ANALYSIS OF AT-ALTITUDE LTE POWER SPECTRA FOR C2 COMMUNICATIONS FOR UAS TRAFFIC MANAGEMENT

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I. Abstract

The National Aeronautics and Space Administration's (NASA) Unmanned Aircraft Systems Traffic Management (UTM) project works to develop tools and technologies essential for safely enabling civilian low-altitude small Unmanned Aerial Systems (sUAS, also known as drones) operations. This paper presents results of work completed in the paper [1] presented at the 2018 ICNS conference where proposed approaches were explored for evaluating and analyzing sUAS Command and Control (C2) links based on commercial cellular networks. This paper focuses on the UTM Project's Technology Capability Level 3 (TCL-3) test results which address the communications portion identified within the same paper. A software defined radio (SDR) was flown as a sUAS payload to capture received signal spectrum in Long Term Evolution (LTE) frequency bands of interest. The purpose was to measure the RF environment at UTM altitudes to characterize the interference potential. The SDR payload was flown at various stationary altitudes where the LTE over-the-air complex (I/Q) samples were captured by the SDR and later post-processed. The SDR received inputs through an omnidirectional antenna. The complex samples captured were an aggregate of transmissions received from all line-of-sight (LOS) towers within the geographic area for the specific radio frequency bandwidth the SDR is programmed to capture. Using this approach, the complex samples captured do not distinguish between the various eNodeB's (Long Term Evolution (LTE) transmitting towers). The complex samples were post processed via a Discrete Fourier Transform (DFT) algorithm to view the captured spectrum along with the power levels across the captured LTE bandwidth. This SDR payload process of capturing complex samples was done at two different regions within the US: 1) NASA's Ames Research Center (ARC) in Moffett Field, CA, and 2) Griffiss Airfield in Rome, NY. The data capture at the ARC site was done at two physical locations within the Ames campus where many stationary altitude captures where done as high as 800 ft. above ground level (AGL). The data captured at the Griffiss Airport (also known as the NY Corridor Site) were acquired at one location with three specific stationary altitude levels – {Ground Level (GL), 300 ft., and 400 ft.}. The LTE spectrum power levels were captured for two LTE carriers, AT&T and Verizon, at both sites where their respective spectra and power levels were measured and compared at various altitudes. The overall results show that there is an increase in LTE spectrum power levels at higher altitudes for drones. A detailed analysis of this data and conclusions drawn from the results are presented in this paper.

II. Introduction

In the past few years, there has been very scarce LTE information available to the public from cellular carriers. Even though the majority of the current LTE cellular infrastructure is setup for terrestrial communications, all LTE carriers state that their infrastructure could handle future sUAS uplink and downlink throughput capacity. However, due to their technical analysis being confidential and proprietary in nature, this information was not given to government agencies for analysis. The NASA UTM project spearheaded an effort to acquire such information in order to assess potential performance of UTM systems.

It is important to note that within the past year, a joint technical analysis of LTE infrastructure concerning drones was completed by the Third Generation Partnership Project (3GPP) [2] and presented to industry in December, 2017. By this time, the UTM project had already begun and was preparing for a March/April payload implementation. Unfortunately, NASA's LTE data collection effort was a more simplified, first step, approach to capture LTE frequency band power information. The 3GPP paper was a more comprehensive uplink/downlink (UL/DL) analysis. The 'Approach' section will explains the simplified approach and its purpose.

III. LTE sUAS Problem

With the LTE infrastructure, there are two main communication channels that may be impacted for both throughput and capacity: 1) UL (sUAS to tower), and 2) DL (tower to user equipment (UE)). The issues are readdressed below, so the reader can quickly reference the main LTE problem concerning drone LTE communications at altitude. Once again, this is the reason for the analysis presented in this paper.

Because drones can fly up to an altitude of 500 ft. in a UTM system, they are able to 'see' more cell tower UL/DL radio frequencies within a LTE carrier's identified communication bands. In seeing more cell towers, due to direct line-of-sight (LOS) to the tower antennas, there is a higher probability that the neighboring cell towers will add interference to the communication links when compared to terrestrial cell communication. Due to the downward pointing of the cellular tower antennas and due to the height of aerial vehicles, geographically undesirable, base stations further out (i.e. serving cell tower), may be spoofed into thinking that a more distant tower is the best cell tower to connect instead of the nearer proximity cell tower. This LOS issue, due to higher altitudes of radio transmission, causes more networking and handover type of congestion and inefficiencies for both UL and DL channels. This has been proven in the 3GPP paper via four sources presented in Table C.2-1 and three sources presented in Table C.2-2 in that reference[2].

For the equivalent 'altitude versus terrestrial' reasoning, UL interference occurs due to the drone seeing more towers. For example, if a drone's payload is capturing video and is streaming it back to a terrestrial cell phone and assuming the drone is utilizing an omnidirectional antenna, the streaming video signal will impact a large amount of neighboring cell towers. If a larger capacity of drones within a localized area are all streaming video to their respective tower, this will add interference to all LOS neighboring cell towers. This UL interference now caused by increasing the capacity of drones in a localized area, requires a higher resource utilization level to deliver the same offered cell data traffic for the current LTE infrastructure, or other software/hardware remediation implementation beyond the scope of this paper. This drone UL interference degrades throughput performance to the terrestrial user equipment (UE). Increased drone capacity will degrade performance for both drones and terrestrial UEs. 3GPP results to confirm the above UL issue are discussed in Annexes D.2.1 and D.2.2[2].

