CLAIRE: Enabling Heterogeneous Communication Network Optimization for Robust and Resilient Operations

INSPiRE – An Approach to Mission Quality Management using Network Slicing for Space Applications

IEEE Cognitive Communications for Aerospace Applications

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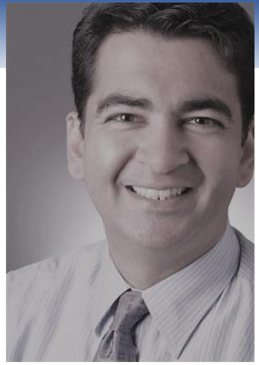

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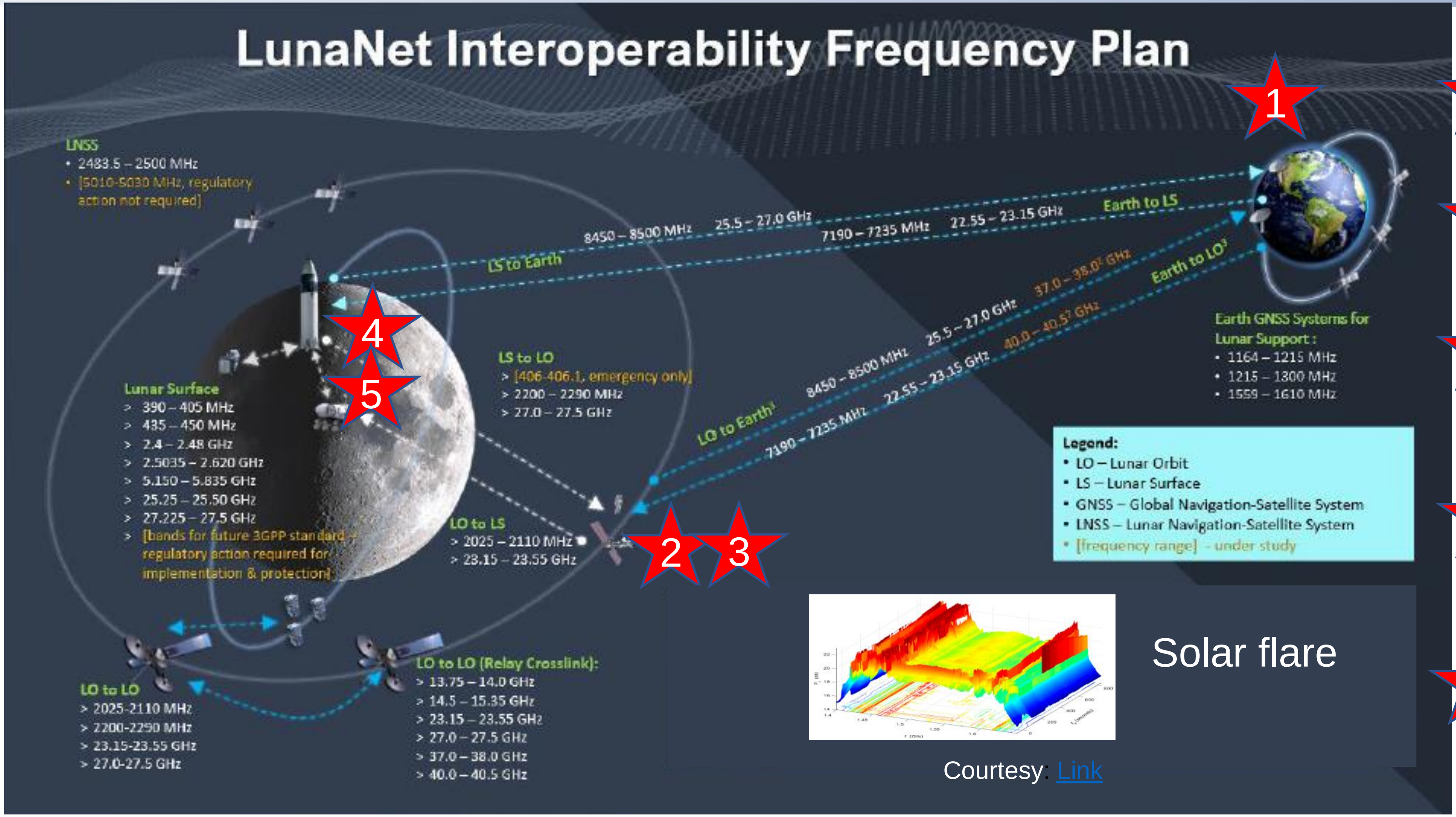
WHAT ARE THE CHALLENGES

HOW IS IT DONE TODAY

Motivation for CLAIRE



Reference: LunaNet Interoperability Specification

Motivations for CLAIRE:

1. **Earth Station**: Distributed interference on the earth impacting the X-Band receive signals,
2. **Orbital Relay**: Solar flare RF interference impacts the entire S-Band requiring data offload to the K-Band,
3. **Orbital Relay / Lunar Surface**: Two S-Band Radios transmit on the same channel from the Moon to an Orbital Relay creating mutual interference,
4. **Lunar Surface**: Unknown electronic device causes interference to the 4G / 5G communications systems on the Lunar Surface,
5. **Non-cooperative sources of interference**: Interference from non-cooperative sources. (e. g. Some other country lunar mission),

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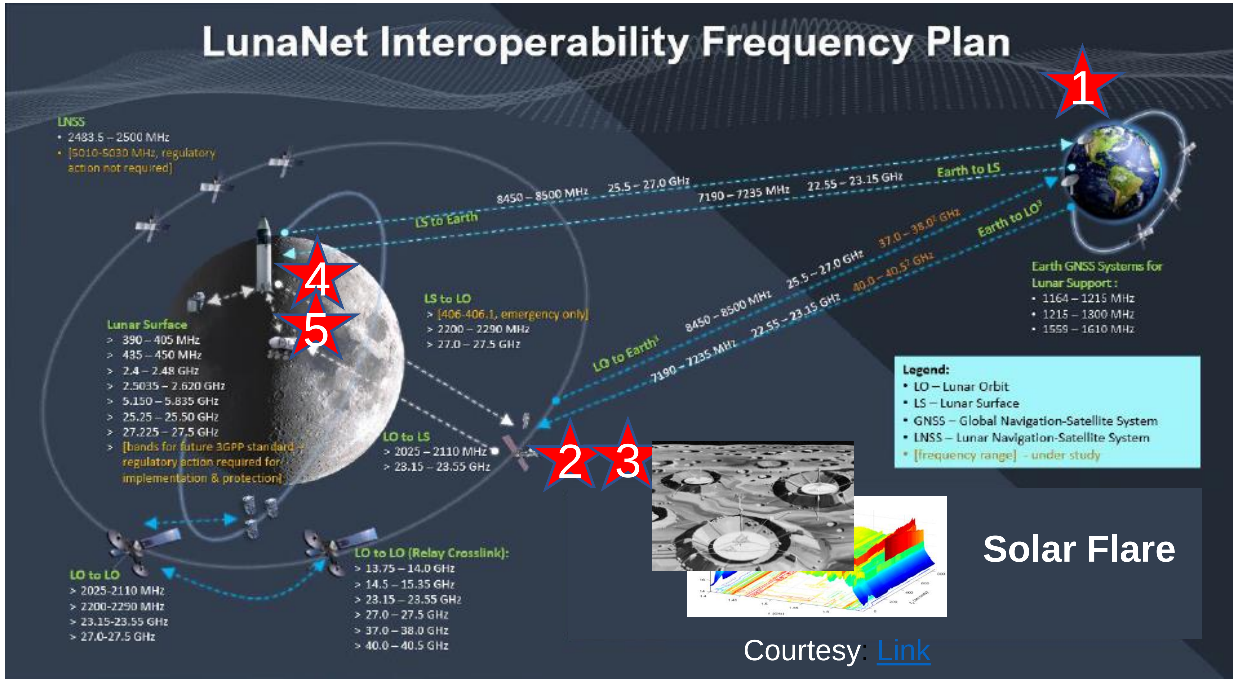
Motivation for INSPiRE

Supernova

Extra Vehicular Activity

Robotics

High-Res Deep Space Images and Videos



Reference: LunaNet Interoperability Specification

- **SCI Slice for 4K Video**: NASA Mission Control (Organization), wants 4K Video stream (Supernova) at an average *throughput of 50 Mbps, with latency of 4 seconds from Moon to the Earth* (Performance).
    - **Command and Control Slice for EVA**: At the same time, Japanese Space Agency has scheduled an Extra Vehicular Activity and needs a guaranteed *throughput of 1 Mbps with 2 second latency*.
    - **Command and Control Slice for Descent and Docking**: Indian Space Agency has scheduled descent and docking of its spacecraft and wants guaranteed *throughput of 1 Mbps and latency of 2 seconds*.
- **Interference on a Channel (Event)**: While all this is happening, NASA finds that the *X-Band Operating Channel for the Lunar Proximity Link is experiencing interference*.
- **Solar Flare (Event)**: Another event, *Solar Flares take out the entire S-Band communications* for the Lunar Proximity Links requiring

Supporting myriads of applications from different organizations with different requirements over a dynamic network is a difficult problem to solve. Network Function Virtualization using Network Slicing can help.

Current NASA Network Optimization Matrix is Too Large

Application Traffic From — **A**

Different Missions & Organizations — **B**

with different QoS and Routing rules — **C**

Dynamically Changing RF

Dynamically Changing Connection Options

Multi-objective optimization in a dynamically changing (link quality, RF environment, different missions, contact graphs and topology) is a challenging problem.

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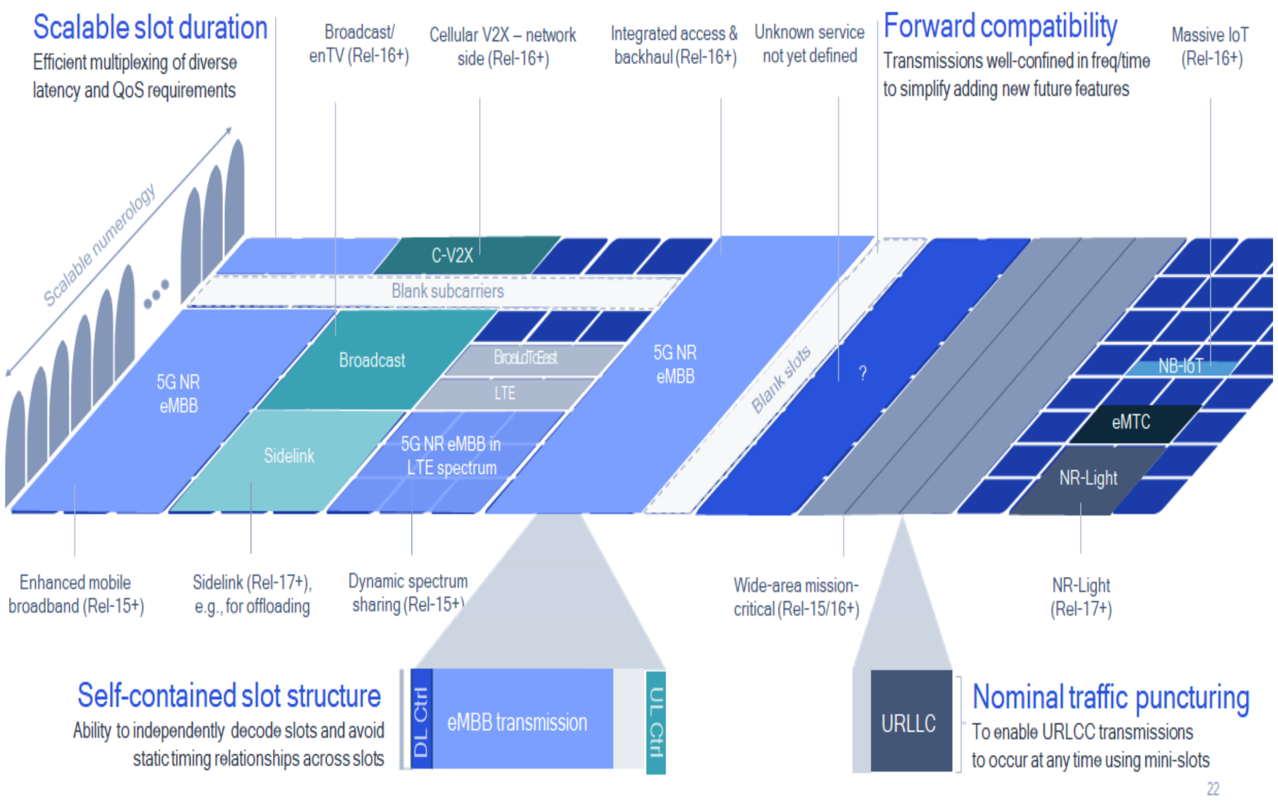
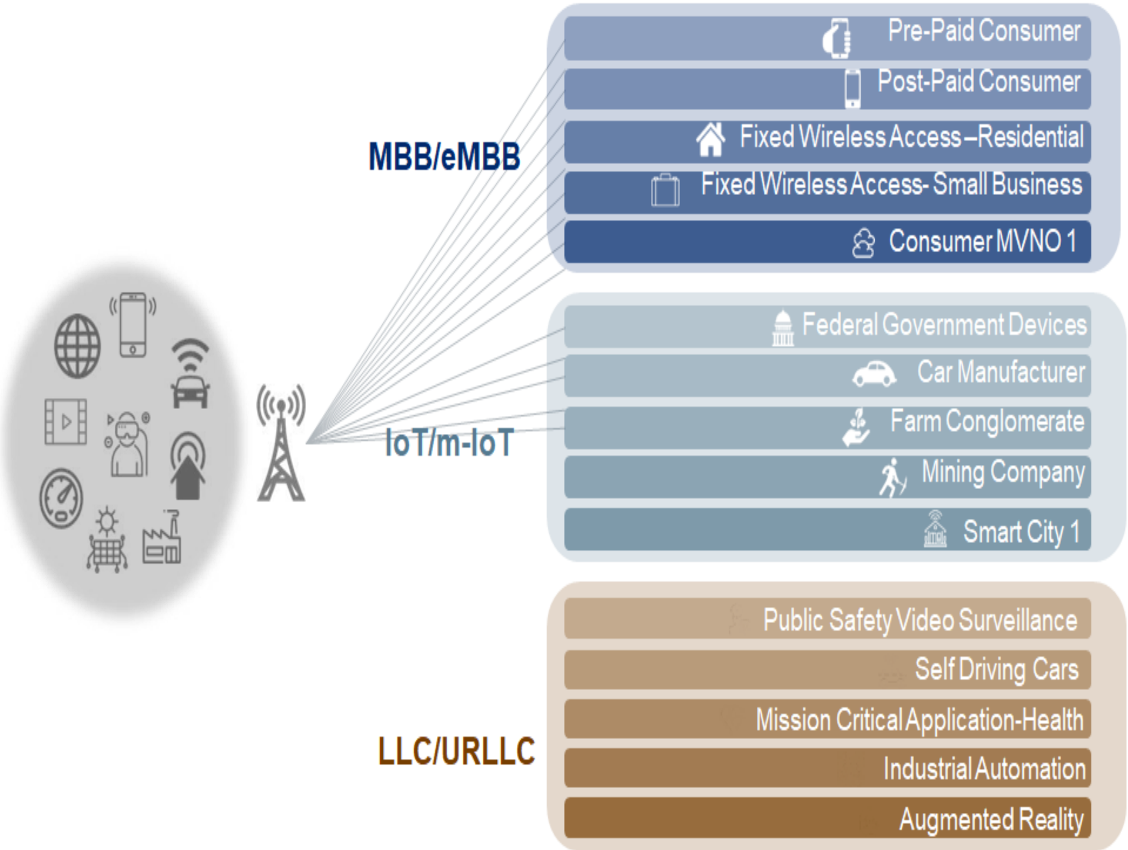
Network Slicing – Potential to Leverage this Paradigm for NASA's Applications





