Test Resource Management Center (TRMC)

National Spectrum Consortium (NSC) / Spectrum Access R&D Program

CRTM Project Summary and Next Steps

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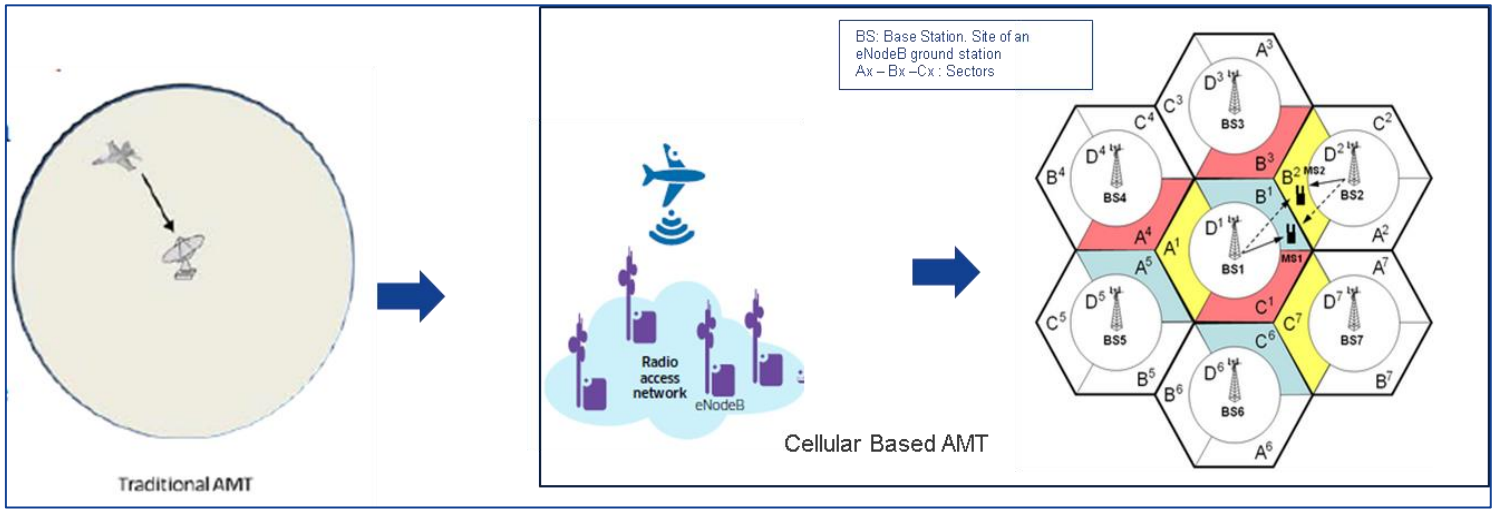
Cellular Range Telemetry (CRTM)

Goal: Demonstrate the use of a cellular network to support Aeronautical Mobile Telemetry (AMT) on test range

Target demonstrations: R-2515 airspace at Edwards AFB



Key capabilities of the cellular concept

- Spectral efficiency increases data throughput per test article and test range capacity
- Automatic assignment of spectrum resources for active test articles in support of "on demand" testing
- Flexible bandwidth allocation for optimal utilization of available spectrum
- Reduced development and sustainment costs by leveraging COTS equipment and commercial feature sets
- Enables resource sharing and efficient coordination of test events / data collection over multiple ranges
- Spectrum sharing and enhanced security using 5G network slicing
- Clear upgrade path from "xG" to "yG" as technology advances

Key program challenges

Operating frequency: DoD AMT spectrum does not fall within 3GPP-defined band designations for LTE - no existing commercial equipment to leverage

- Custom frequency variant of an existing radio platform developed for the ground network
- 5GHz Airborne Transceiver (AT) RF components utilized

Doppler compensation: MACH2 translates to worst case ~12kHz CFO at 5GHz, which is way beyond what is needed for commercial terrestrial systems

- Approach chosen implements full Doppler estimation and compensation at the AT
  - Allows "blind" estimation and compensation – no knowledge of test article speed or location relative to ground network base stations required
  - Must allow AT to make accurate measurements of handover candidates while in a Doppler-shifted environment
  - Must be able to resolve CFO greater than half the OFDM sub-carrier spacing
  - Allows ground network to be designed for RF coverage and handover independent of test article trajectory

Airborne transceiver: Integration of Doppler compensation with LTE UE stack; operation in non-3GPP spectrum