IV. Approach

There were a total of four sites that independently, captured LTE spectrum data. These four sites are: 1) NASA Ames Research Center (ARC) in Moffett Field, CA, 2) Griffiss Airfield in Rome, NY, 3) Reno, Nevada, and 4) Corpus Christi, Texas. For this paper, only the first two sites were analyzed. The design and capture of data for the two sites were done independently, but the analysis of data was done by NASA's Glenn Research Center (GRC). The ARC site's design and approach will be explained first.

a. ARC's Approach and Details

The ARC flight tests lasted three days (4/3/2018-4/5/2018). A various number of flights were flown at two different sites within the ARC grounds. The flight tests were executed through collaboration between GRC and ARC teams.

The main purposes of these first flight tests were: 1) to develop and gain experience on the overall NASA flight procedure process, 2) integrating flying a payload on a drone, and 3) to capture LTE band complex sample data where post processing of data would occur in order to baseline and understand what type of signal levels were being received from LTE towers. In addition, the industrial, scientific, and medical (ISM) band was also examined for the presences of measurable transmissions.

The S1000 drone, manufactured by Da-Jiang Innovations (DJI), is an octocopter which allows a light payload to be flown for about 10-12 minutes. The light payload consisted of an Ettus E310 SDR with an external Lithium Onyx battery to power the unit. Each flight was conducted in a vertical and hold flight plan. Each flight day began at approximately 8:30 a.m. and lasted till 2 p.m. After that time, winds originating from nearby San Francisco Bay begins to exceed safe operating levels (<20knots).

Figure 1-DJI S1000 Drone

Using Internet resources[3], it was determined that there were a total of four LTE carrier towers in the general vicinity of ARC. Likewise, as a result of an audit of towers, it was decided in what priority order carriers will be tested, due to time limitations. It was determined the spectrum capture would be for AT&T, Verizon, and the ISM bands.

The two ARC test sites were: 1) Disaster Assistance and Rescue Team (DART) and 2) Moffett Air Field. These sites are within the ARC campus and are in flat locations where no large buildings are nearby, thus allowing a better LOS to nearby towers. Below are the identified towers per carrier in reference to ARC where both sites are shown relative to the tower information gathered from Internet sources [3]. It is important to note that the neighboring cell towers are within a one-half to three mile radius of both test sites.

Figure 2- AT&T Towers around ARC Site

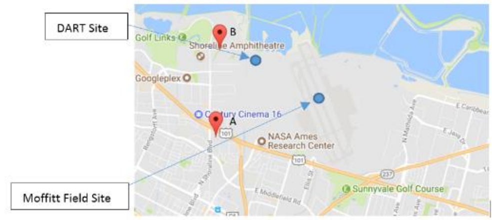

Figure 3- Verizon Towers around ARC Site

Initial GL audit spectrum plots were captured by the Keysight N9918A hand-held spectrum analyzer at each site over the entire LTE and ISM spectra at a previous visit. Using this information, the correct scanning spectra were programmed and completed during the actual flight tests.

The samples of data collected were complex samples at baseband. The Ettus E310 software defined radio (SDR) internal hardware automatically converted the LTE intermediate frequency (IF) captured samples to baseband before it saved the data to its internal micro secure digital (SD) card. The specific E310 SDR model was found to be limited to a complex 500 kHz bandwidth due to the read/write speed of the micro SD card. Each data sample was captured at Nyquist minimum to get the maximum bandwidth (BW) capture.

Figure 4 shows a complex baseband post processed signal using Matlab's 'fft' function. Notice on each edge side of the 500 kHz BW there is a sloping of the spectrum. This is due to the internal processing of the Ettus E310's analog to digital (ADC) filtering process. Due to this fact, when analyzing our spectrum data, we chose to mathematically analyze a total of 80% of the spectrum, per side, for all DFT and power spectral density (PSD) plots. Thus, for the negative and positive sides' samples were observed from -200 kHz to -50kHz and 50kHZ to 200kHz respectively.

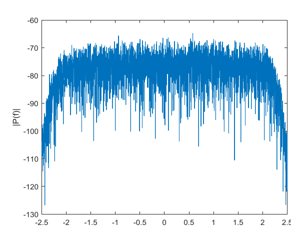

Figure 4- Complex Baseband DFT of Captured Samples

There were many limitations to the test in this first implementation. One limitation was not having the software defined radio (SDR) global positioning system (GPS) capturing data and time stamping the transmitted sample data in a synchronized way. For this permutation of flight testing, only the captured sample data was saved to the micro SD card by the Ettus E310 SDR. The work-around for this limitation utilized the drone's software called Mission Planner, which captured GPS positioning data including time, latitude/longitude coordinates, and altitude. As a post processing event, the Mission Planner GPS data was combined with the SDR's captured complex samples syncing the captured complex sample data to the GPS data. It is important to note that the GPS data has a timestamp resolution of every 0.2 seconds. This means with a sample rate of 500 kHz (samples/sec), there are a total of 100,000 samples that have the same timestamp in the combined database. Since we were capturing data during a hovering position, the resolution of the GPS data was sufficient.

