An Overview of Cognitive Networking Demonstrations and Testbeds

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Professional Experience

- Member of NASA Glenn Research Center's Cognitive Signal Processing Branch
- High-rate Delay Tolerant Networking Product Lead Engineer
- Networking Lead for Cognitive Communications project
- IEEE Cleveland Joint Chapter Chair for Antennas and Propagation, Microwave Theory, Electron Devices, Aeronautical Electronics, and Communication
- Conference Chair of IEEE Cognitive Communications for Aerospace Applications

Publications

- Many publications on delay tolerant networking, space network simulation and emulation, artificial intelligence/machine learning, future networks
- https://www1.grc.nasa.gov/space/scan/acs/tech-studies/dtn/
- https://ccaaw.ieeecleveland.org/
- https://github.com/nasa/HDTN

Introduction

- Challenges of space networks creates complex test environment
- Delay tolerant networking mitigates disruptions in the future space networks
- Cognitive networks add autonomy to existing space communication framework
- Incorporates multiple components into a system
- Test approaches require specialized tools, defined metrics and objectives
- Software exists at a variety of technology readiness levels
- Tools and testbed must match required fidelity level

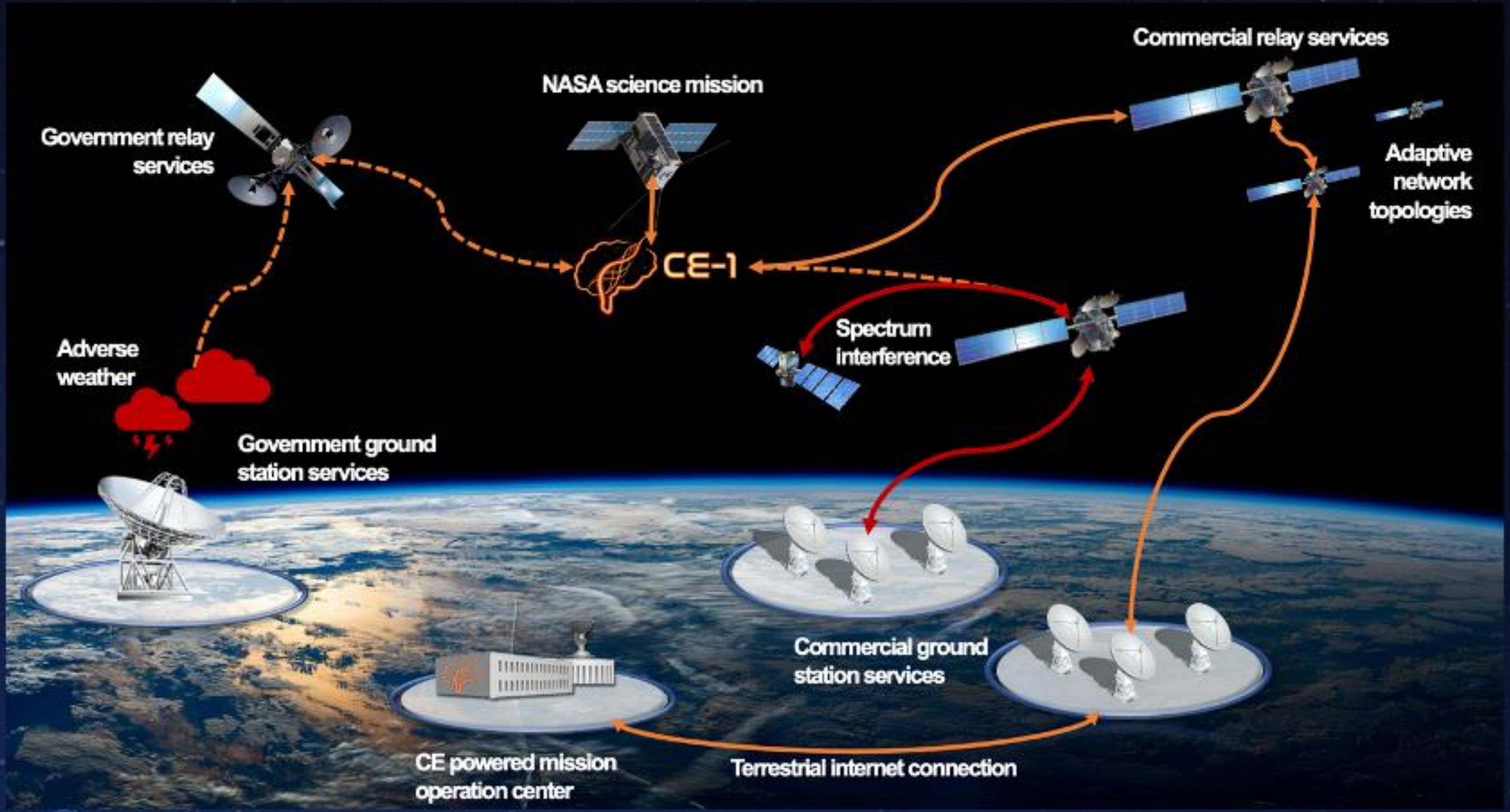
A view of NASA Glenn’s new Aerospace Communications Facility.
Credits: NASA/Sara Lowthian-Hanna

System Overview

Cognitive communications technology supports NASA operations in complex, crowded, and dynamic space-environments.

Managing spacecraft communications is increasingly challenging

Commercialization trends are making space a more complex, crowded, and dynamic environment. Operators must handle routine tasks such as scheduling service and selecting optimal service providers for a larger number of assets and adverse events such as spectral interference are becoming more common.



CE-1 Near-Earth Challenges

Proposed solution is an autonomous communication system, Cognitive Engine 1 (CE-1)

NASA CE-1 will deliver high-speed, robust, and cost-effective communications while providing seamless roaming between networks.

No more schedule forecasting

CE-1 works with emulated NASA and commercial networks to schedule services without requiring input from mission or network operators.

Increases network efficiency

Spacecraft increases network efficiency by only scheduling time required to meet data needs. Reschedule in case of failed pass makes best effort to meet latency constraints.

CE-1

Block out noisy neighbors

CE-1 detects, mitigates, and learns to avoid or mitigate interference from other spacecraft and ground assets.

Autonomously fulfill communication needs

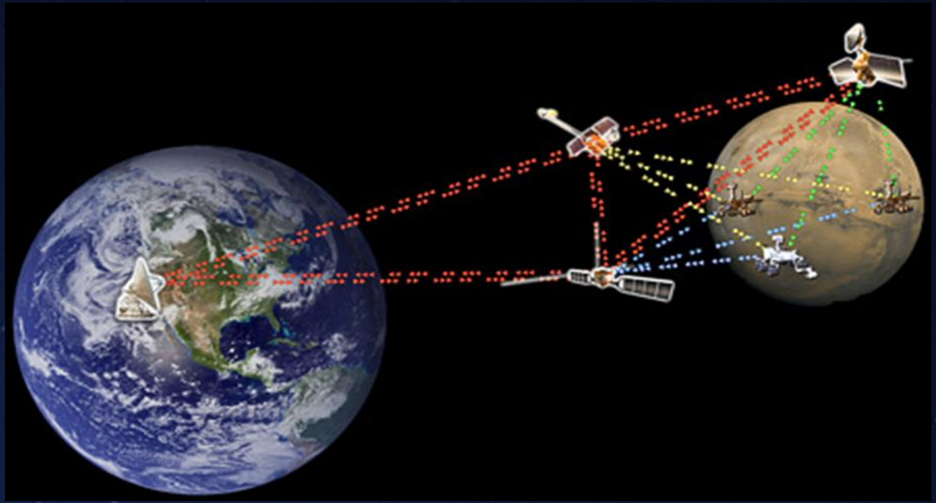
CE-1 components on spacecraft and ground autonomous fulfills communication needs – no human in the loop.

Seamlessly roam and adapts to a changing environment

Provides seamless roaming between government and commercial providers of both relay and DTE links. Cognitive algorithms allow CE-1 dynamically reconfigure based on observed performance, discover new network assets, and adapt to bad weather.

Delay/Disruption Tolerant Networking (DTN)

- DTN is NASA's solution for automated and reliable communication in high latency space networks without end-to-end connectivity
- Suite of communication protocols to support an interoperable space network
- Buffers data until a transmit opportunity arises
- Uses the bundle protocol, an approach for space network transport that forms a store-and-forward overlay network
- High-rate Delay Tolerant Networking (HDTN) is GRC's performance optimized DTN implementation



