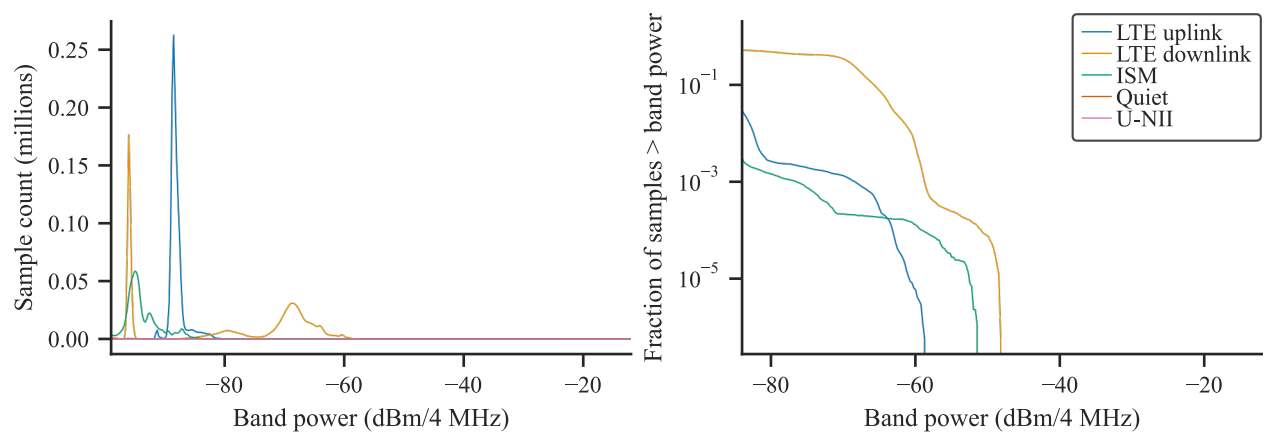


Figure D.199: Histograms (left) and empirical survival functions (right) of all samples received in site hospital in each type of band under test. No samples were collected in the U-NII or quiet bands in this site.

Appendix E

Network Profiling Data by Site

This appendix shows distributions of network profiling data that were not shown in Chapter 5.

Cellular Network Profiling

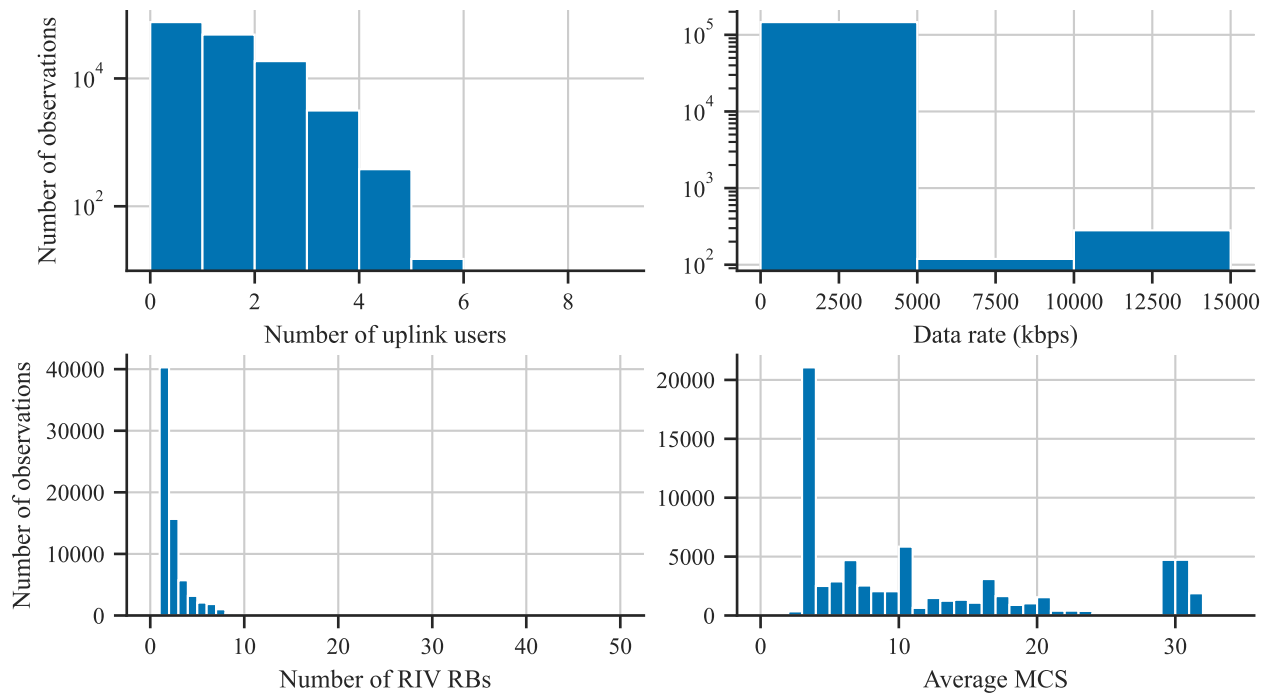


Figure E.1: Histograms of LTE uplink resource grants from site 07 observed at 866.3 MHz

WLAN Profiling

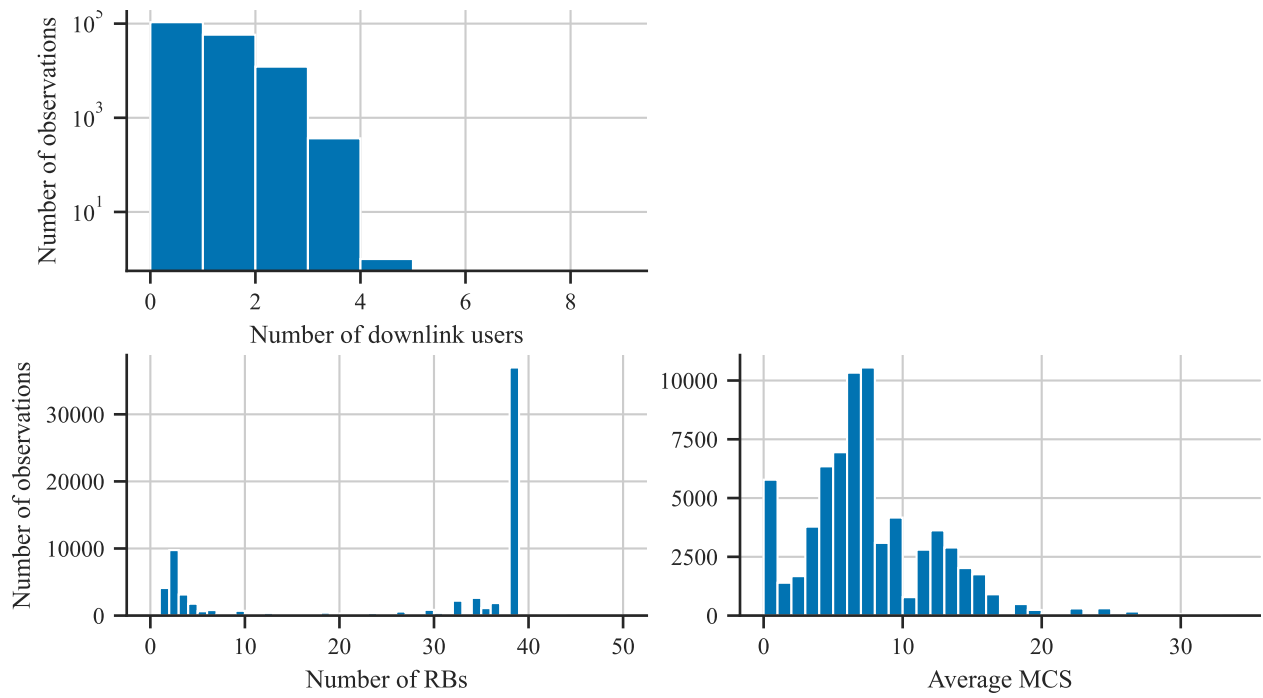


Figure E.2: Histograms of LTE downlink resource grants from site 07 observed at 866.3 MHz