By taking the DFT of time series data, we are able to understand the frequency components along with the voltage magnitude across the complex 500 kHz spectrum. By taking the DFT again, we got the power spectral density (PSD). The PSD measurement not only captured the sinusoidal signal power, but also the additional physical portions of the signals in the air such as electromagnetic, acoustic, etc. An analysis, that is not shown here, was done to see if there was a difference between power measurements. It was found that there was no noticeable difference between the DFT and PSD relative measurements. That analysis is not presented here.

The mathematical analysis tool used was Matlab. Matlab has an internal function called 'fft' where the 'dft' of the time analysis is accomplished. A parameter used for the 'fft' function is the number of bins. The input is a value in the power of two. An analysis of what DFT bin value to use was completed to understand the least number of bins that allowed for the best resolution to ensure most efficient processing, since the time series values were fairly large. The results are not be shown here, but were found that any bin resolution less than 112 Hz is sufficient to analyze our 500 kHz complex BW. There are 2^L bins being processed where L=12. Thus, the bin/Hz resolution is 112 Hz for the analysis.

Due to this 500kHz BW limitation, there were two different IF's per LTE carrier that were captured to understand the dynamic range of the LTE carrier's voltage/power of signals: 1) the edge of the downlink (DL) channel, and 2) what is called the 'sweet spot' – the portion of the DL that is close to the center of the overall DL BW. Due to the payload limited BW of our capture and by capturing these two values, we will be able to capture the overall dynamic range of spectrum at various altitudes.

b. Rome, NY Site's Approach and Details

As part of NASA's UTM project, a similar task of capturing LTE over-the-air complex samples were taking place in April 2018, simultaneously at Rome, NY called the 'New York Corridor'. This effort was overseen by NuAir Management and the technical implementation was managed by a contractor, AX Consulting.

The approach was very similar to the ARC approach whereby the payload was an SDR integrated on a drone, with the drone hovering at various altitudes capturing complex samples. A significant difference in drone payload for the NY test was there were two Ettus B210 mini SDR's per flight test. By utilizing a B210 mini, the hardware captured a larger amount of data at higher sample rates, thus allowing a larger spectrum to be captured per payload run. Likewise, due to size, two SDR's were able to fit within the same payload. Also, a more sophisticated GNU radio programming was utilized to allow for better capture and automation, allowing multiple adjacent spectrum captures that were done in one flight test.

The NY site used the same model DJI S1000 drone that was used at the ARC site, thus an average drone flight time was also approximately 10-12 minutes. A total of four specific IF spectrum captured of a complex BW of 46.08MHz by each SDR. A total of 68 spectrum captures were performed at three altitudes within one flight; 1) at a hovering altitude of 90 m., 2) at a hovering altitude of 120 m., and 3) at ground level (GL). The total size of data saved per flight to each SDR's microSD card drive was approximately 112.5GByte/SDR. Each sample was captured at Nyquist minimum to get the maximum BW capture. Thus, each complex sample in the captured time series is 1/Fs, where Fs=46.08 Msps. Each I/Q sample was transformed by the SDR at baseband to a 16 bit floating point resolution.

Each adjacent BW payload was overlapped by 24.04MHz (1/2 the sample rate), thus allowing the concatenation of the adjacent complex samples appropriately to handle the SDR's ADC filtering issue, as identified above. Table 1 shows all the LTE and ISM spectrum IF's that were captured. For example, IF 691.2 MHz has a complex BW range {667.16 MHz to 714.24 MHz}. The next 'half-adjacent' BW capture begins at IF = 714.24 MHz, where the complex BW range is {690.2 MHz to 737.28 MHz}. There were a total of three contingent spectrum ranges that were captured via this staggered IF approach. The three ranges are: 1) 667.16 MHz to 967.68 MHz, 2) 1681.92 MHz to 2718.92 MHz, and 3) 5690.88 MHz to 5990.40 MHz.

Finally, these same three chosen spectra were captured at two different times, thus ensuring the detection of any anomalies from one time to the other.

It is important to note that this concatenating of sample data together, since it is not time-aligned, will not allow for LTE frame extraction of parameters like received signal strength indicator (RSSI) and the reference signal receive quality (RSRQ). However each 48.08MHz complex BW capture may be investigated to extract LTE framing information such as RSSI.

Table 1 – All Intermediate Frequencies Captured at NY Rome Site

IF #	IF(MHz)	IF #	IF(MHz)	IF #	IF(MHz)	IF #	IF(MHz)
1	691.20	18	1820.20	35	2211.88	52	2603.56
2	714.24	19	1843.24	36	2234.92	53	2626.60
3	737.28	20	1866.28	37	2257.96	54	2649.64
4	760.32	21	1889.32	38	2281.00	55	2672.68
5	783.36	22	1912.36	39	2304.04	56	2695.72
6	806.40	23	1935.40	40	2327.08	57	5713.90
7	829.44	24	1958.44	41	2350.12	58	5736.94
8	852.48	25	1981.48	42	2373.16	59	5759.98
9	875.52	26	2004.52	43	2396.20	60	5783.02
10	898.56	27	2027.56	44	2419.24	61	5806.06
11	921.60	28	2050.60	45	2442.28	62	5829.10
12	944.64	29	2073.64	46	2465.32	63	5852.14
13	1705.00	30	2096.68	47	2488.36	64	5875.18
14	1728.04	31	2119.72	48	2511.40	65	5898.22
15	1751.08	32	2142.76	49	2534.44	66	5921.26
16	1774.12	33	2165.80	50	2557.48	67	5944.30
17	1797.16	34	2188.84	51	2580.52	68	5967.34

