Radio Bursts in Residences During COVID-19: Measured Characteristics for Resiliency Testing

Daniel G. Kuester, Xifeng Lu, and Dazhen Gu
NIST, Communications Technology Laboratory, Boulder, CO, US
daniel.kuester@nist.gov, xifeng.lu@nist.gov, dazhen.gu@nist.gov

***Abstract*—We present an analysis of the time parameters observed in radio spectrum occupancy measurements of 13 residential sites from June 2020 through September 2021. The focus of the analysis is on implications for electromagnetic immunity testing of medical devices and household electronics. We demonstrate that the bursted nature of household transmissions, together with wide gap times between transmissions, stands in significant contrast to the continuous periodic disturbances used in immunity testing. Further, we identify that the most active band, 2.4 GHz, is not yet prescribed as a test frequency in all immunity standards.**

I. Introduction

In the first months of the COVID-19 pandemic, the authors and 10 of their colleagues undertook a measurement campaign to assess radio spectrum occupancy in their home telework environments. This represented an under-studied class of environments, during a time of notably high demand. Press reports pointed to increased home data traffic and decreased service performance. Increases of around 50% in both home broadband data consumption [1] and calls placed over Wi-Fi [2] corresponded with decreases in broadband data throughput between 10% and 40% for urban users [3].

The first outcomes of this effort were its data products [4] and accompanying assessment report [5]. The focus of this first analysis of the measurement data was on the distribution of measured power levels at the frequencies under test. The primary application of this type of analysis was on the assessment of spectrum availability. However, we also included summary analysis of the time duration of the observed radio transmissions, with some remarks on their relationship to electromagnetic compatibility (EMC) immunity standards.

In this paper, we present an extended investigation of the timing characteristics of the measurement data and their relationship with immunity testing. The approach is to expand the set of timing parameters under study, in the context of describe disturbances that might be experienced by household products and medical equipment. The scope includes include the time duration of radio transmission occupancy events, the gap time between them, the number of occupancy events that occurred during the short 105 ms acquisition periods. It also extends to joint statistics between the parameters.

We struggled to find prior work on this topic that focused on indoor residential settings. Most dealt with field data that were collected outdoors [6]–[10]. These provide useful context for outdoor deployments of wireless networks, and for coexistence and interference studies in which other systems are located outside. It is difficult to extrapolate these results to predict behavior in indoor household settings, however, where wireless networking electronics mingle with other nearby electronic devices.

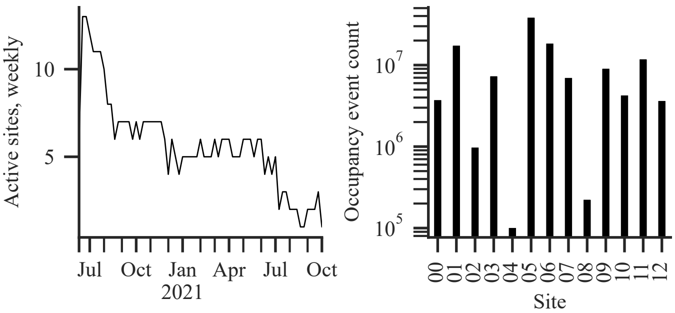

Fig. 1. Overview of size of the data set as distributed across time and site, from 2020-06-09 through 2021-09-22. Sample counts from each site are summed across all frequencies.

To help fill gaps in understanding in the above areas, our study here extends the analysis of [4] for application to EMC immunity testing standards. These define immunity tests for two types of device under test (DUT): medical devices, which are specified by IEC 60601-1-2 [11], and second, household products, which are covered by CISPR 14-2 [12]. In order to focus our effort toward transmissions that originate *inside* households, we target frequency bands that are (i) unlicensed or (ii) used in cellular uplinks.

II. Test Method and Data Overview

This section summarizes key test parameters with the goal of making this paper self-contained. Our previous report [5] gives more detail. An overview of the sample size of the field observations is shown in Fig. 1, split across time and site.

