Greenman: A Sector-based LTE Emission Model

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Abstract— ISART 2022 Call for Papers Topic Area: Model Standardization. **This paper describes the Greenman Sector Emission model (Greenman) which can be used to estimate LTE sector uplink emissions. Greenman, which requires only a few key pieces of information about base station antennas in an LTE deployment, is based on knowledge of how LTE systems manage UE uplink power. These items, along with an assumption that any two LTE sectors that generate the same power, as measured at the base station antenna, are equivalent when assessing emissions for a distant location, are used to estimate total LTE sector uplink emissions. In addition to a description of the model, validation data in the form of comparisons to measured data for several of LTE deployments is provided.**

Keywords—Advanced Wireless Services 3 (AWS-3), Spectrum Sharing Test and Demonstration (SSTD), Spectrum Sharing, Long Term Evolution (LTE), Aggregate Interference, LTE Network Parameters, Modeling, Measurements, Model Validation.

I. Introduction

In July 2012, the Department of Commerce, National Telecommunications and Information Administration (NTIA), Commerce Spectrum Management Advisory Committee (CSMAC) convened working groups with membership from Federal agencies and commercial wireless operators to investigate the feasibility of sharing spectrum between commercial and federal systems. Working groups 2, 3, 4, and 5 considered the compatibility of federal systems in the 1755-1780 MHz band with commercial LTE User Equipment (UE). The working groups published their final reports in 2013 [2][3][4][5]. These reports provided much of the technical basis for the Federal Communications Commission (FCC) Report and Order (R&O) (FCC 14-31), dated 31 March 2014. This R&O established service, allocation, and technical rules for the AWS-3 bands: 1695-1710 MHz, 1755-1780 MHz, and 2155-2180 MHz. It also established requirements for commercial wireless broadband operators to coordinate with the Federal agencies when seeking to build out systems in the 1755-1780 MHz band.

On 29 January 2015 the FCC completed an auction of AWS-3 bands. The auction, which was designated Auction-97, raised (in net bids) a total of $41,329,673,325, with 31 winning bidders winning a total of 1,611 licenses. The auction exceeded all expectations in terms of money raised and its completion initiated a 10-year transition period where most DoD systems operating in 1755-1780 MHz will cease or move operations to another band. Auction-97 winners that want to commence operations in pre-defined geographic Coordination Zones (CZ) must engage in the coordination process by submitting coordination requests (CR) to DoD and other Government agencies to be granted early access, or early-entry to the spectrum licenses they purchased within defined CZ. Commercial deployments outside of the CZs are available immediately and not required to go through the CR process. Within Department of Defense (DoD), Defense Spectrum Organization (DSO) and each Military Service assesses whether the expected aggregate interference (AI) from User Equipment (UE) operating within a laydown specified in a CR will exceed the designated Interference Protection Criteria (IPC) for incumbent DoD receivers and identifies which of the LTE sectors within a CR are approved for early-entry.

The Spectrum Sharing Test and Demonstration (SSTD) Program was established to 1) Facilitate Expedited and Expanded Entry (FEEE) of commercial deployments into the 1755-1780 MHz band, 2) Identify, Assess, Test/demonstrate, and Operationalize (IATO) coexistence assessments, interference mitigation, and other spectrum sharing enablers that support increased sharing between LTE and incumbent DoD systems, and 3) to support DoD's use of LTE technologies.

To achieve its objectives, the SSTD Program focuses on four broad technical areas for improvements, referred to as initiatives, focused on AWS-3 spectrum sharing. These are:

1) Assessment of the Aggregate Interference from early-entry LTE systems

2) Characterization of LTE systems and their uplink emissions

3) Propagation Modeling between early-entry LTE systems and DoD receivers

4) Characterization of DoD Receiver performance in the presence of LTE uplink emissions.

Multi-organizational technical teams have been formed in each of these four initiatives to conduct research and analyses in support of an increasingly realistic assessment of spectrum sharing between DoD and AWS-3 LTE early-entry commercial deployments. Figure 1 illustrates the technical focus of each of these teams. In addition to their technical work, each team facilitates, engages, and collaborates with government communities of interest as well as AWS-3 licensees.