The ***Network Slicing*** paradigm within the 3gpp Rel. 17 (5g) spec defines three categories. These three categories (eMBB, URLLC and mMTC) may not be enough to meet the needs of Deep Space Networks

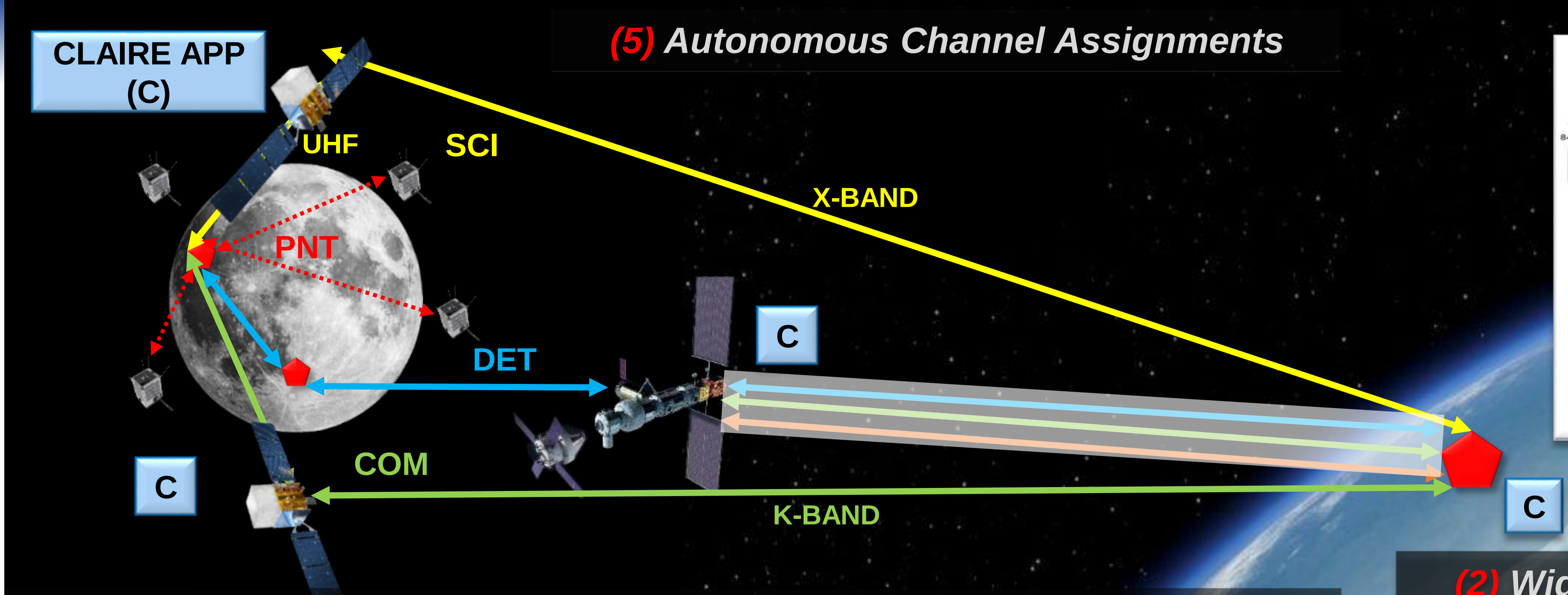
WHAT ARE WE DOING

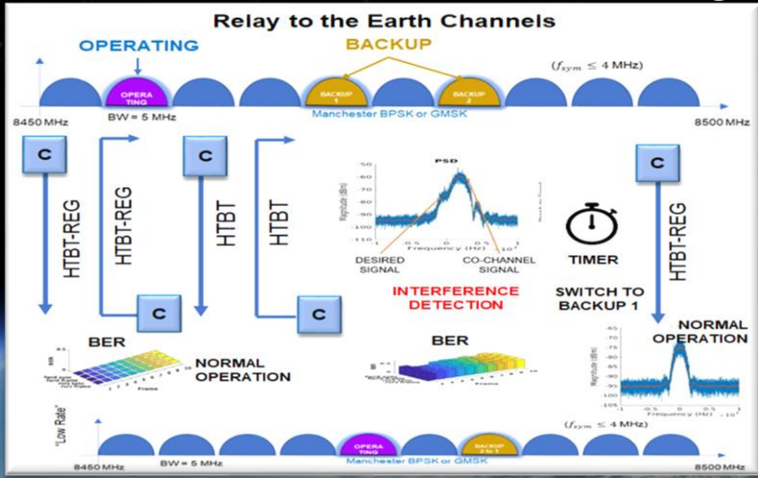
CLAIRE AND INSPiRE INNOVATIONS

CLAIRE Innovations and Value Adds

(3) Dynamic Spectrum Access
(4) Spectrum / Buffer Aware Packet Forwarding

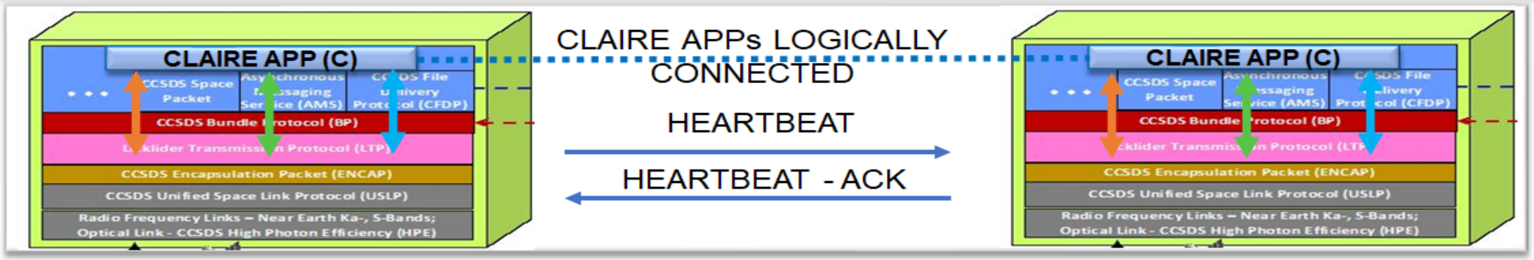
(5) Autonomous Channel Assignments

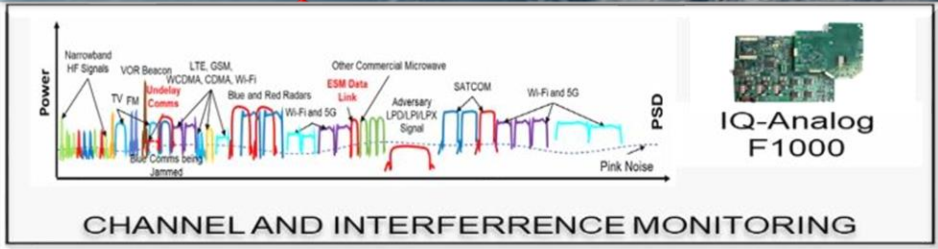




(1) CLAIRE APP enabled Cognitive Control Plane

(2) Wide-Band Sensing and Interference Monitoring using Direct Digital Transceiver





CLAIRE provides a framework for spectrum and network optimization to increase the mission science data return and to improve resource efficiencies for NASA' s communication (Comms) networks

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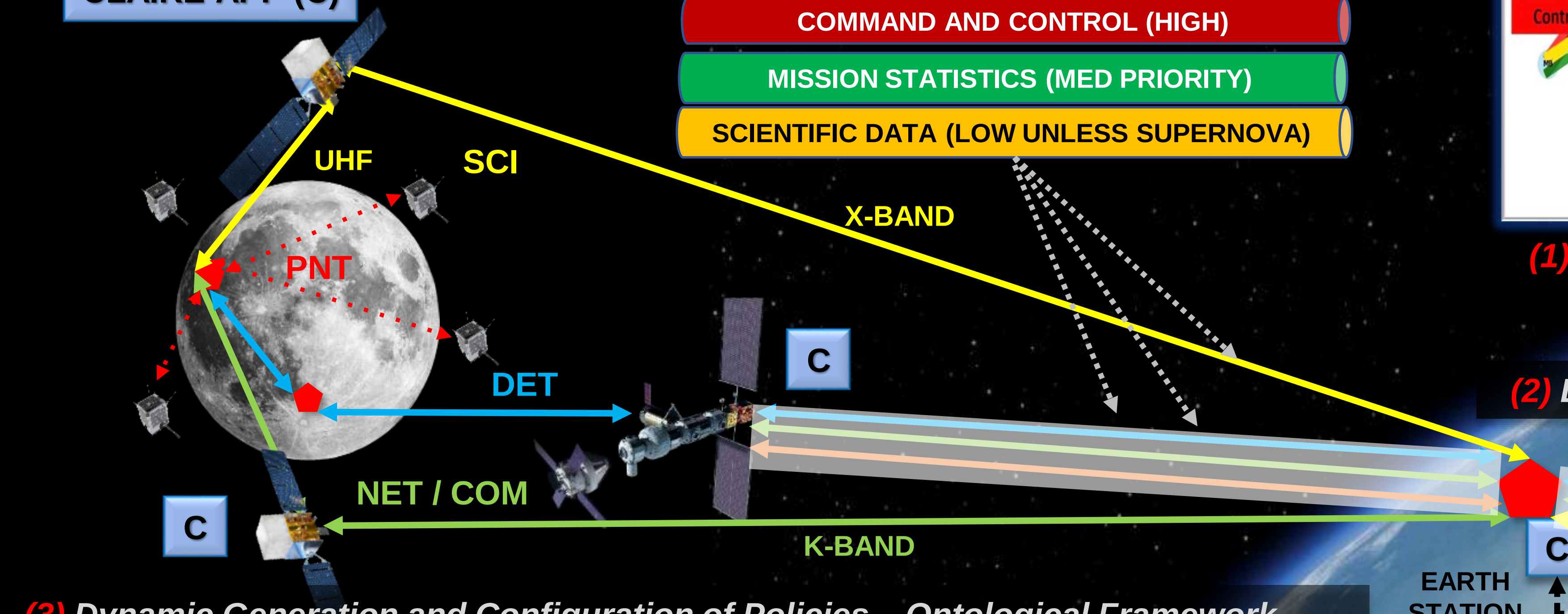
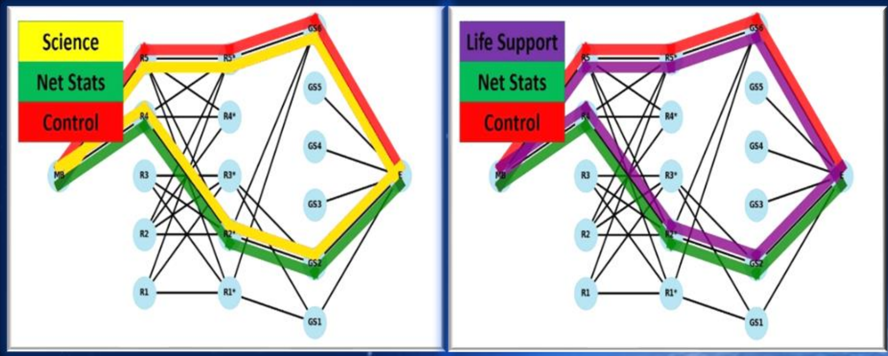
INSPiRE Innovations

CLAIRE APP (C)

Network Slices

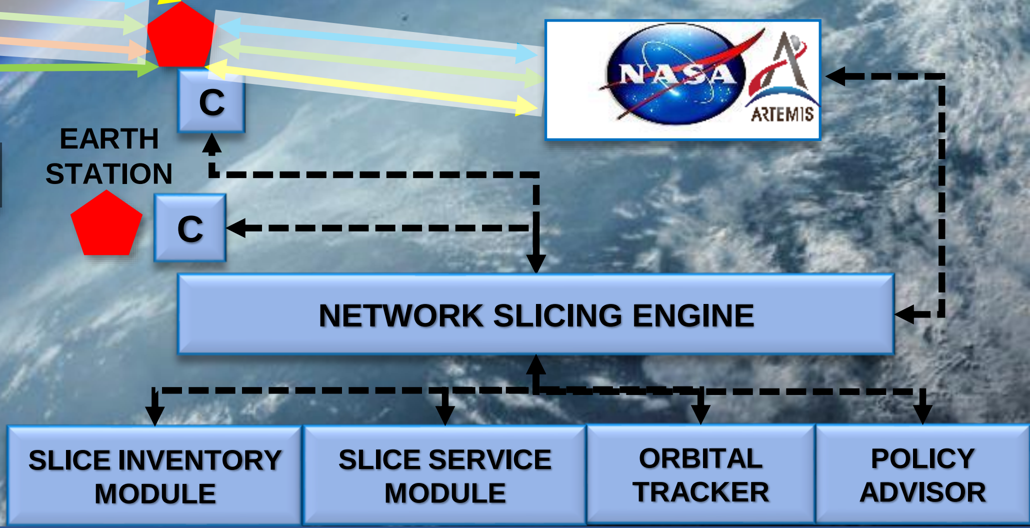
- HUMAN LIFE SUPPORT (HIGHEST PRIORITY)
- COMMAND AND CONTROL (HIGH)
- MISSION STATISTICS (MED PRIORITY)
- SCIENTIFIC DATA (LOW UNLESS SUPERNOVA)