Store
Carry
Forward…

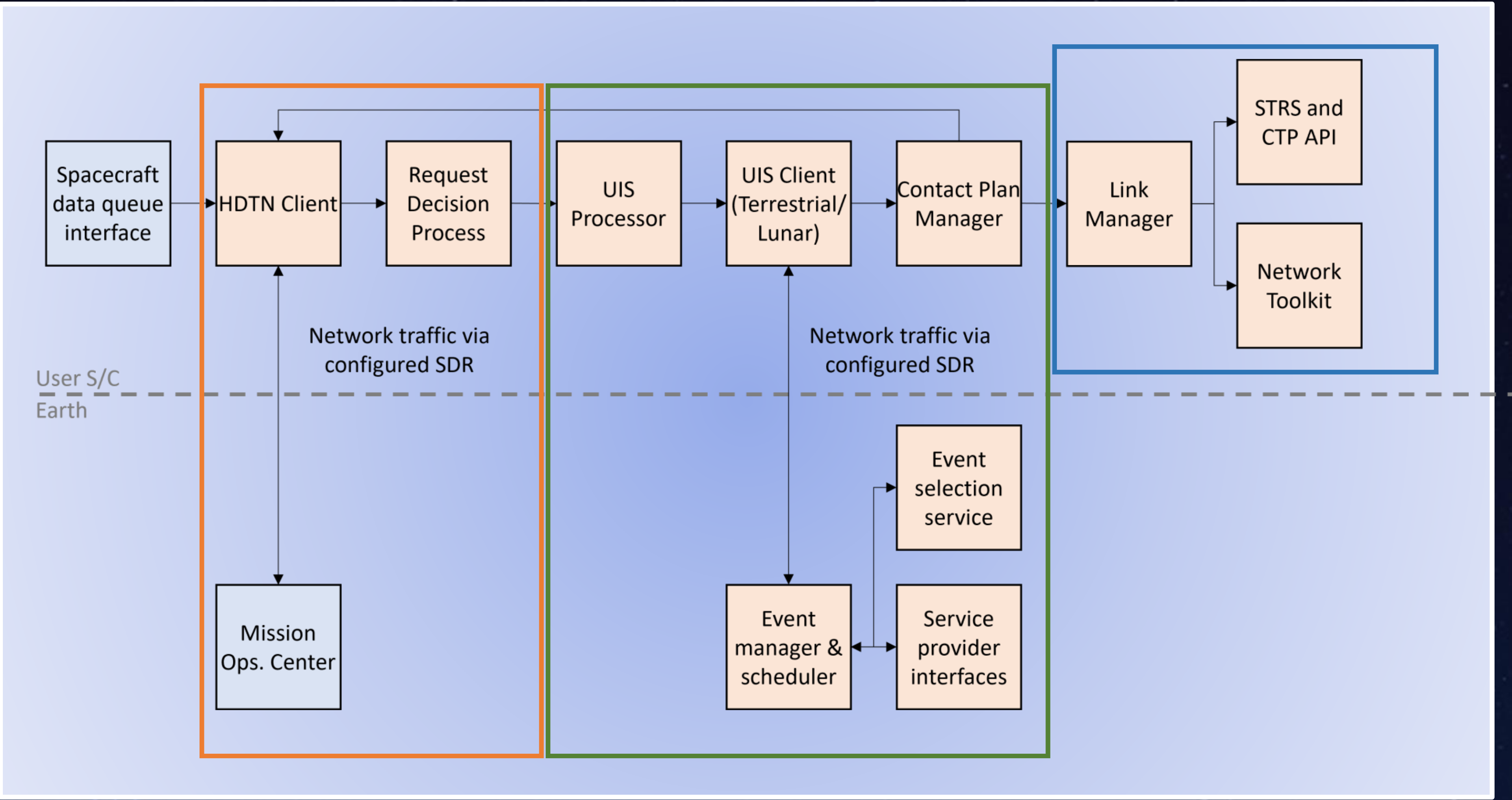
Cognitive Engine-1 Automated System

Handle Incoming Data:

- DTN makes store-or-forward and next-hop destination decisions.
- Data from an underperforming contact will remain in HDTN storage, which will trigger an additional request for service. System automatically reacts to failed contacts.

Fulfill Requests for Service:

- UIS server selects a suitable contact. Confirms contact with provider. Repeats process if rejected.
- Spacecraft receives confirmation. Updates contact plan to include the newly-scheduled contact.



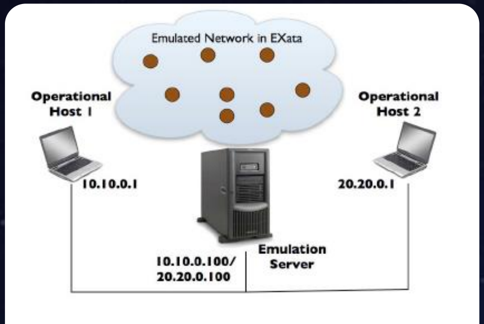
Establish Radio Links:

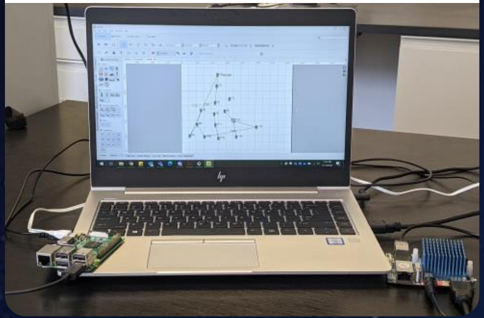
- Contact plan contains all scheduled contacts plus on-demand contacts when applicable.
- Providers may require certain parameters at physical, link, and network layer for compatibility. Link Manager reads contact plan and brings up SDR with provider-specific waveform a few seconds before the scheduled contact begins.

Testing Capabilities

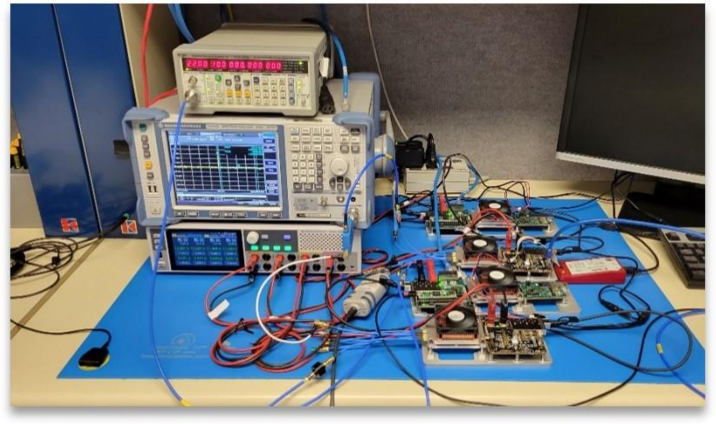
Our Labs at Glenn Research Center

Network Emulation



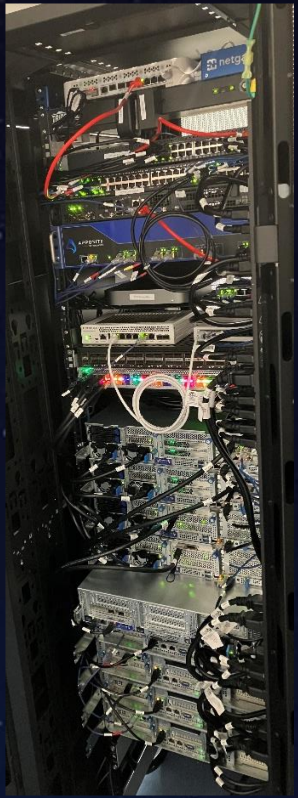


Software Defined Radio



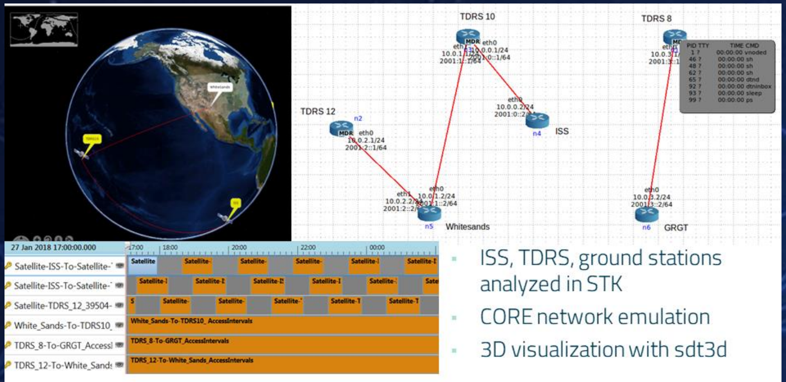
Software and Protocol Development

Virtualization and High-Performance Networking



Optical Communication

Modeling and Simulation



- ISS, TDRS, ground stations analyzed in STK
- CORE network emulation
- 3D visualization with sdt3d