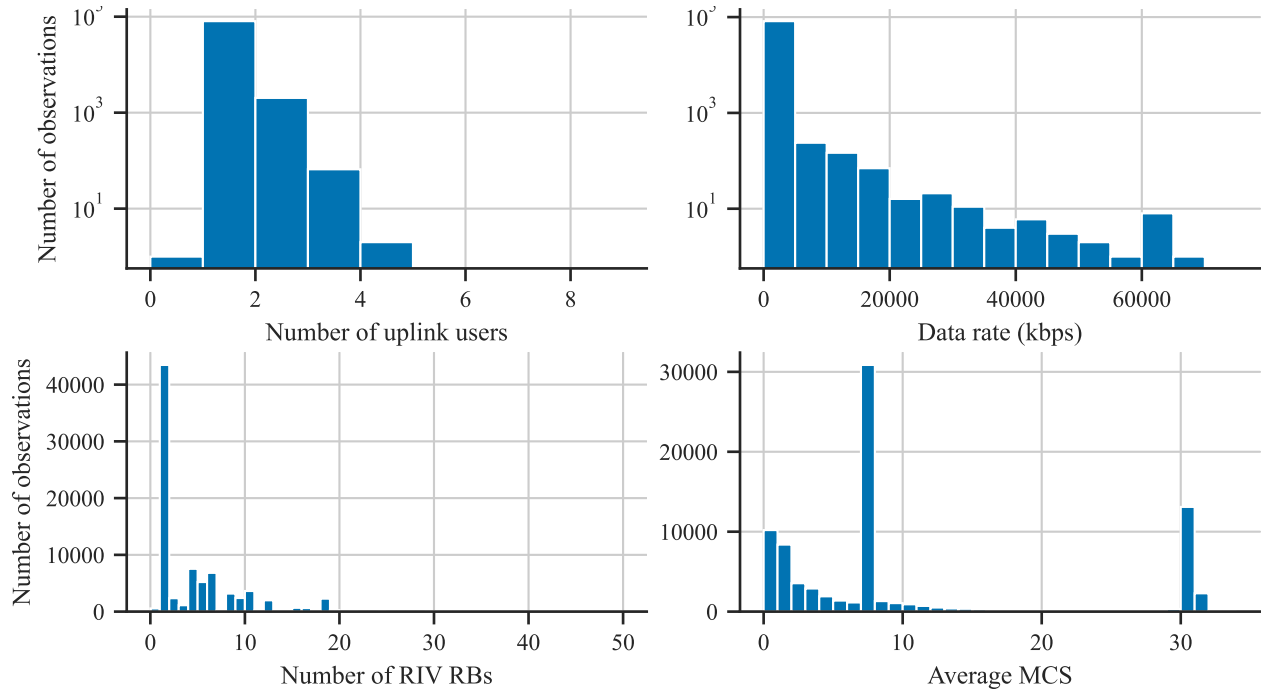


Figure E.3: Histograms of LTE uplink resource grants from site 07 observed at 731.5 MHz

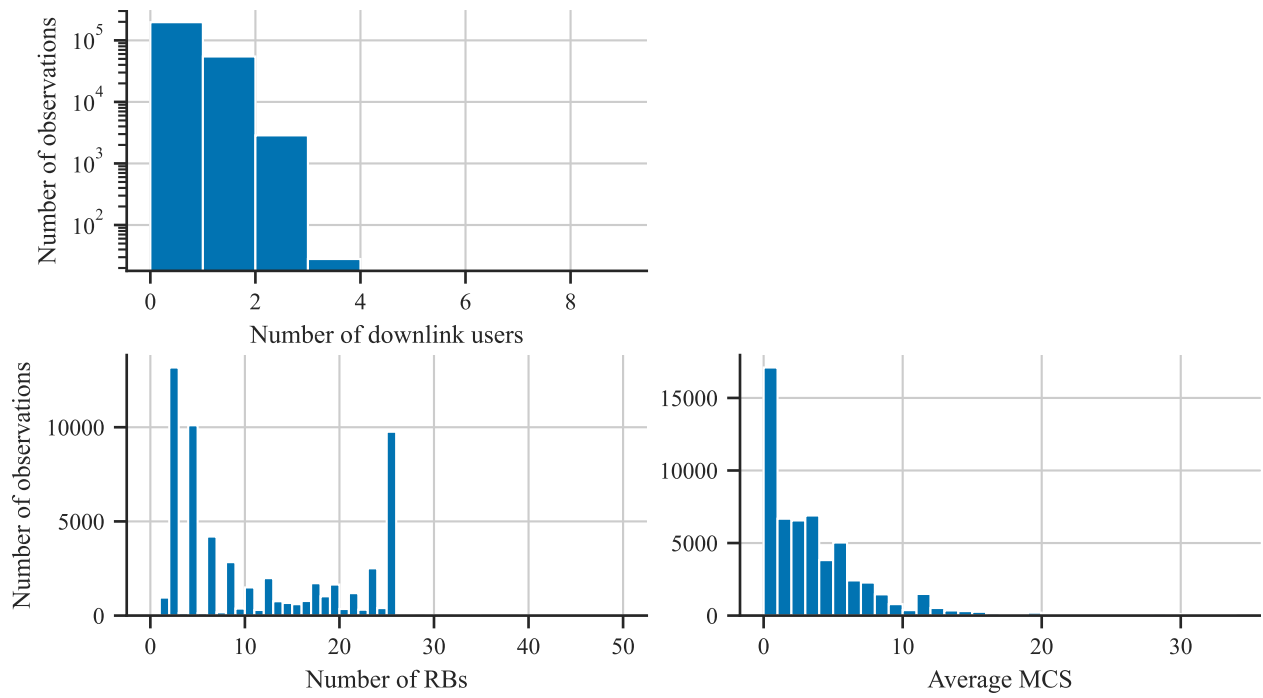


Figure E.4: Histograms of LTE downlink resource grants from site 07 observed at 731.5 MHz