A. Sample Size

Measurements began in early June, 2020 at 13 different residential sites and continued for 15 months. Across this time span, fewer sites produced data, which echoed the decreasing fraction of work time at home. However, many other factors also impact the number of sites collecting data. For example, many student participants completed internships and returned to school in autumn 2020. Hence, the number of active sites

TABLE I
SENSOR RADIO AND ACQUISITION PARAMETERS

Channelization	2-channel, swept-frequency
RF frequency tuning range	RX1: 700 MHz - 900 MHz RX2: 2 GHz - 6 GHz
Center frequencies	Cellular FDD uplinks channels: 701.5, 709, 782, 821.3, 842.5 MHz 2.4 GHz ISM channels: 2.412, 2.437, 2.462 GHz 5 GHz U-NII channels: 5.17, 5.19, 5.21, 5.23, 5.24, 5.775, 5.795 GHz
Resolution bandwidth	4 MHz
Power detector bin size, T_i	500 µs
Dwell period	105 ms
Dead time	77%
Out-of-band IP3	-12.4 dBm (701.5 MHz) [14]
Input compression level	-20.9 dBm (701.5 MHz) [14]
Sample depth	12 bits

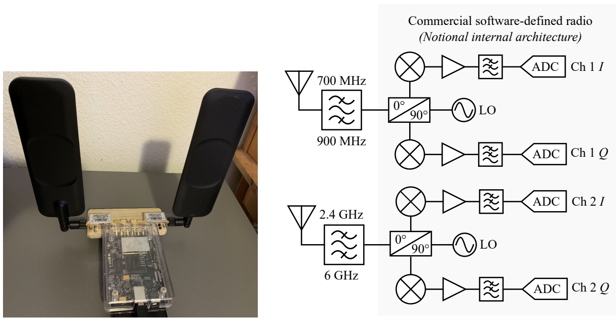

Fig. 2. Radio front-end architecture of a sensor node

was largest in July and early August of that year. Further, some test participants needed to pause data acquisition intermittently in order to free their computers for other tasks.

B. Locations

The test sites were the residences of staff, research associates, and student interns; all of them work at the National Institute of Standards and Technology (NIST). Each location was in or near the city of Boulder, Colorado, in the United States. One analysis of census data reported that this region experienced the highest rate of telework in the United States [13], so we expect that wireless data network usage by neighbors may have also had a significant impact on the results. The residences included examples of single- and multi-family homes, and single- and multi-story structures. In all cases, measurements were conducted indoors. All sensors were on the ground level or 2nd floor, except one, which was in a basement.

C. Sensor Parameters

Table I lists the key test parameters, and the sensor designed to implement the measurement is illustrated by Figure 2. This custom instrument supported two input channels to help isolate impacts of any overload events: channel RX1 covered cellular activity below 900 MHz, while channel RX2 targeted transmissions in unlicensed bands around 2.4 GHz and 5 GHz.

Custom software on the telework computers of NIST staff implemented the simultaneous acquisition and real-time signal processing. Samples of complex-valued baseband voltages streamed to a host computer. A GNURadio flow graph defined and executed signal processing for the incoming data stream, and output a real-time stream of power readings. Processing limitations of the lowest-performing computers determined the 4 MHz sampling bandwidth.

The frequency list given by Table I was shuffled into random order on each frequency sweep; this process repeated continuously unless stopped by the user. To avoid spurious readings, the radio required a 350 ms wait after each frequency change. Then the data were acquired and recorded as a time-series of 210 power readings in root mean square (RMS) detector time bins of $T_i = 500\,\mu\text{s}$, spanning 105 ms.

D. Characteristics Under Study

We flag occupancy for each i^{th} power bin by simple thresholding, evaluated as

$$O_i = \begin{cases} 0 & P_i : P_i < P_{\text{th}} \\ 1 & \text{otherwise.} \end{cases} \qquad (1)$$

An $O_i = 1$ flag indicates apparent transmission in the channel, though it could also be a false-positive caused by noise or imperfect frequency selectivity.

