Jet Propulsion Laboratory
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On-Board Wireless Communications for Spacecraft Test and Operations

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Presentation Outline

- Objectives and Approach
- Link Reliability
- Network Scalability
- Electromagnetic Compatibility
- Wireless Ground Support Equipment (GSE) Case Studies
- Summary

Objectives and Approach

- Retire key risks in the use of wireless technologies for spacecraft design & test
  - Link Reliability:
    - Model RF propagation in spacecraft test and operations environments
    - Measure and analyze representative propagation environment
    - Develop link budget analyses
  - Network Scalability:
    - Analyze Quality of Service (QoS) provided by available protocols
    - Evaluate high data rate and multi-user performance via network simulation
  - Electromagnetic Compatibility (EMC):
    - Survey existing spacecraft instruments, radios and other subsystems for susceptibility to interference
    - Analyze and measure proposed wireless applique for compatibility and incorporate results into design approach

- Develop and demonstrate wireless cable replacement for Integration and Test
  - Develop concepts for EGSE cable replacement
  - Develop and demonstrate wireless prototype for EGSE cable replacement

Link Reliability: Overview

Objective: Analytically model RF propagation in spacecraft test and operations environments

- Assess impact of spacecraft structure on antenna patterns
- Assess frequency response and loss characteristics between multiple accommodated antennas in line-of-sight (LOS) and non-line-of-sight (NLOS) configurations
- Assess sensitivity to antenna placement
- Validate Friis transmission calculations for the various case studies

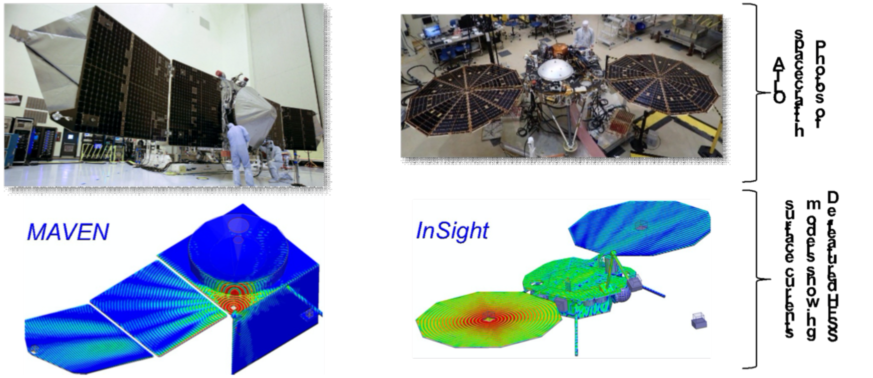
Modeling approach:

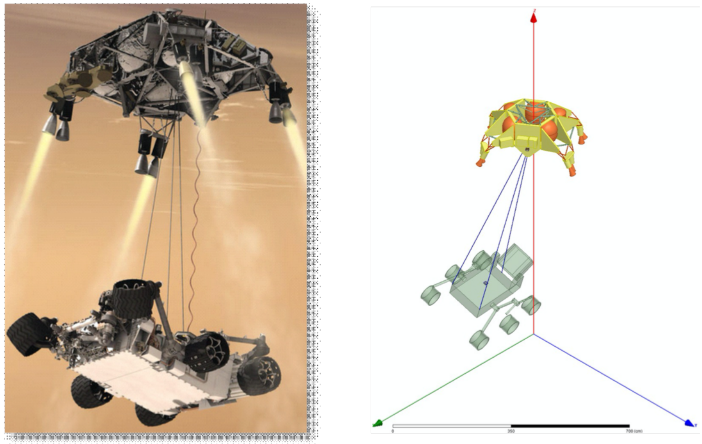
- Modeling whole or large fractions of spacecraft using finite element and hybrid integral equation full wave solvers
- Investigate propagation results using shooting-bouncing-ray modeling methods
- Using simplified representative antenna elements (patch, dipole)
- Using frequency bands commensurate with commercial ISM wireless parts / operation

Case Studies:

- InSight (Mars lander)
- MAVEN (Mars orbiter)
- Mars 2020 (descent stage - rover)

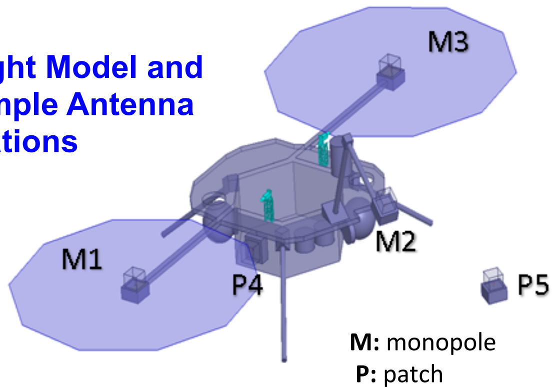
Propagation Modeling Case Studies





Link Reliability: Margin Evaluation

InSight Model and Example Antenna Locations



Point-to-point losses

Link	Distance (m)	FSPL (dB)	Min loss (dB)	Max loss (dB)	Best case fading (dB)	Worst case fading (dB)
1-2	2.6	48.7	52	52	3.3	3.3
1-3	4.4	53.4	59	66	5.6	12.6
1-4	1.7	44.8	52	60.5	7.2	15.7
1-5	3.6	51.4	59	66	7.6	14.6
2-3	3.7	51.7	50.5	52	-1.2	0.3
2-4	2.0	46.3	69	77.5	22.7	31.2
2-5	1.4	43.0	47	50.5	4.0	7.5
3-4	2.9	49.6	71.5	84	21.9	34.4
3-5	3.6	51.4	62.5	79	11.1	27.6
4-5	2.6	48.6	66.5	75.5	17.9	26.9

Line-of-sight (LOS)
LOS + multipath
Non-LOS + multipath

Margin Summary Examples (LOS + multipath, 10-meter range)