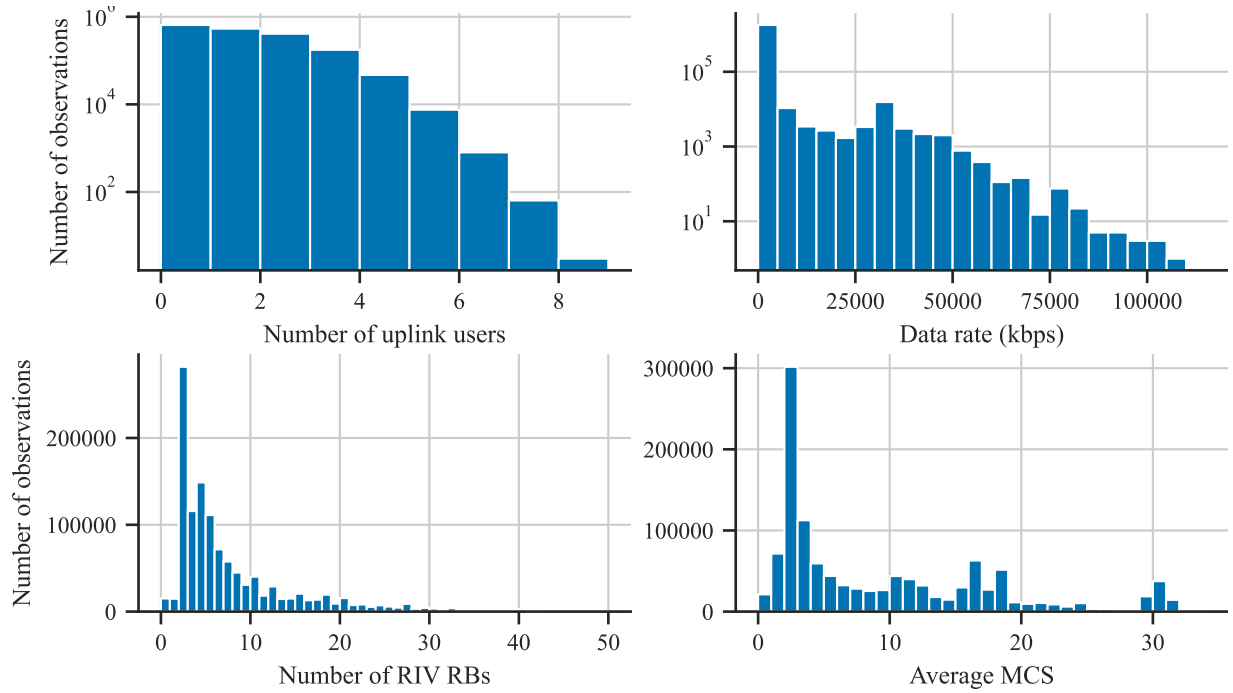


Figure E.5: Histograms of LTE uplink resource grants from site 07 observed at 751.0 MHz

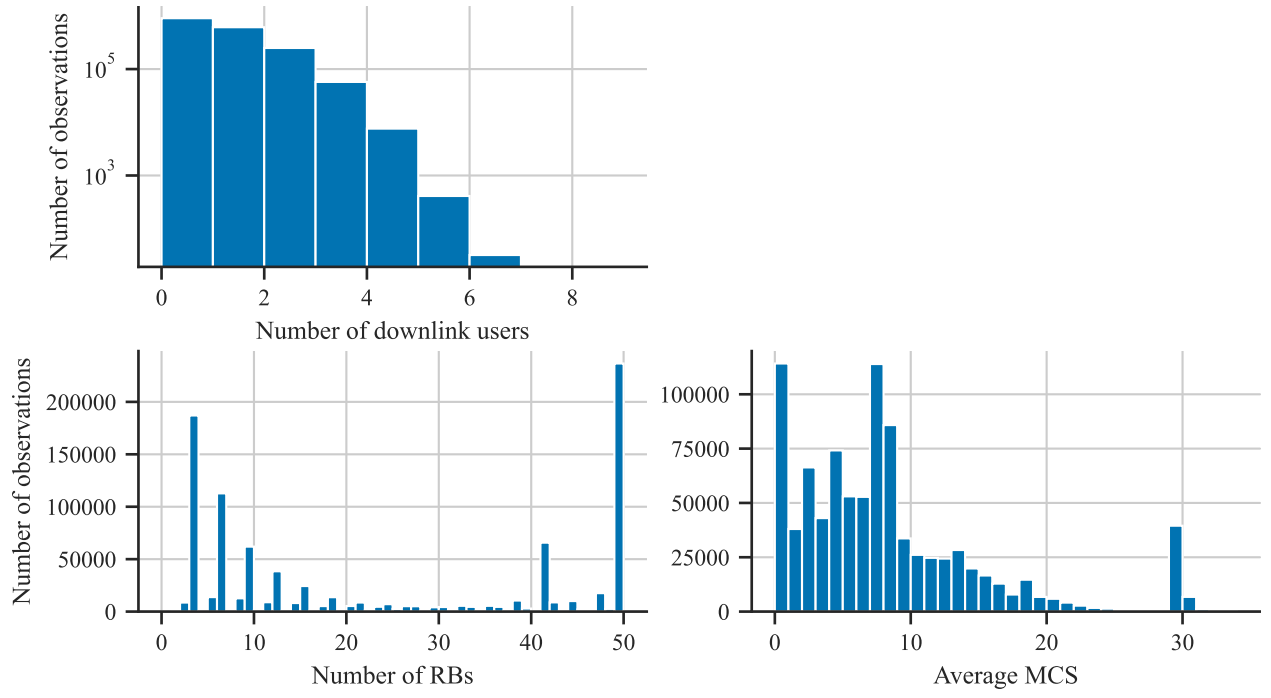


Figure E.6: Histograms of LTE downlink resource grants from site 07 observed at 751.0 MHz