Once the data was captured and the file names were saved (in a very critical fashion where each file is uniquely named and understood), the data was post processed using the Matlab software tool. The post processing including the concatenating of all the IF spectrum complex samples together was completed to get a full spectrum view of the three contingent spectra. From this full spectrum view, it was determined what smaller spectra should be analyzed. These smaller spectra were considered after zooming into LTE bands where signal spectra were captured. The analysis of the captured samples were mapped back to specific LTE bands. Since we were looking at OFDM type modulated data which includes LTE frequency bands and ISM bands, a DFT bin resolution of approximately 700 kHz was chosen (46.08 MHz/2^16 =703 Hz / DFT bin) . It is important to note, that each LTE OFDM subcarrier is 15 kHz in bandwidth, thus there was enough resolution for an LTE spectrum analysis.

In a similar fashion as to how ARC's towers were identified, the Griffiss Field LTE carrier towers were captured. Below are plots of both LTE carriers where it shows the number of towers within the vicinity of the data capture site using http://www.cellreception.com[3].

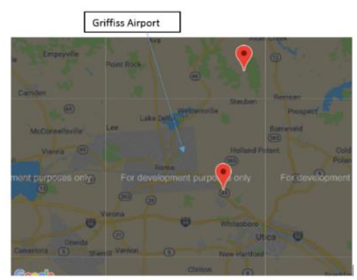

Figure 5- Verizon Towers at Rome, NY Site

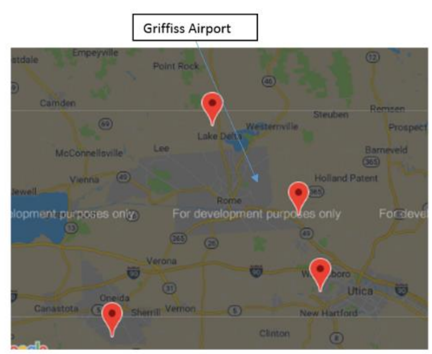

Figure 6- AT&T Towers at Rome, NY Site

V. Results and Analysis

The data was captured between the two sites were captured in similar ways from a technological perspective, but was post processed in a slightly different 'power' spectrum approach. For the ARC data analysis, only the spectrum bandwidth power measurements were analyzed using the complex spectrum data. The DFT algorithm was utilized to transform the captured time series complex samples to the frequency domain.

The captured LTE power spectra were analyzed at multiple altitudes and investigated to see if there were any differences in power levels. It is important to note, that the data capture was done while hovering and not while flying in any x, y or z, direction.

a. ARC Site Results and Analysis

There were two sites within the ARC campus where payload captures occurred: 1) DART site and 2) Moffett Air Field site. Both these sites have no large obstacles nearby, thus simulating a more rural type environment. Due to the continental separation between ARC and GRC NASA sites, the flight tests were done within a three day one-time visit to ARC. A pre-flight visit to ARC was completed that allowed the team to understand and validate what LTE carrier spectra are being used within the area, so the payload code could be appropriately configured. The hand-held spectrum analyzer results were captured at GL and are used as a double check at flight time. For the ARC site, it was confirmed that AT&T and Verizon LTE carriers were to be scrutinized where certain DL bandwidths were identified for capture.

DART Site

There were a total of five good flight tests that were completed at the DART site for the day. The drone was tethered for every flight test for this site where the highest hovering altitude was up to 52 m. (170 ft.). Again, two LTE carrier DL spectrum information was captured at this site including AT&T, Verizon, and spectrum information captured in the ISM band.

As mentioned in the Approach section, an initial spectrum scan at each site was performed to ensure that LTE signals were present before sending the payload to flight to capture spectrum information. Figure **8** displays the frequency blocks of AT&T's bands 12/17 which are their main 4G LTE bands [4],[5].

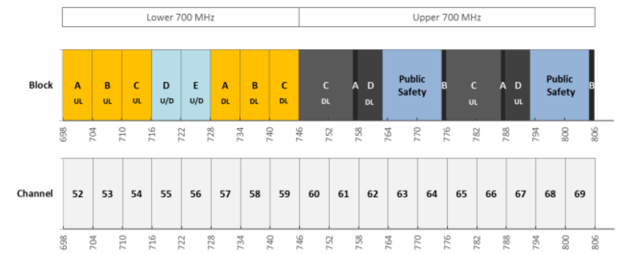

Figure 7- AT&T (Bands 12/17) and Verizon (Band 13) GSM Lower and Upper 700 MHz Bands

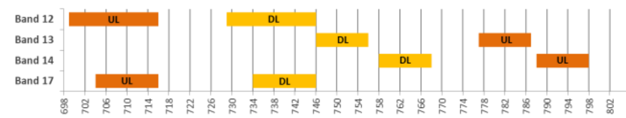

Figure 8- GSM Lower and Upper 700 MHz Band Designations

Block B (AT&T channel) has the DL 734 MHz-740 MHz and Block C (Verizon channel) has DL of 740 MHz-746 MHz where it seems both blocks are being used on the day of the payload flight (Channels 58 and 59), as can be seen in Figure **9** and Figure **10**.