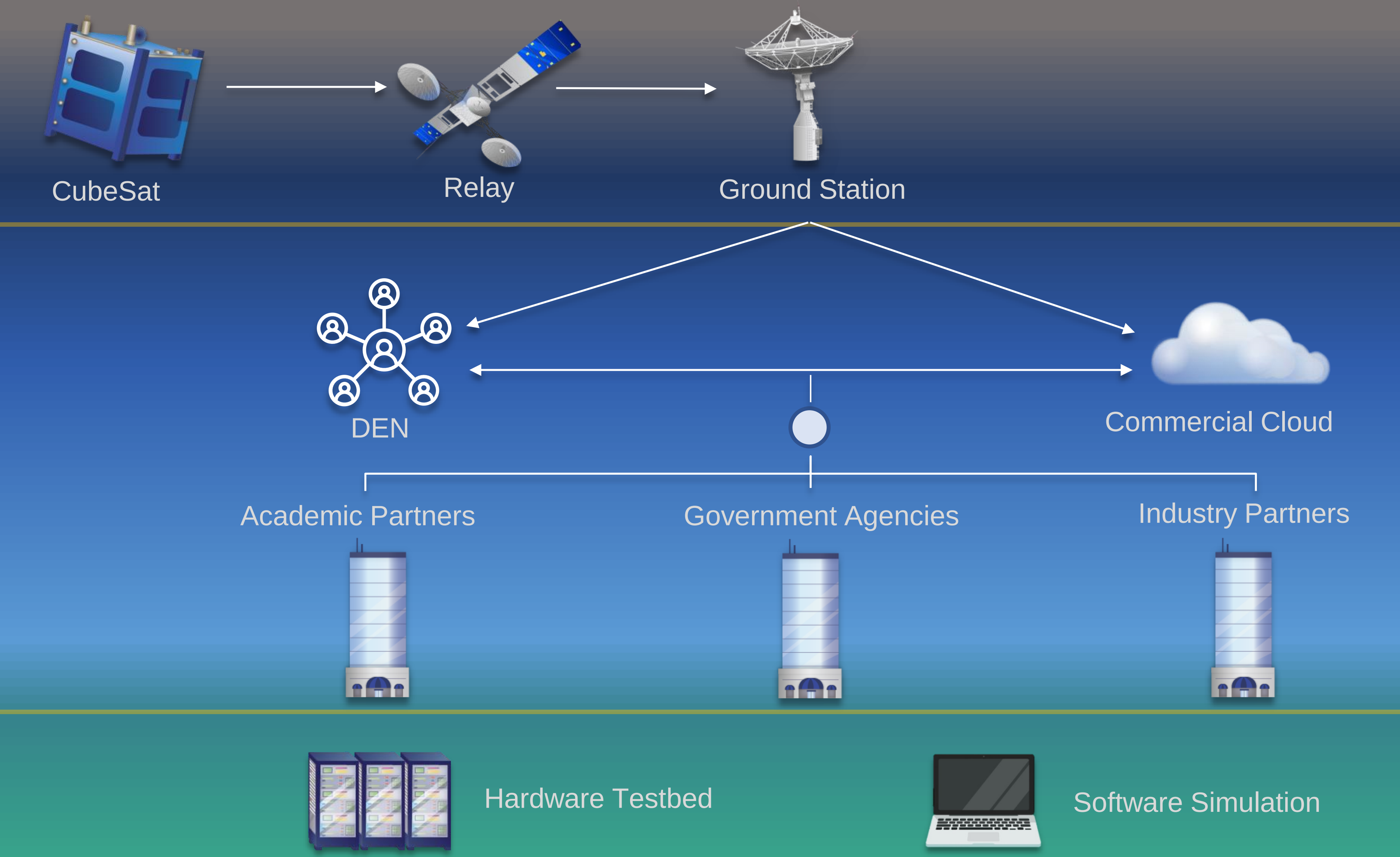
Flight Preparation and Testing

OPEN-ACCESS TESTBED

Flight Demo
Capabilities
HIGH TRL

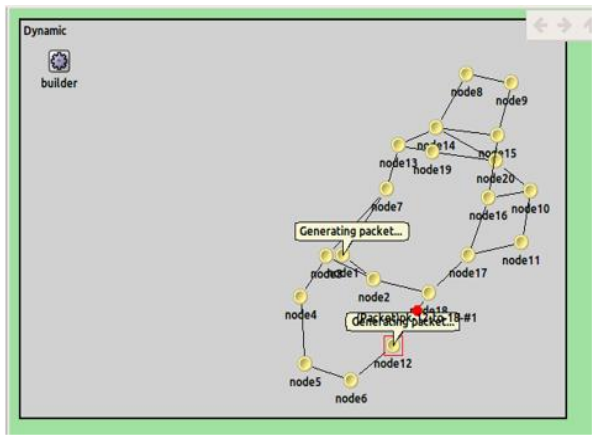
Ground and
Interoperability
Testing
MID TRL

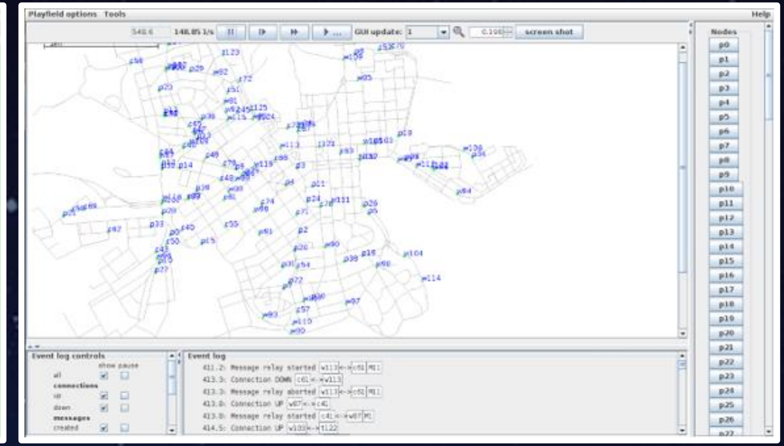
LOW TRL

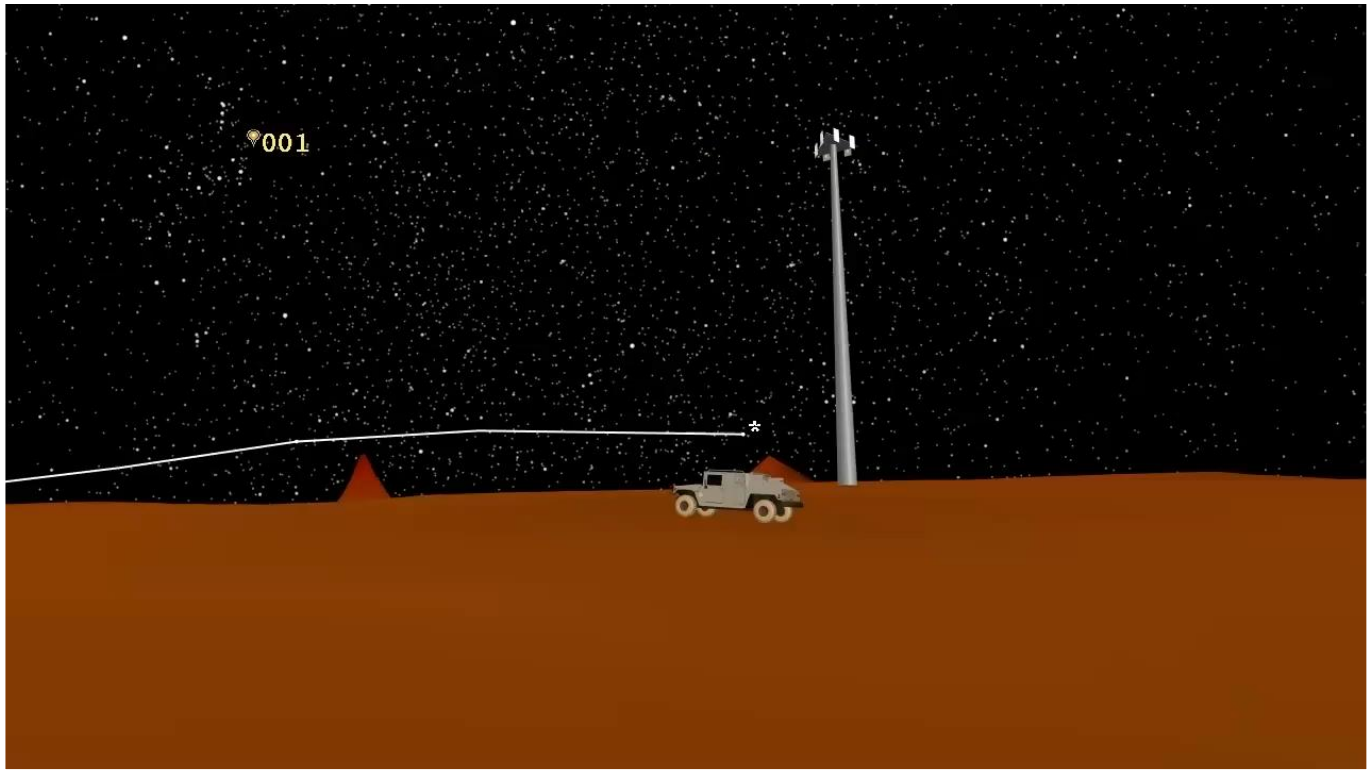


Simulation Platforms

- **Open source discrete event simulators**: ONE, DTNSim and ESTNeT based on OMNeT++ provide framework for low TRL algorithm and protocol proof-of-concept
- **Commercial simulators**: System Tool Kit provides extensive physical layer modeling, integration with other packages
- **Custom developed digital twin**: Modeling of complete spacecraft communication system spanning multiple layers including orbital assets, links, network protocols, and onboard storage.

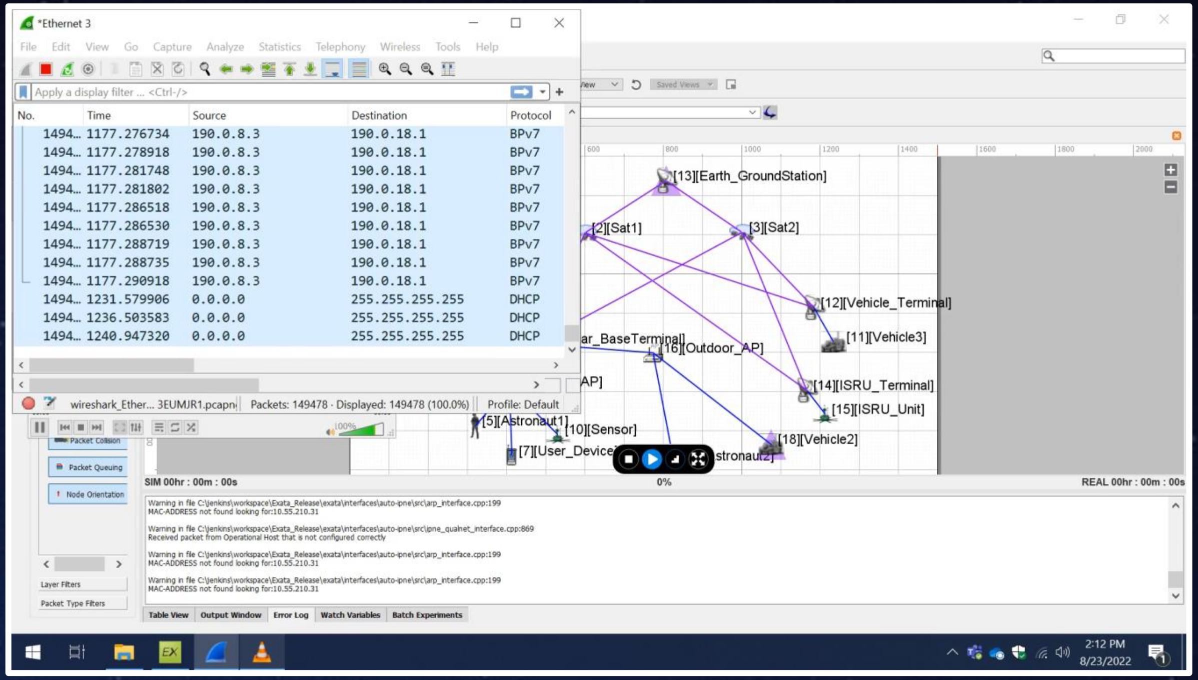


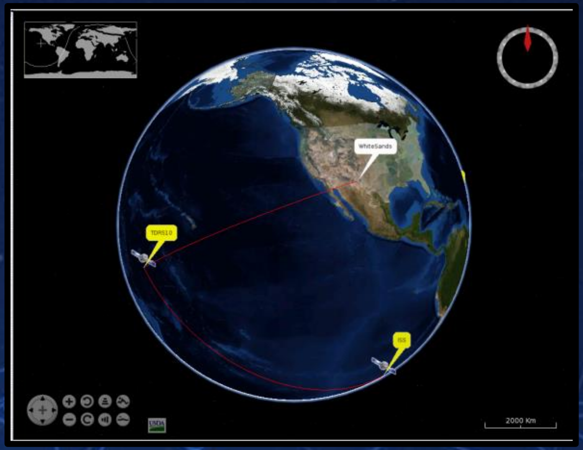


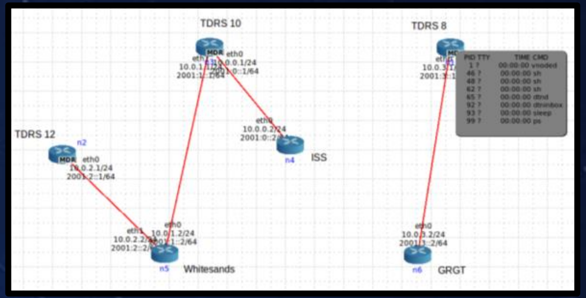


Emulation Platforms

- **Open source network emulators:** CORE/ EMANE uses OS network stack and containers for network level emulation with configurable radio models.
- **Commercial emulators**: EXata is integrated with STK and Wireshark, provides built-in visualization and metrics. Netropy emulator easily connects to LAN devices.
- **Custom testbeds and emulators**: Full system combining commercial components, custom scripts and software, and flight-like hardware.