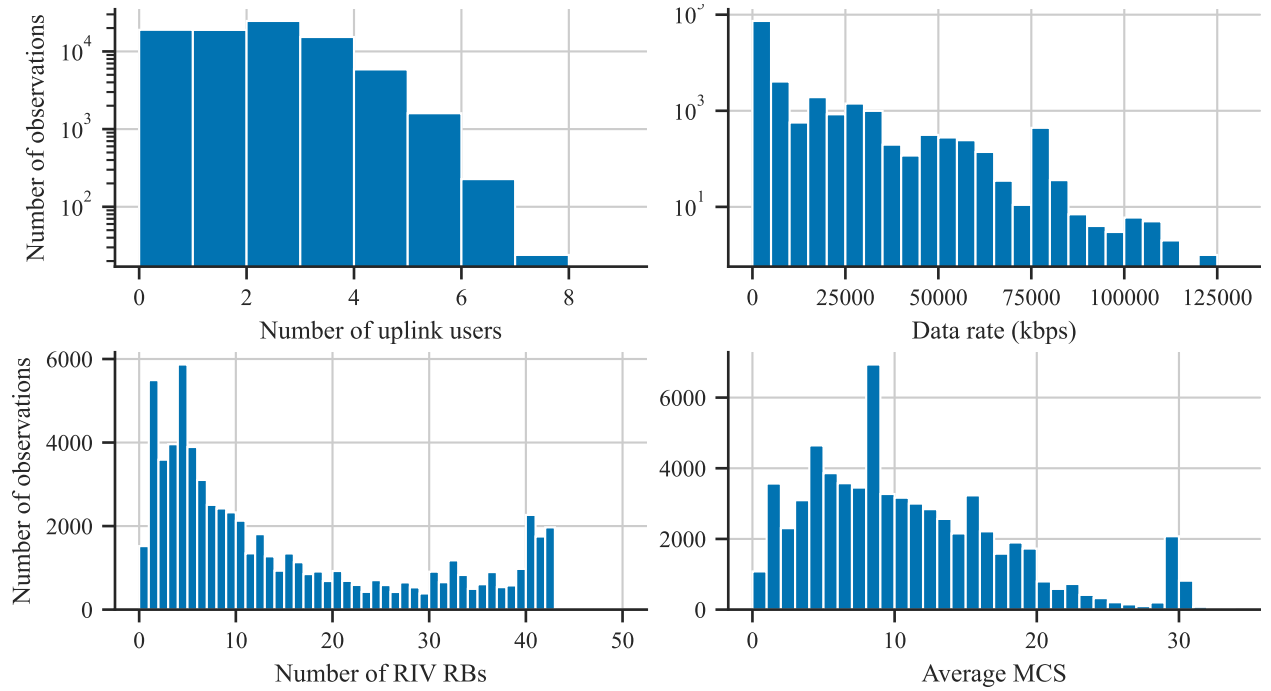


Figure E.7: Histograms of LTE uplink resource grants from site 11 observed at 739.0 MHz

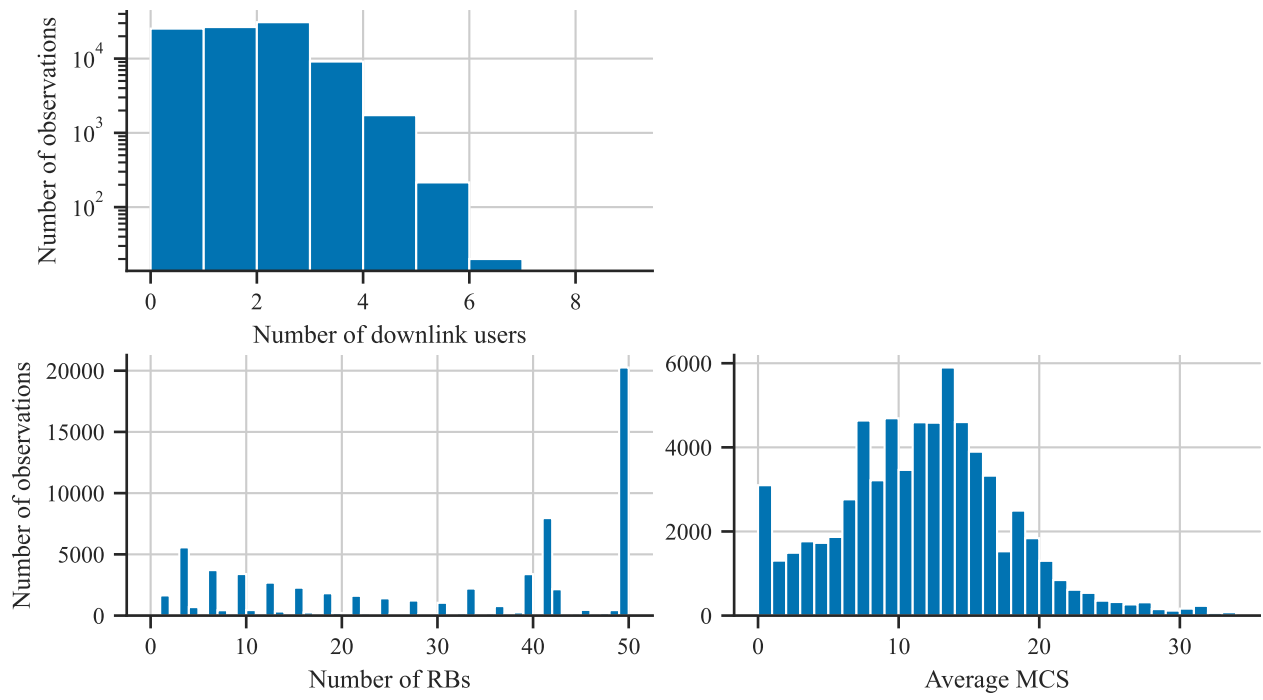


Figure E.8: Histograms of LTE downlink resource grants from site 11 observed at 739.0 MHz

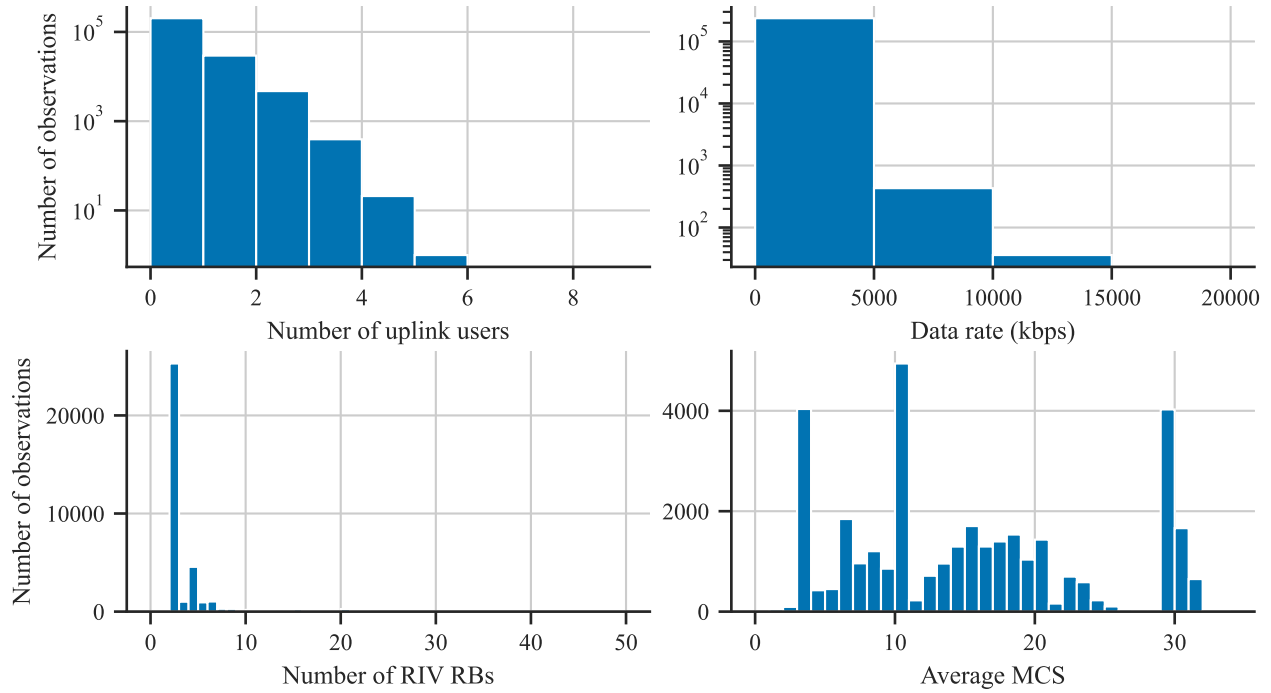


Figure E.9: Histograms of LTE uplink resource grants from site 11 observed at 866.3 MHz