(1) INSPiRE provides Predictive Policy-based Network Slicing Orchestration

(2) Deep Learning Driven Network Optimization



(3) Dynamic Generation and Configuration of Policies – Ontological Framework

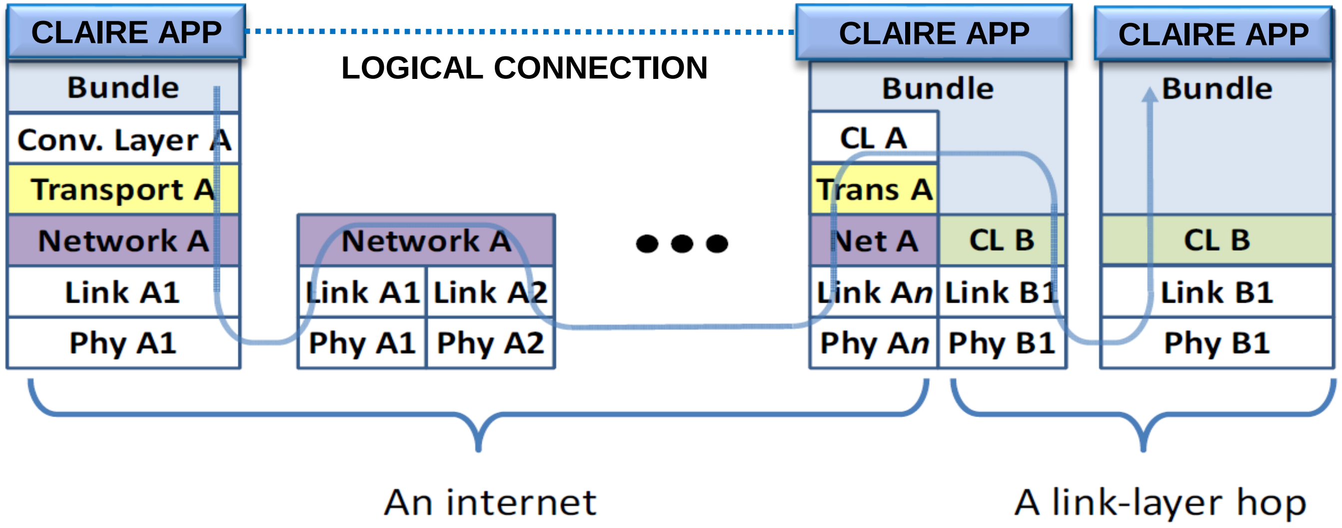
Mission Req	Org.	QCI	Application	Source IP Address	Destination IP Address	Time Start	Time Stop	Priority	Packet Delay	Packet Loss	Throughput	Description
1	NASA	65	Mission Critical Voice	100.xx,...	200.yy	T1	T2	0.7	75 ms	10^{-2}	[MIN, MAX]	GBR
2	JSA	7	Voice / Video / Tele-robotics	201.aa	300.bb	T2	T3	7	100 ms	10^{-3}	[MIN, MAX]	Non-GBR
3	NASA	75	V2X Messages	IP-5	IP-6	T4	T5	2.5	50 ms	10^{-2}	[MIN, MAX]	GBR
4	ESA	3	Tele-robotics	IP-7	IP-8	T6	T7	3	50 ms	10^{-3}	[MIN, MAX]	GBR
5	NASA	2	Crew Conversational Video	IP-9	IP-10	T8	T9	4	150 ms	10^{-3}	[MIN, MAX]	GBR
6	NASA	85	Electrical Distribution	IP-11	IP-12	T10	T11	2.1	5	10^{-5}	[MIN, MAX]	Non-GBR
7	NASA	69	Mission Critical Delay Sensitive Signalling	IP-13	IP-14	T12	T13	0.5	60 ms	10^{-8}	[MIN, MAX]	Non-GBR

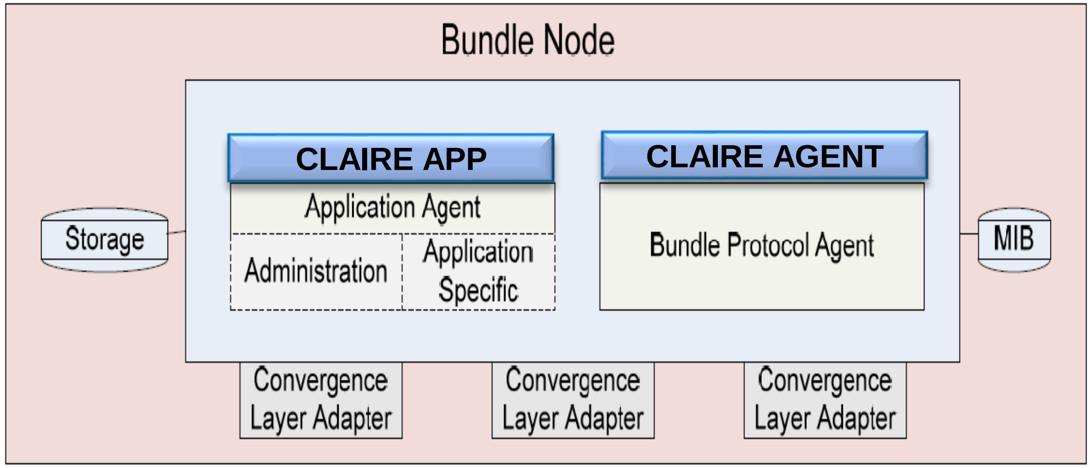
NASA INSPiRE and CLAIRE bring 5G Architectures to Deep Space.

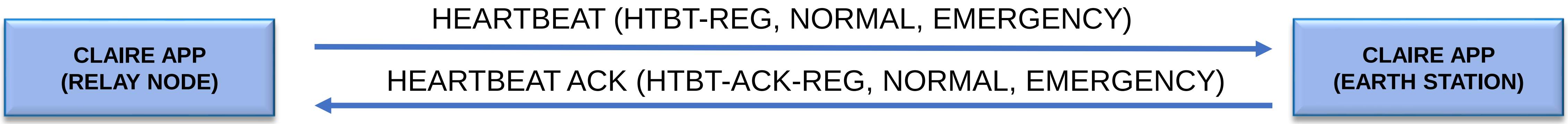
WHAT IS NEW IN OUR APPROACH

CLAIRE AND INSPiRE SYSTEM ARCHITECTURE

Cognitive Control Plane - *less than 1% network overhead*

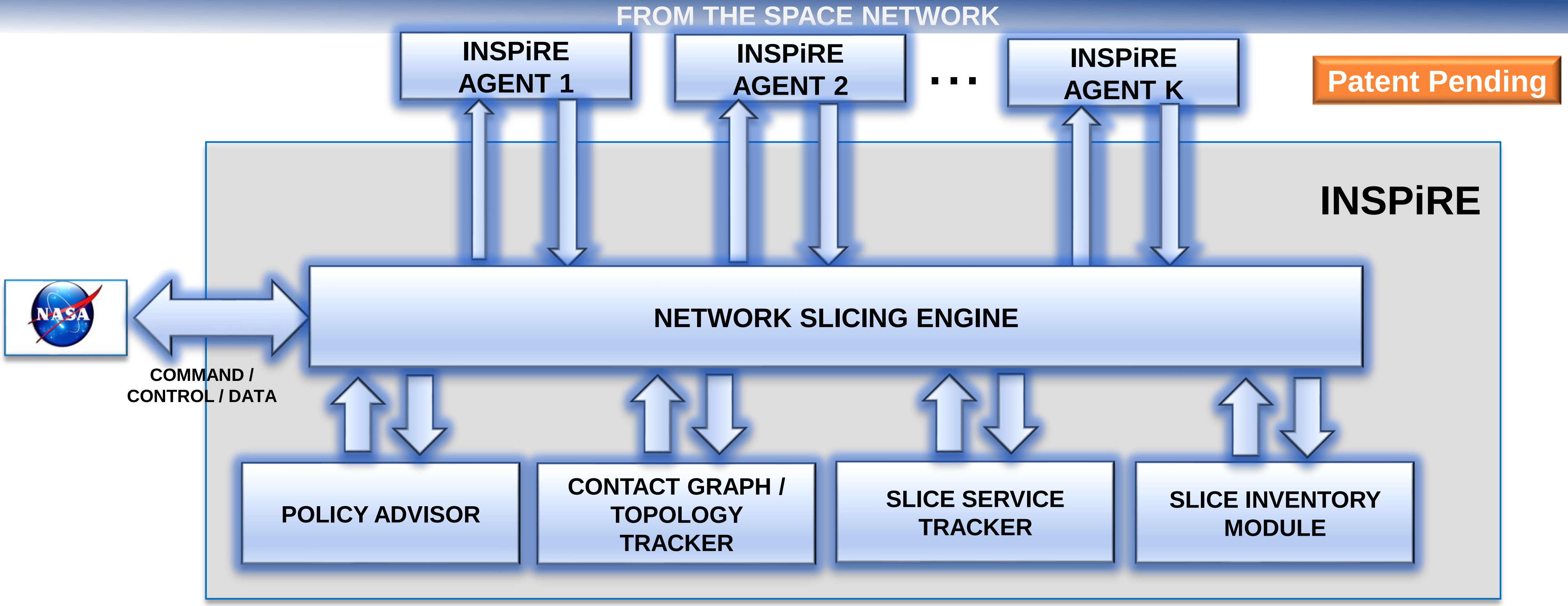






Designed to minimize overhead while maintaining all the information necessary for node pairs to coordinate. Total size for a 2 link configuration is ~ 255 Bytes + 75 Bytes ACK (2.5kbps).

INSPiRE Extends the 5g Network Slice Concept to a Heterogeneous Multi-Vendor Network



INSPiRE introduces a few new components: 1. Slice Service Tracker, 2. Slice Inventory 3. Policy Advisor and 4. Contact Graph / Topology Tracker, and 5. Network Slicing Engine that performs optimization and orchestrates Network Slices

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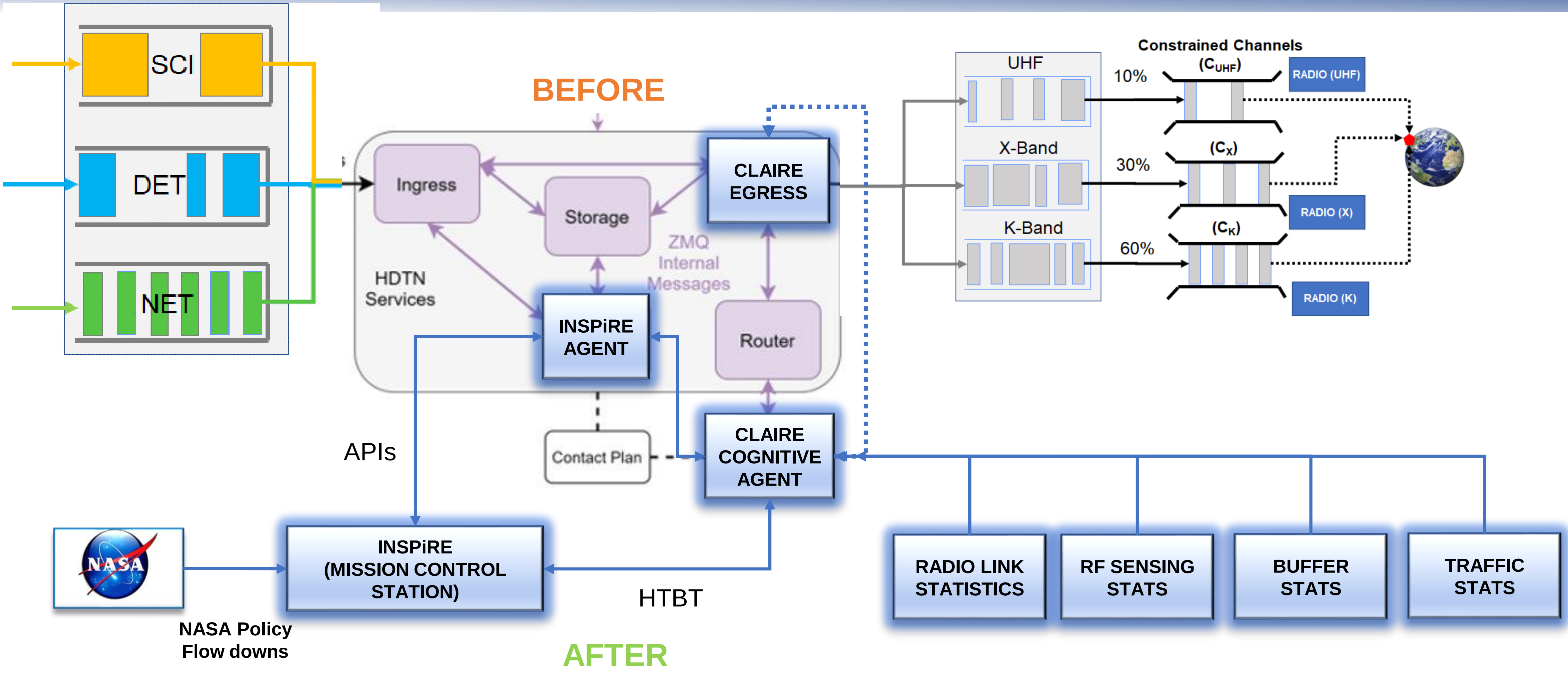
How do CLAIRE and INSPiRE provide System Enhancements to the LunaNet? How do they fit into the LunaNet architecture? Are any changes required?