Waveform	Bandwidth (MHz)	Frequency (MHz)	Raw Data Rate (kbps)	Path Loss (dB)	No Diversity Eb/N0 (dB)	Target Eb/N0* (dB)	No Diversity Link Margin (dB)	Diversity Link Margin (dB)
802.11n (43 Mbps, 2.4 GHz)	20	2450	43300	60.2	23.7	10.7	13.0	29.0
802.11n (72 Mbps, 2.4 GHz)	20	2450	72200	60.2	21.5	15.4	6.1	22.1
802.11n (90 Mbps, 2.4 GHz)	40	2450	90000	60.2	20.7	10.7	10.0	26.0
802.11n (120 Mbps, 2.4 GHz)	40	2450	120000	60.2	19.4	12.3	7.1	23.1
802.11n (135 Mbps, 2.4 GHz)	40	2450	135000	60.2	18.9	14.8	4.1	20.1
802.11n (90 Mbps, 5 GHz)	40	5500	90000	67.2	13.6	10.7	2.9	18.9
802.11n (135 Mbps, 5 GHz)	40	5500	135000	67.2	11.9	14.8	-2.9	13.1

- Ansys HFSS and Savant electromagnetic (EM) modeling software is used to calculate point-to-point losses between arbitrarily placed antennas
- EM propagation results are assessed for frequency selective behavior (e.g. multipath)
- Loss allocations for multipath are estimated and incorporated in link analysis

Link Reliability: Testing & Studies

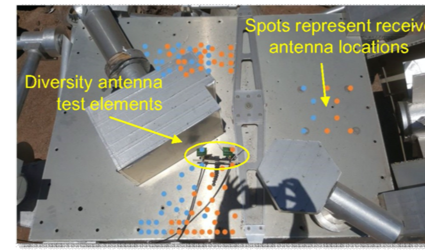
Propagation measurements

- Performed measurement of short-range RF signal propagation in operational and test venues
- Measurements intended to measure spatial distribution of short range signals and provide insight into multipath signal behavior
- Modest 20 MHz bandwidth signal used as the reference waveform
- Analysis of results shows the advantage of antenna diversity in improving link margin for short-range communications

Propagation Measurement Venues

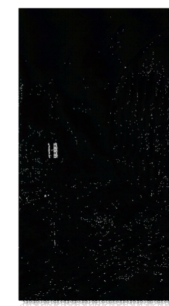
Field test configuration

Rover top deck receiver locations



Ten foot environmental chamber

Transmit/Receive antennas located within test chamber



Wireless Imager Link Design Study

Configuration settings and system margins for an intermittent 1% PER outage channel

Required Throughput (Mbps)	Waveform Configuration	Achievable Throughput (Mbps)	Throughput Margin (%)	Diversity Link Margin (dB)	Bandwidth Utilization (MHz)
25	802.11n (72 Mbps, 2.4 GHz)	36	44%	22.1	20
50	802.11n (120 Mbps, 2.4 GHz)	60	20%	23.1	40
60	802.11n (135 Mbps, 2.4 GHz)	67.5	13%	20.1	40

Configuration settings and system margins for a "clean" channel environment

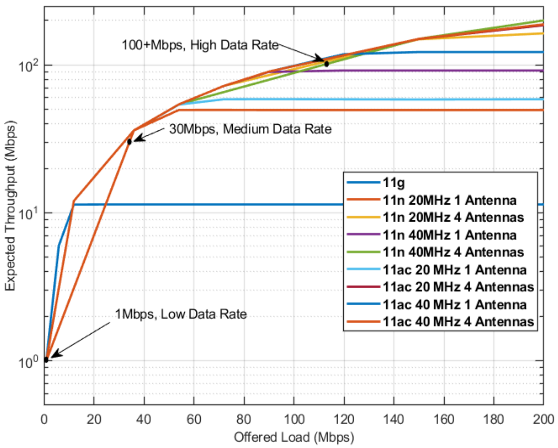
Required Throughput (Mbps)	Waveform Configuration	Achievable Throughput (Mbps)	Throughput Margin (%)	Diversity Link Margin (dB)	Bandwidth Utilization (MHz)
25	802.11n (43 Mbps, 2.4 GHz)	34.6	38%	29.0	20
50	802.11n (72 Mbps, 2.4 GHz)	57.8	16%	22.1	20
60	802.11n (90 Mbps, 2.4 GHz)	72	20%	26.0	40

Wireless Video Link Study

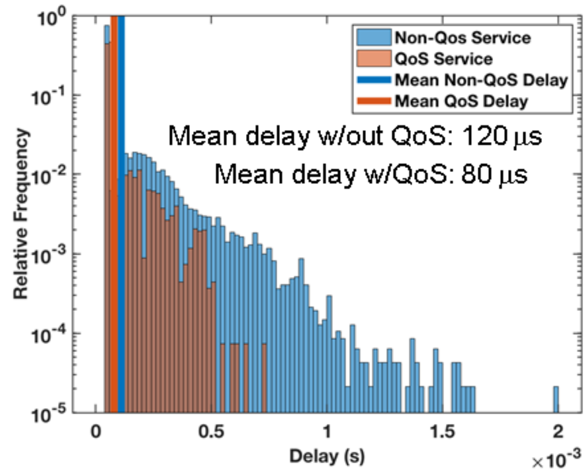
- Performed link design study for the use case of off-loading video imagery from an MSL/M2020 class Skycrane to the rover platform
- Evaluated WiFi waveform selections and assessed link margin taking into account protocol overhead
- Estimated margins above 20 dB for data link requirements ranging from 25 – 60 Mbps

Network Scalability: Throughput and Latency

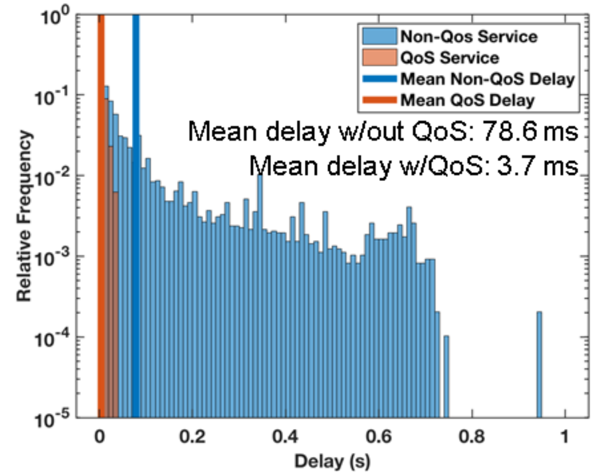
Single User Throughput vs. offered load



Eight User Traffic Latency (< 1 Mbps aggregate)