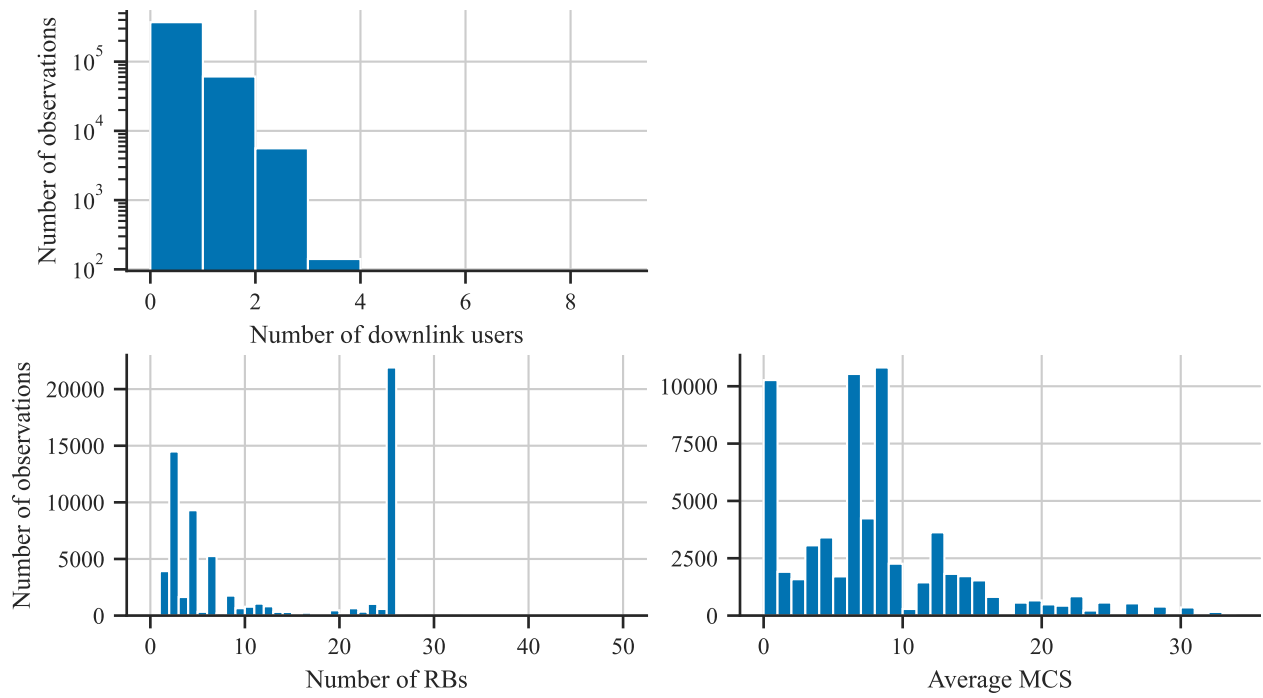


Figure E.10: Histograms of LTE downlink resource grants from site 11 observed at 866.3 MHz

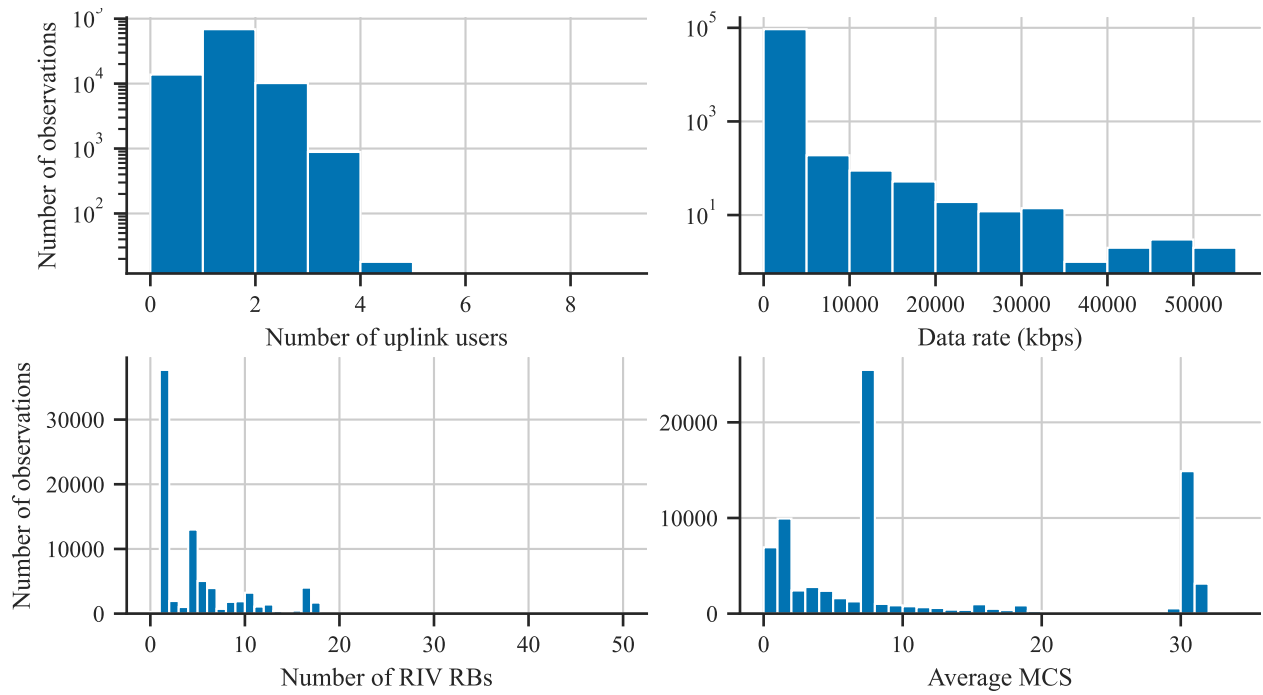


Figure E.11: Histograms of LTE uplink resource grants from site 11 observed at 731.5 MHz