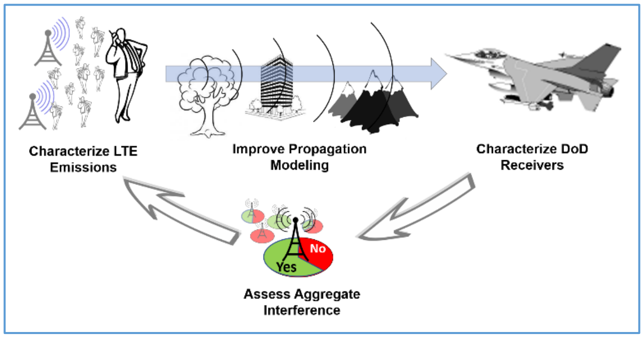

Fig. 1. SSTD Working Groups

This paper describes the Greenman Sector Emission model (Greenman) which is a sector-based emission model that can be used to estimate LTE sector uplink emissions. The model was developed as part of the advanced emission model effort conducted in the SSTD LTE Characterization initiative. The paper provides a description and a measurement-based validation of the Greenman model.

II. Organization of this Paper and Related ISART 2022 Papers

This paper describes an advanced LTE emission model developed under the SSTD Program, which is an example of a new model standard for predicting LTE aggregate interference. The paper and is organized as follows: Section III describe the Greenman model. Sections IV describes the validation and results of the model.

There are several other ISART 2022 papers related to the processes, findings, and lessons learned during the SSTD Program. These papers include:

- *AWS-3 Spectrum Sharing Assessment Process Improvement* – describes the approach and processes used on the SSTD Program
- *SSTD Observations on Improved Spectrum Sharing* – describes SSTD observations and lessons learned.
- *SSTD Findings on AWS-3 Spectrum Sharing Assessments* – describes findings relative to AWS-3 spectrum sharing assessments.
- *Pathloss-Based Sector Uplink Emissions Model (PBSUEM) for LTE Aggregate Interference Prediction* – describes an uplink LTE emissions model for predicting aggregate interference.
- *Application of Gaussian Mixture Modeling Methods to Analysis and Prediction of Cellular Communications Pathloss Distributions* – describes machine learning techniques used for predicting LTE interference.
- *A Comparison of Data-driven Clutter Loss Clustering Models for New Site Interference Assessment* – describes a Machine Learning techniques used for predicting clutter loss

III. Model Description

Calculating the aggregate emission from a large number of emitters in a geographical area of interest, like a 4G or 5G sector, is a difficult task. One approach, a ground-up model, begins with an estimate of each emitter's Effective Isotropic Radiated Power (EIRP) and location over some time. From the time-based location information, a time-based propagation path loss model is combined with the time-based EIRP to produce a time-based model of the interference power at a victim DoD receiver. The uncertainty and variability associated with path loss make the calculation of emitter EIRP and ultimately interference power, challenging at best. Another approach to modeling interference power is described below.

A. Power@Tower

In Greenman, in order to remove some of the uncertainty associated with calculating aggregate emissions, knowledge of how LTE 4G and 5G systems implement UE uplink power control is used. In the LTE Uplink Power Control Tutorial contributed by AT&T during CSMAC 2012 the LTE Open Loop Power Control equation shown in Equation 1 was provided.

$$P_{OL}(i) = min\,\{P_{max}, 10log_{10}\big(M(i)\big) + P0 + \alpha PL + \Delta_{TF}(i)\} \quad (1)$$

Where:

- i refers to the ith scheduling Transmission Time Interval (TTI)
- P_{OL} is the LTE open loop power in dBm
- Pmax is the maximum transmit power per UE (typically 23 dBm),
- M is the number of resource blocks scheduled for the UE in that particular scheduling interval (called transmit time interval or TTI)
- P0 is the desired per PRB power in dBm to be received at the base station
- α determines the degree of compensation for propagation loss
- PL is the propagation loss
- ΔTF is a power adjustment that may be added based on the selected modulation and coding scheme (transport format)

In simple terms, an LTE scheduler leverages a near-continuous stream of information from each UE to target a per Physical Resource Block (PRB) power at the base station receiver for each uplink emission. For sectors with an alpha of 1.0 the per PRB power is P0. For sectors with alpha less than 1 the per PRB target power is reduced as a function of the path loss. What this means, is that for sectors with an alpha of 1.0, for a given Transmission Time Interval (TTI), the uplink power at the base station receiver is equal to P0 times the number of PRBs occupied during that TTI. This holds true no matter what the propagation loss and antenna gains are between the UE and the base station since this is calculated in advance of the scheduled emission and factored into the uplink grant. We refer to this as the power at the tower (Power@Tower).