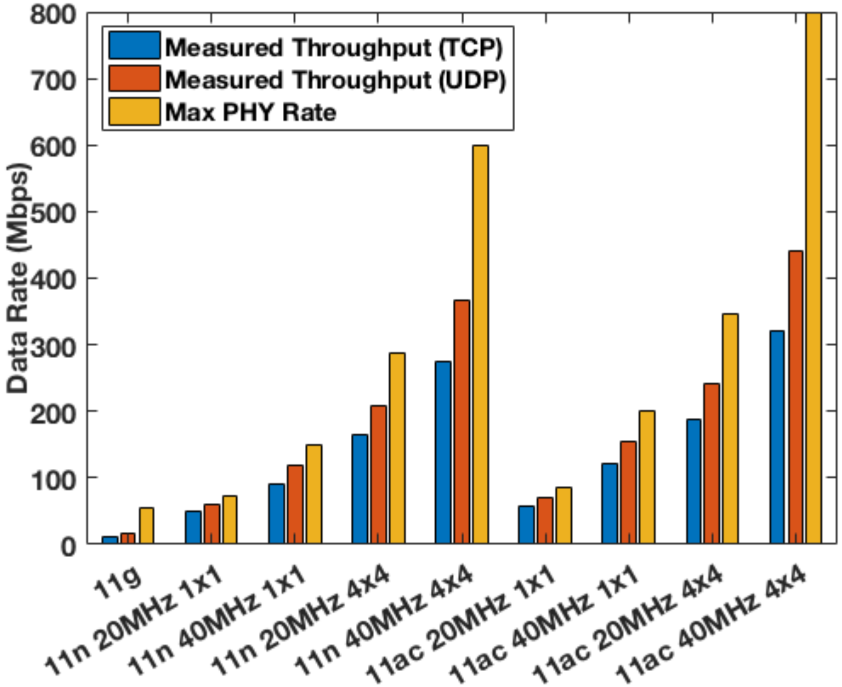
Eight User Traffic Latency (30 Mbps aggregate)



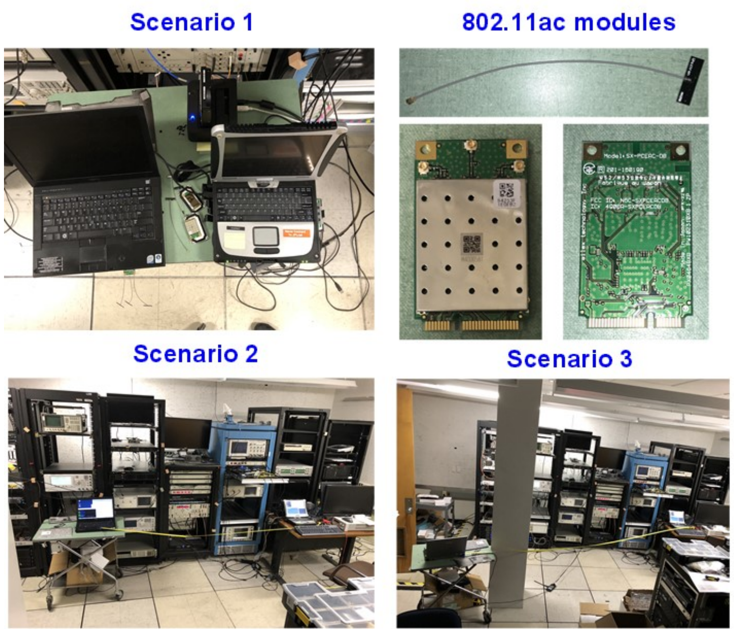
- Developed a multi-user network simulation to evaluate system throughput for different WiFi standards (802.11g/n, 20/40 MHz, MIMO)
- Utilized traffic from a critical timing event scenario to evaluate data latencies with and without Quality of Service (QoS) priorities
- Under lightly loaded conditions average data latency is under 80 µs for priority traffic while all traffic is delivered with latency of less than 2 milliseconds
- For the eight user traffic distribution, aggregate system throughput is approximately 20 - 30% of the channel data rate

Network Scalability: Point-to-point throughput

Maximum TCP/UDP throughput (802.11g/n/ac, ns-3 simulation)



Measured 802.11ac MIMO throughput



- Evaluated point-to-point links for achievable throughput via simulation and test
  - Utilized ns-3 simulation under "high SNR" conditions
  - Tested COTS wireless client modules in peer-to-peer networking mode
- Usable data rate can be considerably lower than the "advertised" maximum physical layer data rate – particularly with respect to MIMO

Network Scalability: Throughput (cont.)

Measured 802.11ac MIMO throughput

Scenario 1

Tranmit x Receive Antennas	Transport	Distance (meters)	Average Throughput (Mbps)	σ (Mbps)
2x3	1 TCP	0.35	109	15.1
3x2	1 TCP	0.35	170	15.4
2x3	1 UDP	0.35	357	20.9
3x2	1 UDP	0.35	358	10.9
2x3, 3x2	2 TCP	0.35	49	7.9
3x2, 2x3	2 TCP	0.35	81	14.5
2x3, 3x2	2 UDP	0.35	156	11.1
3x2, 2x3	2 UDP	0.35	166	5.2

Scenario 2

Tranmit x Receive Antennas	Transport	Distance (meters)	Average Throughput (Mbps)	σ (Mbps)
2x3	1 TCP	2	83	5.2
3x2	1 TCP	2	140	6.9
2x3	1 UDP	2	242	3.8
3x2	1 UDP	2	321	2.8
2x3, 3x2	2 TCP	2	56	6.1
3x2, 2x3	2 TCP	2	50	9.8
2x3, 3x2	2 UDP	2	147	1.5
3x2, 2x3	2 UDP	2	158	3.3