Recommended Capabilities

Use-case	Capability	Tools
Scenario Design/ ConOps	3D visualization of assets, link state, and mobility	Unity 3D, STK, SOAP, sdt3d , GMAT, EXata, others
Mathematics / Foundational Concepts	Large suite of built-in functions, variety of plots, reporting	Python, MATLAB, Mathematica, others
Physical Layer Modeling	Antenna, radio, propagation, interference modeling, high fidelity orbital analysis	STK, SOAP, EMANE, GMAT
Algorithm/Protocol Proof of Concept	Modeling of link state and node mobility, discrete events, framework for software modules, metrics reporting, simulations faster than real-time	OMNet++, NS3, EXata, ONE, Python, MATLAB, others
Software Development	Emulate real-time delays, link state, protocol stack, storage and buffering, realistic platform, access to debugging information	Docker, CORE, Netropy, AWS EC2, EXata, custom networks
Flight Preparation & Testing	Realistic delays, complete network scenarios, realistic hardware platforms	DEN, SDIL, Netropy, CGT, others
System/Spacecraft Emulation	Full stack emulation, flight-like hardware	CGT, MATRICS, Propsim

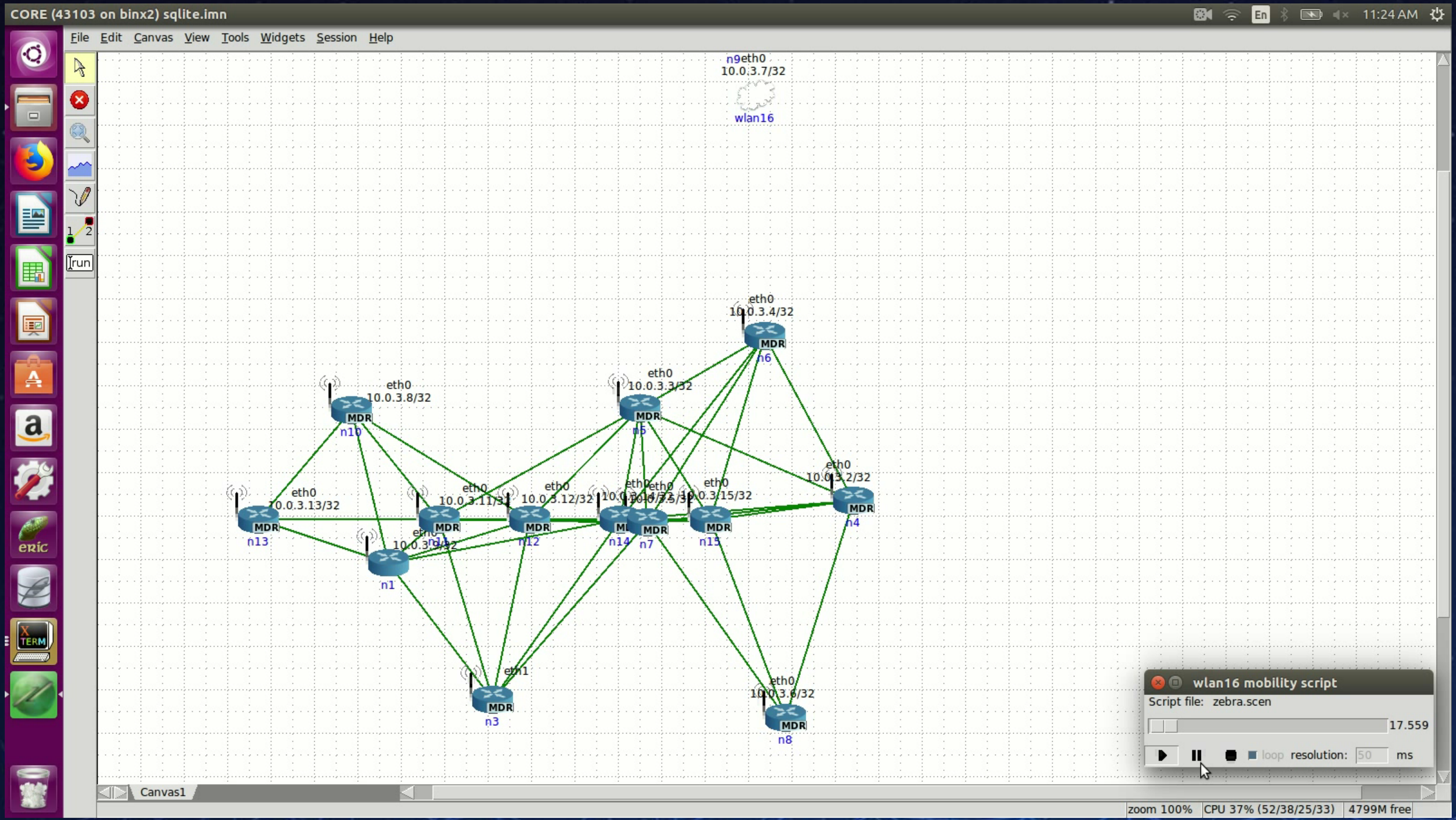
DTN Performance Metrics

Delivery ratio	Percentage of messages successfully delivered
Latency	Time for message delivery is higher in DTNs due to high latency
Message overhead	Additional in-packet data needed to manage bundles
Protocol overhead	Overhead originating from extra control messages
Buffer usage	Memory used for extra storage and forwarding
Routing Efficiency	Measured by path length hops and energy consumed to deliver bundles
Message drop data rates	Rate of message loss during transmission

DTN Performance Metrics

Data delivery time	Time for successful message delivery
Resource utilization	Use of bandwidth, energy and storage
Security	Data integrity and confidentiality
Scalability	Performance as DTN network scale in nodes, time horizon and traffic
Fairness	Evaluation of resource allocation equality among nodes
Contact duration	Duration of contacts is a limiting factor in message forwarding capacity

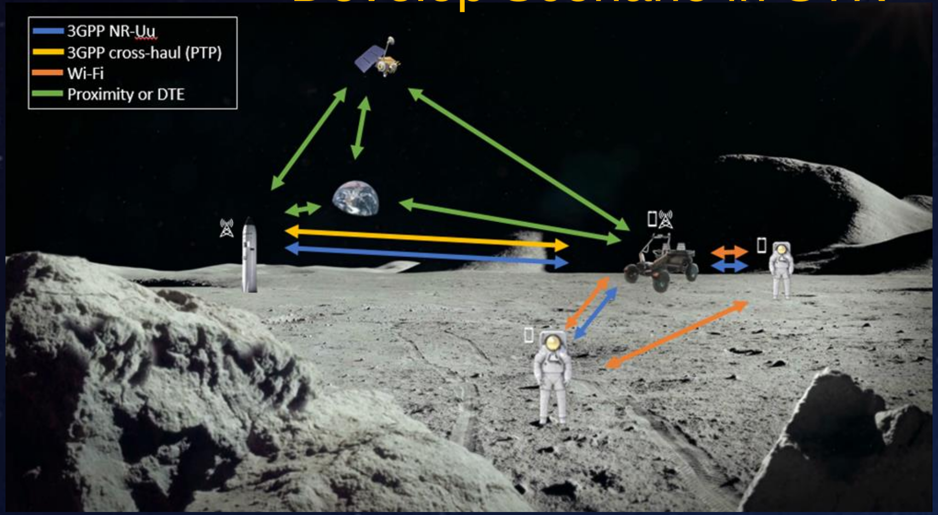
Experiences with Selected Tools
CORE/EMANE

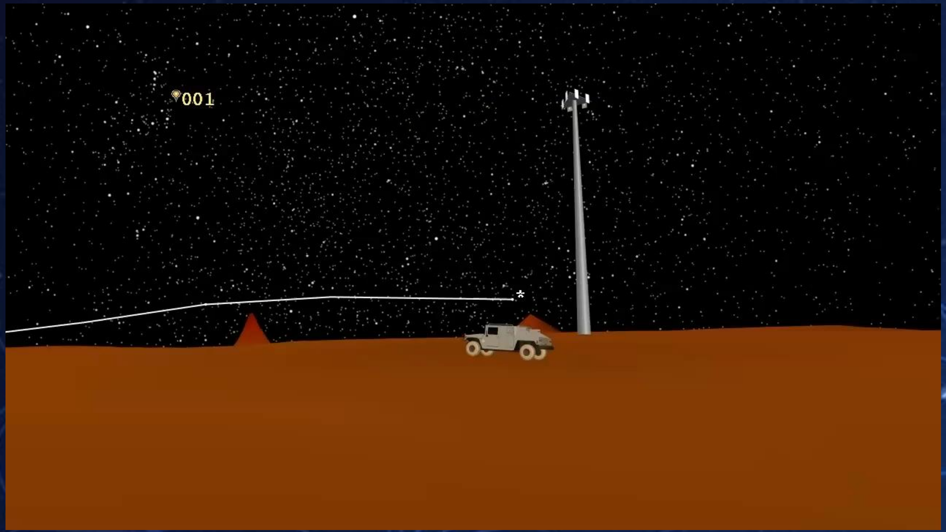


- CORE uses Linux namespaces and containers to emulate nodes
- Supports scripted mobility files
- EMANE interfaces to CORE for more realistic radio models
- CORE/EMANE are open source and free to use