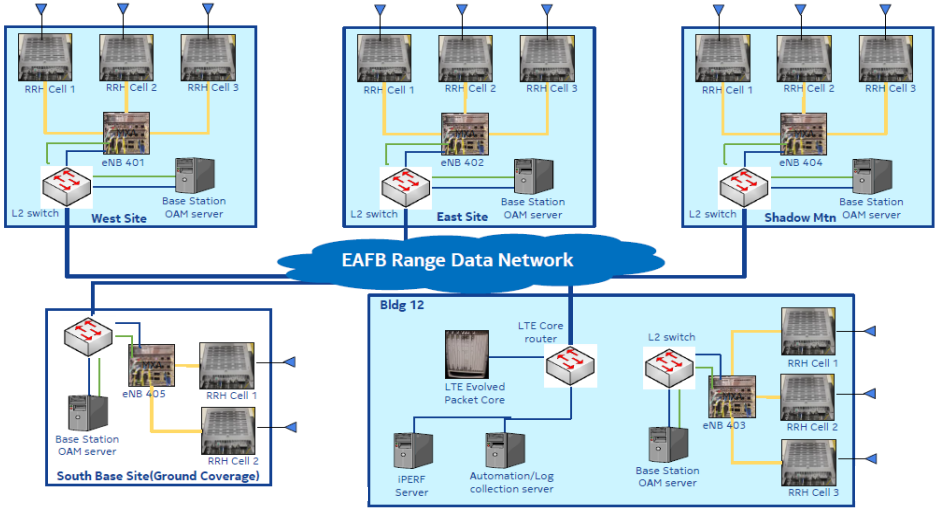
- Approach chosen leverages commercially available LTE UE stack that runs on an SDR platform
- Hardware platform composed of COTS components

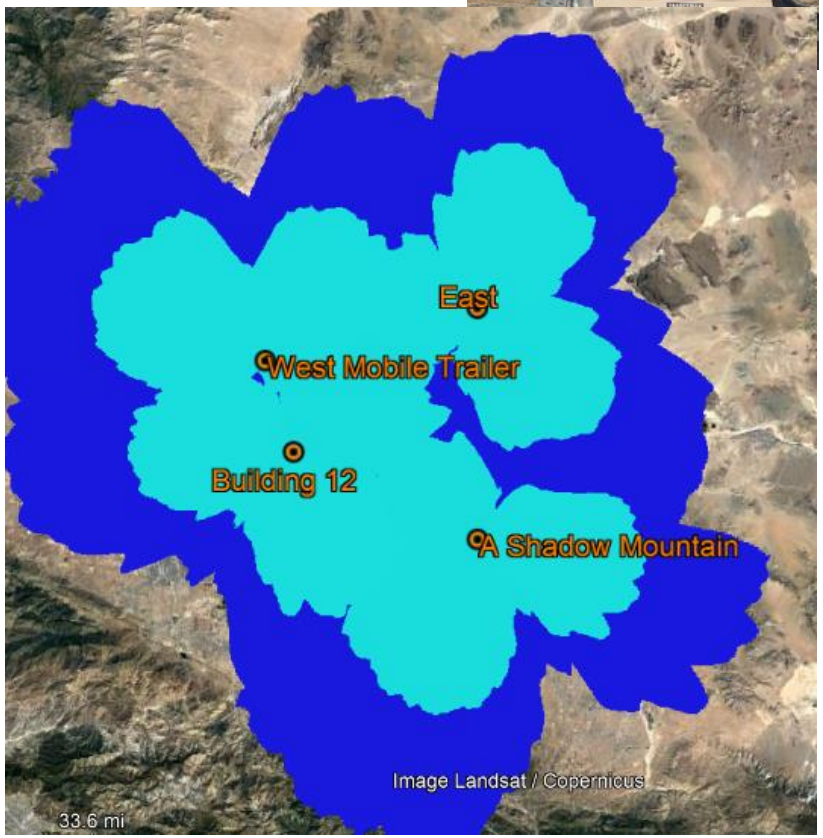
RF coverage / throughput: Need much more vertical coverage than required for commercial terrestrial systems

- Approach chosen leverages antenna design used for commercial airborne coverage in the European Aviation Network
- RF planning tools modified to predict coverage at various altitudes

Project overview

- Ground network
  - R-2515 range coverage from four Nokia LTE-Advanced [LTE-A] base stations at Edwards AFB – 2 at existing site locations and 2 on portable towers
  - Nokia-developed LTE-A radios operating in DoD lower C-band spectrum
  - Nokia-provided 4G core network
- Airborne terminal
  - SDR-based LTE UE with 5W transmit output power
  - Integrated Doppler estimation and compensation mechanism
- Testing
  - Lab testing in simulated flight conditions
  - C-12 flight test





Doppler compensation results

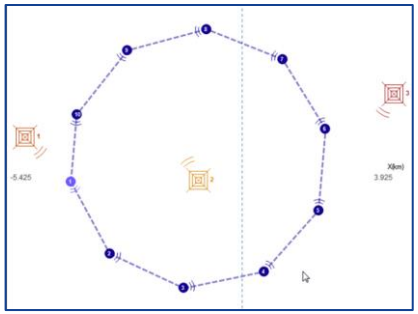
- Doppler compensation testing done in a wired lab due to limited flight test capability
- Test variables include
  - Center Frequency Offset (CFO)
  - Cell radius
  - Downlink SNR
  - Handover scenarios