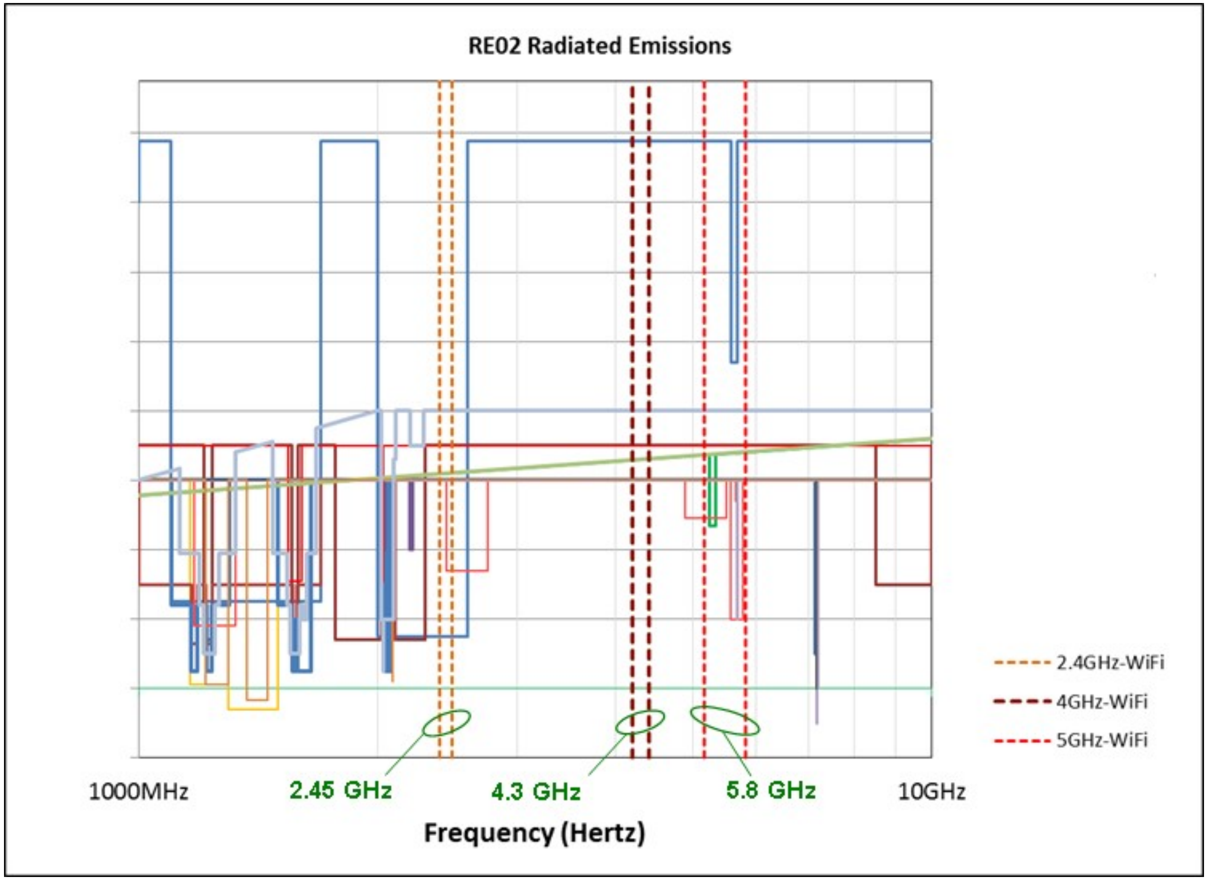
Scenario 3

Tranmit x Receive Antennas	Transport	Distance (meters)	Average Throughput (Mbps)	σ (Mbps)
2x3	1 TCP	3.6*	92	4.3
3x2	1 TCP	3.6*	182	7.4
2x3	1 UDP	3.6*	241	0.7
3x2	1 UDP	3.6*	371	10.4
2x3, 3x2	2 TCP	3.6*	56	7.7
3x2, 2x3	2 TCP	3.6*	33	8.2
2x3, 3x2	2 UDP	3.6*	138	2.6
3x2, 2x3	2 UDP	3.6*	150	4.3

- Testing of COTS 802.11ac modules utilizes iPerf to evaluate single and dual flow throughput with UDP and TCP transport layer protocols
- Dual data flow configurations are sent bi-directionally
- For reliable delivery (TCP), aggregate throughput data rates are in the 100 – 200 Mbps range

EMC: Radiated Emissions Mission Survey

Radiated Emissions Limits for 15 Missions around 2.4, 4.3, and 5.8 GHz

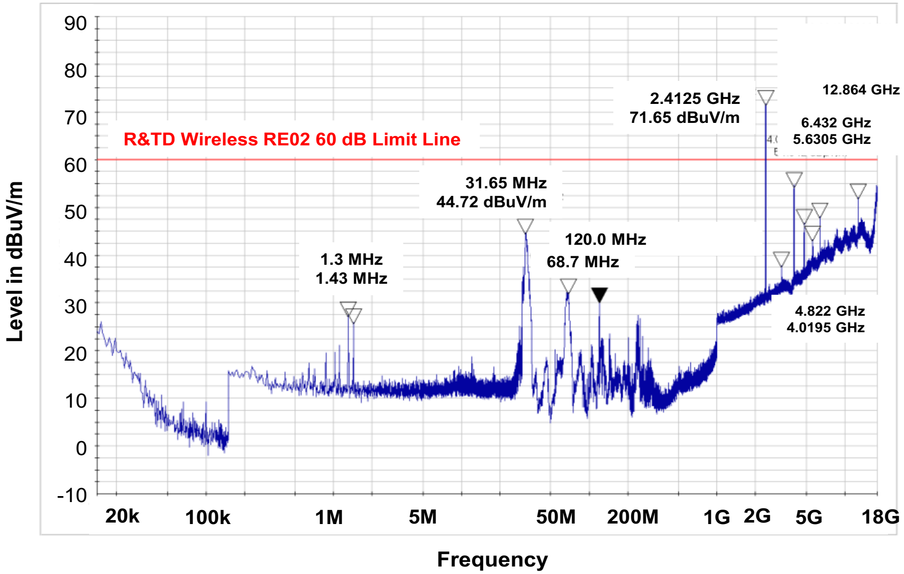


The pairs of vertical dashed lines indicate the boundaries of the 2.45, 4.3, and 5.8 GHz bands.