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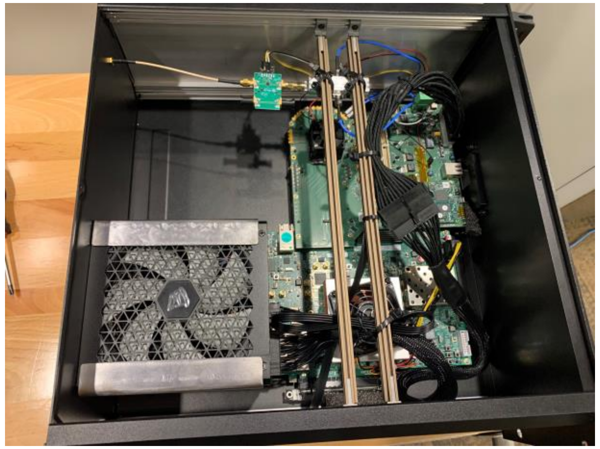
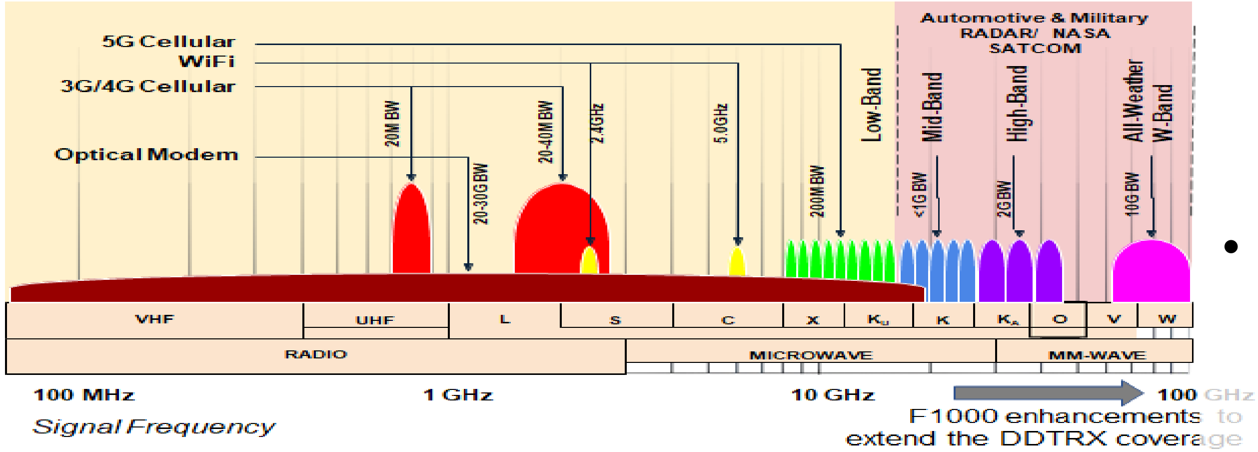
Wideband RF Sensing Module
Ka Enhanced F1000 Design + NVIDIA CLARA

IQ-ANALOG DDTRX

WIDEBAND RF SENSOR





- **IQ-Analog Wideband RF Sensing** is based on their ASIC, the **F1000.**
- **Direct Digital Transceiver (DDTRX)**: The **F1000 is a 4x4 transceiver** system that consists of **four 48Gsps ADCs and four 48Gsps DACs** that handles the RF front end interface to the F1000s DSP and data transport. The wide-band, high sample rate capability allows us to sense a much larger bandwidth (**3 GHz IBW**) than is commercially available today without the need for external components
- **Ka-Band enhancements**: For NASA CLAIRE Project, we extended the observable bandwidth to **Ka Band (50GHz)**, using an Auxiliary Frontend.

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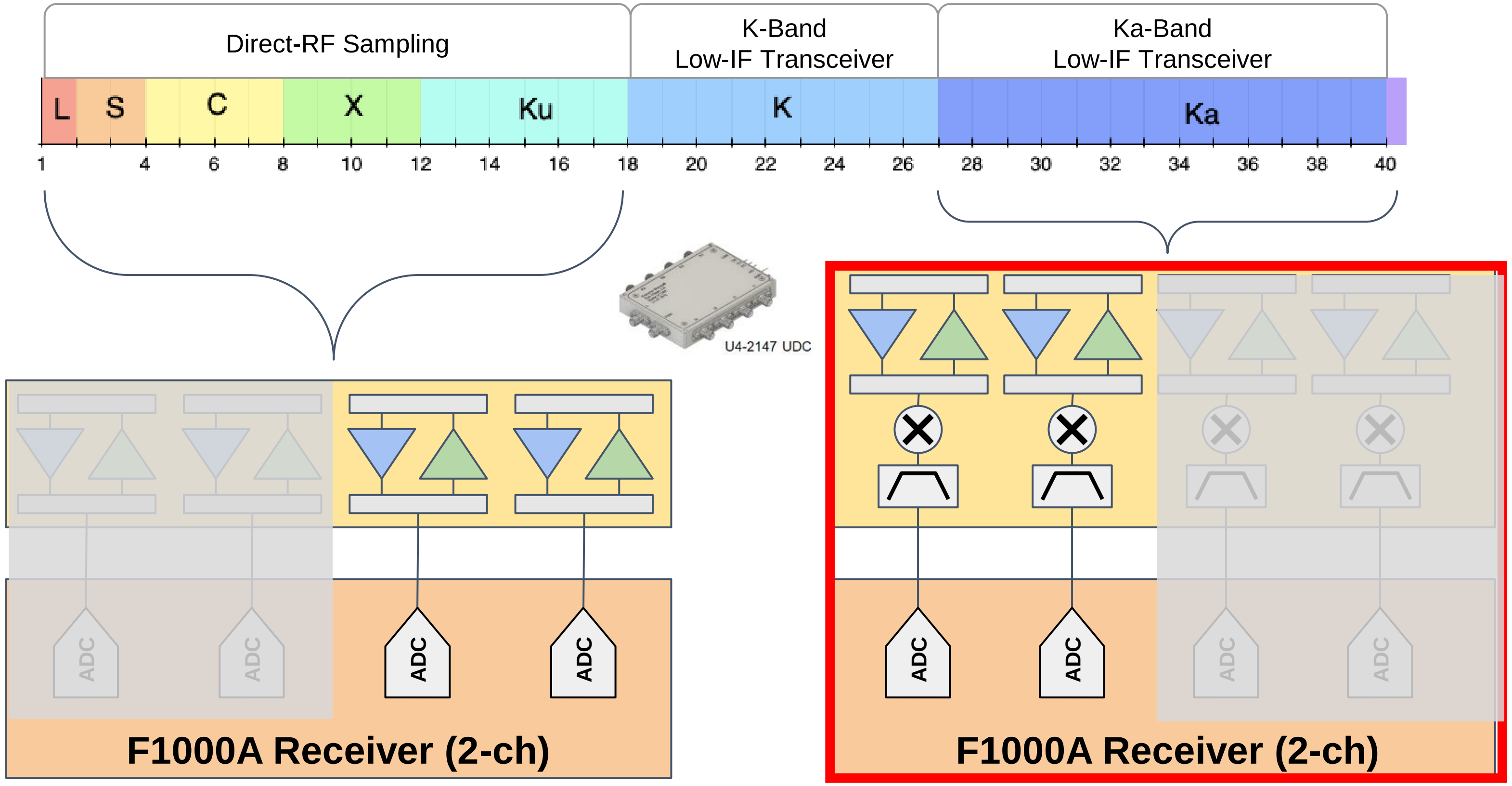
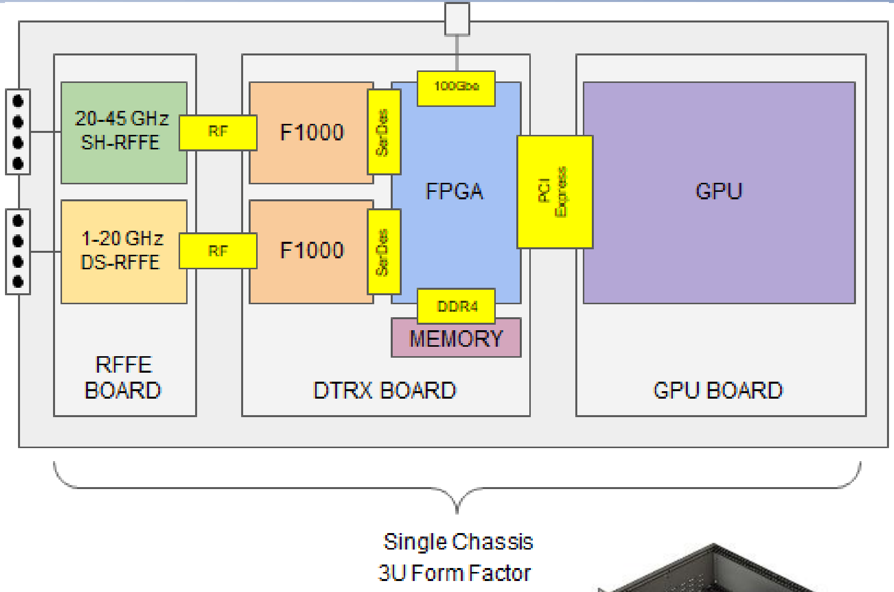
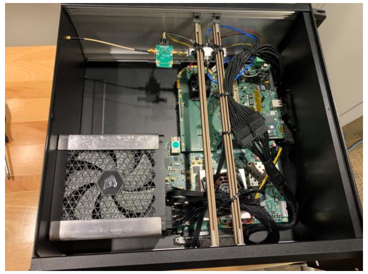
Wideband RF Sensor using IQ-Analog F1000 Chipset





3-D Rendering of the Chassis with IQA F1000 and NVIDIA CLARA



The CLAIRE WBS uses four channels of a single IQA F1000 chip with COTS front-end which allows complete RF coverage. Simultaneous RF sensing of 4 Bands / Channels with NVIDIA GPGPU enabled parallelization

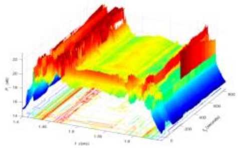
New Way to Organize the Service Oriented Architecture: Mission / Applications / Organization / Performance Priorities

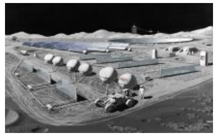
ORGANIZATION

MISSION / APPLICATION

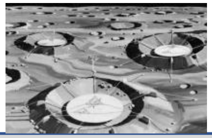

EVA – Human Life Support


Robotics


Interference and Weather Patterns (Solar Flares)


Moon Base Network


High-Res Deep Space Images and Videos


Radio Telescope

PERFORMANCE METRIC

- Throughput
- Latency
- Jitter
- Resilience

Quality of Experience = ***f*** (all of the above)

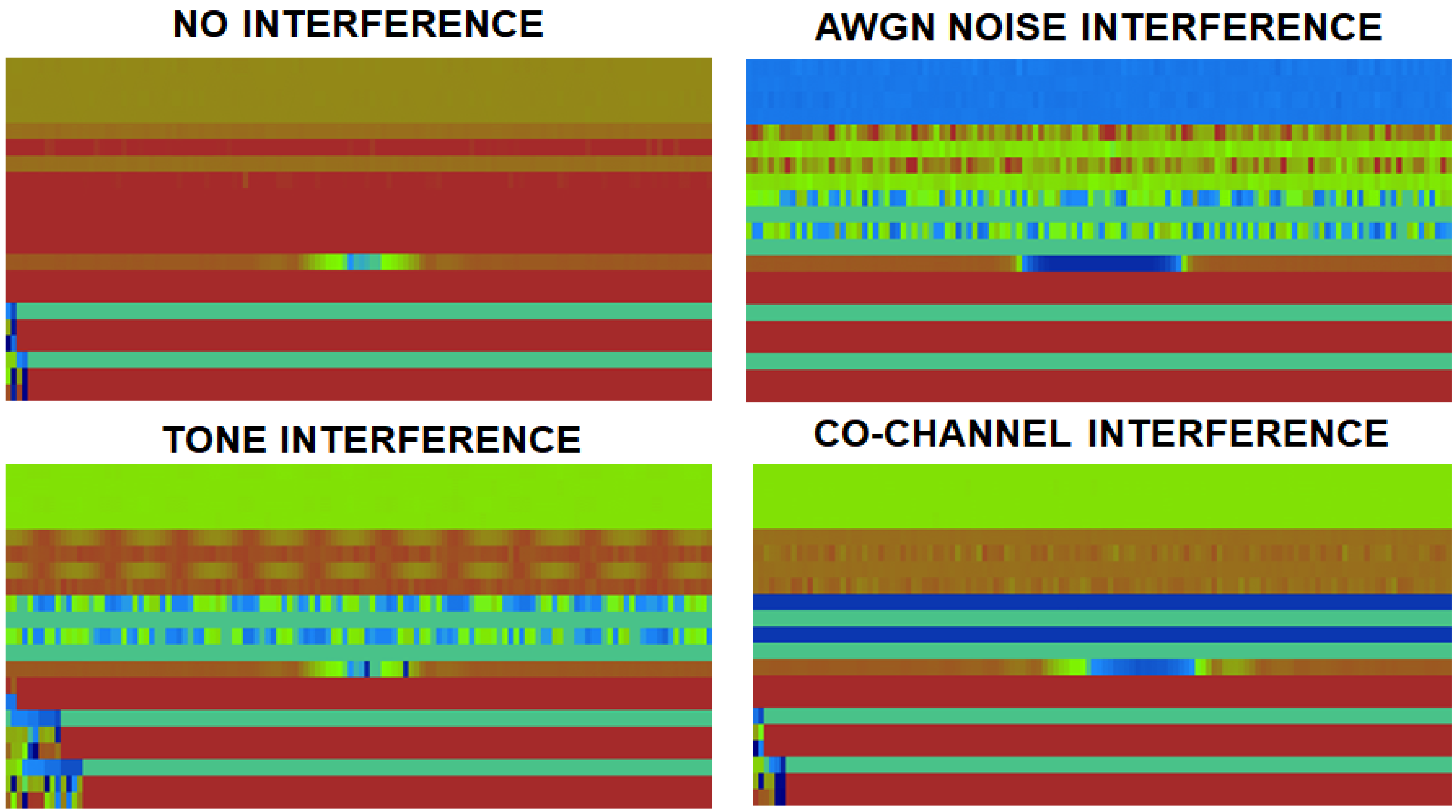
INSPiRE develops an ***Architecture for a Flexible Framework*** that allows Organization / Mission / Applications / Performance Priorities and Attributes to change Dynamically.