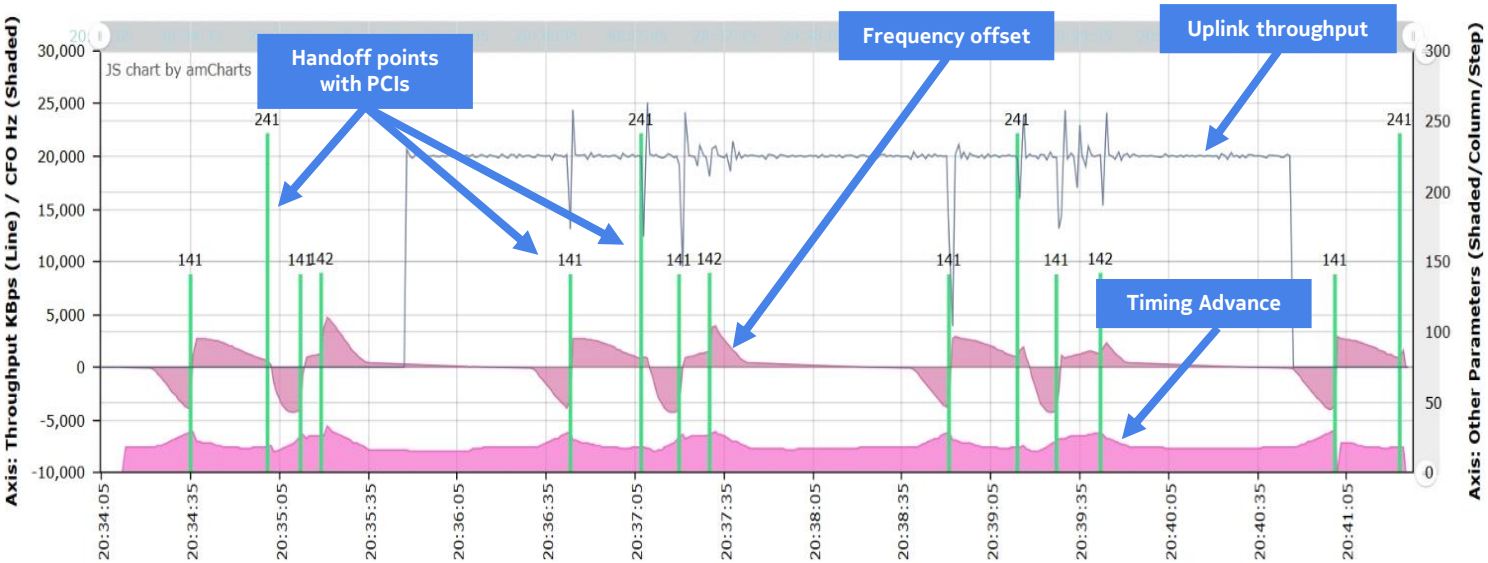
Results:

- ***AT capable of compensating for up to 12kHz CFO over all expected operating conditions***