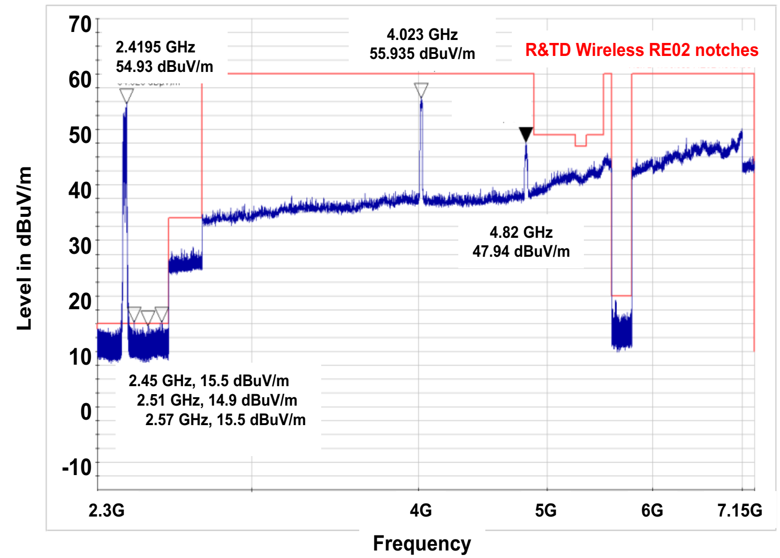
- Completed survey & transcription to spreadsheet of RE02 requirements for 28 missions
- In-band overlap identified for the following applications:
  - 4.3 GHz landing radar (InSight only)
  - 5.8 GHz launch vehicle beacon/TT&C (various)
  - 2.4 GHz imaging radar (M3)
- Additional comparative analysis revealed available spectrum for wireless usage within the overlapping bands for all surveyed missions except InSight
- Transmit power and receiver sensitivity specifications for wireless components were utilized to produce candidate EMC requirements

EMC: Radiated Emissions Measurement

Radiated Emissions Testing: 14 kHz to 18 GHz



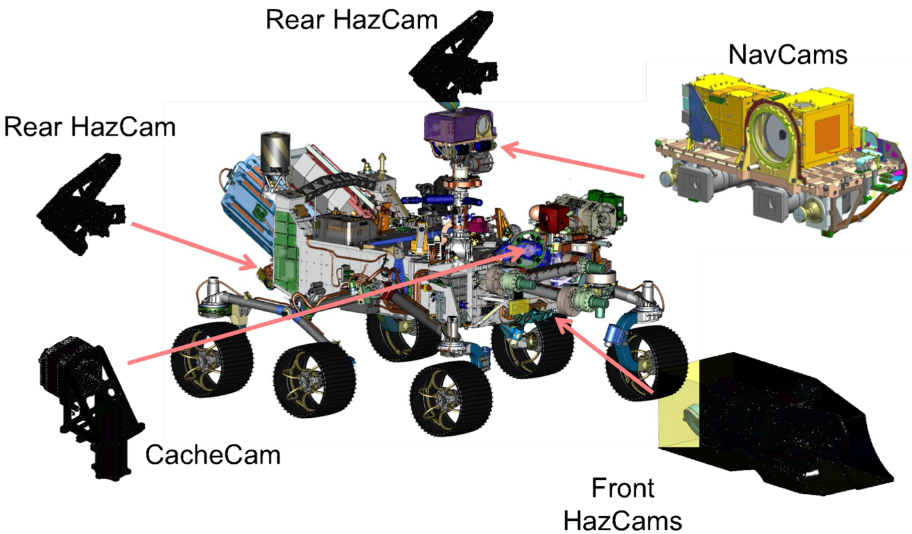
Radiated Emissions Testing: Detail View Compared to Composite Multi-mission Limit



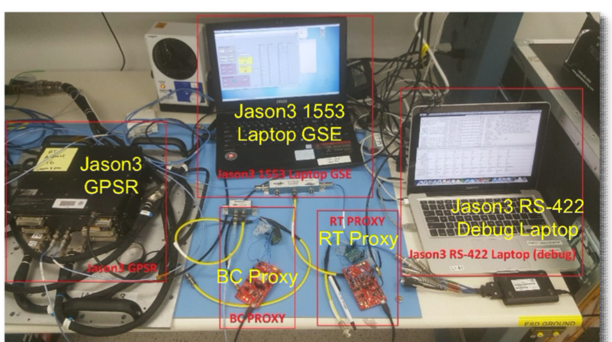
- Evaluated several commercial wireless components for radiated and conducted emissions and radiated and conducted susceptibility
- Determined that wireless emitters in the sub-100 mW class do not present an overly stringent constraints for operational use – does require specific component testing for each application
- Developed recommendations for Radiated Emissions (RE) and Radiated Susceptibility (RS) limits in the 2.4 GHz band

Wireless GSE: Overview

EECAM examples on M2020



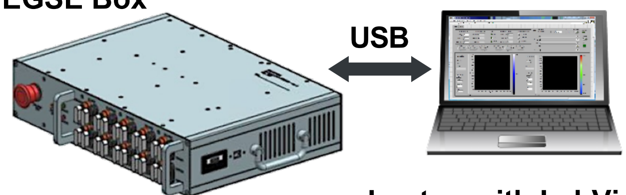
Jason3 GPSR wireless 1553 GSE

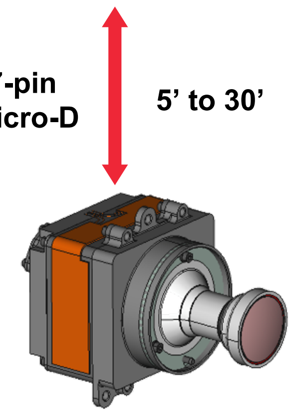


- EECAM (Engineering Camera) family of instruments identified as a potential application for wireless electrical ground support equipment (EGSE) to support development and ATLO calibration activities
- Developed benchtop prototype to perform protocol conversion and wireless transfer of 1553 data
- Demonstrated transfer of 1553 data between Jason3 GPSR and 1553 EGSE laptop computer system