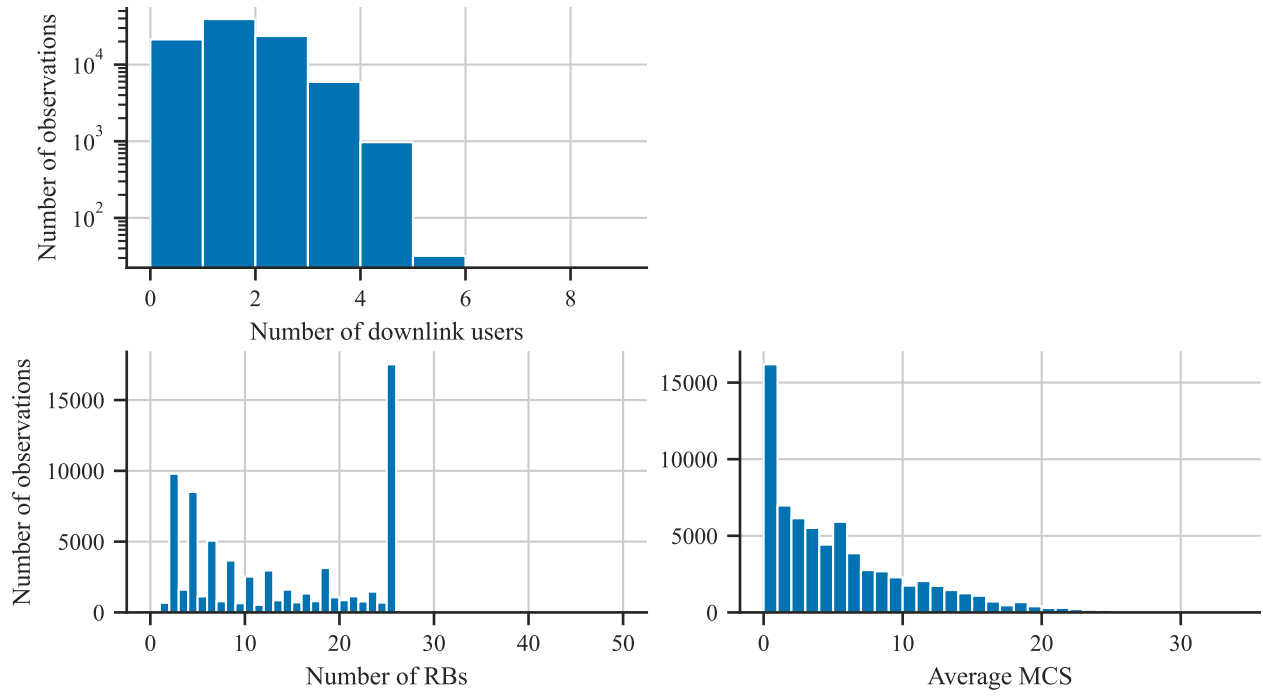


Figure E.12: Histograms of LTE downlink resource grants from site 11 observed at 731.5 MHz

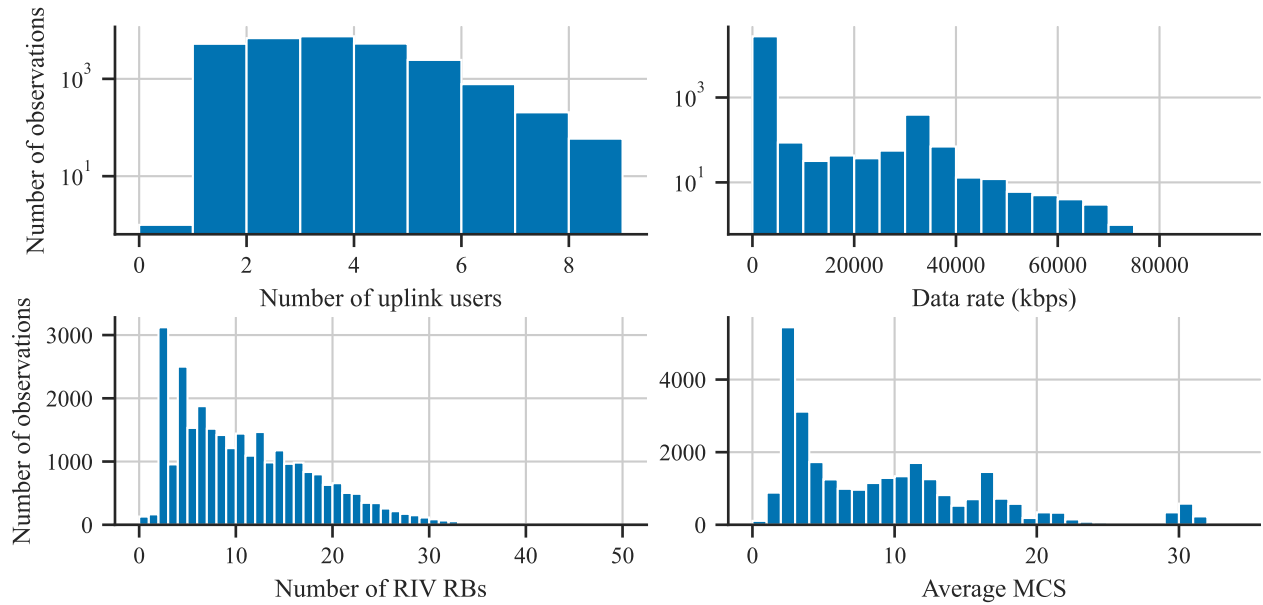


Figure E.13: Histograms of LTE uplink resource grants from site 11 observed at 751.0 MHz

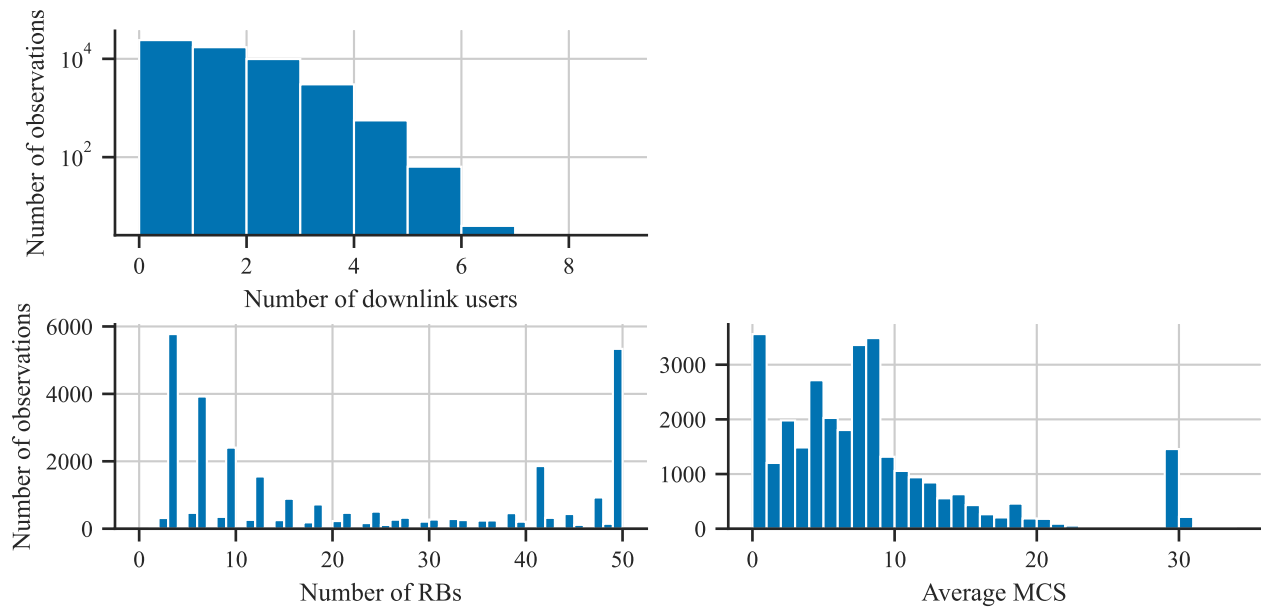


Figure E.14: Histograms of LTE downlink resource grants from site 11 observed at 751.0 MHz