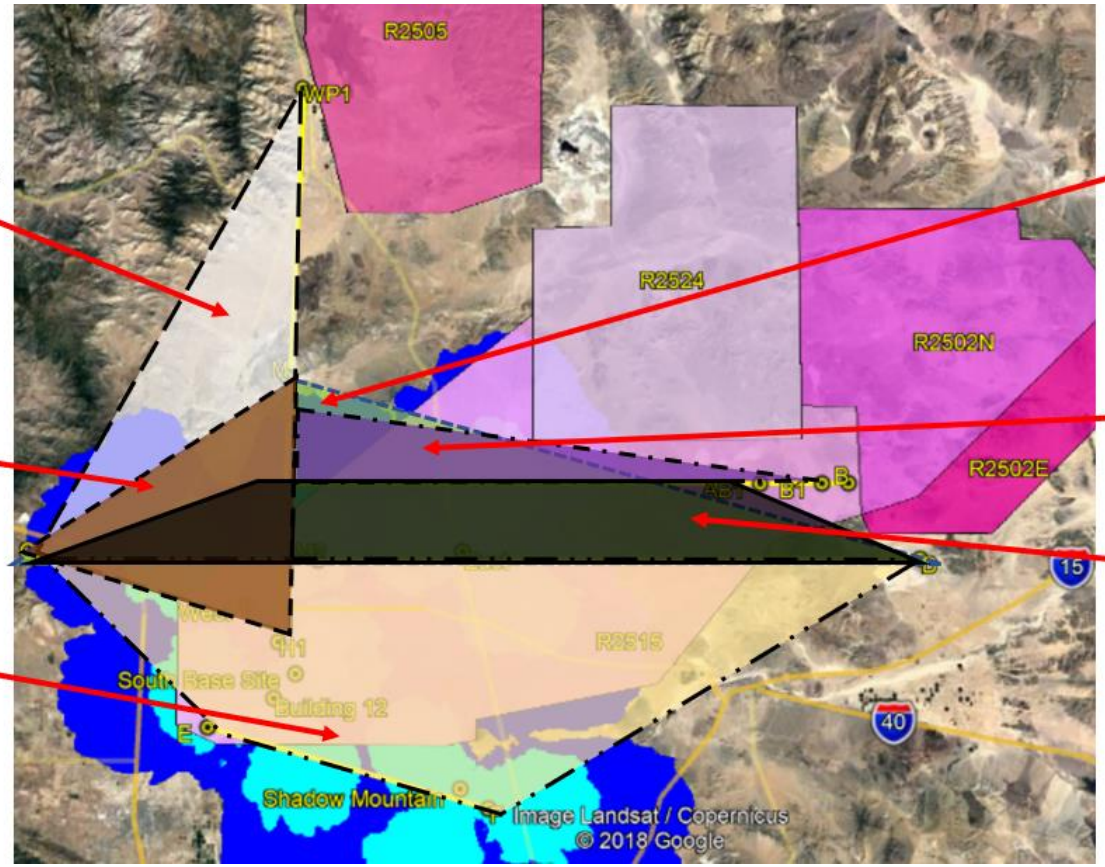
		Near RF Condition			Middle RF Condition				Far RF Condition		
	A	B	C	D	E	F	G	H	I	J	K
152		DL Throughput (kbps)									
153	DL RSRP (dBm)	-85	-90	-95	-100	-105	-110	-115	-120	-125	-130
154	Speed (km/h) /Gain (dBm)	-10	-15	-20	-25	-30	-35	-40	-45	-50	-55
155	0	44985.02	45382.64	44901.31	44812.51	44911.13	36657.55	25309.51	14799.93	7602.27	2846.73
156	500 (Mach 0.4)	44346.65	44754.22	44781.91	44681.47	44472.76	47628.67	25005.69	14581.69	7532.33	2812.13
157	1000 Mach 0.8)	45170.65	44926.80	45012.33	44783.76	44542.95	36284.76	25191.07	15054.02	7465.75	2795.89
158	1500 (Mach 1.2)	44492.55	44768.36	44993.87	44990.91	44748.07	35446.07	24678.64	14996.35	7215.16	2712.25
159	2000 (Mach 1.6)	44532.62	44329.58	44733.93	44281.15	44077.24	34928.18	24553.69	14850.95	7298.69	2600.20
160	2500 (Mach 2.0)	44358.31	44550.73	44257.73	43995.25	41723.18	34195.71	23445.91	14832.91	7230.29	2325.36
161											
162	PUSCH SNR (dB)	UL Throughput (kbps)									
163	Averaged Over Speed Points	27.95	25.60	24.71	19.84	17.60	13.45	9.74	5.33	1.06	-3.56
164	Speed (km/h) /Gain (dBm)	0	0	0	-5	-10	-15	-20	-25	-30	-35
165	0	28320.64	28055.00	28296.44	28006.02	28305.67	27173.47	21337.80	13751.11	8031.07	2181.11
166	500 (Mach 0.4)	28172.64	28069.45	28083.11	28204.42	28314.75	36054.67	20662.20	13721.18	7607.25	2287.35
167	1000 Mach 0.8)	28174.27	28373.02	28000.78	28089.02	27924.85	27104.22	21190.42	14379.25	7402.56	2250.11
168	1500 (Mach 1.2)	28135.82	28182.76	28459.60	28281.22	28119.00	27171.38	20782.44	13890.87	7191.98	2228.82
169	2000 (Mach 1.6)	27985.64	28043.15	28028.27	27693.87	27728.89	26980.55	20823.69	14148.78	7694.00	2145.95
170	2500 (Mach 2.0)	28057.05	27952.98	27958.65	28139.09	27126.24	26200.40	20497.35	15189.35	7784.27	1931.56

Example Simulation run





Flight test overview



- Flight Path H1-C-WP1-H1
- Flight Path H1-C-M-H1
- Flight Path C-D-F-E-C
- Flight Path C-M-D-C
- Flight Path A-AM1-B-A
- Flight Path A-AB1-D-C-A

Flight characteristics

- 12.5 hours in flight patterns
- 19 flight test "loops"
- Altitude: 7.5K Ft to 26.5K Ft MSL
- Speed: 230-280 knots

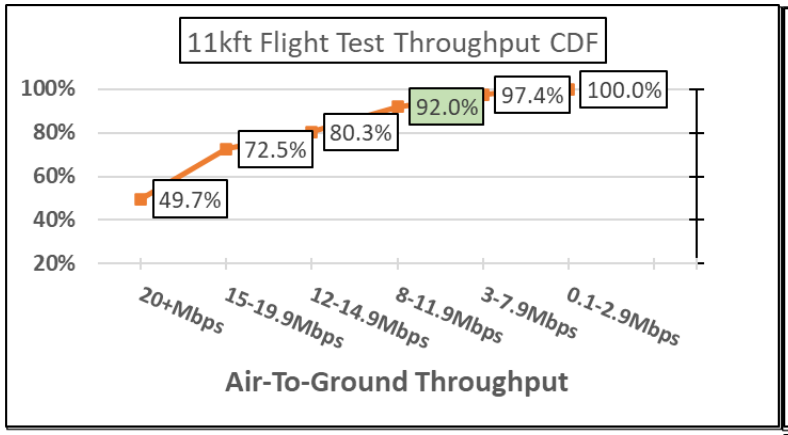
Test Condition Variables:

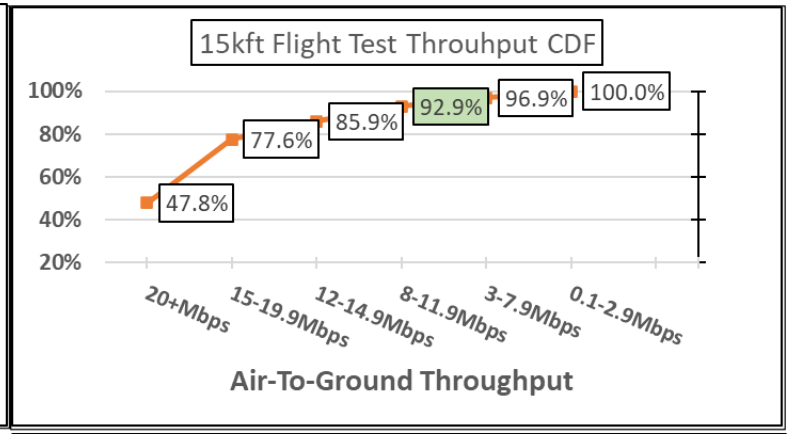
- Offered Packet Size: 1392 and 400 Bytes
- Offered Air to Ground Throughputs: 20 and 30Mbps
- Single and Multi AT Scenarios

RF Coverage

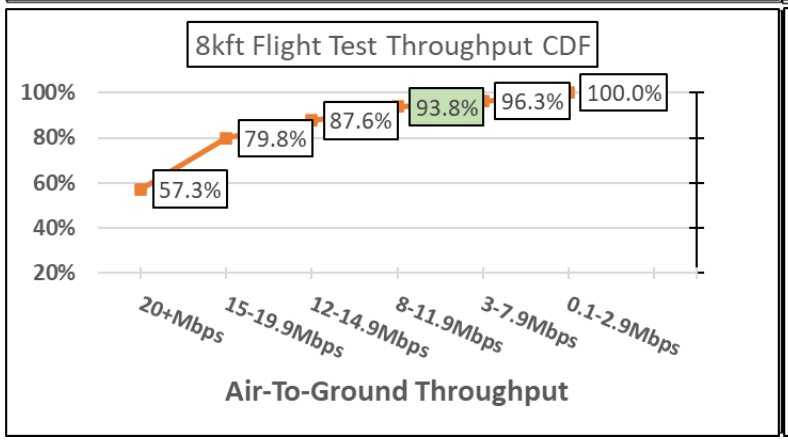
Demonstration Target: >8Mbps 92% of time in 10kft-15kft range - Achieved

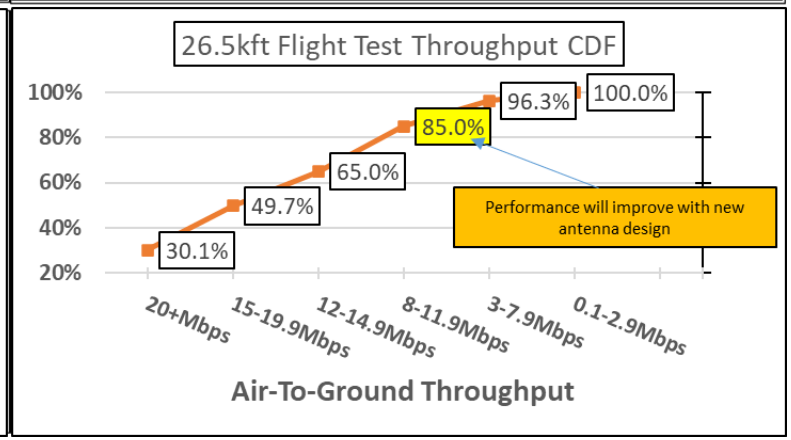
CRTM Demonstration Required/Designed Coverage: 10-15kft





CRTM Demonstration Expanded Coverage Assessment: 8kft and 26.5kft





8Mbps, 92% derived from iNET threshold expectations

Uplink throughput and handovers

Flight Test Configuration:

- 11kft Altitude MSL
- Offered Throughput: 30Mbps Air to Ground

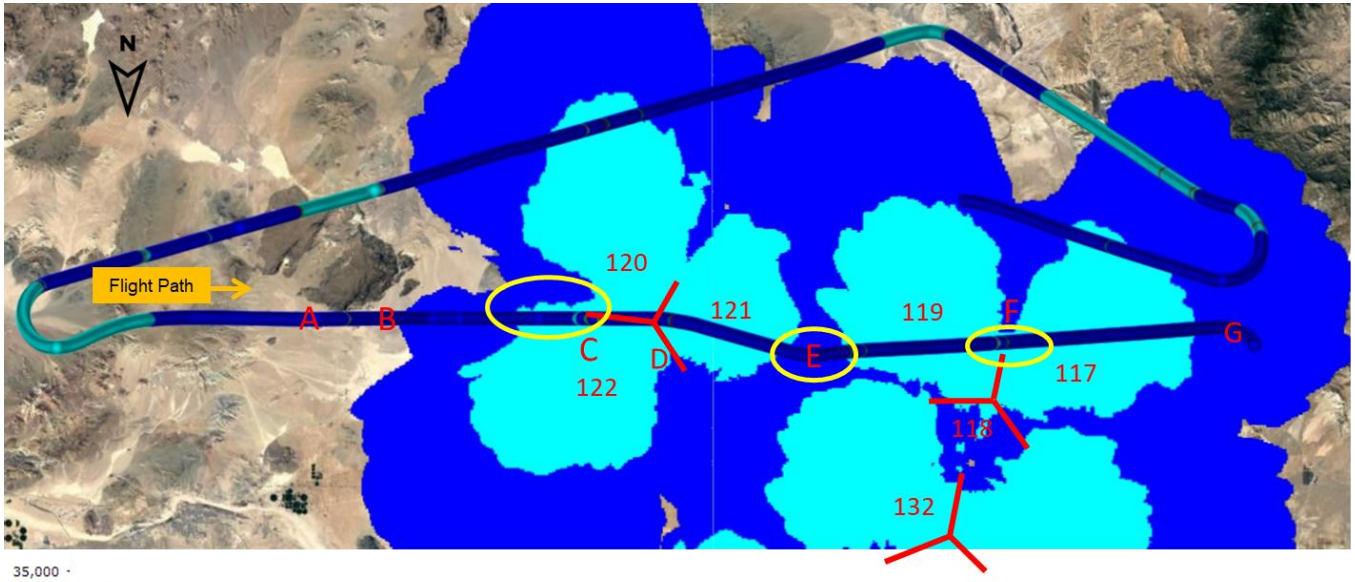
Results:

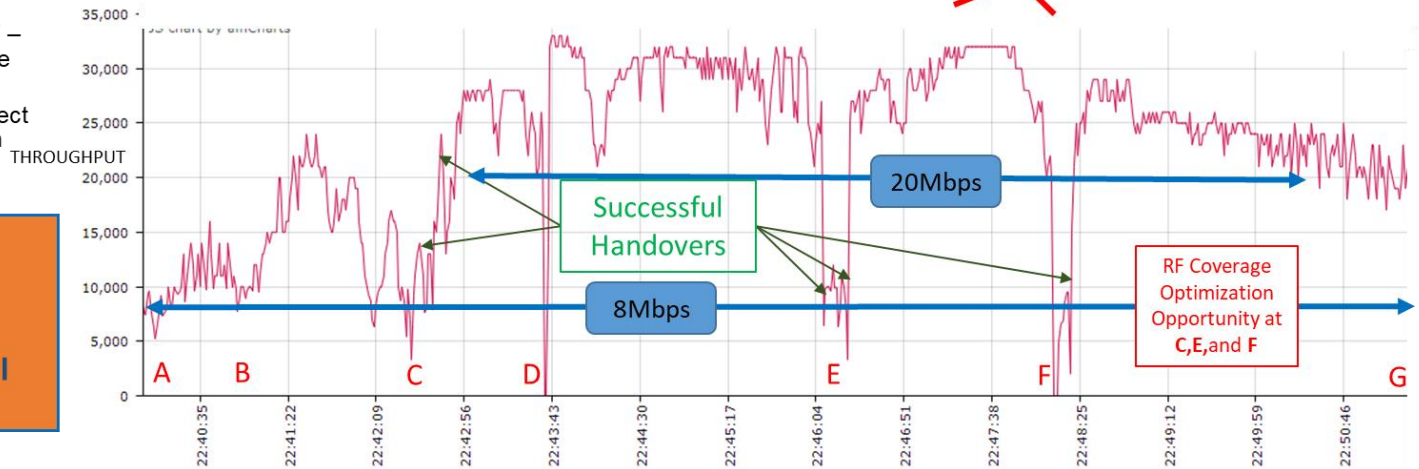
- ✓ Demonstrated maximum throughput of >28Mbps
- ✓ Demonstrated Intra and Inter eNB Handovers
- ✓ HO Success rate across all flights: **94.4%**
- ✓ Demonstrated automatic re-establishment as AT came back into coverage area

Observations:

- ✓ RF coverage as expected
- ✓ Noted lower throughput as approaching C due to proximity of coverage seam – RF Optimization opportunity
- ✓ Noted non-optimal handover at E and F – RF optimization required to minimize the low throughput segment
- ✓ Observed 1 prototype AT functional defect intermittently causing HO failure (not an LTE limitation)

- **LTE supports data throughput for AMT applications**
- **HO Success rate across all flights: 94.4%**





Latency

Flight Test Configuration:

- 11kft Altitude MSL
- Ping Test(for **Latency Calculation**)
  - Disable UL and DL data
  - Enable pings from EPC to Airborne AT

End to End Latency Target:

- One way Latency < 50 msec

Results:

✓ RTT Measurements:

- ✓ Mode 48.9 msec
- ✓ Median 45.9 msec
- ✓ Average 72 msec

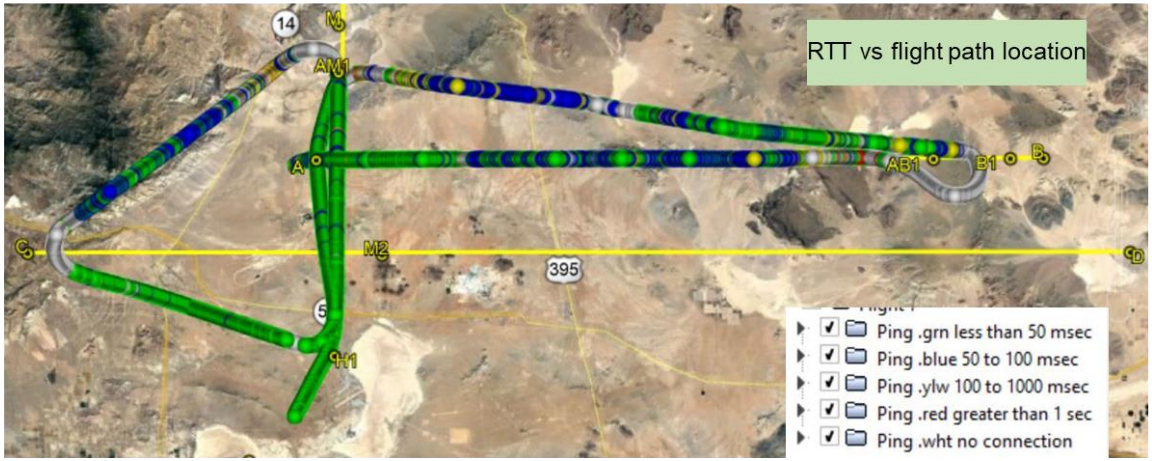
✓ **64.7% of the time, one way latency was less than 25 msec**

✓ **93% of the time, one way latency was less than 50 msec**

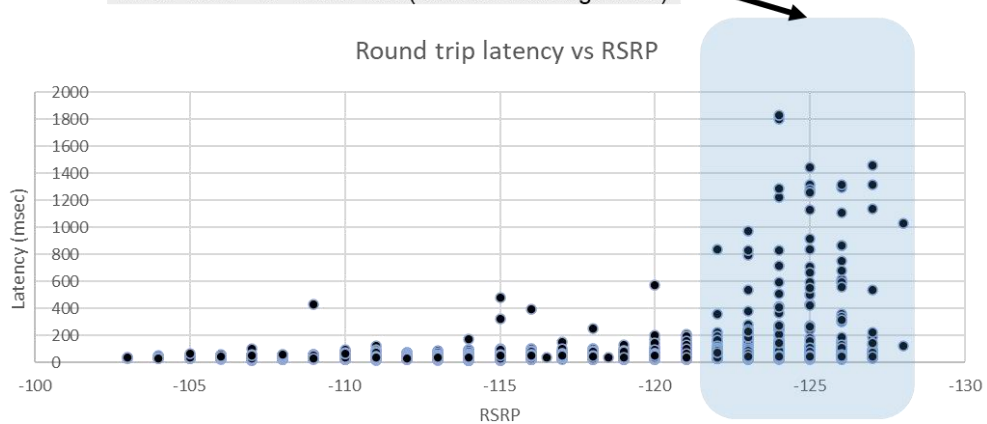
Observations:

- ✓ Latency for telemetry data is ½ the measured RTT
- ✓ Latency increases when the offered data throughtput is close to exceeding the channel capacity under given channel conditions
- ✓ Operating within the limits of channel bandwidth and coverage area keeps latency to a minimum

One way latency for telemetry data expected to be less than 50msec



Vast majority of occurrences of high latency occur when RSRP is -122 or less(ie out of coverage area)



Multiple AT

Flight Test Configuration:

- 11kft Altitude MSL
- **Multi AT Scenario**
  - Offered throughput: 20Mbps from Airborne AT
  - Offered throughput: 25Mbps from ground based AT