Wireless EGSE: EECAM Lab Development Use Case

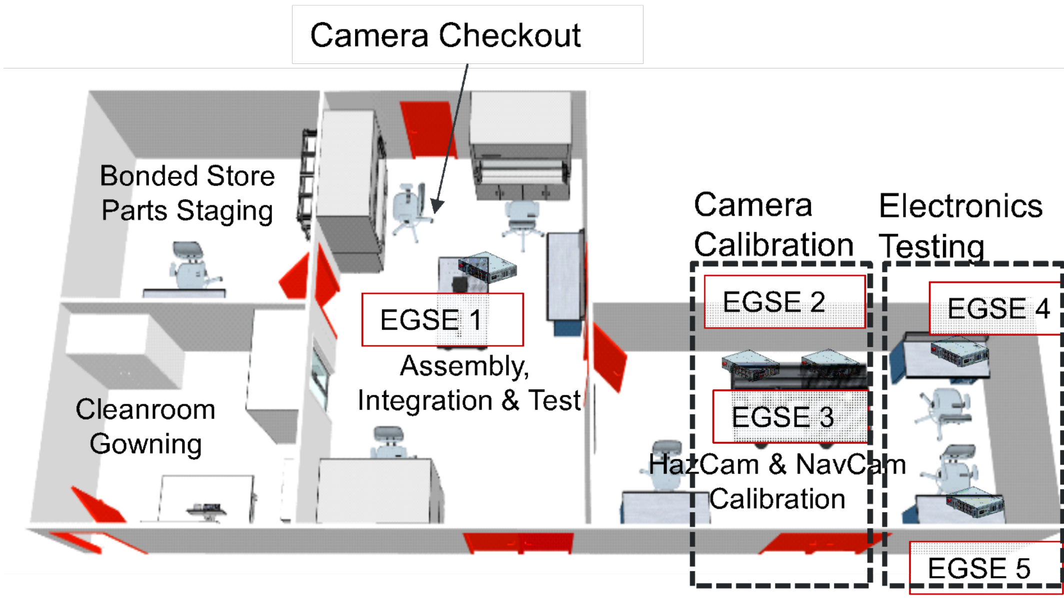
EECAM Wired EGSE Configuration





- **Operator Interface:** LabView GUI
- **Camera Data Rate :** 500kpixel/sec (10MHz clock)
- **Image Readout Time:** 3.5 seconds
- **Connector:** 37-pin Micro-D
- **Data Physical Layer:** LVDS (2X CMD, 3X TLM)

EECAM Test Lab Wireless Opportunities



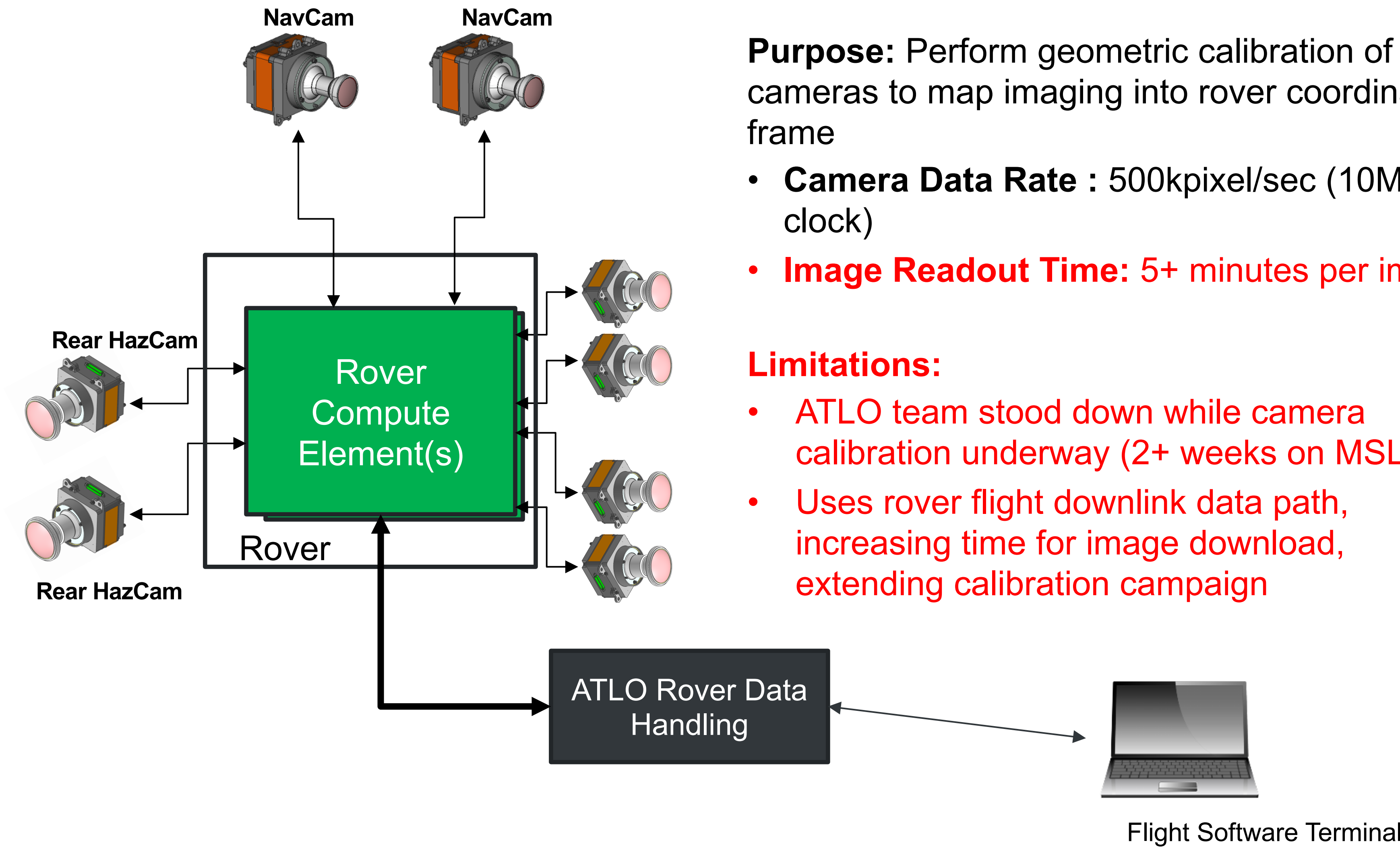
Limitations:

- Requires co-location of EGSE with unit under test
- Cable length limited to ~30 ft (LVDS data integrity)
- Multiple cameras under test requires multiple EGSE setups
- EGSE provides power and data

- Multiple test stations require duplication of EGSE
  - Five (5) stations in EECAM lab (EGSE hardware + dedicated laptop)
- Opportunities for Wireless – build into EGSE

Wireless EGSE: EECAM ATLO Use Case

MSL/M2020 ATLO Camera Calibration Setup



Purpose: Perform geometric calibration of cameras to map imaging into rover coordinate frame