CLAIRE WIDE-BAND RF SENSING USING DIRECT DIGITAL TRANSCEIVER

Wideband RF Sensing - Algorithms

Wideband RF Sensing - Algorithms

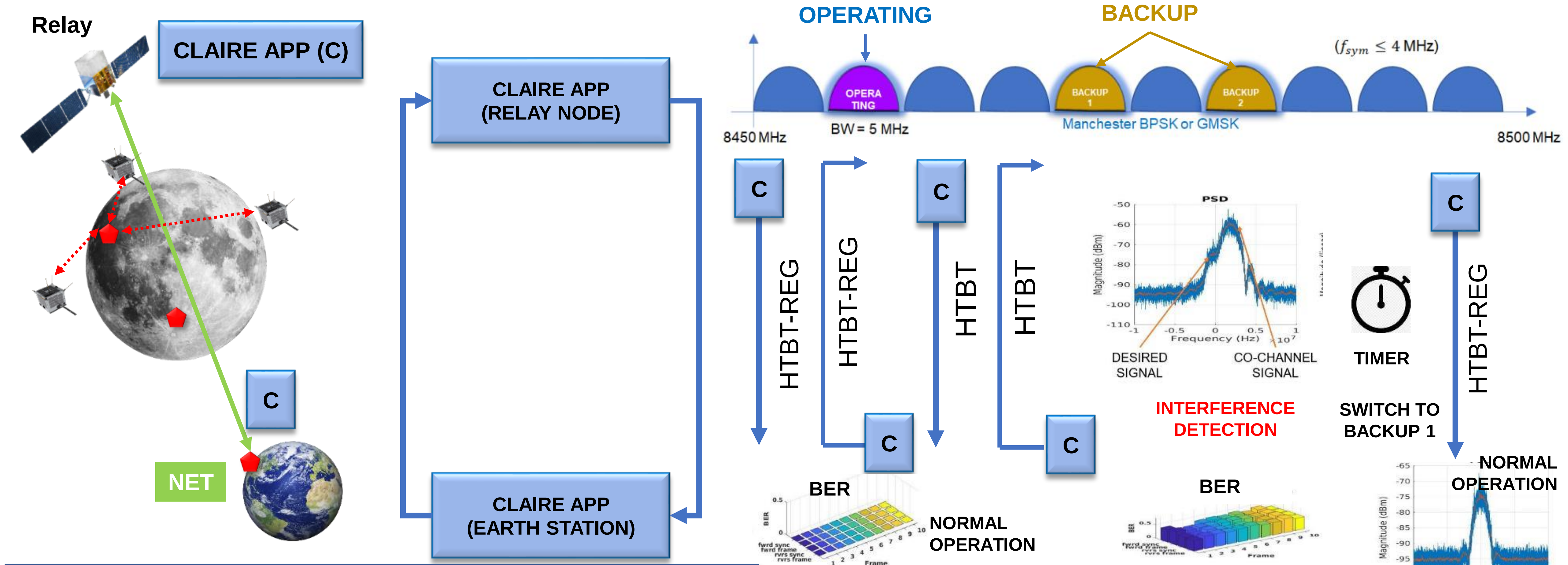
FEATURE MATRICES



- AiRANACULUS uses a Multi-Modal Approach for Interference Detection and Characterization,
- Our approach combines Statistical Signal Processing features such as Cycle Frequencies and Power Spectral Density (PSD) with Radio Statistics to ***Detect and Characterize 16+ Types of Interferers with Greater than 95% Accuracy.***

CLAIRE ENABLED DYNAMIC SPECTRUM ACCESS ORCHESTRATION

CLAIRE – Dynamic Spectrum Access Orchestration in a nutshell
(Example using Lunar Proximity Links)



CLAIRE performs interference mitigation using Dynamic Spectrum Access in the same band or load balancing across bands

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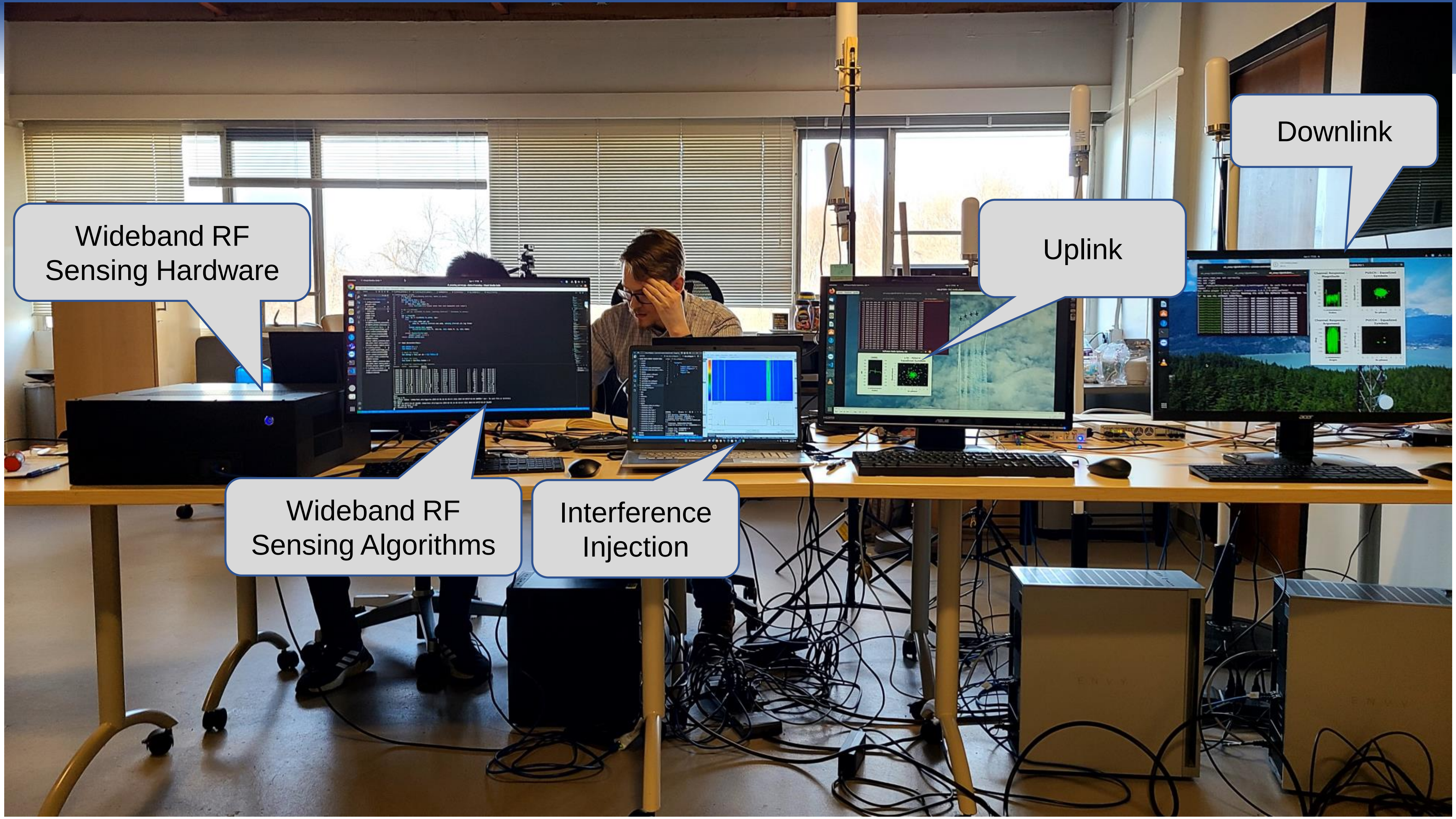
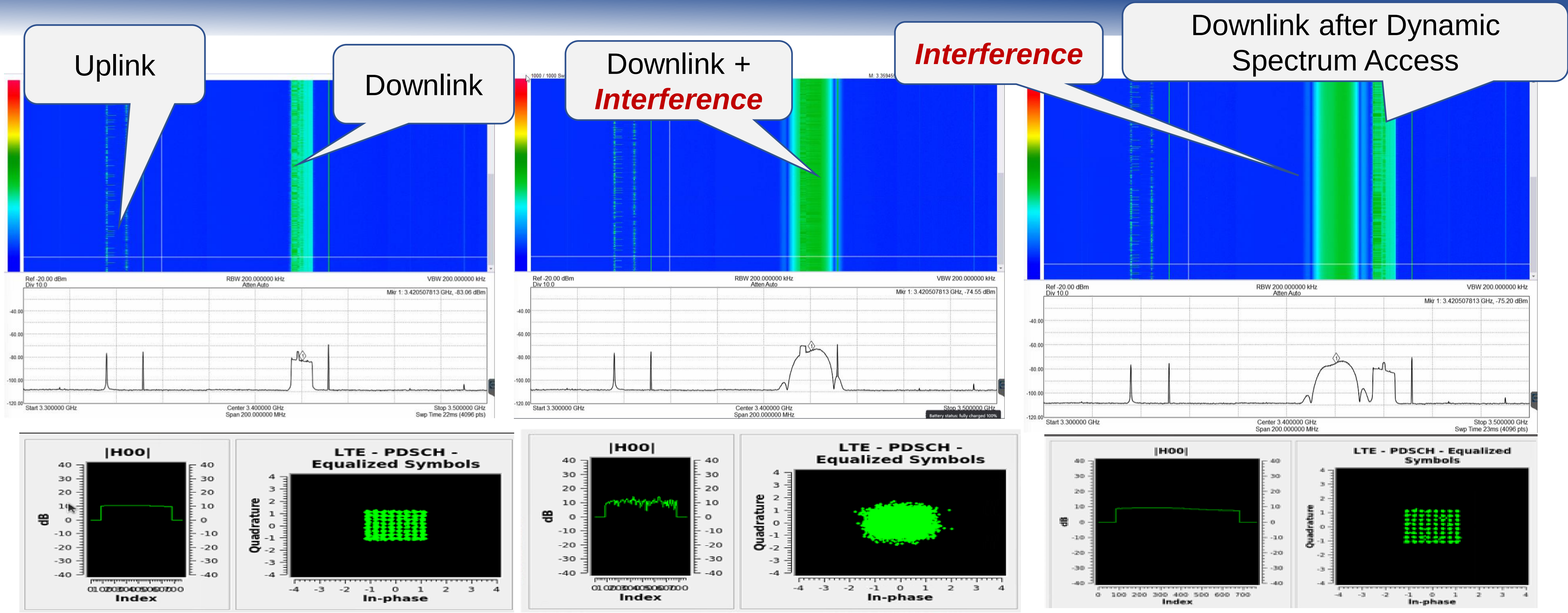
Test Setup at the AiRANACULUS Facility