B. Greenman Equivalent Sector Model

The Greenman concept is illustrated in Figure 2. To assess aggerate emissions, an estimate of how Power@Tower relates to the source UE emissions is required. Since, as noted above, the variability and uncertainty of in-sector propagation are challenging, Greenman adopts the use of a proxy or equivalent sector that "could" produce the observed Power@Tower. A simple equivalent sector allows for the easy conversion of Power@Tower to in-sector emission and from the perspective of distant receivers is assumed to have approximately the same emission profile.

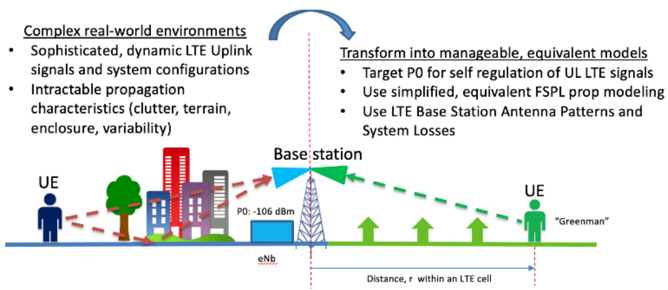

Fig. 2. Greenman Model Concept

The Greenman equivalent sector model does not contain any complex propagation characteristics. It is assumed to be Free Space Path Loss (FSPL) because it is completely flat with no terrain or clutter interactions between a single UE emitter located in the sector and the base station antenna.

C. Greenman Interference Power

The Greenman Interference Power (GMIP) is calculated by assessing the Radio Frequency (RF) Centroid of the Greenman equivalent sector and combining it with the Power@Tower. The RF Centroid of a sector (illustrated in Figure 3) is the RF center relative to the base station receiver and is calculated by taking the average basic transmission gain of all the paths in a Greenman sector to the base station receiver. Once the RF centroid for a sector is known, the location in the sector that corresponds to this value can be identified and be a point source location for all sector emissions.

$$RFC_{Sec} = 10log_{10}(\frac{\sum_{i=1}^{N} 10^{-(AntG_i - FSPL_i - BSSL)/10}}{N}) \quad (2)$$

$$GMIP_{Sec} = P0_{Sec} + 10log_{10}(PRBO_{Sec}) + RFC_{Sec} \quad (3)$$

Where:

- $i\ is\ a\ grid\ point\ in\ a\ sector\ (sec)$
- $N\ is\ the\ total\ number\ of\ grid\ points\ in\ a\ sector$
- $P0_{Sec}$ is the desired *per PRB power* in dBm to be received at the base station
- $PRBO_{Sec}$ is the PRB Occupancy of the sector (%)
- RFC_{Sec} is the RF Centroid of the sector in dB
- $AntG_i$ is the base station antenna gain in dBi at the i_{th} grid point of the sector
- $FSPL_i$ is the Free Space Path Loss in dB between the base station antenna and the i_{th} grid point of the sector
- $BSSL$ are the combined base station systems losses in dB
- $GMIP_{Sec}$ is the Greenman Interference Power in dBm

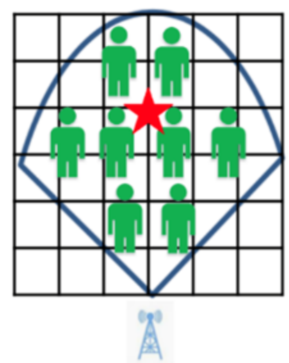

Fig. 3. RF Centroid of a LTE Sector

D. Ground-up vs Greenman Emission Modeling

Greenman Interference Power (GMIP) in lieu of UE EIRP, Network Loading (NL), Propagation Clutter Loss, and number of UEs. The calculation for GMIP is given above.