We use the above to define derived parameters for calculating occupancy and burst characteristics:

- Occupancy event: a time window comprising a contiguous group of sample indices bounded by indices j and k such that $O_{j,\ldots,k} = 1$, and $O_{j-1} = O_{k+1} = 0$. This excludes any O_i abutting the edge of a dwell window;
- Gap event: a time window containing contiguous samples not included in an occupancy event;
- Occupancy duration: $T_i(k - j + 1)$;
- Gap duration: the time delay between recorded time-adjacent occupancy events;

Figure 3 illustrates these concepts on example measurements from licensed cellular and unlicensed bands.

III. FIELD OBSERVATIONS COMPARED TO STANDARDIZED TEST PARAMETERS

This section begins with an overview of test excitation parameters in immunity test standards, and then compares them with measured field data.

A. Electromagnetic Disturbance in Test Standards

IEC 60601-1-2 specifies immunity tests standards for medical equipment [11]. The electromagnetic excitation specified for testing at a given frequency is adjusted based on the type of wireless networking technology that is expected in that channel. In each cases, the field excitation is a single carrier tone with pulse modulation defined as {4.6 ms or 55.6 ms period, 50% duty cycle}. The list of test frequencies in that standard includes almost all of the center frequencies tested in this paper (Table I).

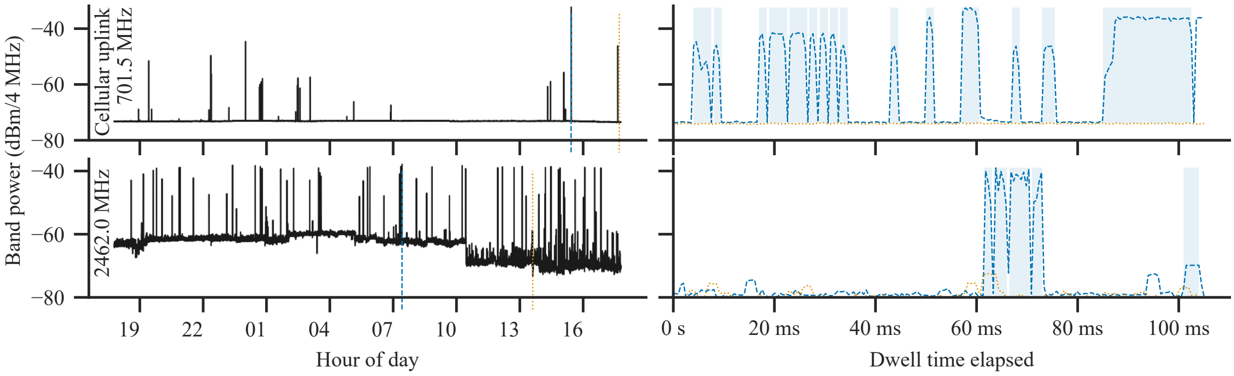

Fig. 3. Example measurements demonstrating dwell window power levels (lines) and occupancy events (shaded regions) of bursts observed at 2 frequencies beginning 2020-11-07. Wide-view traces of peak power per 105 ms dwell window (left) demonstrate the sparseness of the bursts. Narrow-view plots (right) show band power in the two dwell windows marked in wide view; these were the most and least active dwell windows.

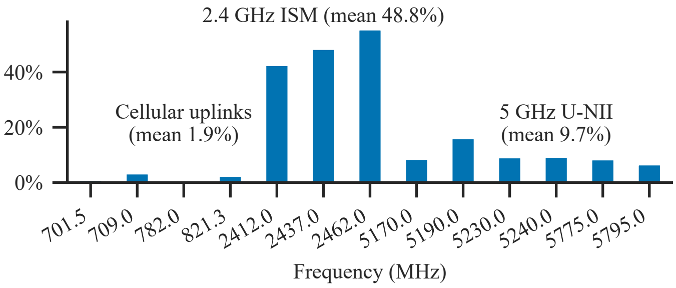

Fig. 4. The percentage of dwell windows containing at least 1 occupancy event, plotted by channel center frequency.

The CISPR 14-2 immunity tests [12] apply to household products, and follow excitation parameters set by the IEC 61000-4 standards family. Carrier frequencies are prescribed from 80 MHz to 1 GHz, and are amplitude modulated with parameters fixed at {1 ms period, 80% modulation depth}.