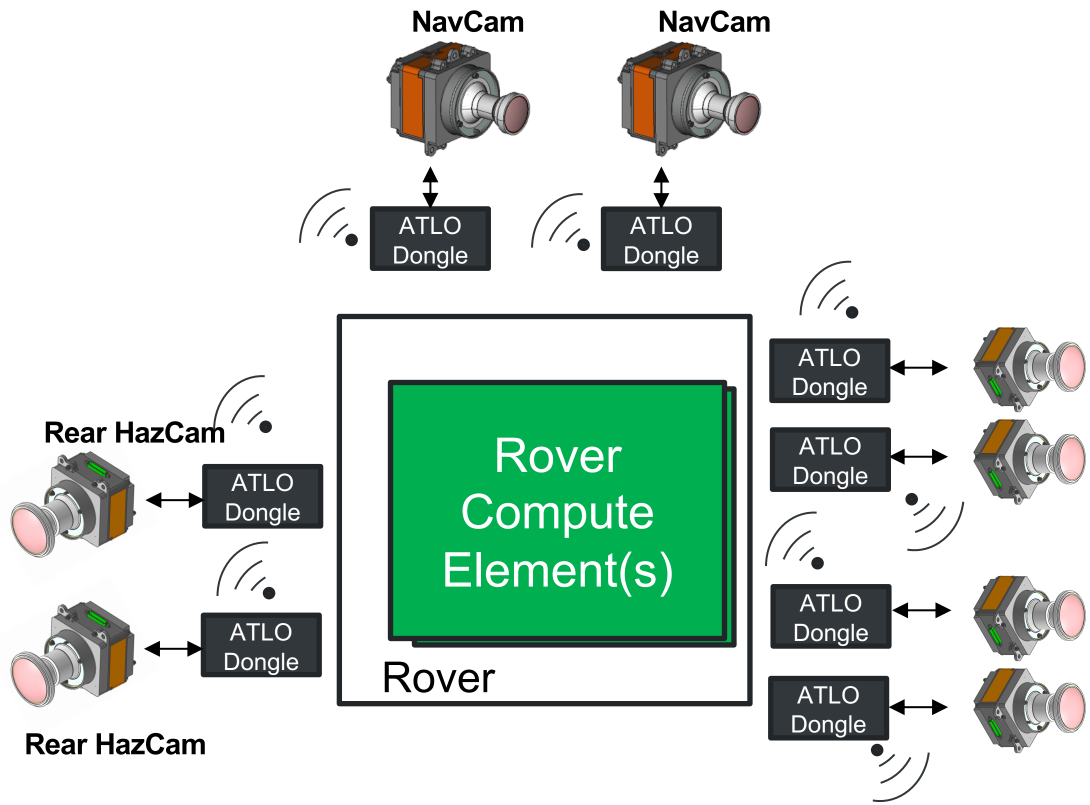
- **Camera Data Rate :** 500kpixel/sec (10MHz clock)
- **Image Readout Time:** 5+ minutes per image

Limitations:

- ATLO team stood down while camera calibration underway (2+ weeks on MSL)
- Uses rover flight downlink data path, increasing time for image download, extending calibration campaign

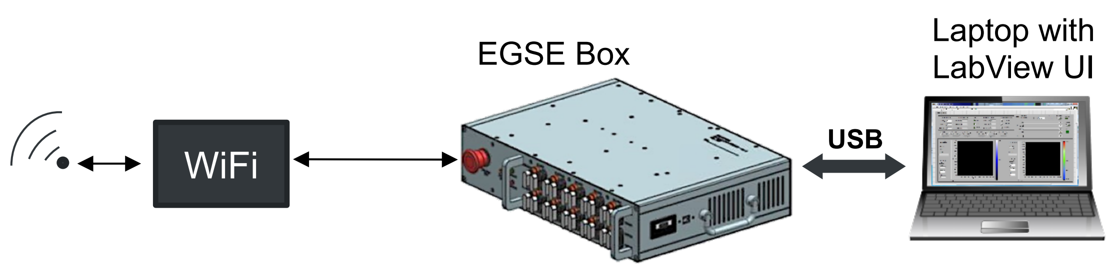
Wireless EGSE: EECAM ATLO Use Case (cont.)

MSL/M2020 ATLO Wireless Interface Configuration



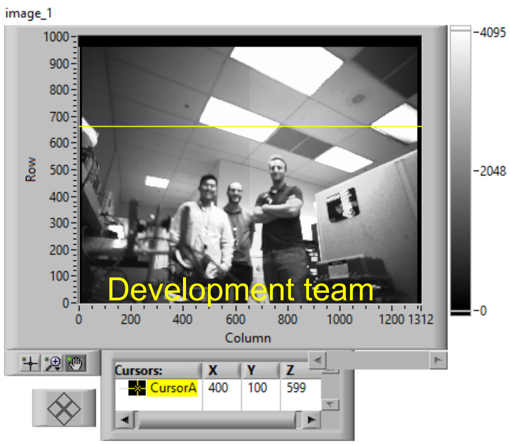
- **Camera Interface:** ATLO Dongle
  - Cameras physically mounted on rover, but not connected to RCE
- **Camera Data Rate :** 500kpixel/sec (10MHz clock)
- **Image Readout Time:** 3.5 seconds

- **Opportunities**
  - Camera ‘dongle’ creates IoT addressable cameras from single EECAM EGSE
  - EGSE operator doesn’t need to be on ATLO floor
  - Dongle powers cameras using batteries
  - Decouples camera data path from limitations of Rover data downlink system

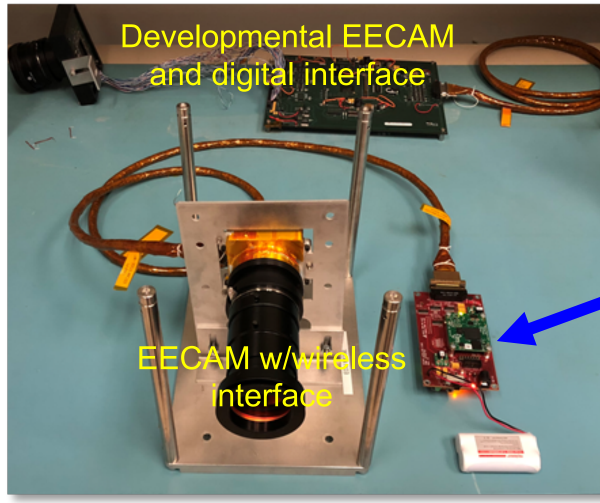


Wireless EGSE: Wireless Interface Development

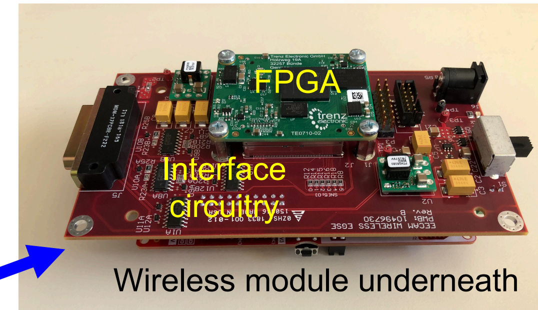
Transmitted Wireless Image



EECAM and Wireless Dongle



Wireless Interface (detail)