The interference power from each sector in the laydown is calculated for each model according to:

Ground Up Model

$$I_{sec} = 10log_{10} \sum_{\#UEs} 10^{Power_{UE}/10}$$

$$Power_{UE} = (NL(P_{Tx}) + EIRP_{UE}(P_{Tx}) - L_{CL}(P_{Tx}) - L_P(P_{Tx,}P_{Rx}) - FDR(\Delta f) + G_r(\Theta, \Phi) - L_{pol} - L_s) \quad (4)$$

Greenman Model

$$I_{sector} = GMIP(P_{Tx}) - L_P(P_{Tx,}P_{Rx,}) - FDR(\Delta f) + G_r(\Theta, \Phi) - L_{pol} - L_s) \quad (5)$$

Where:

- I_{sec} is the predicted interfering signal level in the DoD receiver from a sector in dBm

- $Power_{UE}$ is the is the predicted interfering signal level in the DoD receiver from a UE in dBm
- $NL(P_{Tx})$ is the network Loading factor in dB
- $EIRP_{UE}(P_{Tx})$ is the modeled UE transmitter effective isotropic radiated power in dBm
- $L_{CL}(P_{Tx})$ is the propagation clutter Loss between a modeled UE and a DoD receiver in dB
- $L_P(P_{Tx,}P_{Rx,})$ is the path propagation loss between a modeled UE and a DoD receiver in dB
- $FDR(\Delta f)$ is the frequency dependent rejection in dB
- $G_r(\Theta, \Phi)$ is the DoD receiver antenna gain in the direction of the interferer transmitter in dBi
- L_{pol} is the DoD receiver antenna polarization mismatch loss in dB
- L_s is the DoD incumbent receiver System Loss in dB
- P_{Tx} is the base station location
- P_{Rx} is the DoD receiver location
- $GMIP(P_{Tx})$ is the Greenman Interference Power in dBm
- Θ, Φ represent the elevation and azimuth angle between the Tx and the Rx

IV Model Validation

Model validation is conducted first by establishing an approach for determining the Greenman required input parameters and then comparing the Greenman aggregate interference predictions, using those input parameter, to measured data.

A. *Greenman Model Input Parameters*

Table 1 list each Greenman model input parameter and the method used when validating against measured data.

Table 1. Greenman Model Input Parameter

Parameter	Method	
P0	-106 dBm	P0 = -90 dBm Alpha = 0.8 Expected same or lower GMIP
Alpha	1	
Sector Shape	Pie Slice	
Sector Central Angle	2 * Horizontal BW	
Sector Radius	0.667*(Nearest Neighbor with Azimuth and Nearest Neighbor when none is found)	
Base Station System Losses	4 dB – 90% of Multi-market data	90% of Multi-market data cable loss 4 dB or less
Base Station Antenna Pattern	ITU-R F.1336-5 3.1.2 with CR Reported Parameters	Antenna Gain Horizontal BW Vertical BW Antenna Height AGL Antenna Down Tilt
Max PRB Occupancy	FY20 NL Recommendation – 26% Urban and 16% Rural	
RF Centroid	Average – Calculated from the entire sector using 5m resolution	

P0/Alpha - P0 is the power per PRB configuration parameter used by 4G and 5G commercial wireless carrier systems. A survey of deployment data provided by SSTD commercial wireless collaboration partners showed an overwhelming tendency for P0/alpha to be -106 dBm/1.0. Occasionally -90 dBm/0.8 P0/alpha configurations were seen. P0/alpha of -106dBm/1.0 will in most cases yield a higher GMIP and since a per sector P0/alpha was not available for the measured data tests, -106 dBm/1.0 is assumed.

Sector Shape – The shape of an LTE sector plays a role in the GMIP calculation. Due to propagation effects and the location of the nearby sectors, the actual shape of a real sector is likely quite complex. For this validation effort, a pie slice sector shape is assumed.

Sector Central Angle – This is used as an input to the Sector Radius parameter. Only sectors that fall within the sector central angle are considered as potential nearest neighbors. For this validation effort, a sector's central angle is assumed to be two times the horizontal beamwidth of the sector antenna.

Sector Radius – The radius of an LTE sector plays an important role in the GMIP calculation. For this validation effort, the sector radius is assumed to be 66.7% of the Inter Site Distance (ISD) between a given sector and its nearest sector that could provide service to UEs in the sector antenna's field of view, twice the horizontal beamwidth.

Base Station System Losses – Base station systems losses are the losses between the input to the base station antenna and the receiver front end and play an important part of the GMIP calculation. A survey of deployment data provided by SSTD commercial wireless collaboration partners showed that 90% of sectors have base station system losses of 4 dB or less. For this validation effort, base station systems losses are assumed to be 4 dB.