B. Dwell Window Duty Cycles

In order to study the incidence rate of short transmission bursts, we looked at the percentage of observed 105 ms dwell periods containing at least 1 occupancy event. The results are illustrated by Fig. 4. The difference across band types was dramatic, ranging from less than 2% for cellular uplinks to nearly 50% in the popular unlicensed bands near 2.4 GHz.

Two aspects of these results have clear bearing on the immunity test standards. Firstly, in terms of occupancy, the continuous modulation excitation specified by current test standards is conservative, given that more than 98% of cellular uplink dwell windows remained fully inactive. This may be deliberate, with the goal of proactive identification of problems, instead of realism. Secondly, CISPR 14-2 does not test against the most active channels in our measurements, which were in the 2.4 GHz band.

C. Occupancy Durations

Plots of empirical complementary cumulative distribution functions (CCDFs) of the field observations of occupancy duration are given by Fig. 5a. Sample medians and 95th

TABLE II
OCCUPANCY PERCENTILE STATISTICS BY FREQUENCY

	Freq (MHz)	Occupancy duration (ms) 50%	Occupancy duration (ms) 95%	Duty cycle in active dwells (%) 50%	Duty cycle in active dwells (%) 95%
Cellular upl.	701.5	0.5	2.5	1.0	2.4
	709.0	1.0	4.0	1.0	2.4
	782.0	1.0	5.0	1.0	4.3
	821.3	1.0	5.0	1.0	4.3
	842.5	0.5	3.5	0.5	3.3
ISM	2437.0	1.0	4.0	1.0	4.3
	2462.0	1.0	4.0	1.0	3.8
	2695.0	0.5	1.5	0.5	1.4
U-NII	5170.0	0.5	1.0	0.5	1.0
	5190.0	0.5	1.5	0.5	1.0
	5210.0	0.5	1.5	0.5	1.4
	5230.0	0.5	2.0	0.5	1.4
	5240.0	0.5	2.0	0.5	1.4
	5775.0	0.5	2.0	0.5	1.9
	5795.0	0.5	1.5	0.5	1.4

percentiles are listed in Table II. In all frequency bands, the 95th percentile of occupancy duration was 5 ms or less.

Immunity testers could consider this range of parameters to when setting the pulse “on time” in excitations. In order to implement this, CISPR 14-2 would need to be extended to include off time in its excitation modulation.

D. Occupancy Within Transmission Bursts

Even during dwell windows with at least 1 occupancy event, duty cycles were still low. Empirical statistics are given listed by percentile (Table II) and shown by empirical CCDFs (Fig. 5b). In 50% of active dwell windows across all frequencies, duty cycle was below 1%, corresponding to 2 or fewer occupancy events. At the 95th percentile, in the most active frequencies, the total duration of occupancy events was still less than 5% of the dwell period.

E. Field Data: Gap Durations

Empirical distribution of intra-dwell gap durations are shown in Fig. 5c. The time scale is shown only up to a small fraction of the dwell period, in order to minimize the window truncation errors. The cellular uplink channels trended toward