Experiences with Selected Tools
EXata/STK

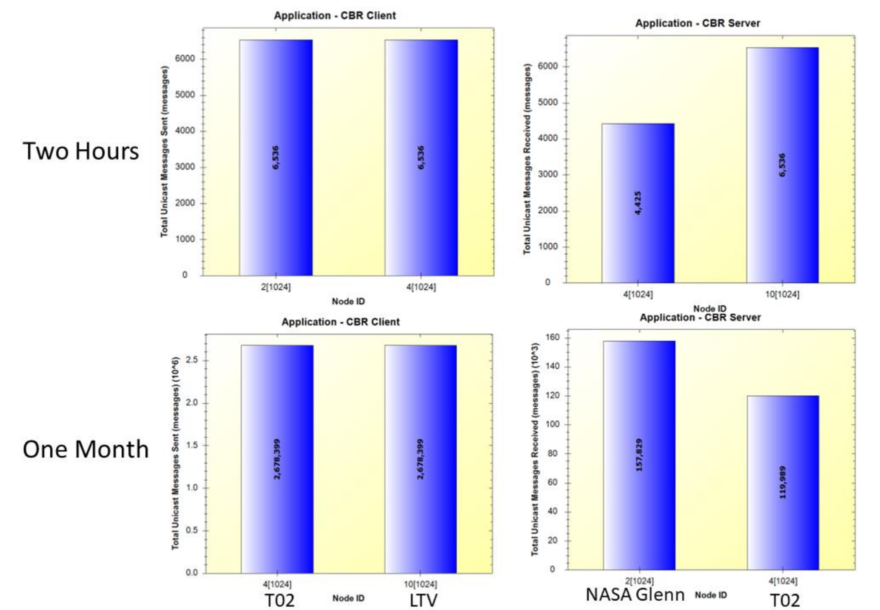
Develop Scenario in STK



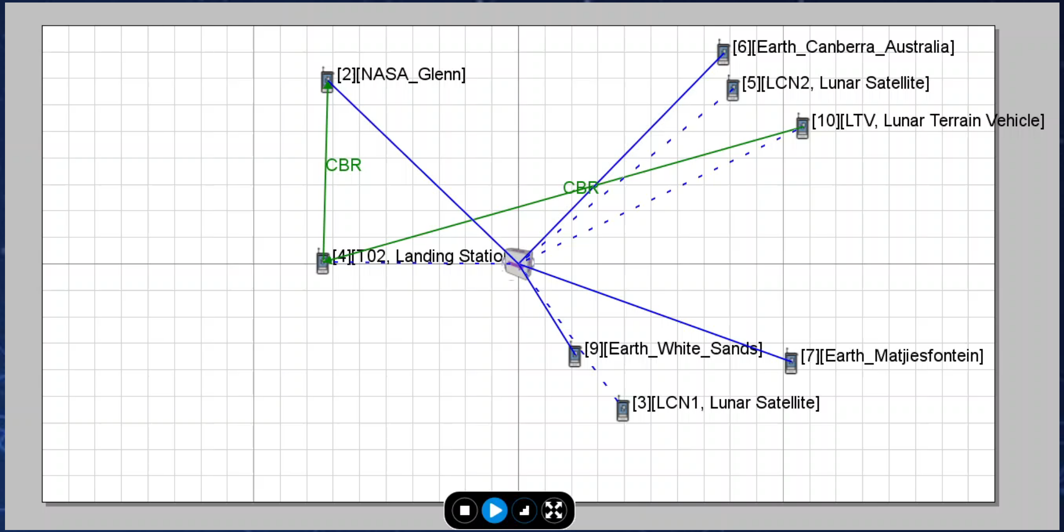


Physical Layer Modeling

Network Layer Metrics

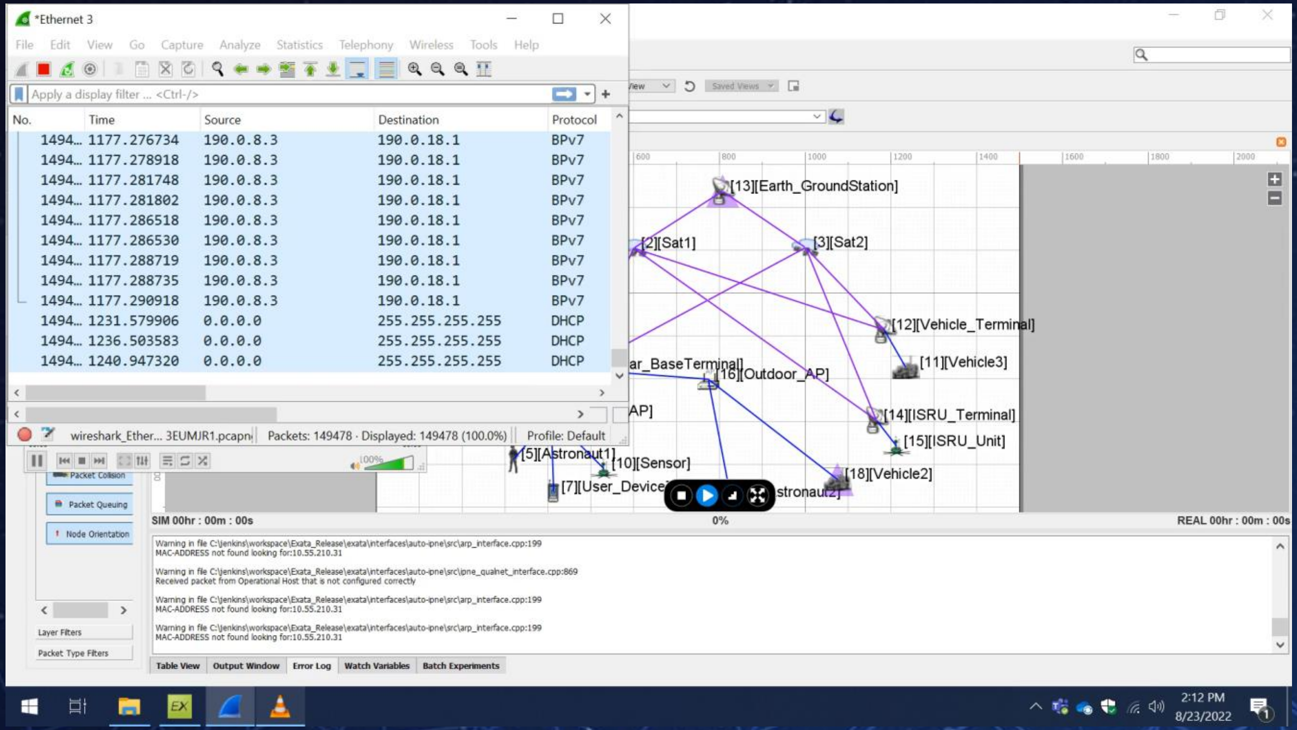


Network Layer Simulation/ Emulation



EXata/STK – Other Features

Hardware-in-the-loop allows real devices to be mapped into emulated scenario



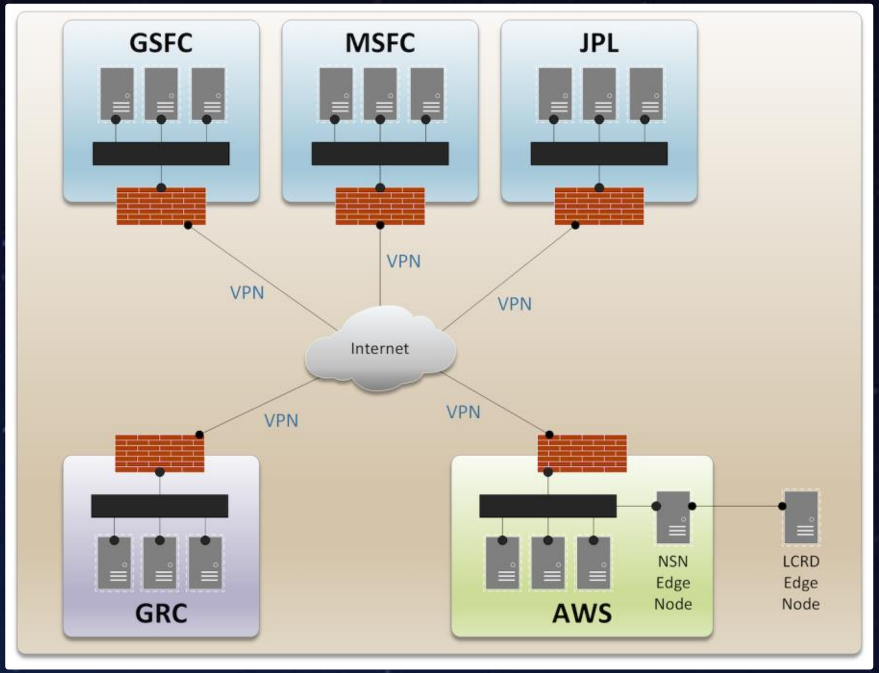
EXata/STK – Other Features

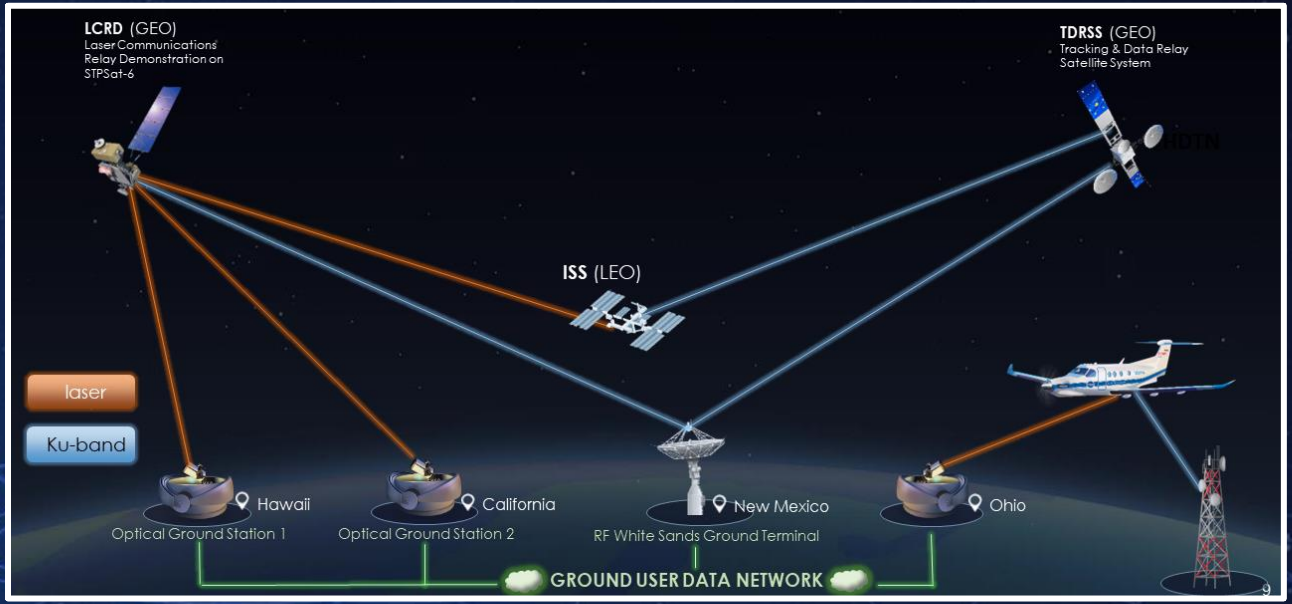
Simulations/Emulations Automatically open in 3D Scenario Viewer

- Future work is to develop 3D lunar scenario in STK and integrate with EXata Scenerio Viewer
- STK portion is done
- EXata emulation portion with hardware in the loop is completed
- Complete mapping of lunar terrain for Scenario Viewer remains

Experiences with Selected Tools
DTN Engineering Network

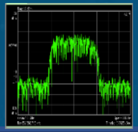
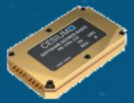
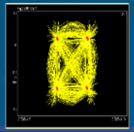
- **Large Scale Interoperability Testing**: The DEN connects multiple NASA centers and partners together via VPN
- **Secure Internal Network**: Allows for connection of internal, secure networks, and connections to commercial services such as AWS