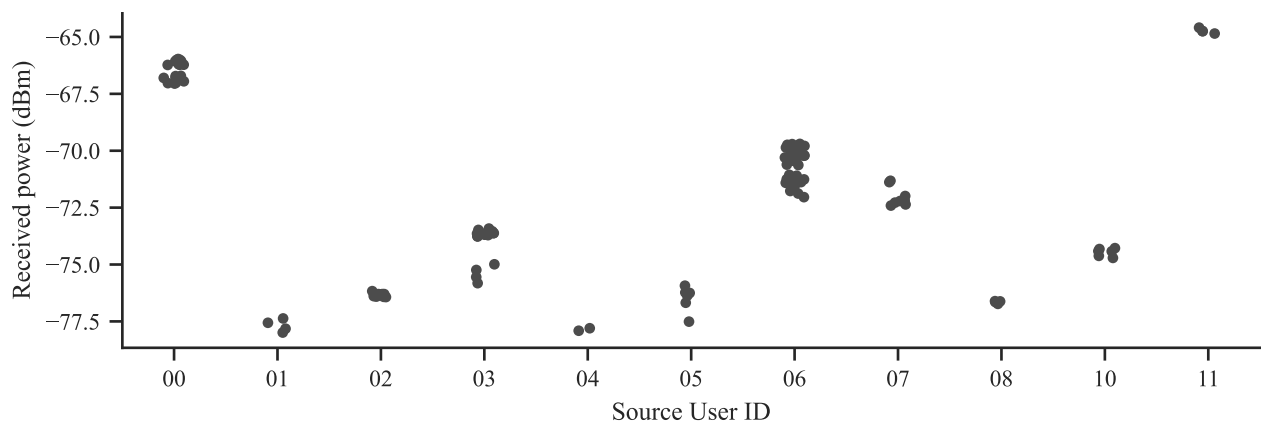


Figure E.15: Received power levels by transmission source in WLAN measured from hospital 2021-09-24 data at 2437.0 MHz

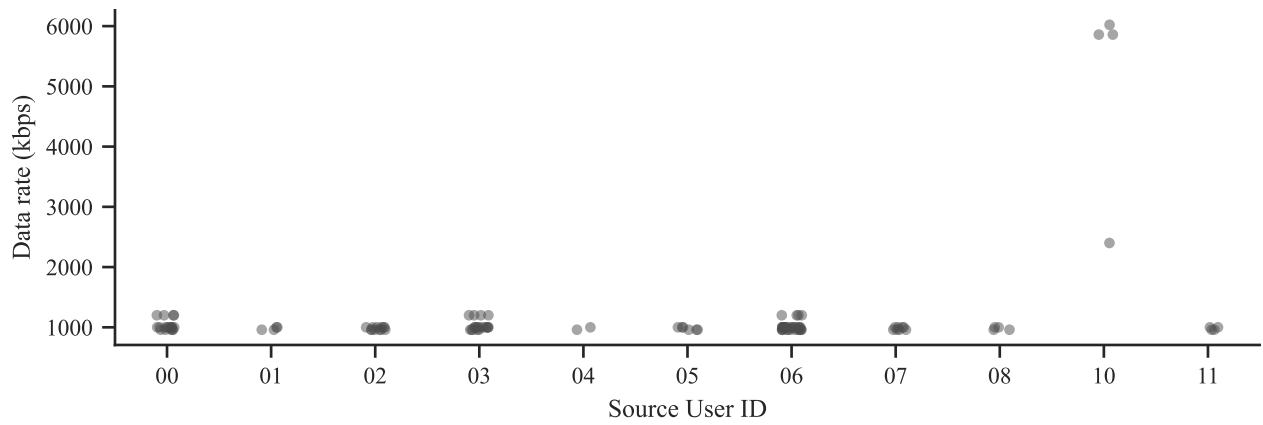


Figure E.16: Data rate by transmission source in WLAN measured from hospital 2021-09-24 data at 2437.0 MHz

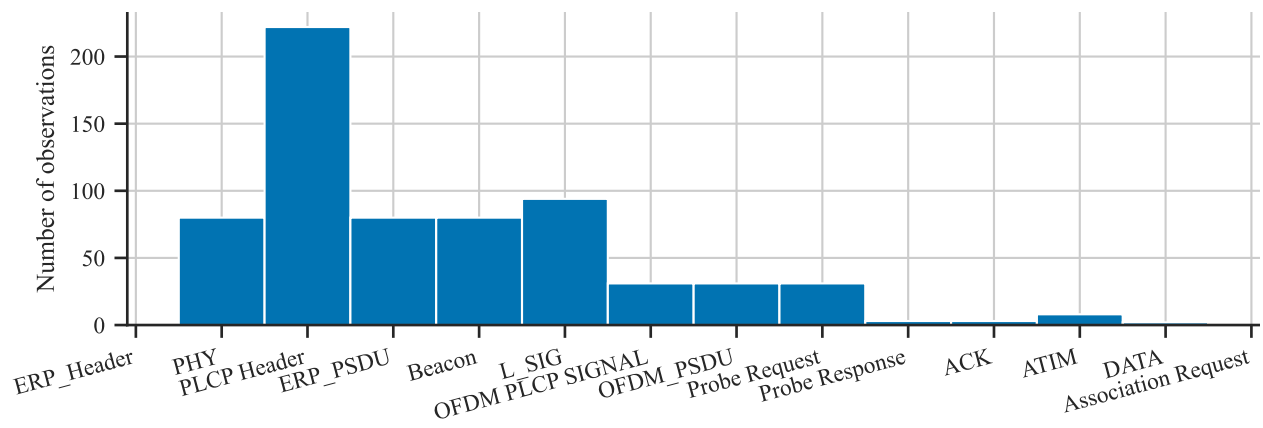


Figure E.17: Histogram of packet types observed in WLAN measured from hospital 2021-09-24 data at 2437.0 MHz