Base Station Antenna Pattern – A sector's antenna pattern plays an important role in the GMIP calculation. For this validation effort, ITU-R F.1336-5 3.1.2 along with sector antenna information gain, horizontal beamwidth, vertical beamwidth, height above ground, and total down tilt is used.

PRB Occupancy – A sector's PRB occupancy when combined with the total number of PRBs yields the number of PRBs used to calculate the Power@Tower. This sector parameter has been shown to be closely related to the number of UEs per TTI in a sector. A survey of Key Performance Indicator (KPI) data provided by SSTD commercial wireless collaboration partners showed that PRB occupancy has a diurnal variation and that the peak average values observed around mid-day local time are 26% for urban areas and 16% for rural areas. These along with the US Census Bureau's designation of urban/rural are used in this validation effort.

RF Centroid – A sector's RF Centroid power value is the calculated average of the difference between the UE EIRP and the base station received power across the entire sector. A sector's RF Centroid location value is the point location where the RF Centroid power value is observed. For this validation effort, the RF Centroid power value is sampled every 5 meters within the assumed geographic bounds of the sector.

B. *Model Comparisons to Measured Data*

Over the last few years, the SSTD program conducted a series of multi-day aggregate interference measurements, known as Carrier Coordinated Testing (CCT). For each event, SSTD worked with a commercial wireless carrier to provide AWS-1 sector configuration and key KPI data for all sectors in the vicinity of the measurement. For each CCT event, three separate assessments were performed and plotted with the measurements. The Greenman lines on the measured data charts shown below were made using the sector configuration and KPIs as inputs to. The FY19 and FY21 lines show the aggregate interference prediction using the SSTD recommendations for each fiscal year, which used the ground-up modeling approach.

Denver July 2021 – Figure 4 gives a map view and Figure 5 shows each model's prediction and the measurements taken by NTIA/ITS from Hayden Park at Green Mtn, west of the greater Denver, CO area in July 2021.

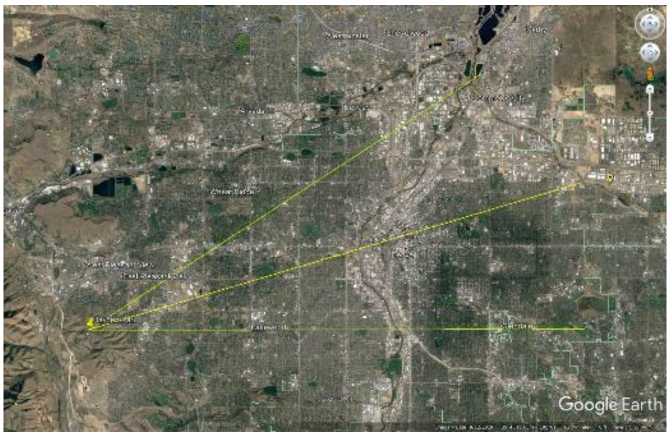

Fig. 4. Denver, CO Carrier Coordinated Testing Area

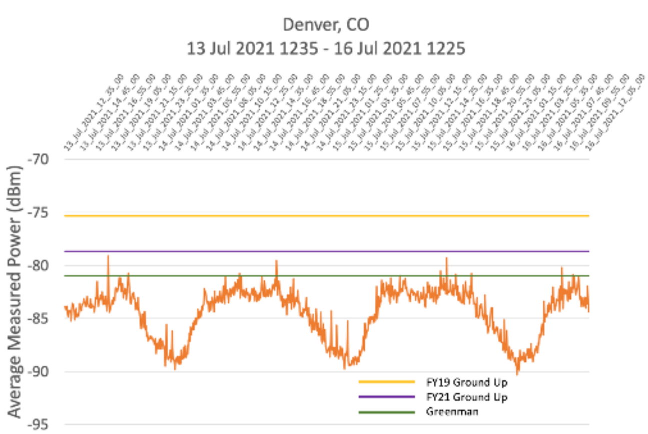

Fig. 5. Denver, CO Model Predictions and Measured Data

For this test, both Greenman and FY21 did a good job predicting the average maximum interference power. The SSTD FY19 models were not as good predicting ~6 dB more interference power than was measured.