CLAIRE enabling Interference Mitigation for srsRAN 4G using DSA



srsRAN Normal Operation

srsRAN + Interference

srsRAN after DSA

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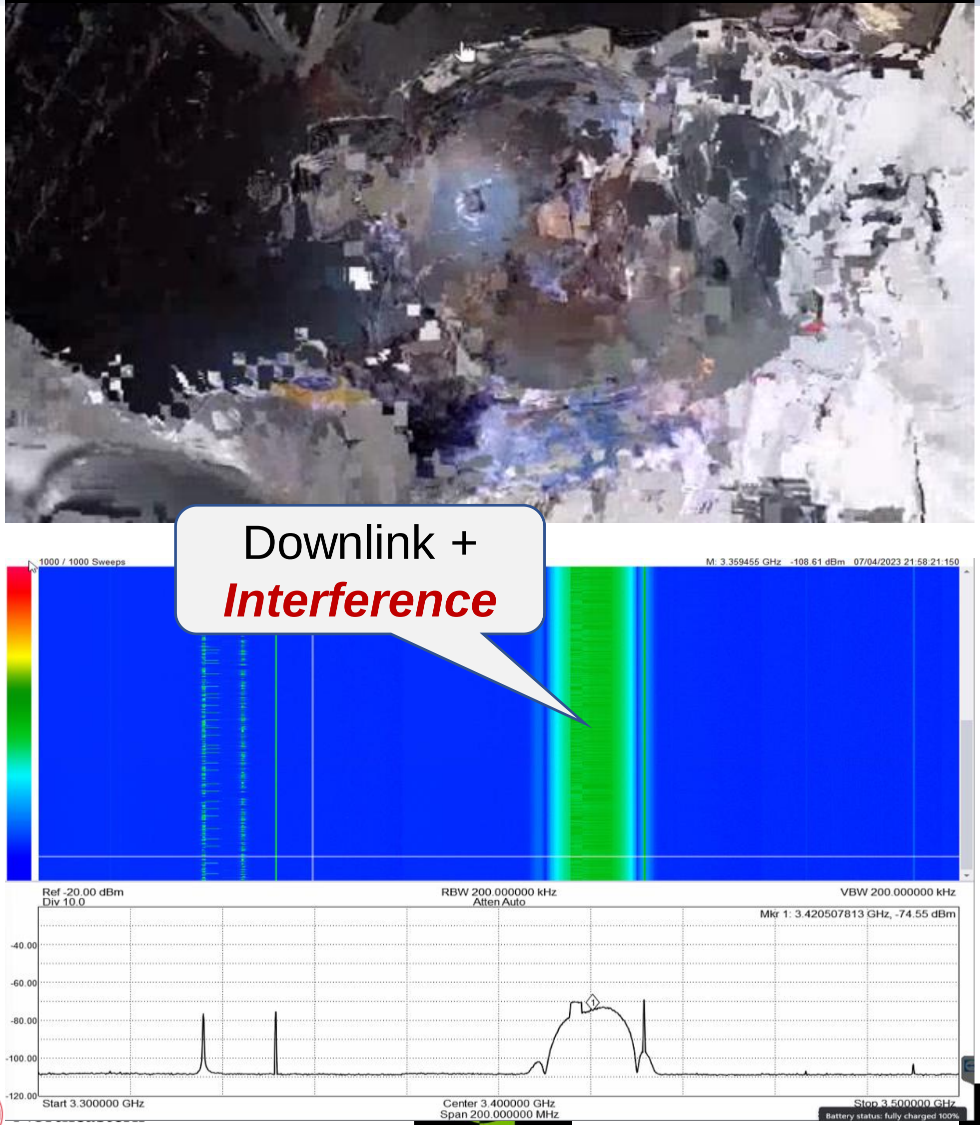
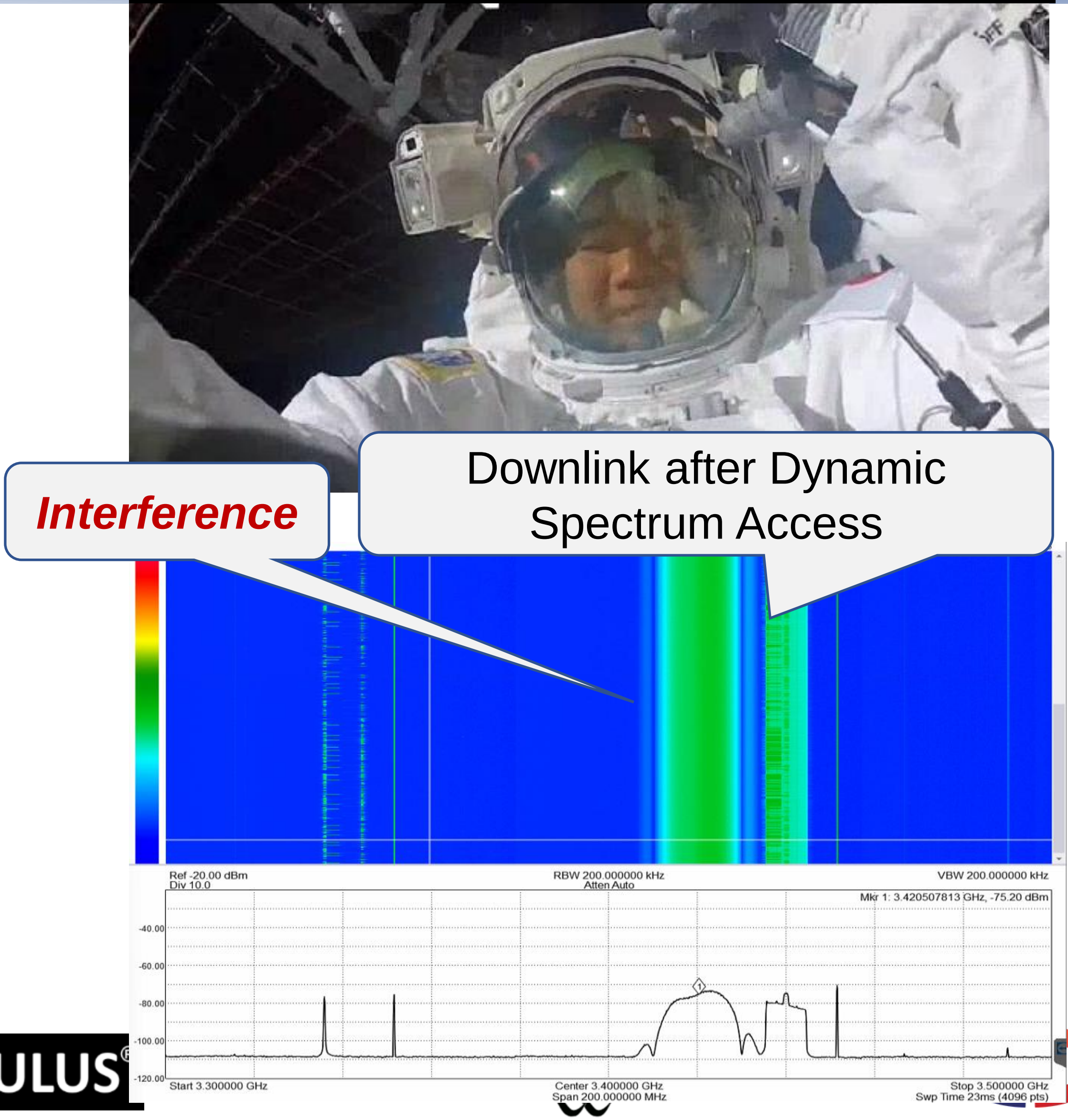
CLAIRE enabling Interference Mitigation using DSA

WITHOUT AiRANACULUS



WITH AiRANACULUS



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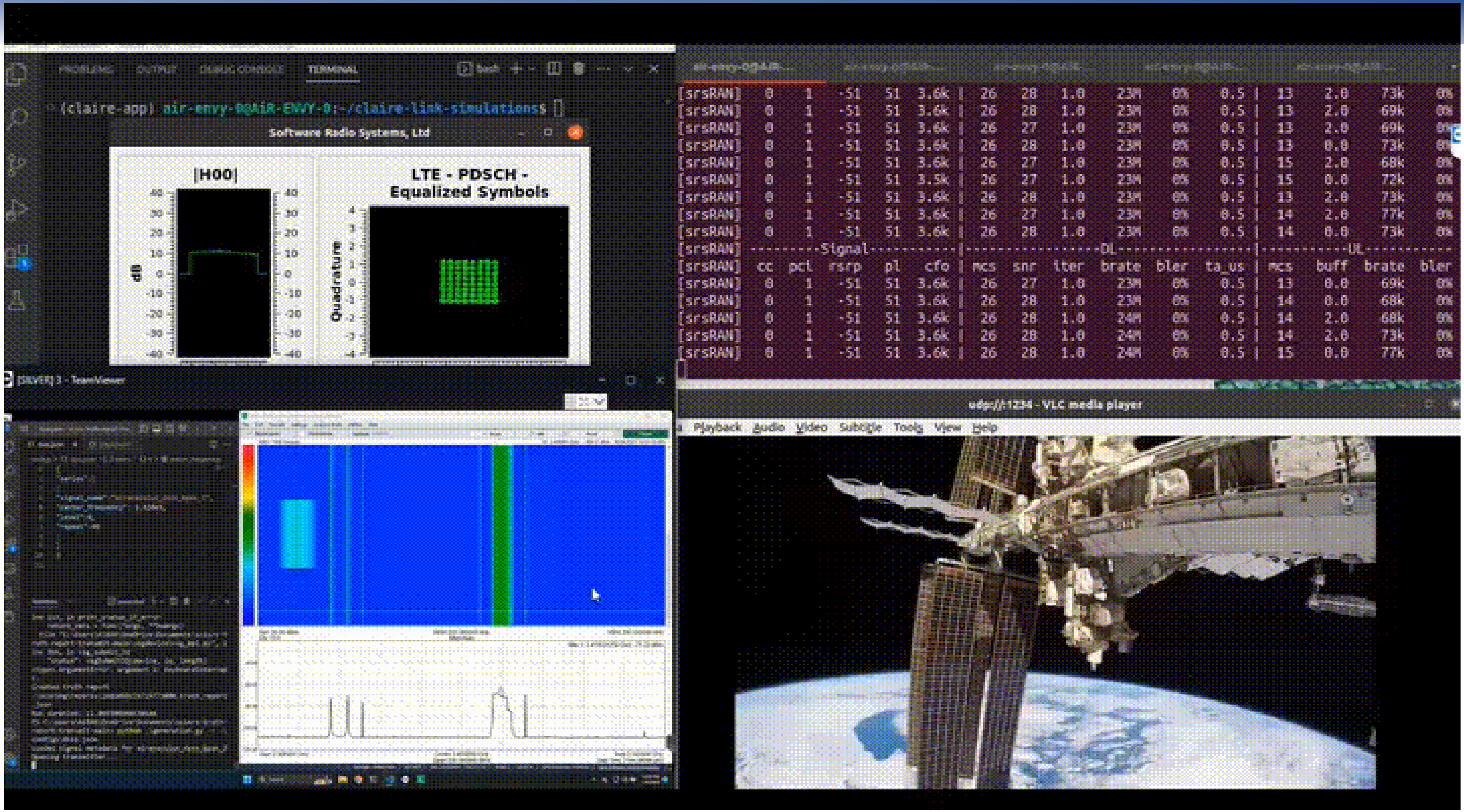
CLAIRE enabling Interference Mitigation using DSA



VIDEO DEMONSTRATION

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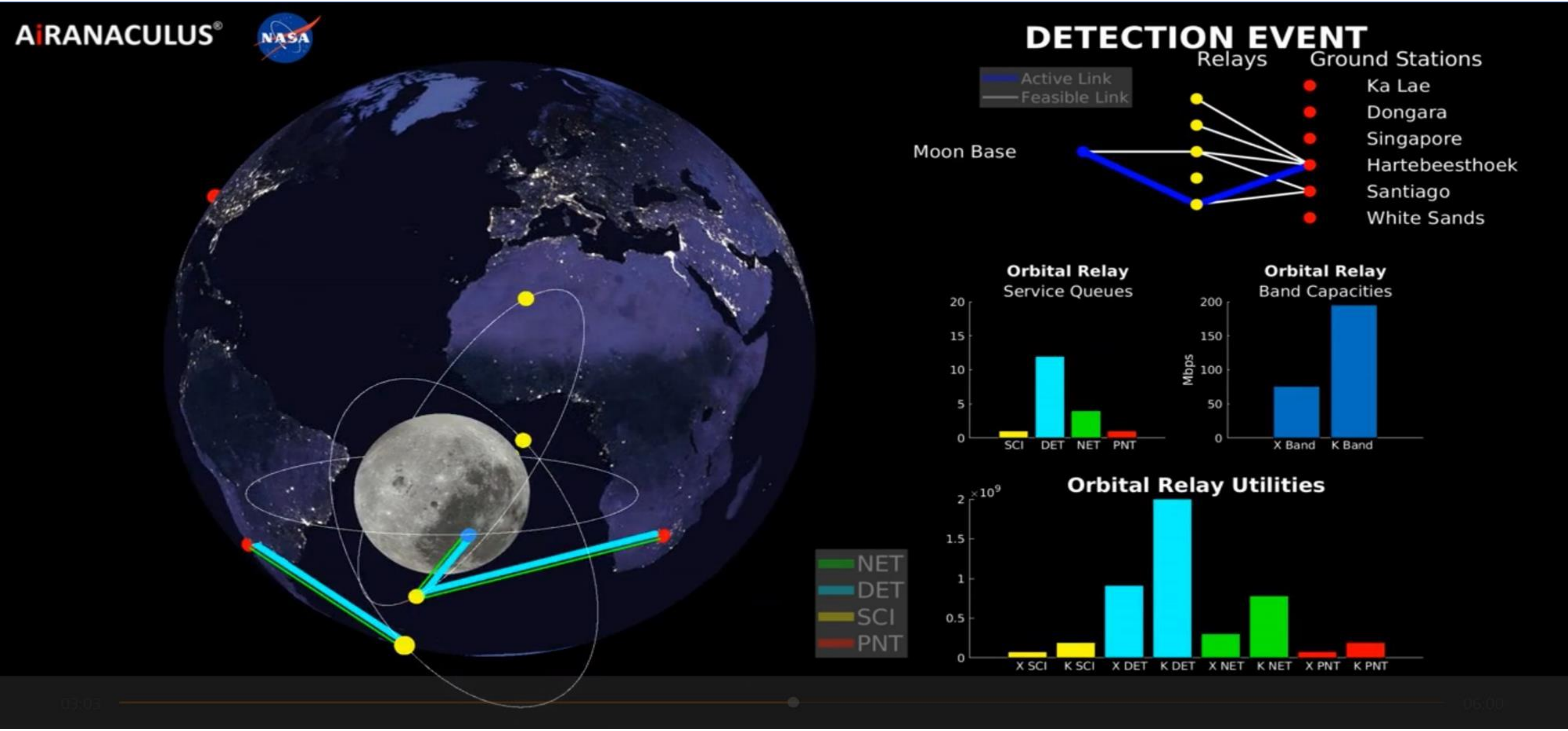
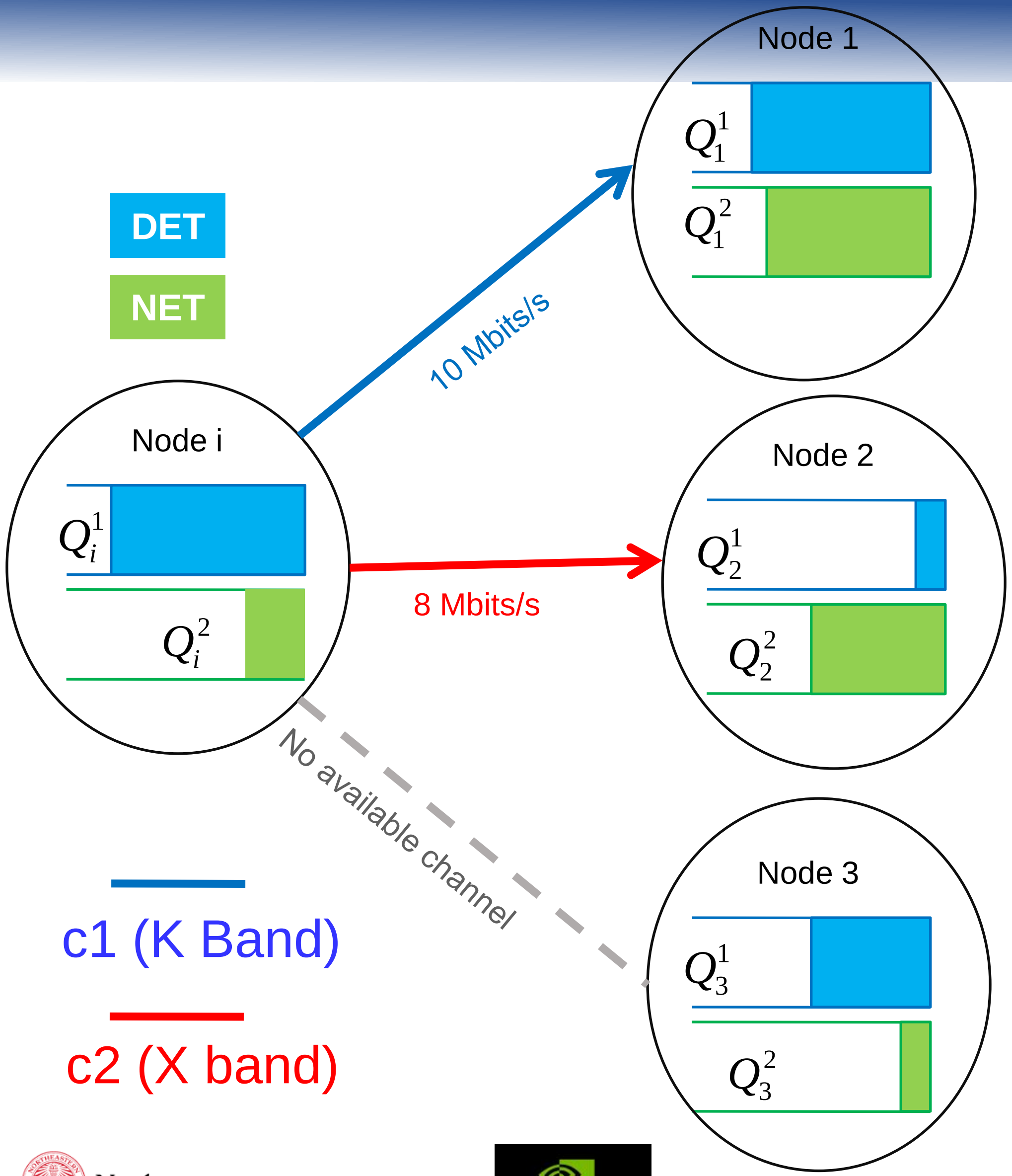
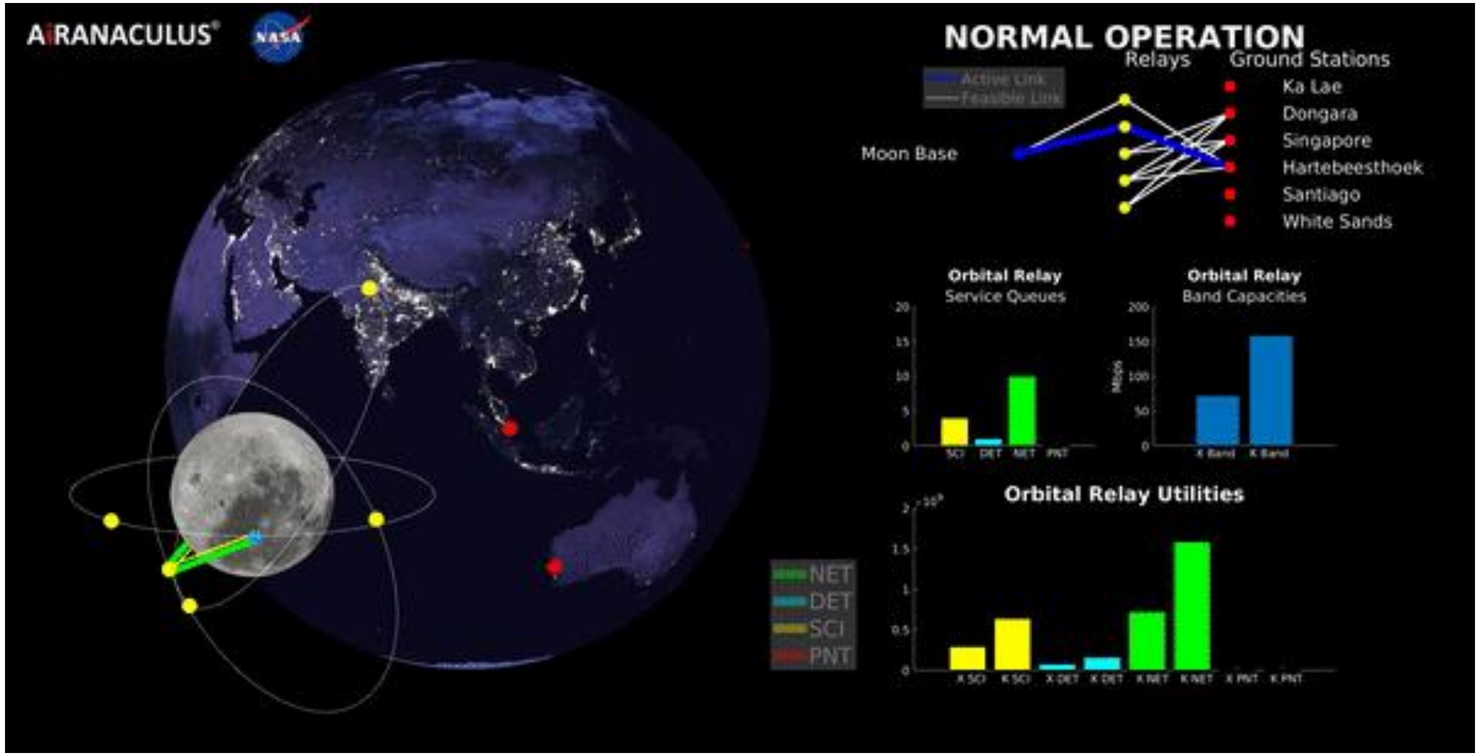
TRAFFIC AND SPECTRUM AWARE ROUTING