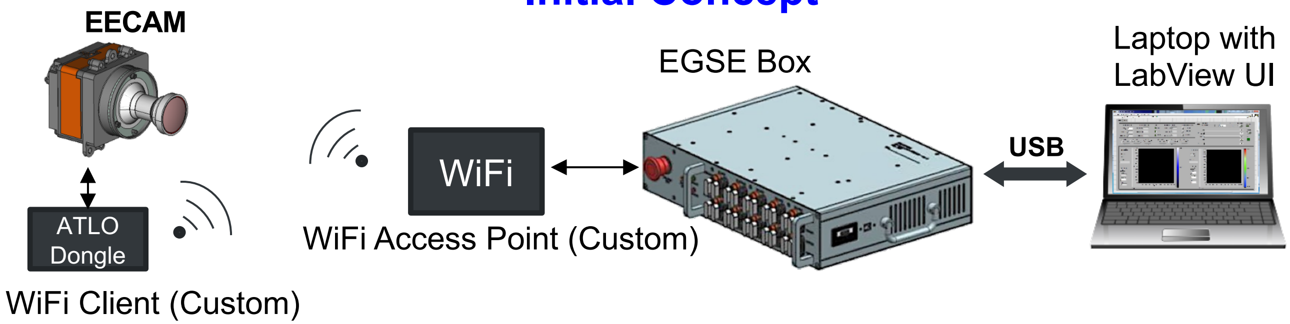
Wireless Interface Features

- Wireless interface design consists of power supply and interface circuitry, FPGA unit and wireless module
- FMEA-compatible OVP, OCP, ESD protection
- Wireless module based on TI-CC3220 IoT (Internet of Things) device
- Wireless module is custom programmed for remote configuration (channel select, sleep modes, etc.)
- Network protocol uses TCP over 802.11g/n WiFi
- Battery-powered (Li-Ion)
  - Rechargeable
  - Wired connection for extended duration operation or charging

- Developed wireless interface between EECAM and EGSE to enable commanding and image retrieval for test and calibration needs
- Eliminates cable length restrictions and provides low-cost developmental interface
- Reuse of cabled EGSE interface circuitry provides FMEA integrity for dongle design
- Wireless system can be employed as standalone or integrated with WiFi infrastructure

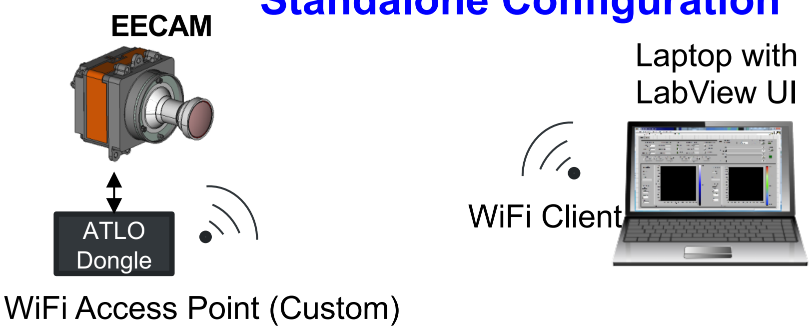
Wireless EGSE: Wireless Network Configurations

Initial Concept



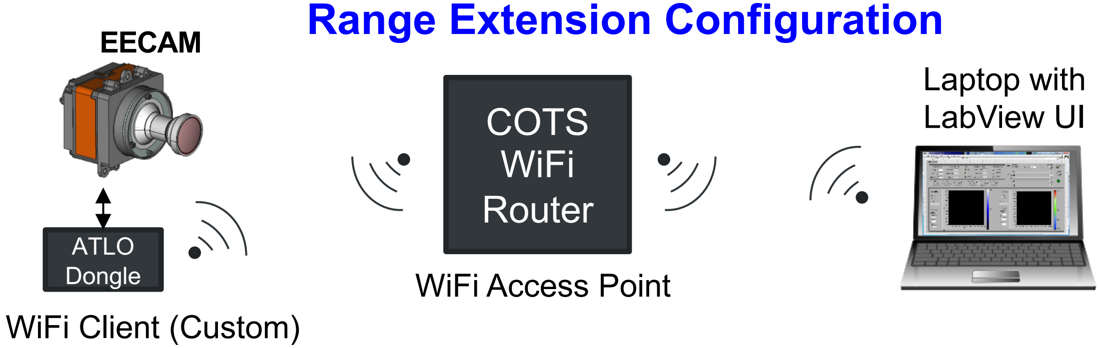
- Original design concept included wireless module within EGSE unit containing the laptop interface
- This approach was intended to minimize modifications to the user interface

Standalone Configuration



- Reprogramming the wireless interface to serve as an access point allows direct connection from the EGSE laptop
- Eliminates additional custom or special purpose hardware on the EGSE laptop side

Range Extension Configuration



- Reconfiguring the wireless interface to a client enables range extension with a COTS WiFi router
- Router can be part of the EGSE suite or from the institutional infrastructure
- Exploring the use of JPL's IoT net
- Potential for offsite access

Selected Findings

Link reliability for operational use:
Wireless waveforms and protocols are suitable for short-range intra-spacecraft communications and can be designed with high margin to insure reliability. Spatial diversity with more than one antenna is recommended to increase margin in the presence of small scale fading.

EMI/EMC considerations:
Wireless frequency bands in the 2.4, 4.3 and 5.8 GHz range are relatively de-conflicted with multi-mission radiated emissions requirements. Wireless emitters in the 10 – 100 mW class do not present overly stringent constraints for operational use.

Multi-user data latencies:
For standard wireless protocols, data latency can be driven down by reducing the wireless network traffic and using prioritization, but has a residual floor in the 1 ms range

Interfacing COTS devices to embedded systems for test:
SOA COTS wireless modules are most easily interfaced to a network processor that shares protocol functions (TCP, UDP) and controls/configures the module through device drivers. Direct interfacing of modules to embedded systems is difficult without replication of the network stack and O/S. Recommend incorporating the network processor function within wireless test interfaces.

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