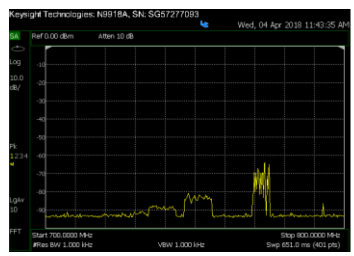

Figure 9- Hand-held Spectrum Capture of 700 MHz-800 MHz Range at DART Site – Lower/Upper 700 MHz Bands

Zooming into band 12, the edge of Block B is shown in Figure 10.

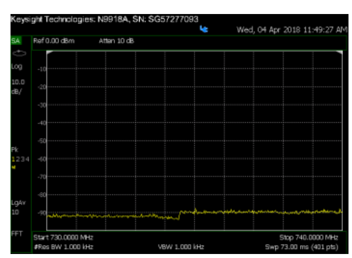

Figure 10- Zoomed-In Hand-held Spectrum Capture of 730 MHz-740 MHz Range at DART Site – AT&T Bands 12/17

The dynamic range (DR) is the power difference between the noise floor and the 'sweet spot' aggregate power which can be seen by Figure **10** to be approximately 5dB.

Due to the limited timeframe of payload flights that can be done per day along with the limited bandwidth of the unit, certain hovering altitudes and certain IF captures were performed for both identified LTE carriers. To capture the noise floor, we chose the 'corner/edge' of the Block B band 12's DL IF = 734.5 MHz. This will allow us to capture a complex BW of 500 kHz. As explained earlier, the Ettus SDR's ADC takes the IF captured samples and records them to a complex baseband. Thus, 250 kHz of complex samples are within the imaginary baseband portion of the baseband plot and 250 kHz of the complex samples create the Real portion of the baseband plot as shown in Figure **4**.

Matlab's Welch PSD plotting algorithm was used to plot non-noisier figures for presentation purposes. Due to the SDR's ADC filtering, the left and right portions of the complex baseband samples are filtered too much. Thus, a consistent 20% to 80% region of the PSD calculated power values are averaged to get the 'Average Noise Floor' power value. The upper and lower limit vertical yellow lines are shown in Figure **11** and Figure **12**. Unfortunately, we were only able to capture the noise floor samples at GL, 120 ft. and 170 ft. were captured. Thus, we will use the 120 ft. noise floor power value for the 40 ft. and 80 ft. were used, which is a worse-case estimate.

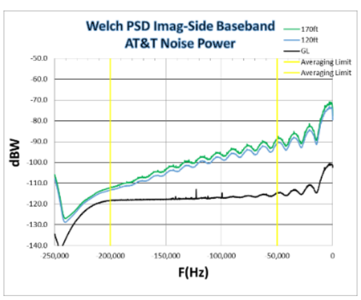

Figure 11 – AT&T IF=734.5 Capture – Imaginary Baseband Samples Capturing Noise Floor Spectrum

The 'aggregate power' values at each altitude are shown in Figure 12 via the real side of the baseband PSD plot. Again, the power values from 20% to 80% of the plot were averaged to get the overall 'aggregate' signal average at each altitude. It is important to note that this is an aggregate of the AT&T signals within this frequency band of all towers transmitting this frequency range which is unknown.

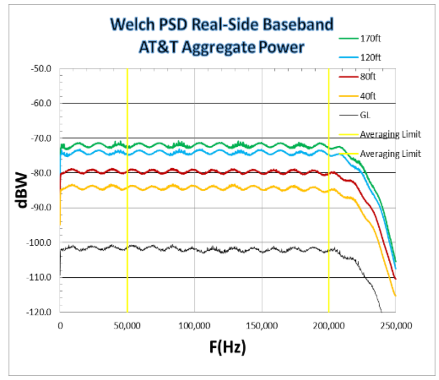

Figure 12 – AT&T IF=734.5 MHz Capture – Real Baseband Samples Capturing Signal Spectrum

Table 2 shows the dynamic range per altitude for the Lower 700 MHz DL AT&T LTE carrier spectrum. Highlighted in yellow, as altitude increases, the aggregate dynamic range in power increases by approximately 9dB for the DL.

Table 2 – AT&T DART Site Results

Altitude		Power		
(ft)	(m)	Signal (dBW)	Noise Floor (dBW)	DR (dBW)
GL	0.0	-102	-117	15
40	12.2	-84	-98	14
80	24.4	-80	-98	18
120	36.6	-74	-98	24
170	51.8	-72	-96	24

In a similar fashion, the Verizon LTE carrier was analyzed at the corner IF frequency point of 746.5 MHz – see Figure **13**. It was found that the Upper 700 MHz DL region band 13 is a Verizon DL (aka Channels 61 and 62) [6].