- **Wide Range of Test Support**: Hosts virtual machines, real hardware, ground networks, and planned aero and space communication systems



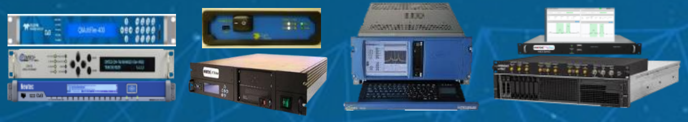


Experiences with Selected Tools
Cognitive Ground Testbed

User Spacecraft Emulation
- Software Defined Radios hosts waveform for each service
- Automation software loads waveforms per event schedule
- Flight computer generates representative data for mission

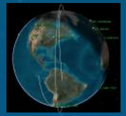




Service Provider Emulation
- Emulate Direct-to-Earth and Space Relay providers
- Provider-unique waveforms and modems
- Government and Commercial services

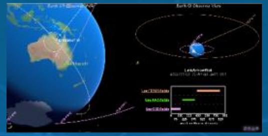
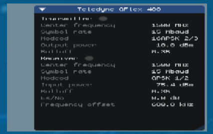


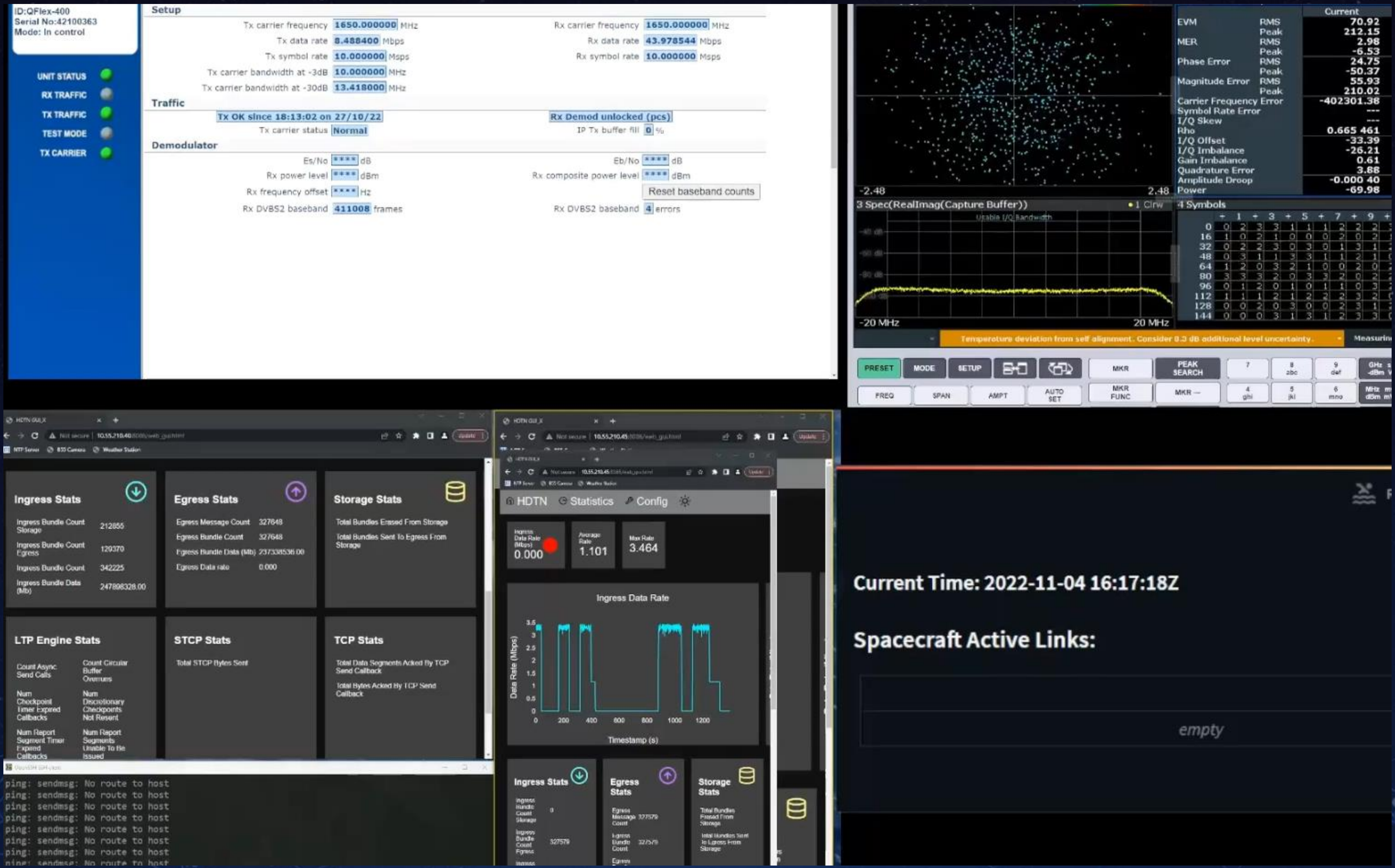
Emulated Spacecraft Communication Testbed for Evaluating Cognitive Networking Technology
https://ieeexplore.ieee.org/document/10219360

Multi-channel RF Emulator
- Spacecraft orbital dynamics modeling, automatically calculated
- Channel impairments: AWGN, delay, Doppler, fading
- Interference Injection, weather impairments, link disruptions




Testbed Controller
- Automates operations of Testbed
- Visualization of link status, scheduled events, data transfer performance
- System monitor / data logging