AiRANACULUS
NASA
DETECTION EVENT
Relays
Ground Stations
Active Link
Feasible Link
Moon Base
Ka Lae
Dongara
Singapore
Hartebeesthoek
Santiago
White Sands
Orbital Relay
Service Queues
20
15
10
5
0
SCI
DET
NET
PNT
Orbital Relay
Band Capacities
Mbps
200
150
100
50
0
X Band
K Band
Orbital Relay Utilities
$\times 10^9$
2
1.5
1
0.5
0
X SCI
K SCI
X DET
K DET
X NET
K NET
X PNT
K PNT
NET
DET
SCI
PNT

Traffic and Spectrum Aware Packet Forwarding Algorithm



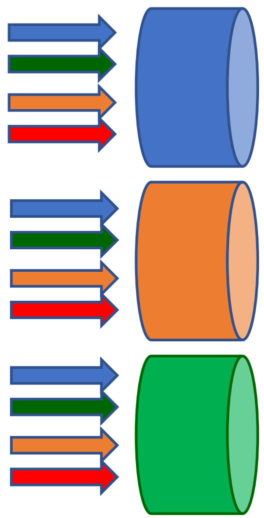


VIDEO DEMONSTRATION

PREDICTIVE POLICY-BASED NETWORK SLICING ORCHESTRATION

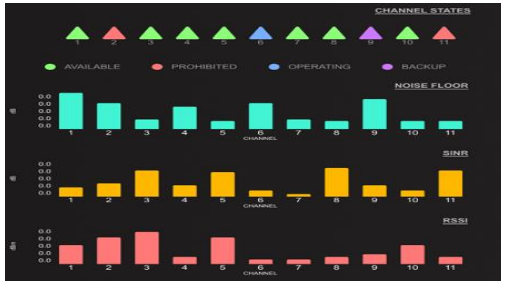
INSPiRE Network Optimization Model

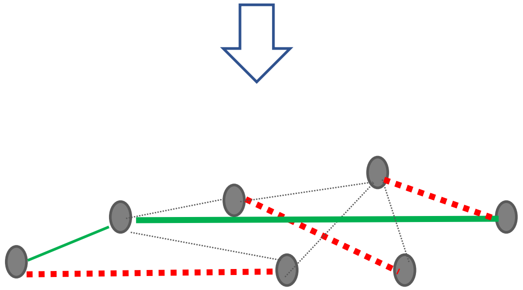
1 Sort Apps / Missions / Organizations into Network Slices



Network Slice Attributes:
Applications + QoS
IP Address Range
Firewall rules

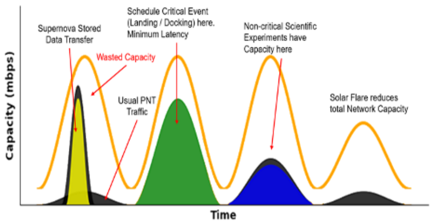
2 Determine quality of RF connections

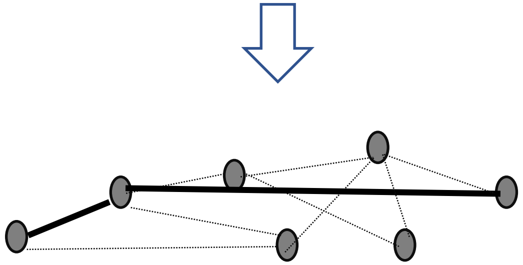




Link Attributes:
SNR
Channel capacity
Buffer Backlog

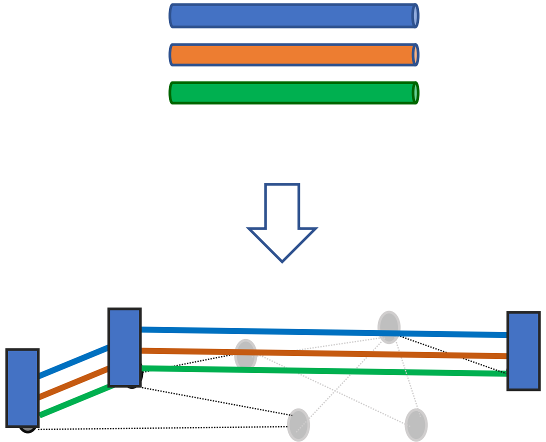
3 Determine the optimal path for Slice based on topology





Network Route Attributes:
Orbital pathway
Link capacity

4 Prioritize application traffic within NS based on available bandwidth



Application QoS Attributes:
Application Prioritization
Network Slice Bandwidth

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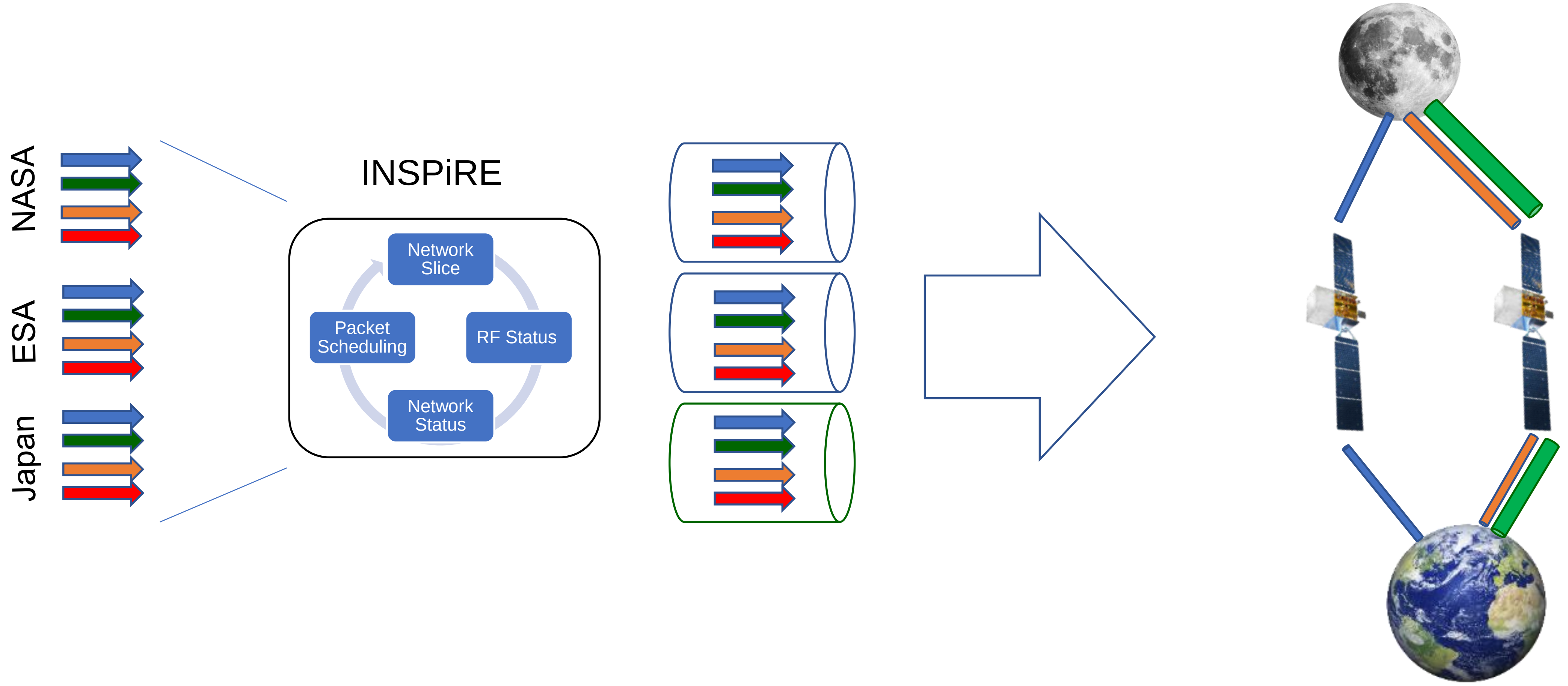
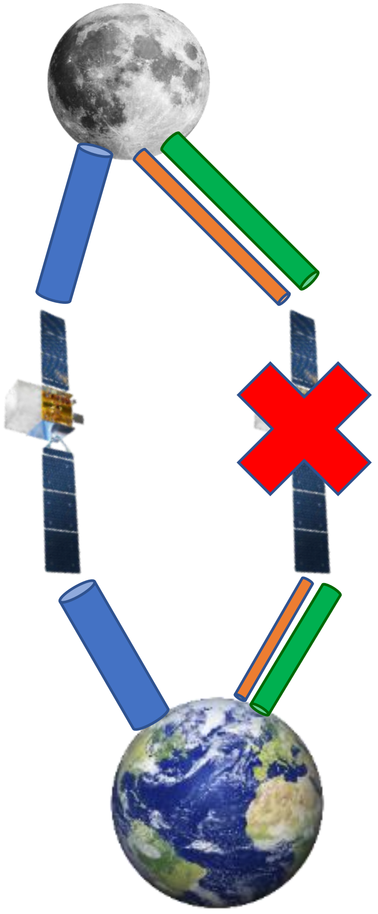
INSPiRE Will Dynamically Optimize Path Selection & Packet Scheduling



INSPiRE Supports Real Time Reconfiguration Via AI Inference



Lost Satellite

INSPiRE

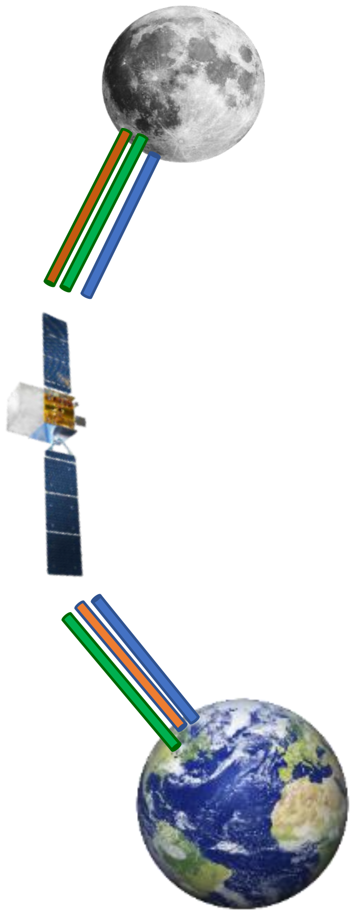
- Network Slice
- RF Status
- Network Status
- Packet Scheduling