Longmont May 2020 – Figure 6 gives a map view and Figure 7 shows SSTD FY19, FY21, and Greenman's model prediction for the measurements taken from Table Mountain just west of Longmont, CO in early May 2020.

Fig. 6. Longmont, CO Carrier Coordinated Testing Area

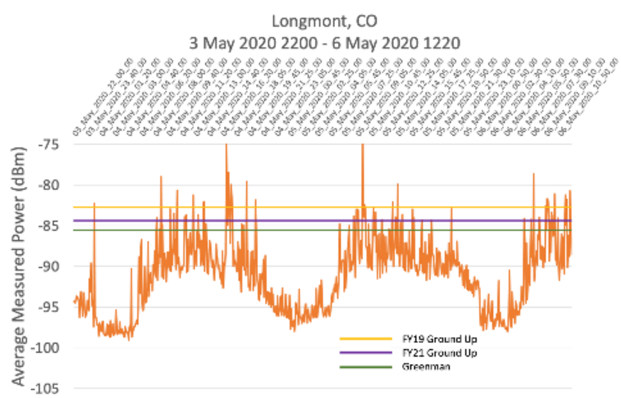

Fig. 7. Longmont, CO Model Predictions and Measured Data

For this test, all three models performed reasonably well and did a good job predicting the average maximum interference power. Note that aggregate interference measurements are very sensitive to emitters that are near the measurement location. Every effort is made to isolate the measurement equipment but sometimes this is not possible. The jagged and spikey nature of this measurement indicates there were frequent nearby interferers during the collection. The impact of nearby emitters on a test like this can be ignored unless the spectrum sharing assessment under consideration includes a provision of interferers in close proximity to the receivers.

Grand Junction June 2019 – Figure 8 gives a map view and Figure 9 show SSTD FY19, FY21, and Greenman's model prediction for the simultaneous measurements taken from locations south (Monument) and Figure 10 shows the same for southeast (Mesa) of Grand Junction CO in June 2019.