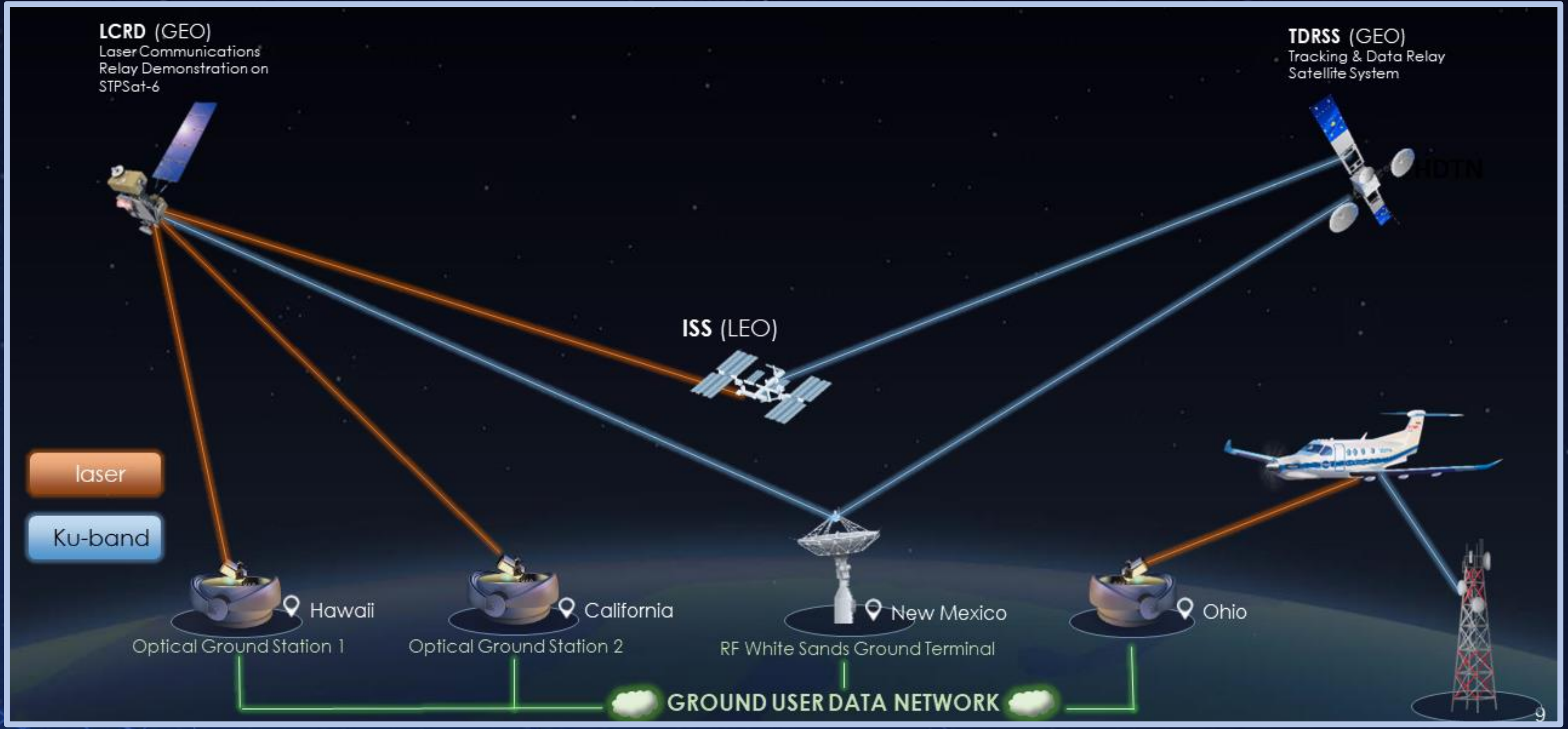




ID:QFlex-400
Serial No:42100363
Mode: In control
UNIT STATUS
RX TRAFFIC
TX TRAFFIC
TEST MODE
TX CARRIER
Setup
Tx carrier frequency 1650.000000 MHz
Rx carrier frequency 1650.000000 MHz
Tx data rate 8.488400 Mbps
Rx data rate 43.978544 Mbps
Tx symbol rate 10.000000 Msps
Rx symbol rate 10.000000 Msps
Tx carrier bandwidth at -3dB 10.000000 MHz
Tx carrier bandwidth at -30dB 13.418000 MHz
Traffic
Tx OK since 18:13:02 on 27/10/22
Rx Demod unlocked (pcs)
Tx carrier status Normal
IP Tx buffer fill 0 %
Demodulator
Es/No **** dB
Eb/No **** dB
Rx power level **** dBm
Rx composite power level **** dBm
Rx frequency offset **** Hz
Reset baseband counts
Rx DVBS2 baseband 411008 frames
Rx DVBS2 baseband 4 errors
Current
EVM RMS 70.92
Peak 212.15
MER RMS 2.98
Peak -6.53
Phase Error RMS 24.75
Peak -50.37
Magnitude Error RMS 55.93
Peak 210.02
Carrier Frequency Error -402301.38
Symbol Rate Error ---
I/Q Skew
Rho 0.665 461
I/Q Offset -33.39
I/Q Imbalance -26.21
Gain Imbalance 0.61
Quadrature Error 3.88
Amplitude Droop -0.000 40
Power -69.98
-2.48
2.48
3 Spec(RealImag(Capture Buffer))
4 Symbols
-20 MHz
20 MHz
Temperature deviation from self alignment. Consider 0.3 dB additional level uncertainty.
PRESET
MODE
SETUP
MKR
PEAK SEARCH
FREQ
SPAN
AMPT
AUTO SET
MKR FUNC
MKR →
Ingress Stats
Ingress Bundle Count Storage 212855
Ingress Bundle Count Egress 129370
Ingress Bundle Count 342225
Ingress Bundle Data (Mb) 247898328.00
Egress Stats
Egress Message Count 327648
Egress Bundle Count 327648
Egress Bundle Data (Mb) 237338536.00
Egress Data rate 0.000
Storage Stats
Total Bundles Erased From Storage
Total Bundles Sent To Egress From Storage
LTP Engine Stats
Count Async Send Calls
Count Circular Buffer Overruns
Num Checkpoint Timer Expired Callbacks
Num Discretionary Checkpoints Not Resent
Num Report Segment Timer Expired Callbacks
Num Report Segments Unable To Be Issued
STCP Stats
Total STCP Bytes Sent
TCP Stats
Total Data Segments Acked By TCP Send Callback
Total Bytes Acked By TCP Send Callback
HDTN
Statistics
Config
0.000
1.101
3.464
Ingress Data Rate
Data Rate (Mbps)
Timestamp (s)
ping: sendmsg: No route to host
ping: sendmsg: No route to host
ping: sendmsg: No route to host
ping: sendmsg: No route to host
ping: sendmsg: No route to host
ping: sendmsg: No route to host
ping: sendmsg: No route to host
Current Time: 2022-11-04 16:17:18Z
Spacecraft Active Links:
empty

Flight Demonstrations

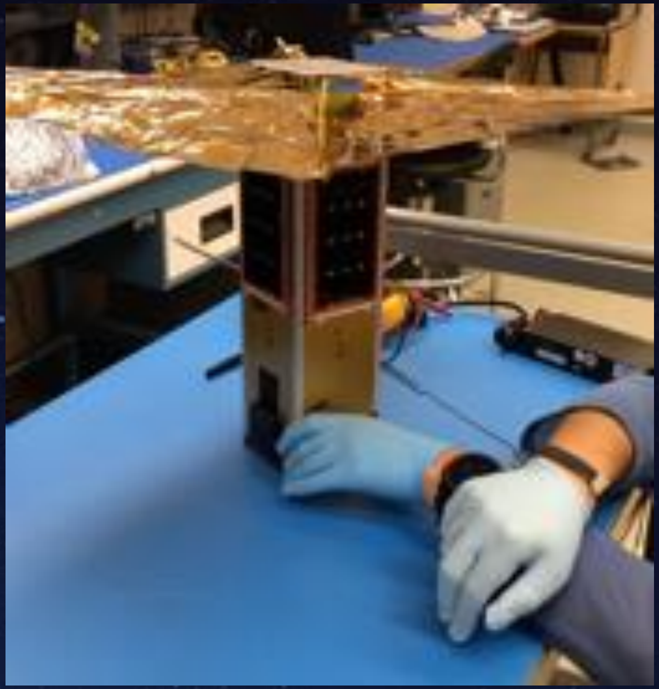
HDTN Experiments on ISS

- HDTN was deployed to the ISS in November 2023
- Flight tests are in progress:
- 1.2 Gbps optical return link
- Bundle Protocol v6 and v7
- BP Security
- Streaming over DTN
- Dynamic contact plan and link updates
- Multi-hop networking



TechEdSat-13

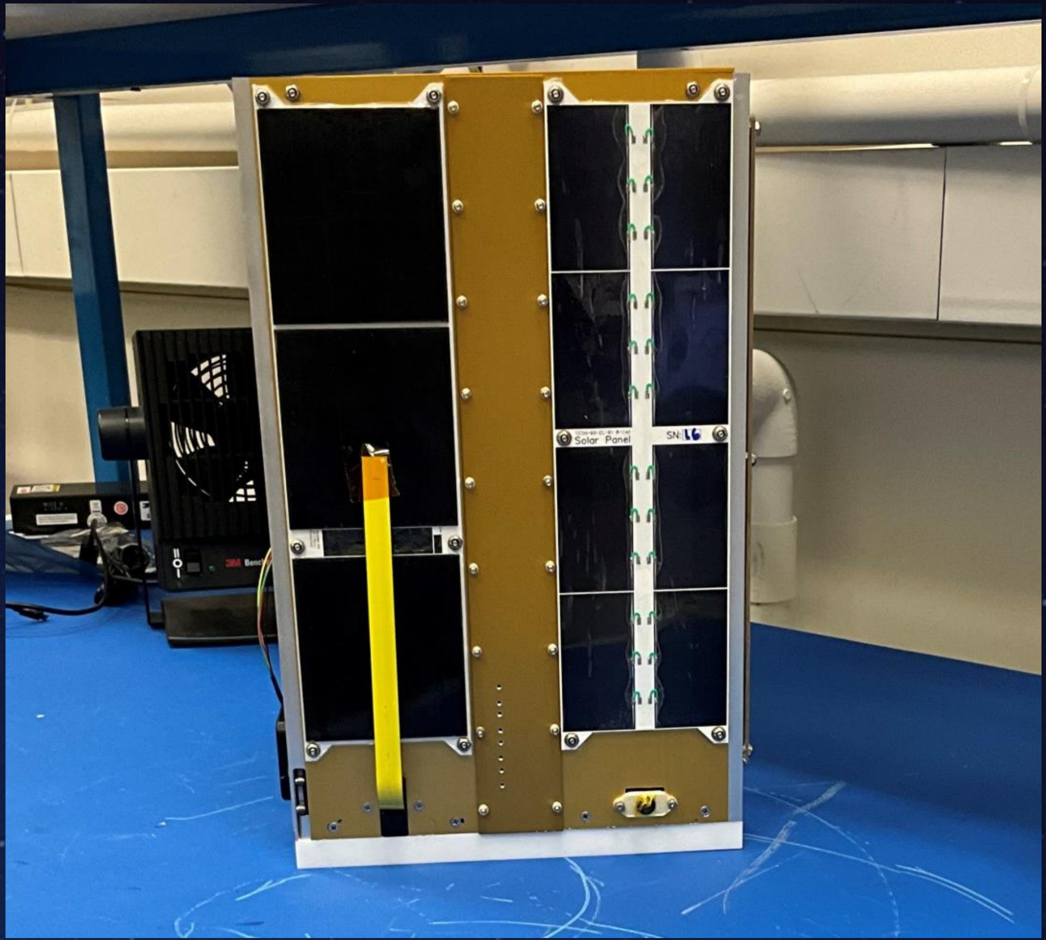
- TES 13 was launched in January 2022
- Avionics stack included experimental Intel Loihi neuromorphic processor
- Demonstrated a Q-learning based cognitive agent for SDN applications
- Loihi based agent was able to route packets to the most optimal path 90% of the time with continuously changing network link latency
- Demodulation of S-band radio via AWS ground station