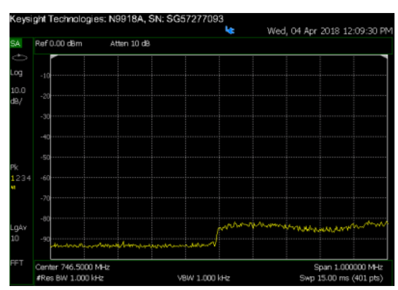

Figure 13- Zoomed-In Hand-held Spectrum Capture of IF=746.5 MHz at DART Site – Verizon Band 13

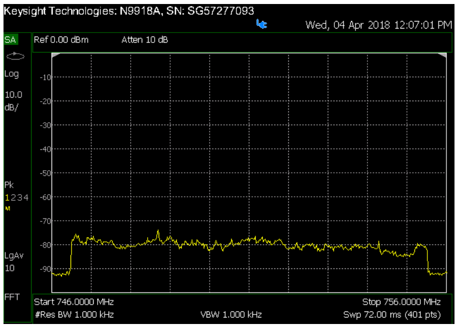

Figure 14- Hand-held Spectrum Capture of Entire Band 13 746 MHz-756 MHz Range at DART Site

The equivalent analysis approach was taken for Verizon data as was for the AT&T analysis. The Verizon results are shown in Table **3**. Again, as altitude increases the power dynamic range also increases by approximately 8dB.

Table 3 – Verizon DART Site Results

		Power		
(ft)	(m)	Signal (dBW)	Noise Floor (dBW)	DR (dB)
GL	0.0	-101	-117	16
40	12.2	-72	-96	24
80	24.4	-72	-95	23
120	36.6	-72	-96	24
170	51.8	-72	-96	24

Figure 15 shows a plot of Verizon data capturing altitude vs. flight time capturing Verizon data. This data was captured for every payload flight, but only this plot is shown here for reference. At this site, the drone was tethered via a line to the ground for safety reasons, thus the stepped incremental altitude approach was taken. Also, because it was the first time flying the drone in this particular area.

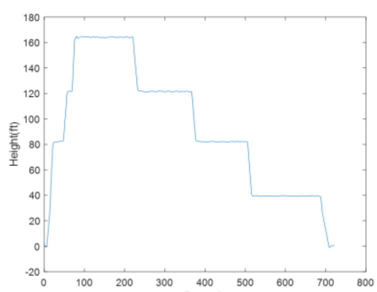

Figure 15- Payload Flight Altitude Plot at DART Site

Finally, we ran a payload test for the ISM band where data was captured, but since no signals were found, no post processed plots are shown. A scan with the hand-held spectrum analyzer is shown in Figure 16 completed at GL. The ISM band portion we scanned was the upper ISM range of 5850 MHz-5925 MHz as shown in Figure **16**.

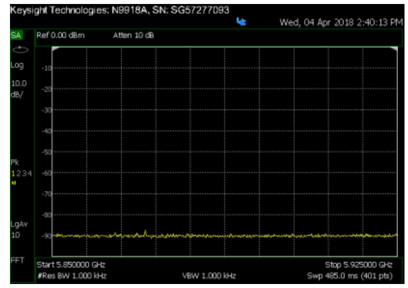

Figure 16- ISM Hand-Held Captured Spectrum Plot at DART Site

<u>Moffett Field Site</u>

Moffett Air Field is an in-use airport with a sufficiently low frequency of flights which allowed the UTM flight testing to be completed. This site was chosen, because the site is flat and wide-open and also allowed untethered drone flight. The initial thought was that there would be much scattering concerning the over-the-air signals. There may not be that much difference as a function of altitude due to LOS reception. The same AT&T and Verizon frequency bands that were scanned at the DART site were again scanned at the Moffett Field site.

The ability to fly untethered at this location enabled the drone to reach higher altitudes than the DART site, as shown below in Figure **17**.

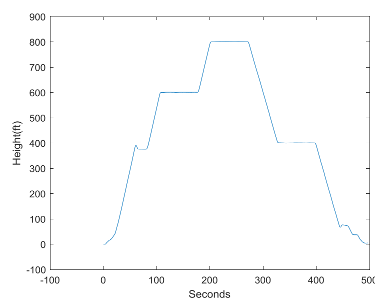

Figure 17- Payload Flight Altitude Plot at Moffett Site

Table 4 and Table 5 show information was captured for both AT&T and Verizon LTE carriers. There was a larger aggregate dynamic range and larger signal strength at higher altitudes (approximately

11dB @ 400 ft.) for AT&T carrier as shown in Table **4**. Notice at the 800ft altitude, the DR increased to approximately 13dB.

Table 4 – AT&T Moffett Site Results

Altitude		Power		
(ft)	(m)	Signal (dBW)	Noise Floor (dBW)	DR (dBW)
GL(0ft)	0.0	-104	-116	12
200	67.0	-77	-100	23
400	121.9	-72	-95	23
600	182.9	-72	-95	23
800	243.8	-71	-96	25

For the Verizon carrier, the results are shown in Table **5**. Notice the noise floor power is much higher than AT&T's. This could be because there are only two towers, which again, are very far away. There is still an increase in power at 400 ft. of approximately 4dB.

Table 5 – Verizon Moffett Site Results

Altitude		Power		
(ft)	(m)	Signal (dBW)	Noise Floor (dBW)	DR (dBW)
GL(0ft)	0.0	-93	-113	20
200	67.0	-71	-95	24
400	121.9	-71	-95	24
600	182.9	-70	-95	25
668	243.8	-70	-95	25

We again scanned the ISM range with the hand held scanner and ran payload flights to see if we captured any ISM signals. For our particular range of IF=5887.50 MHz, there were no measurable signals found. However, there were some signals found being used that are likely to be either military or maritime, due to the proximity of the San Francisco Bay and Pacific Ocean.