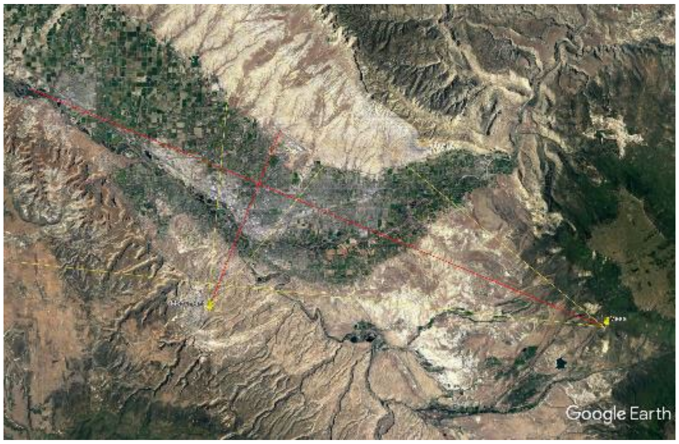

Fig. 8. Grand Junction, CO (Monument and Mesa) Carrier Coordinated Testing Area

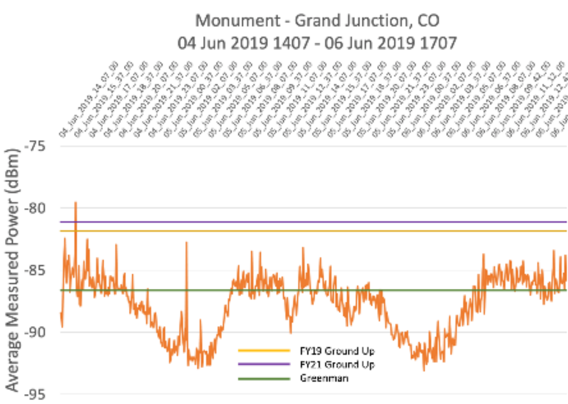

Fig. 9. Grand Junction, (Monument) CO Model Predictions and Measured Data

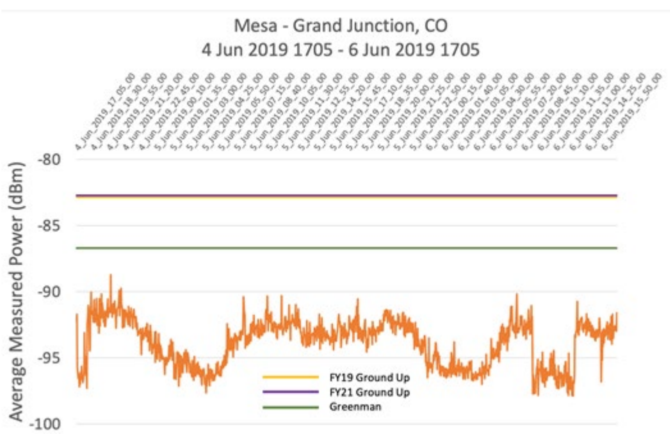

Fig. 10. Grand Junction, CO (Mesa) Model Predictions and Measured Data

For the measurement taken from Monument, all three models performed reasonably well with the FY19 and FY21 predictions coming in a little high and Greenman coming in 1-2 dB below the peak measurement. In contrast, the Mesa measurement had all three models predicting much higher interference. Relative to the modeling assessments of Grand Junction, the only modeling difference between the two measurement sites is the prediction of propagation loss between each sector and the measurement location. Given the mountainous terrain in the area, it is possible that the terrain data used by the propagation models had errors that could explain why the predictions yielded quite different answers. It is also possible that there was an undetected issue with the measurement equipment at one of the sites.

Boulder August 2020 – Figure 11 gives a map view and Figure 12 shows the SSTD FY19, FY21, and Greenman's model prediction for the simultaneous measurements taken from a location south of Boulder CO in August 2020.

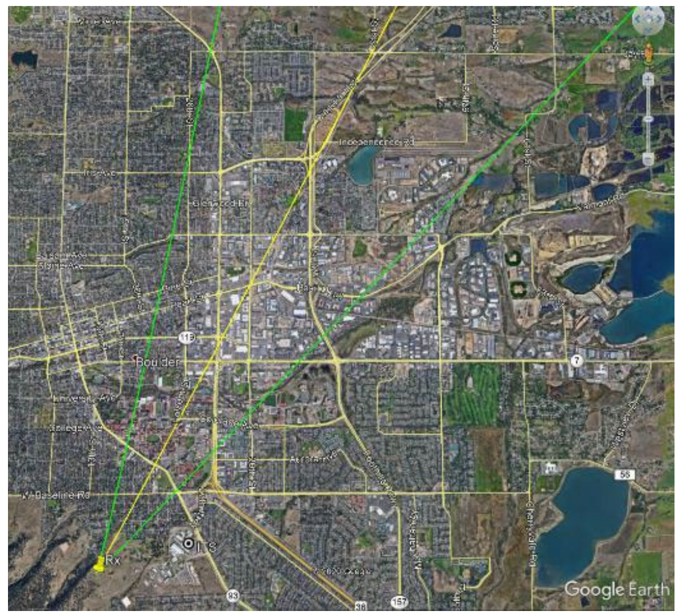

Fig. 11. South of Boulder, CO Carrier Coordinated Testing Area

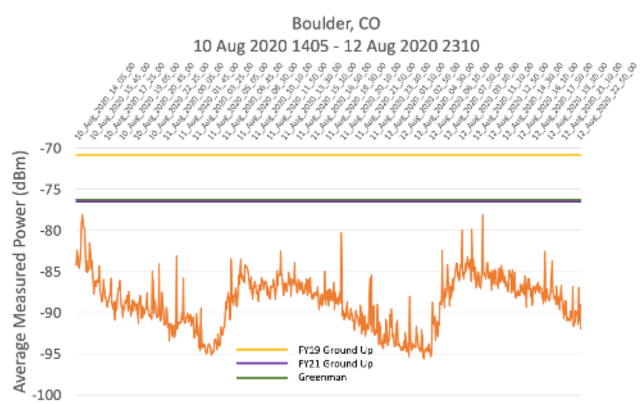

Fig. 12. South of Boulder, CO Model Predictions and Measured Data

For the Boulder measurement, all three models over-predicted aggregate interference. Both Greenman and FY21 are ~8.5 dB above the peak average value and FY19 is ~14 dB above. An important consideration for this measurement location is the foliage near the receiver. The propagation loss associated with this foliage is not included in any of the models and could account for this over prediction.

Salt Lake City October 2021 – Figure 13 gives a map view and Figure 14 shows the SSTD FY19, FY21, and Greenman's model prediction for the simultaneous measurements taken from a location north of Salt Lake City, Utah in October 2021.