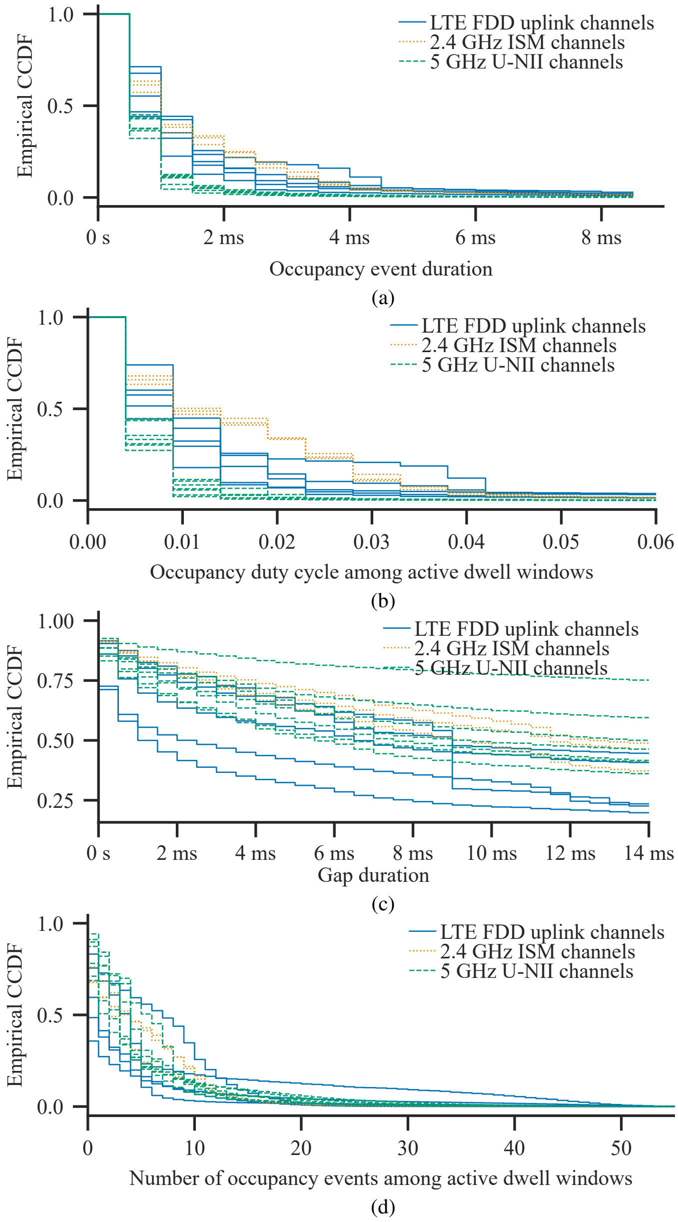

Fig. 5. Empirical distributions of (a) occupancy duration, (b) occupancy rate among active dwell windows, (c) gap durations, and (d) occupancy events per active dwell window. Each line corresponds with a frequency listed in Table I.

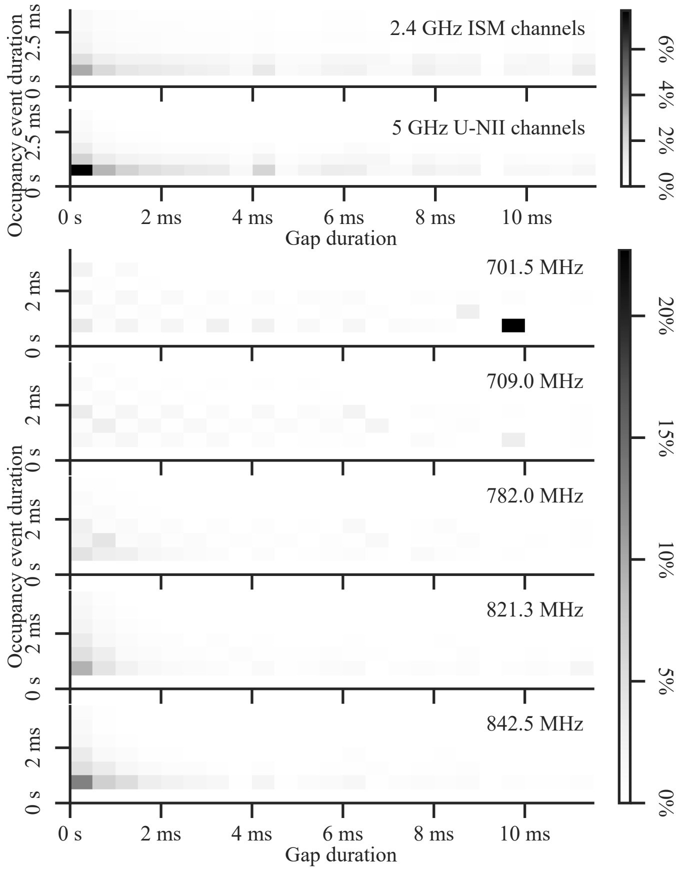

Fig. 6. Empirical distributions of occupancy counts aggregated across all test sites, further aggregated across unlicensed bands (top) and separated by licensed cellular band (bottom), jointly by event duration and occupancy gap duration.

the shortest gap durations, with median values between 1 ms and 9 ms. The unlicensed channels trended toward longer gap times, though in most cases the truncation effect prevented a strightforward estimate of median values.