Lost Satellite

Remove Satellite B + Links From Inventory Reduce Network Slice to Fit Satellite A

Network Slicing Engine

Updated Network



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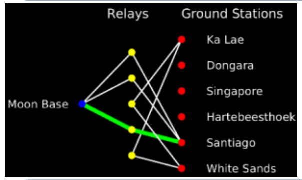
A Day in the Life of Network Slice

1 NASA Mission Manager provides a list of all the activities that the network needs to support over a certain time frame

Mission Req	Org.	QCI	Application	Source IP Address	Destination IP Address	Time Start	Time Stop	Priority	Packet Delay	Packet Loss	Throughput	Description
1	NASA	**65**	Voice-GBR	100.xx,…	200.yy	T1	T2	0.7	75 ms	10^{-2}	[MIN, MAX]	**Mission Critical PTT**
2	JSA	**7**	Voice / Video / Telerobotics	201.aa	300.bb	T2	T3	7	100 ms	10^{-3}	[MIN.MAX]	**Voice/ Video**

INSPiRE NETWORK SLICING ENGINE

2 INSPiRE Network Slicing Engine asks the Contact Graph to map the routes that are available over the course of the time duration



ORBITAL TRACKING

3 INSPiRE Network Slicing Engine updates the Slice Inventory Module. Can these Network Slices can be supported

SLICE INVENTORY MODULE

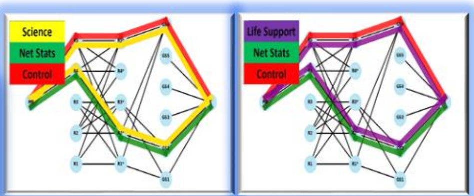
YES

NO

POLICY ADVISOR

4 Policy Advisor to reprioritize the List. Network Slice Inventories are Re-prioritized. ARP adjusted

SLICE SERVICE TRACKER



5 INSPiRE Network Slicing Engine develops the Network Slice definitions and sends these to the Slice Service Tracker

INSPiRE AGENT

6 INSPiRE Network Slicing Engine also sends the Network Slice definitions to the INSPiRE Agent

7 INSPiRE Agent configures the Policy-based Packet Scheduler and informs CLAIRE on how Packets need to be forwarded

POLICY BASED PACKET SCHEDULER

8 INSPiRE Agent sends various status information to the INSPiRE Network Slicing Engine

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DYNAMIC GENERATION AND RECONFIGURATION OF POLICIES

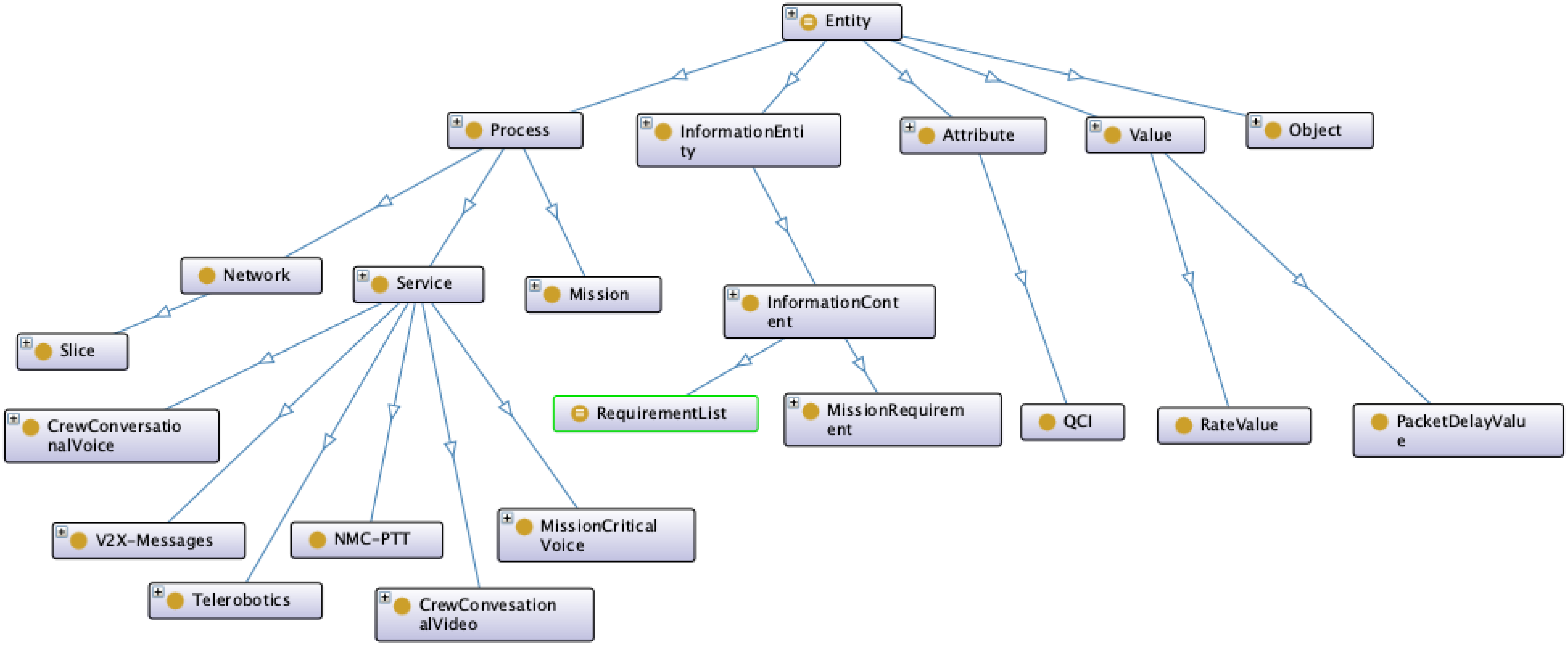
Policy Advisor (PA) Approach

- **Policy** – set of rules that prescribe responses to specific patterns when they are observed
- Nodes in Policy-based Cognitive Network execute (interpret) the policies (using policy engines)
- Cognitive nodes “understand” the policies because they share a common vocabulary
  - Standardized vocabulary is preferred
  - A formalized vocabulary is called **Ontology**
  - Include concepts (classes) and relationships among the instances of the classes (properties) that are known

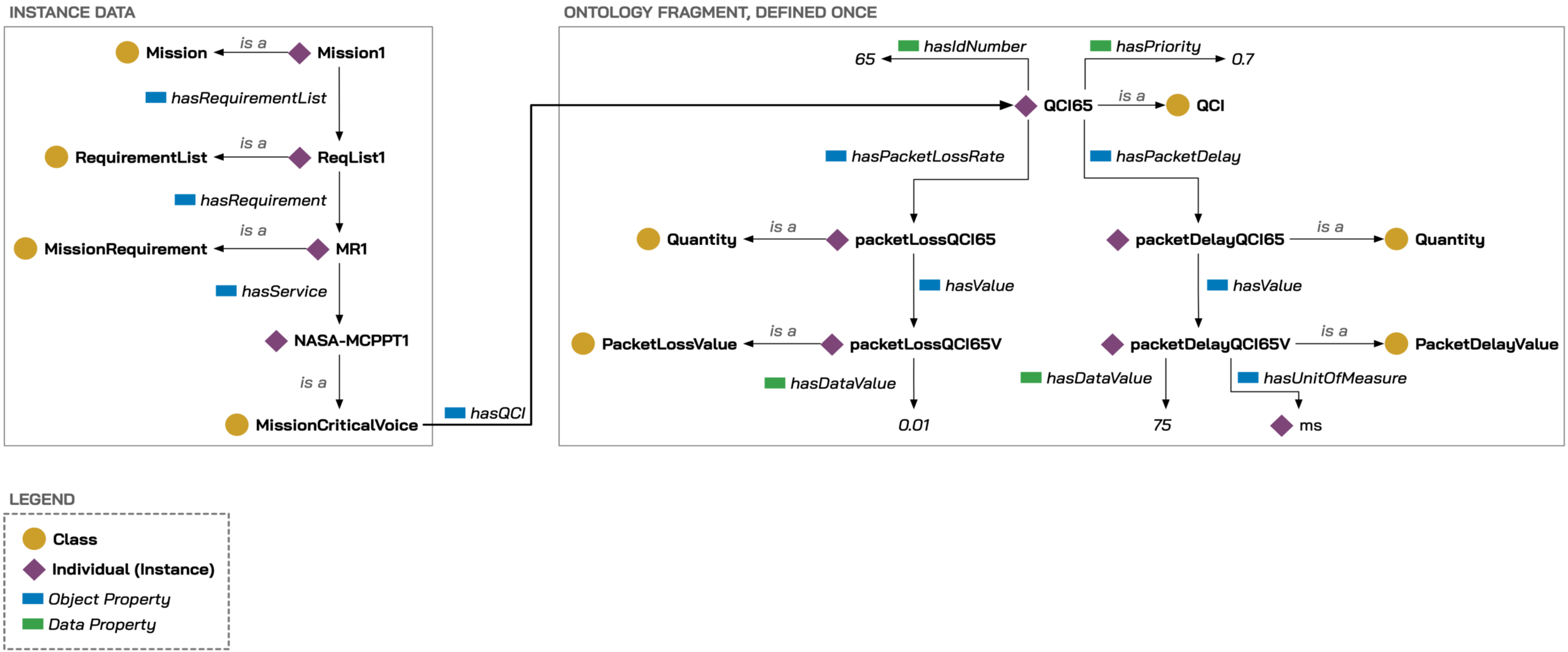
- Policy Examples:
  - *NASA is more important than international partners.*
  - *Mission traffic is more important than academic traffic.*
  - *Human life is more important than robot.*
  - *Deemphasize the Application with the lowest priority. If impossible, select the next one on the list.*
  - *Deemphasize an Application associated with non-essential organizations and assigned with the lowest priority. If not applicable, select the next available one.*
  - *An occurrence of Supernova Start Event, the slices should be assigned to Very Important Organizations with high throughput and low latency*

- **Bottom Line Up Front:**
  - **If a new policy needs to be added, just express it in the policy language.**
  - **No policy engine code modification required!**

Classes (partial); links not shown



Requirement Representation – Example



An Example of a Very Simple Policy

SELECT ?mission ?reqList ?req ?sdf ?qci ?priority	[Return variables (columns)]
WHERE	[such that:]
{ ?mission a Mission; hasRequirementList ?reqList .	[a Mission has list RequirementList]
?reqList hasRequirement ?req.	[with Requirements]
?req hasService ?sdf .	[each list entry has a Service]
?sdf hasQCI ?qci .	[whose QCI is]
?qci hasPriority ?priority	[with priority]
}	[as shown in the following table]

Policy (in text): *Deemphasize the Application with the lowest priority. If impossible, select the next one on the list.*

Execution Results

ID	mission	reqList	req	sdf	qci	priority
5	**:Mission1**	**:ReqList1**	**:MR2**	**:JSA-VVTR**	**inspire:QCI7**	**7 (xsd:decimal)**
1	:Mission1	:ReqList1	:MR5	:NASA-CCV1	inspire:QCI2	4 (xsd:decimal)
3	:Mission1	:ReqList1	:MR4	:ESA-TR	inspire:QCI3	3 (xsd:decimal)
2	:Mission1	:ReqList1	:MR3	:NASA-V2X	inspire:QCI75	2.5 (xsd:decimal)
7	:Mission1	:ReqList1	:MR6	:NASA-ElDistr	inspire:QCI85	2.1 (xsd:decimal)
6	:Mission1	:ReqList1	:MR1	:NASA-MCPPT1	inspire:QCI65	0.7 (xsd:decimal)
4	:Mission1	:ReqList1	:MR7	:NASA-MCDSS	inspire:QCI69	0.5 (xsd:decimal)

CONCLUSIONS

Conclusions

- ***CLAIRE Provides***: 1. CLAIRE APP-enabled Cognitive Control Plane with overhead of less than 1%, 2. Wide-Band sensing and Interference Monitoring using Direct Digital Transceiver, 3. Interference Mitigation using Dynamic Spectrum Access, 4. Traffic, Spectrum and Buffer Aware Packet Forwarding and 5. Autonomous Channel Assignments,
- ***INSPiRE Provides***: 1. INSPiRE provides Predictive Policy-based Network Slicing Orchestration, 2. Deep Learning based Wireless Optimization, 3. Dynamic Generation and Configuration of Policies
- CLAIRE and INSPiRE together, provide wireless optimization for heterogeneous multi-vendor wireless network consisting of 4G/5G, Wi-Fi, SATCOM and other technologies,
- We are looking forward to furthering this technologies through NASA and Non-NASA funding.

Thank You NASA !!!

References

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- Preliminary Lunar Relay Services Requirements Document
- LunaNet: Empowering Artemis with Communications and Navigation Interoperability: Link
- Lunar Communications Relay and Navigation Systems (LCRNS), May 2022.
- Draft LunaNet Interoperability Specification, March 2022, Link
- Space Communications and Navigation (SCaN) Network Architecture Definition Document (ADD)
- Report of the Interagency Operations Advisory Group Lunar Communications Architecture Working Group
- The Future Lunar Communications Architecture, September 2019
- LunaNet Concept of Operations and Architecture, September 2020
- LunaNet: A Flexible and Extensible Lunar Exploration Communication and Navigation Infrastructure
- NASA CCSDS Bundle Protocol Specification: CCSDS 734.1-B-1
- IETF RFC-5050 Bundle Protocol Specification
- IETF RFC 5326 Licklider Transmission Protocol
- IETF RFC 6260 Compressed Header

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AiRANACULUS Capabilities

AiRANACULUS (www.airanaculus.com) is at the forefront in Intelligent RF solutions for applications ranging from Space communications to Smart Cities. The company has assembled the world's leading experts in signal processing, cross-layer analysis, cybersecurity and networking to create Intelligent RF solutions that are spectrum aware and capable of re-configuring radio systems for optimal performance even in highly contested environments.