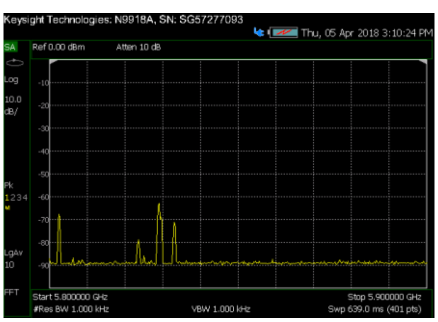

Figure 18- ISM Spectrum Hand-held Spectrum Capture of 5800 MHz-5900 MHz

b. Rome, NY Site Results and Analysis

The NY Corridor approach was similar to that employed at ARC, but differed in what spectra of samples that were captured. There were three large contingent spectrum regions that were captured.

Focusing on spectrum 1 which is 667.16 MHz - 967.68 MHz., showed that there were only two possible LTE spectra that were noticed within the entire 300MHz range. In Figure 19 shows the three DFT baseband plots of the one captured IF=714.24 MHz for capture #1. Again, each spectrum was captured at two different flight times. The three plots are shown for only one iteration and for each altitude. Notice the two most visible BW's are noticeable at 120m altitude, due to the signal strength being higher due to altitude, as we now expect.

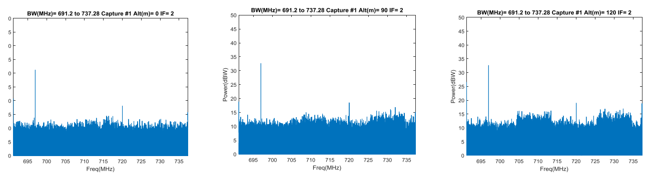

Figure 19- Zoomed-In Hand-held Spectrum Capture of 730MHz-740MHz at Rome, NY Site

Table **6** summarizes the 'zoomed-in' in average power between the start and stop frequency range, per altitude, per capture number. We then took the average power per start/stop frequency range, and then we averaged the entire two captured start/stop LTE ranges per altitude. Notice that there is an average power increase of approximately 2.5 dB between GL and 120 m. for the Lower 700 MHz range.

Table 6 – AT&T Lower 700MHz NY Rome Site Results

				Power of Spectrum (dBW)		
Capture #	Start Freq (MHz)	Stop Freq (MHz)	Bandwidth (MHz)	120m/394ft	90m/295ft	GL
1	704.0	714.0	10.0	3.8	2.4	1.4
2	704.0	714.0	10.0	3.5	2.1	1.4
			Ave Power (dBW)=	3.7	2.2	1.4
1	725.0	735.0	10.0	4.1	3.3	1.0
2	725.0	735.0	10.0	3.5	2.8	1.0
			Ave Power (dBW)=	3.8	3.1	1.0
			Overall Ave Power (dBW)=	3.7	2.6	1.2

The 704 MHz-710 MHz spectrum is suggested to be an UL spectrum and the 725 MHz-735 MHz is suggested to be AT&T's 4G DL spectrum per Figure **8** – lower 700 MHz Bands 12/17. Table **6** shows a difference of approximately 2.5 dB increase in average

power for both the UL and DL spectra at 120 m. altitude. The dynamic range at the NY Corridor was smaller when compared to the similar spectrum captured at ARC.

For Spectrum 2, the following two 4G LTE downlink bands were captured: 1) PCS 1900 Band 2 [6] and 2) AWS Band 66 [7]. It was assumed that both of these bands were for Verizon's 4G network [8], [9]. Table **7** shows the post processed results for both bands. There were two measurements of the same spectrum captured at 2 different times to make sure there was no noticeable differences between capture runs.

Table 7 – Verizon's PCS Band 2 Power Captured Spectrum Data at Rome, NY Site

					Power of Spectrum (dBW)		
ARFNC	Capture #	Start Freq (MHz)	Stop Freq (MHz)	Bandwidth (MHz)	120m/394ft	90m/295ft	GL
555-568	1	1938.8	1941.4	2.6	12.1	11.0	4.4
555-568	2	1938.8	1941.4	2.6	11.5	11.3	4.7
				Ave Power (dBW)=	**11.8**	**11.2**	**4.6**
574-598	1	1942.6	1947.4	4.8	12.4	11.3	4.3
574-598	2	1942.6	1947.4	4.8	10.4	10.8	4.5
				Ave Power (dBW)=	**11.4**	**11.0**	**4.4**
599-643	1	1947.6	1956.4	8.8	11.8	12.3	3.9
599-643	2	1947.6	1956.4	8.8	9.5	9.5	3.8
				Ave Power (dBW)=	**10.7**	**10.9**	**3.8**
676-726	1	1963.0	1973.0	10.0	12.5	10.7	5.3
676-726	2	1963.0	1973.0	10.0	13.3	12.1	5.1
				Ave Power (dBW)=	**12.9**	**11.4**	**5.2**
671-696	1	1962.0	1967.0	5.0	12.1	14.3	4.2
671-696	2	1962.0	1967.0	5.0	11.5	15.0	4.0
				Ave Power (dBW)=	**11.8**	**14.6**	**4.1**
786-789	1	1985.0	1987.5	2.5	13.3	10.2	3.9
786-789	2	1985.0	1987.5	2.5	9.7	9.6	4.2
				Ave Power (dBW)=	**11.5**	**9.9**	**4.1**
		Total Band 2 Ave Power(dBW)=			11.7	11.5	4.4

Notice that there is an average power difference between 120 m. and GL of approximately 7.3 dB. This is a higher level than the above AT&T DL 700 MHz lower band average power captured at 120 m. altitude.