The gap duration and occupancy duration, together, form an upper limit on the occupancy rate observed in the previous sub-section. These can be used to compute the number of occupancy events per dwell window. The CCDF of this derived statistic, which includes only samples from active dwell windows, is shown by Fig. 5d. One outlying cellular uplink channel achieved a greater number of occupancy events; the others may have been truncated by the dwell window.

The significant gap time between occupancy events tended to be long relative to the duration of the occupancy events. This serves to further emphasize the lack of gap time specified in CISPR 14-2, and relatively large duty cycle specified by IEC 60601-1.

F. Joint Statistics

To investigate joint statistics between the parameters in this paper so far, we turn to 2-parameter histogram heat maps.

Figure 6 illustrates {occupancy duration, gap duration}. Channels within 2.4 GHz and 5 GHz were aggregated because unlicensed transmitters in these bands may move between channels. Occupancy events in unlicensed bands and *most* cellular data networks were most likely to cluster closely together. However, resource scheduling at 701.5 MHz favored occupancy grants only once per 10 ms radio frame.

Figure 7 shows the empirical distribution across {occupancy duration, occupancy events per dwell window}. In this case, the characteristics of each plot seem distinct, making it difficult to identify a single pair-value that would accurately represent the behaviors in EMC testing.

IV. Conclusion

We presented statistics of time parameters from our residential spectrum monitoring campaign in the context of EMC

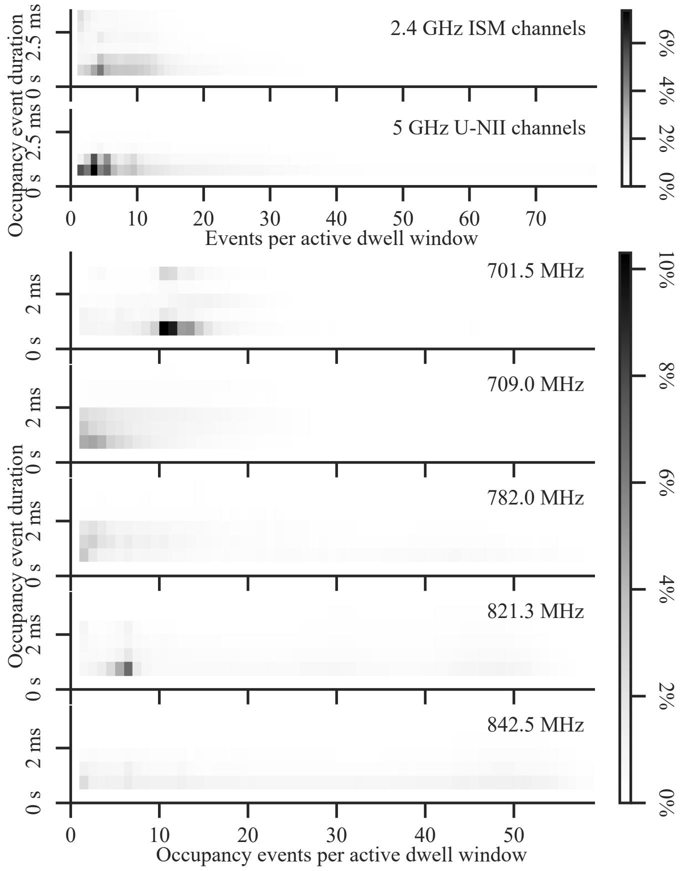

Fig. 7. Empirical distributions of occupancy counts by frequency aggregated across all test sites, aggregated across unlicensed bands (top) and by licensed cellular band (bottom), jointly by event duration and occupancy count per dwell window.