https://ieeexplore.ieee.org/document/10219299

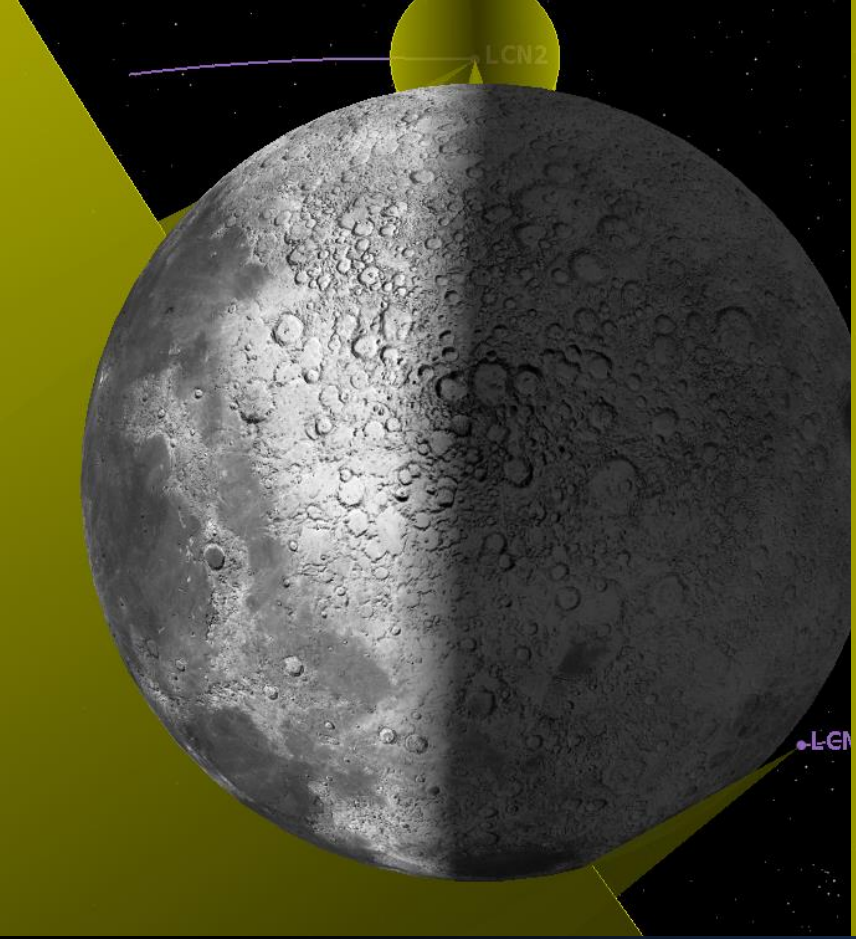
TechEdSat-11

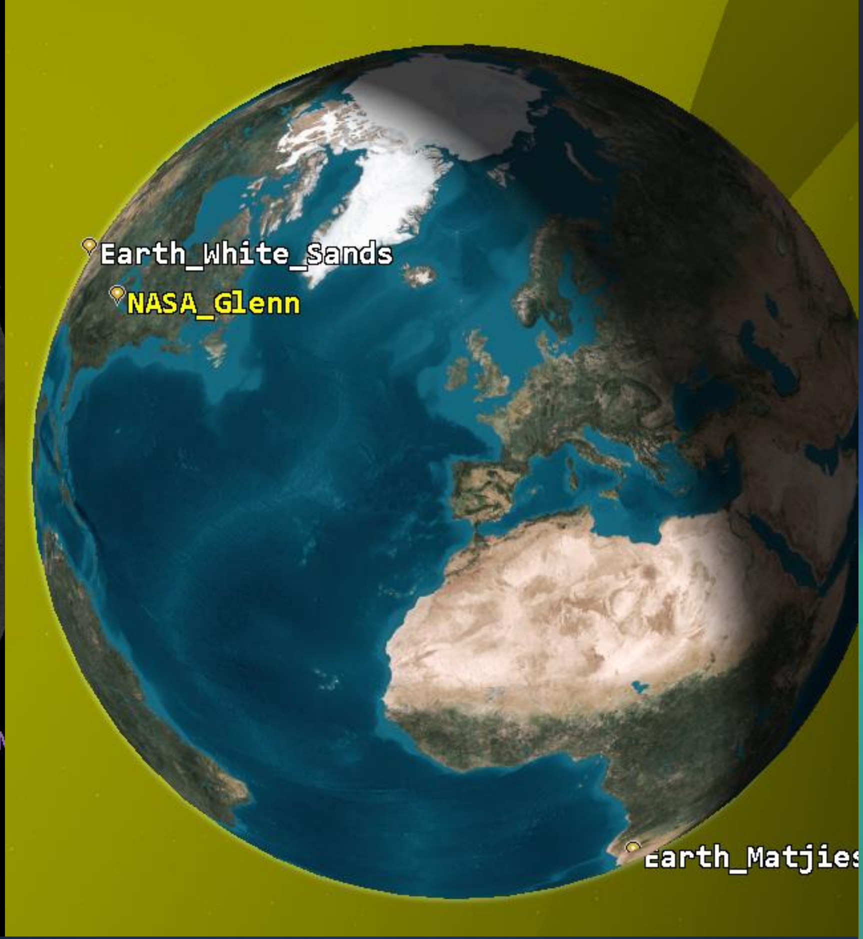
- TES 11 launch is scheduled for June 2024
- CubeSat has been fully tested and integrated
- Experiments feature automatic scheduling of AWS ground station via Iridium short burst modem and user initiated services (UIS)
- HDTN will flow real-time bundles to AWS ground station with forward error correction
- In final test phase, HDTN will use link autonomously scheduled by UIS

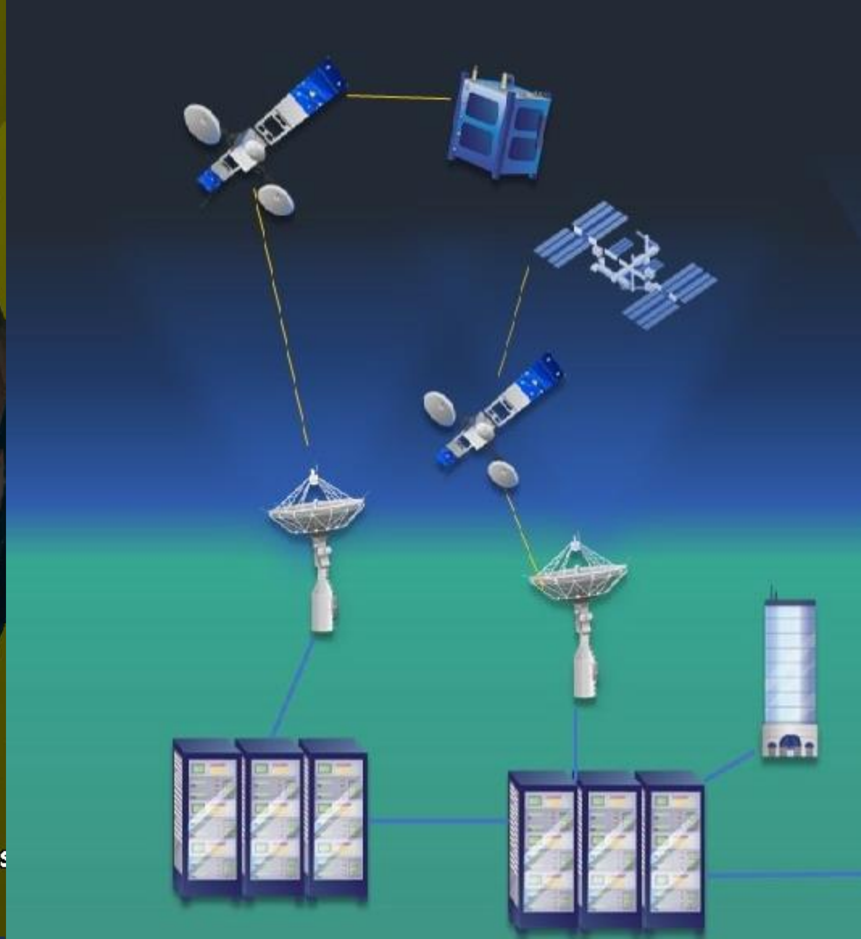


Conclusions

- Cognitive Communications encompasses a multi-layer system including radios, networking, and scheduling
- A wide range of simulation, emulation, and hardware testbeds have been utilized for low to mid TRL development
- Aspects of the system have reached higher levels of maturity including flight demonstrations and preparations for operational deployment
- DTN is a main component of the network layer, providing store and forward capability and other enhancements







Future Work

- Develop and release standard scenarios for LEO, Lunar, and Mars
- Increase DEN awareness and outreach
- Increase interoperability between diverse laboratories and tool chains
- Perform internetworking flight tests
- Integrate 3D visualizations

Contacts and Resources

- GRC DTN: https://www1.grc.nasa.gov/space/scan/acs/tech-studies/dtn/
- HDTN: https://github.com/nasa/HDTN
- HDTN PI – Daniel Raible
- HDTN PLE – Rachel Dudukovich, rachel.m.dudukovich@nasa.gov
- GRC DEN – Robert Kassouf-Short

GRC DTN Team

- IEEE Cognitive Communications for Aerospace Applications Workshop: https://ccaaw.ieeecleveland.org/
- Cog Com PI- Janette Briones
- Cog Com PLE- Joe Downey

GRC Cognitive Com Team

- https://www.nasa.gov/centers-and-facilities/ames/what-are-nasas-technology-educational-satellites/
- TES PI – Marcus Murbach

ARC TechEd Sat Team

Delay Tolerant Networking (DTN)

We get your data home