Table 8 – Verizon's AWS 2100 MHz (DL) Band 66 Captured Power Spectrum Data at Rome, NY Site

					Power of Spectrum (dBW)		
EUTRA	Capture #	Start Freq (MHz)	Stop Freq (MHz)	Bandwidth (MHz)	120m/394ft	90m/295ft	GL
66671-66762	19	2133.5	2142.7	9.2	**7.4**	**8.6**	**4.0**
66671-66762	19	2133.5	2142.7	9.2	**9.4**	**9.0**	**3.7**
				Ave Power (dBW)=	**8.4**	**8.8**	**3.9**
66556-66656	1	2122	2132	10.0	13.3	7.4	3.0
66556-66656	2	2122	2132	10.0	13.1	11.0	3.1
				Ave Power (dBW)=	**13.2**	**9.2**	**3.1**
66781-66861	1	2144.5	2152.5	8.0	14.4	11.1	3.2
66781-66861	2	2144.5	2152.5	8.0	10.9	9.6	3.2
				Ave Power (dBW)=	**12.6**	**10.3**	**3.2**
67016-67116	1	2168	2178	10.0	9.3	8.5	2.9
67016-67116	2	2168	2178	10.0	10.2	8.2	2.7
				Ave Power (dBW)=	**9.7**	**8.3**	**2.8**
67131-67231	1	2179.5	2189.5	10.0	9.6	9.8	3.2
67131-67231	2	2179.5	2189.5	10.0	8.0	8.8	3.2
				Ave Power (dBW)=	**8.8**	**9.3**	**3.2**
		Total Band 66 Ave Power(dBW)=			10.6	9.2	3.2

The average power difference for the AWS band 66 between GL and 120 m. is approximately 7.4 dBW as shown in Table 8.

For the ISM spectrum (300 MHz BW), there were no signals captured for both payload timeframes.

VI. Known Issues with Analysis

This was a first attempt to fly an SDR payload with a drone within the NASA environment. Thus, there were many unknown factors going in that were recognized as the task concluded. The LTE carrier tower information: 1) is only as good as was found on the Internet, 2) does not include information on how many transmitting antennas per frequency are on each antenna, 3) does not include pointing direction or azimuth pointing 4) show that most towers are at one-half mile away or more from flight test sites, thus not allowing the capture of just one tower's power / altitude but captures the aggregate of all towers in the vicinity.

From a power measurement perspective, the ARC results did not collect as large of a BW as did the NY corridor site due to SDR hardware limitations, but the BW was large enough to sufficiently capture DL noise floor BW.

Finally, the LTE band information was found from the Internet (see References section), and no coordination was done for confirmation with any of the LTE carriers to confirm that the assumed bands are their actual bands. Due to the vicinity of AT&T and Verizon towers to the capture areas and the information referenced, the most logical assumption of which DL bands refer to which carriers were made. Also, the number of towers in the geographic area was taken from the Internet, so there may have been new towers added and/or removed from the time the website was updated.

VII. Conclusions and Next Steps

These SDR payload LTE scanning tests were the first time NASA attempted to fly drones to capture over-the-air LTE information. These tests were performed to understand what power levels are available for sUAS being flown at higher altitudes while using the LTE infrastructure for command and control (C2) and to understand possible LOS issues. Both sites were successful in collecting the expected sample data for what is called first generation LTE collection hardware.

It is somewhat counterintuitive to think that at higher altitudes there would be higher aggregate power levels due to the LTE antenna infrastructure being designed for terrestrial UE's, with antennas tilted downward, but we can say that it was found that due to altitude and LOS of nearby towers (lack of ground clutter creating signal shadowing compared to GL), there is an increase in power levels for C2 for sUAS's within the LTE environment due to side lobe aggregate power from nearby towers – for 400 ft. found for both carriers can have an increase up to 11dB, where at the Moffett Field site, the drone flew as high as 800 ft. where it was found to have an approximate 13 dB increase in power. Thus, it is suggested that future higher altitude captures may be performed to see where the power starts decreasing due to the AGL height of the antenna and the AGL of the sUAS and taking into consideration tower antennas side lobe projections.

As explained, the LOS issue to nearby LTE towers will negatively impact UL throughput and capacity. For the next generation of hardware, one needs to capture more specific UL and DL administrative power measurements, such as RSSI/RSRQ for both serving and neighboring towers to better understand throughput issues.

Another future implementation would be to analyze the UL throughput of both video and C2 signals with an LTE carrier. But there would need to be coordination between NASA and the specified LTE carrier to not only schedule testing to avoid impacting actual users, but to also understand serving eNodeB information and neighboring towers to gather all technical needed information.

For the Rome, NY captured sample data, a next step would be for NASA to coordinate with Verizon to understand what their nearby serving towers spectrum information, so a demodulation of the complex samples can be used to possibly extract LTE framed information like RSSI/RSRQ.

At the time of the writing of this paper, NASA's UTM project has designed next generation payload platforms that capture LTE administrative information such as RSSI/RSRQ, and depending if the band is 3G or 4G, may collect more interference data. It is recommended coordination with an LTE carrier should be a prerequisite to better coordinate to send video and/or packet testing information and monitor throughput and capacity with the LTE carrier and outside resources such as Iperf.

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