Fig. 13. Salt Lake City, Utah Carrier Coordinated Testing Area

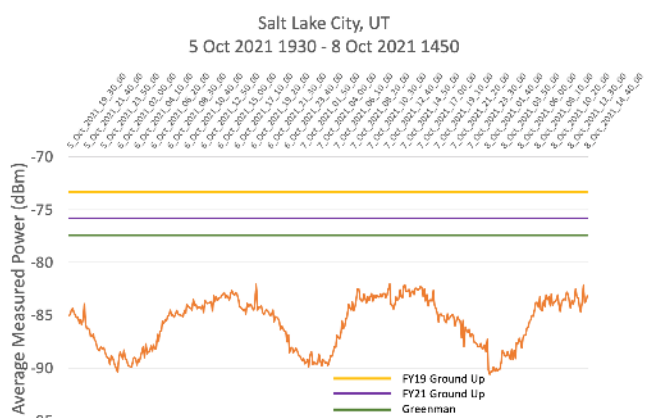

Fig. 14. Salt Lake City, Utah Model Predictions and Measured Data

For the Salt Lake City measurement, all three models over-predicted aggregate interference. With Greenman doing the best at ~6.5 dB above the peak average value. Note that this measurement, like the Denver measurement, shows a smoother aggregate interference curve due to the larger set of interferers and the isolation of the measurement location relative to nearby UEs.

Summary Results Discussion – Table 2 shows the estimated peak average measurement, which typically occurs around noon local time, for each test along with each model prediction.

Table 2. PEAK AVERAGE MEASUREMENT AND MODEL PREDICTIONS

	Peak Average Measured (dBm)	FY19 (dBm)	FY21 (dBm)	Greenman (dBm)
Denver July 2021	-81 dBm	-75.78	-77.95	-80.98
Longmont May 2020	-86 dBm	-82.73	-84.04	-85.56
Grand Junction (Mesa) June 2019	-91 dBm	-82.88	-82.73	-86.71
Grand Junction (Monument) June 2019	-85 dBm	-81.85	-81.12	-86.64
Boulder August 2020	-85 dBm	-70.84	-76.47	-76.27
Salt Lake City 2021	-83 dBm	-73.72	-75.81	-77.45

The estimated peak average values are taken from the trend over time and do not consider spikes associated with emitters near the measurement location. In contrast to these measurement events, most spectrum sharing scenarios have a much larger set of interferers with a substantially larger stand-off distance. Due to this, the interference power observed at the DoD systems over time is expected to be a smooth diurnal ebb and flow. The Denver and Salt Lake City measurements come the closest to a real DoD commercial wireless spectrum sharing scenario but even those tests were small in scale compared to the real thing.

The results show that, in general, the Greenman Sector-based Emission model using the given input parameters not only leads to a reliable prediction of the peak average interference power but outperforms the best Ground Up models. Given the simplicity of Greenman as compared to the Ground Up models Greenman is a good choice for assessing LTE 4G and 5G uplink spectrum sharing.

IV. CONCLUSIONS

This paper described the Greenman Sector Emission model (Greenman) which can be used to estimate LTE sector uplink emissions. Greenman, which requires only a few key pieces of information about base station antennas in an LTE deployment, is based on knowledge of how LTE systems manage UE uplink power. These items, along with an assumption that any two LTE sectors that generate the same power, as measured at the base station antenna, are equivalent when assessing emissions for a distant location, are used to estimate total LTE sector uplink emissions. In addition to a description of the model, validation data in the form of comparisons to measured data for several of LTE deployments was provided.

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References

[1] "Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 1 (WG 1) 1695-1710 MHz meteorological-satellite". https://www.ntia.doc.gov/publications

[2] "Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 2 (WG 2) 1755-1850 MHz law enforcement video, explosive ordnance disposal, and other short distance links". https://www.ntia.doc.gov/publications

[3] "Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 3 (WG 3) Report on 1755-1850 MHz Satellite Control and Electronic Warefare". https://www.ntia.doc.gov/publications

[4] "Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 4 (WG 4) Report on 1755-1850 MHz point-to-point microwave". https://www.ntia.doc.gov/publications

[5] "Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 5 (WG 5) Report on 1755-1850 MHz airborne operations". https://www.ntia.doc.gov/publications