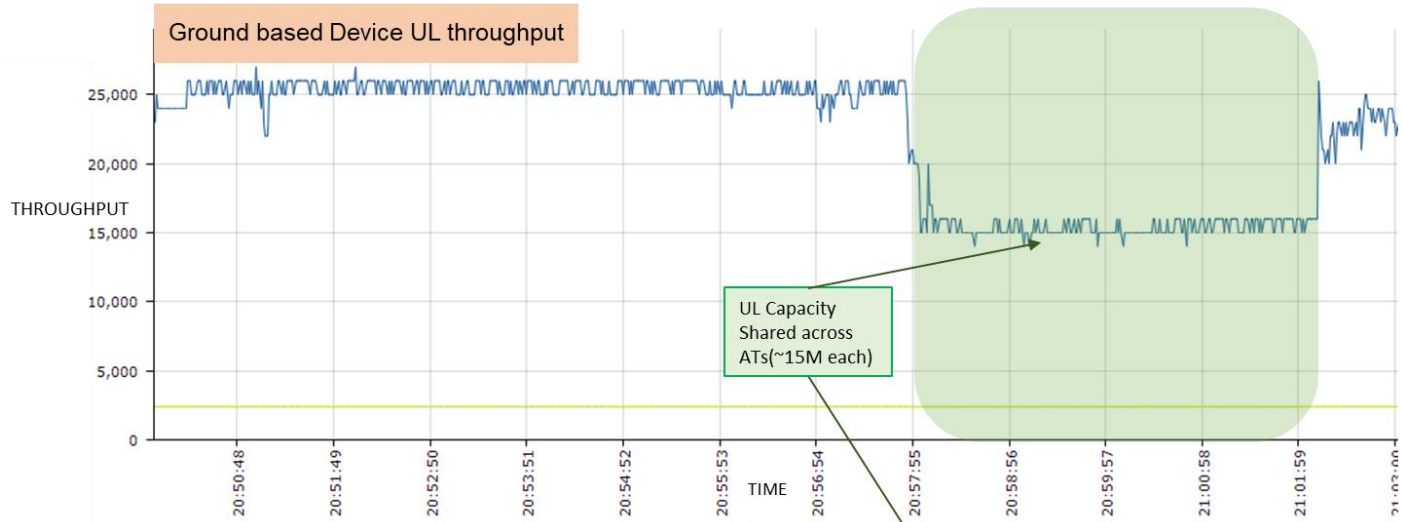
Multi AT Target:

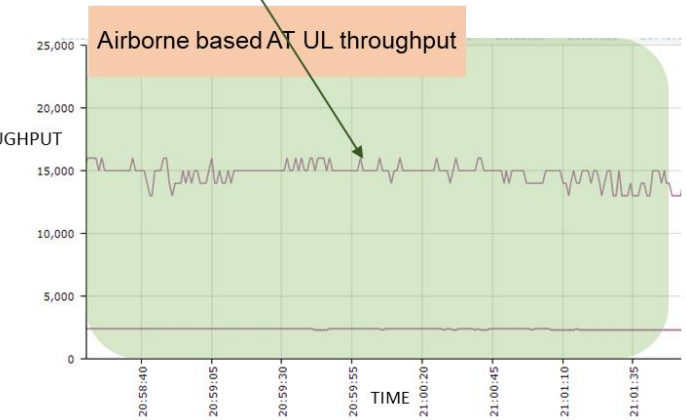
- 2 ATs in the same cell will share the UL capacity
- 2 ATs in different cells will be unaffected

Results:

- ✓ 25Mbps UL through ground-based AT unaffected while airborne AT is in other cells
- ✓ ATs share 30M UL when in same cell (~15M each)
- ✓ Ground-based AT returns to 25Mbps UL when airborne AT leaves cell

LTE-A based CRTM system automatically supports spectrum re-use and spectrum sharing





Lessons learned

Field and Lab demonstrations have shown LTE-A waveform can be adapted to provide a spectrally efficient advanced radio link for Aeronautical Mobile Telemetry.

- +/-12kHz CFO due to Doppler effects for speeds > MACH2 at lower C-Band can be corrected
- Seamless mobility is possible at MACH2 speeds.
- Throughput of 8Mbps or greater can be achieved reliably with 35km ground station inter-site distances using a 15MHz LTE channel. Higher throughput is possible by lowering inter-site distances and using a 20MHz LTE bandwidth channel.
- One way end-to-end latency of under 50ms when the AT is within the coverage area. A robust RF coverage deployment will reduce the occurrences of poor RF coverage and thus reduce the occurrences of >50ms latency.
- Simplified concept of operation because no early frequency planning and pre-configuration is needed for the ground or airborne terminal equipment for each test run.

Limitations and Opportunities

- Test flights were limited to 280knots, so field demonstration up to the capability of the equipment (MACH2) was not possible. Airborne Terminal platform options available for a rapid prototype did not support use in a fast mover.
- Building a low SWaP Airborne terminal on a high performance computing platform will enable test and use of CRTM on a fast mover aircraft.
- Some of the Handover Failures and connection drops were attributed to poor RF coverage. Building out the CRTM network with enhanced antenna design and an optimized RF network, would provide high throughput and reduced radio link drops through all flight paths.
- Seamless telemetry offload capability from the point when the aircraft is on the ground and when it takes flight can be supported with a buildout of the Flightline radio network.
- Non-interrupted telemetry offload between flights from/to EAFB and China Lake test ranges can be achieved with a buildout of the CRTM network for the Southwest Ranges.

CRTM next steps

Move to 5G Stand Alone network:

- 3GPP Band n79 (4400-5000MHz) available for 5G NR use outside of NA – commercial equipment available
- 30kHz and 60kHz sub-carrier spacing options – enables performance under higher Doppler conditions
- Higher carrier bandwidth configuration options – increased throughput
- Low latency communications with smaller RF resource granularity

Low-SWaP Airborne Terminal

- Modify Doppler compensation for 5G waveform
- Implement dual antenna configuration to address shadowing effects while maneuvering
- Enables flight testing in a higher performance aircraft (target F-16)

Range build-out

- Increase altitude coverage to 50kft
- Optimize bases station laydown for desired throughput