immunity testing standards CISPR 14-2 and IEC 60601-1-2. We point to the following key outcomes:

1) For testing in household environments, an impactful target for extending the frequency coverage would be to be to include the 2.4 GHz unlicensed band. In our measurements, this band exhibited the greatest incidence rate of active dwell windows (by far).
2) Further study is needed to investigate the impacts of randomized burst disturbances on DUT immunity when compared to simple continuous modulation. If some DUTs are more vulnerable to certain timing parameters, then it may be important to consider more realistic disturbances.
3) In order to study the implications of the complex bursting characteristics on DUT immunity, it may be necessary to investigate capabilities for generating more dynamic electromagnetic disturbances during test.

In the future, the measurement approach could be improved by decreasing the time bin period T_s, in order to capture occupancy characteristics of lower-latency networks. Further, in order to capture the long tails of the gap durations between occupancy events, longer dwell times would be helpful.

References

[1] J. Cohen, “Bandwidth use increased 47pct in 1q20 thanks to coronavirus,” Accessed Jun. 2020. [Online]. https://www.pcmag.com/news/data-usage-has-increased-47-percent-during-covid-19-quarantine

[2] M. Alleven, “AT&T: Wi-Fi calling up 53% over Memorial Day,” 5, Accessed Jun. 2020. [Online]. https://www.fiercewireless.com/operators/at-t-wi-fi-calling-up-53-over-memorial-day

[3] T. Cooper, “Internet speed analysis: Rural, top 200 cities april 12th – 18th,” 4, Accessed Jun. 2020. [Online]. https://broadbandnow.com/report/internet-speed-analysis-april-12th-18th/

[4] D. G. Kuester, X. Lu *et al.*, “Distributed Sensing of Radio Spectrum Occupancy amid COVID-19 (Data Release),” 2022. [Online]. https://doi.org/10.18434/mds2-2553

[5] ——, “Radio Spectrum Occupancy Measurements Amid COVID-19 Telework and Telehealth,” NIST, Boulder, CO, Tech. Rep. TN 2240, Oct 2022.

[6] J. Kokkoniemi and J. Lehtomäki, “Spectrum Occupancy Measurements and Analysis Methods on the 2.45 GHz ISM Band,” *Proc. CROWNCOM*, no. 7, pp. 285–290, 2012.

[7] A. A. Ayeni, N. Faruk *et al.*, “Spectrum Occupancy Measurements and Analysis in the 2.4-2.7 GHz Band in Urban and Rural Environments,” *Intl. J. Fut. Comput. and Commun.*, vol. 5, no. 3, pp. 142–147, 2016.

[8] D. A. Arista Ramirez, M. Cardenas-Juarez *et al.*, “Spectrum Occupancy Measurements in the Sub-6 GHz Band for Smart Spectrum Applications,” *Proc. IEEE LATINCOM*, no. 10, pp. 2–7, 2018.

[9] O. T. Pacurar, C. Balint *et al.*, “Spectrum Occupancy Measurements in the Wi-Fi Band with a PCB Antenna,” *Proc. 2020 Intl. Symp. Electronics and Telecomm.*, pp. 2020–2023, 2020.

[10] S. Kozłowski and K. Kurek, “Channel Occupancy Measurements in 868 MHz ISM Band in Residential Areas,” *Sensors*, vol. 21, no. 7805, 2021.

[11] “Medical electrical equipment – Electromagnetic disturbances – Requirements and tests,” Std., IEC, Tech. Rep. 60601-1-2, 2020.

[12] “Requirements for household appliances, electric tools and similar apparatus – Part 2: Immunity,” Std., IEC, Tech. Rep. CISPR 14-2, 2016.

[13] “Where Did the Most People Work From Home During the Pandemic?” financialforce.com, Accessed Apr. 2022. [Online]. https://www.financialforce.com/library/where-did-most-people-work-from-home-during-pandemic/

[14] M. McNulty, D. Gu, and D. G. Kuester, “Measurements of IP3 and P1dB for Spectrum Monitoring with Software Defined Radios,” in *Proc. EuCAP*, no. 16, 2022.