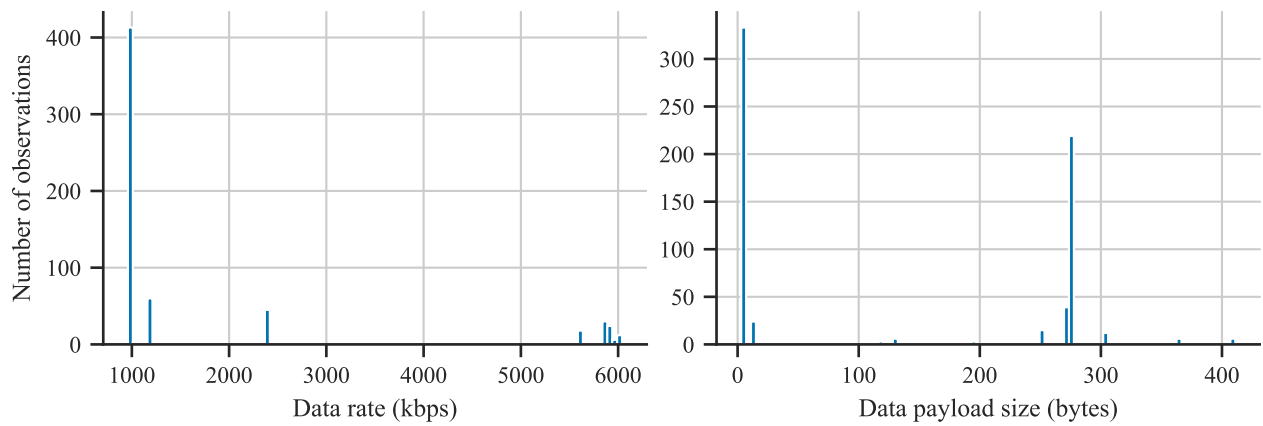


Figure E.18: Histograms of WLAN data rate and payload sizes from hospital 2021-09-24 observed at 2437.0 MHz

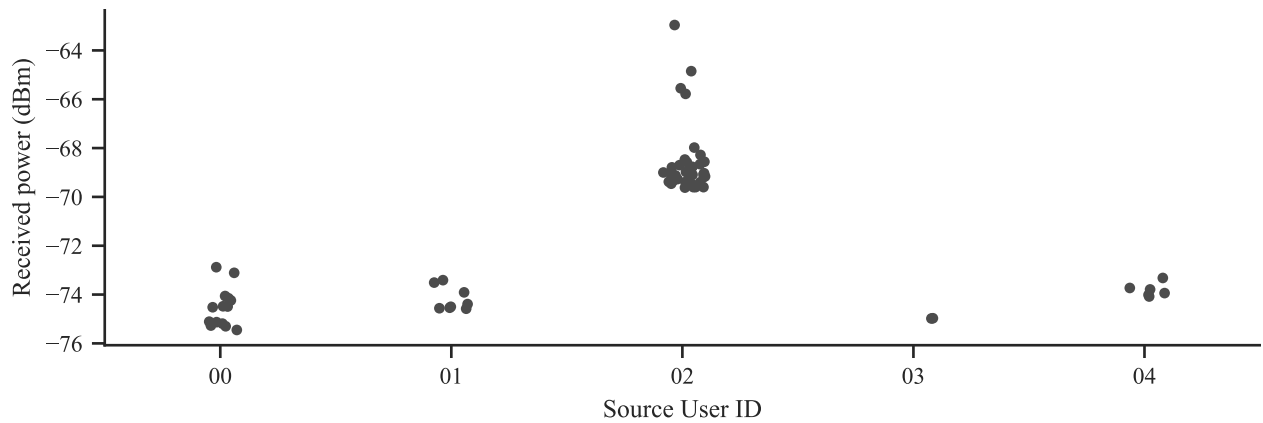


Figure E.19: Received power levels by transmission source in WLAN measured from hospital 2021-09-24 data at 2462.0 MHz

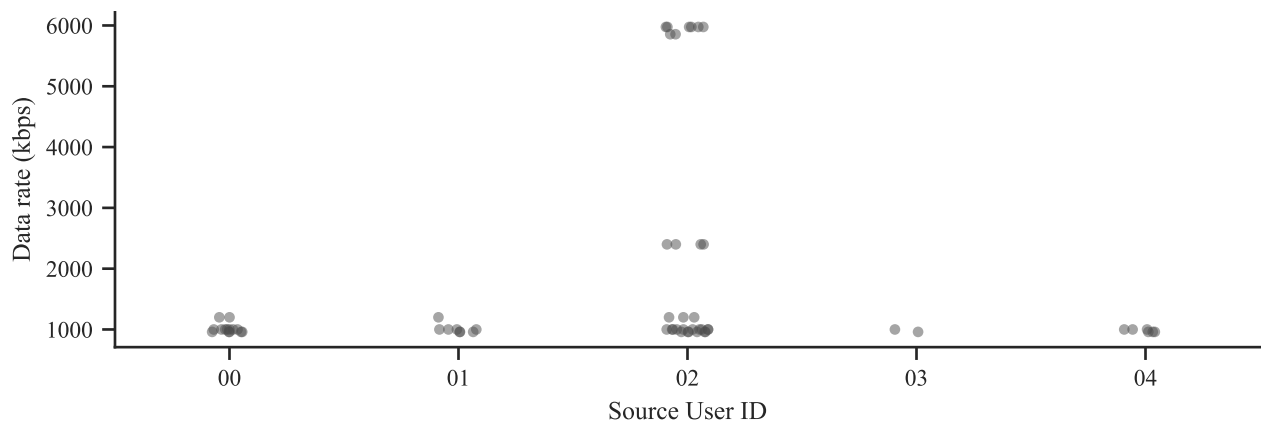


Figure E.20: Data rate by transmission source in WLAN measured from hospital 2021-09-24 data at 2462.0 MHz



Figure E.21: Histogram of packet types observed in WLAN measured from hospital 2021-09-24 data at 2462.0 MHz

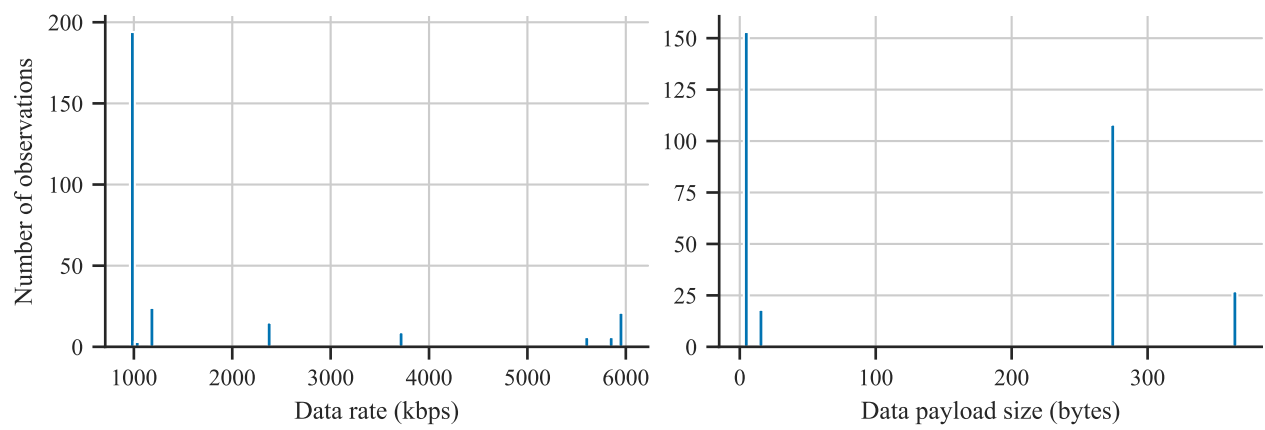


Figure E.22: Histograms of WLAN data rate and payload sizes from hospital 2021-09-24 observed at 2462.0 MHz