

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

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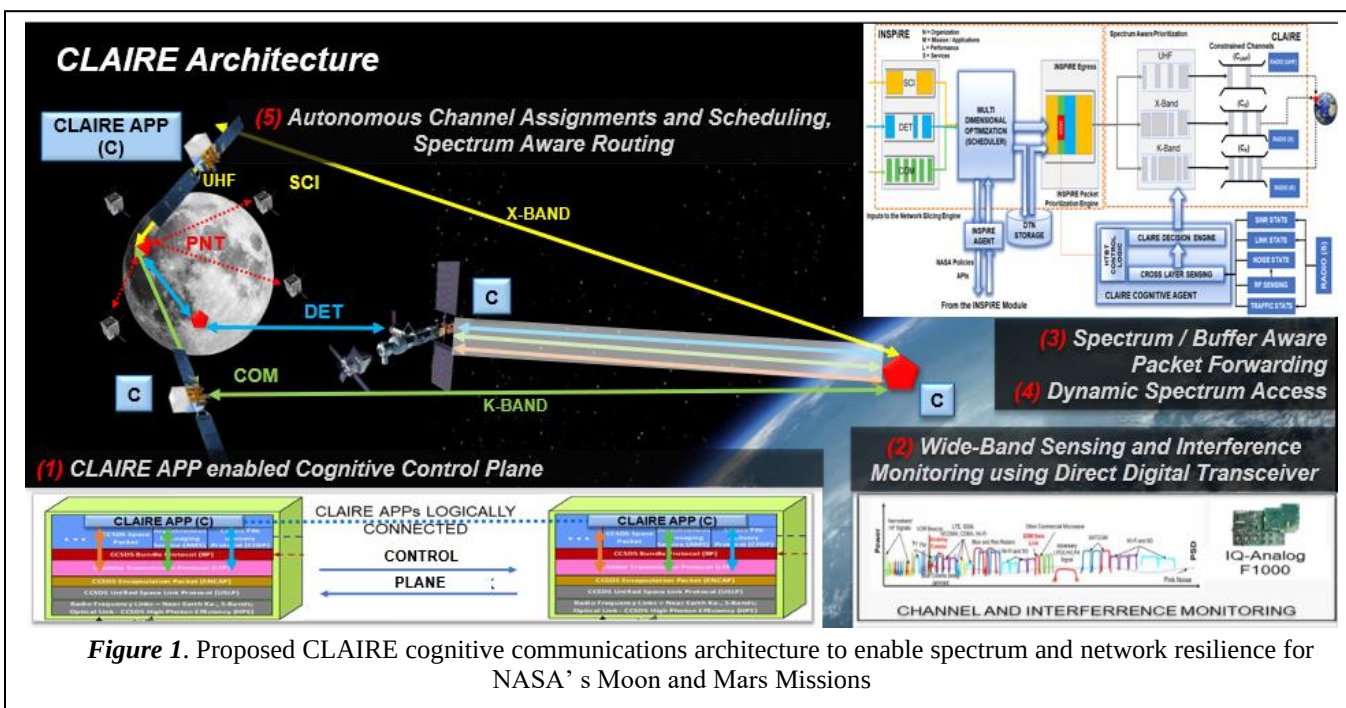
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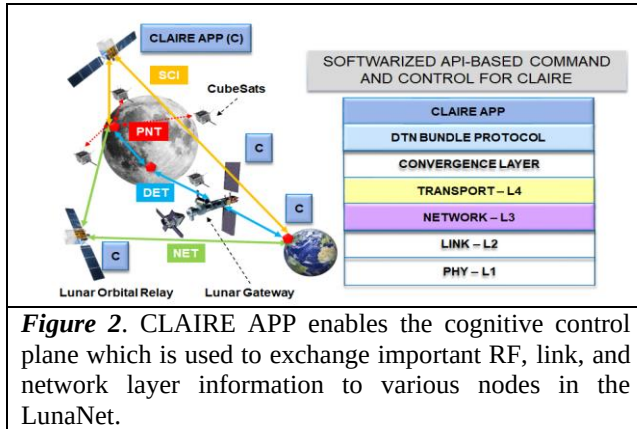
Abstract— In this paper, we present the capabilities of the CLAIRE System which provides resilient communications for NASA in presence of interference and congestion for a heterogeneous multi-vendor network. CLAIRE increases mission science data return to improve resource efficiencies and ensures resilience in the unpredictable space environment for NASA missions and communication networks. CLAIRE provides technology / waveform agnostic cognitive control plane that is instantiated at the Application Layer (APP) so that it can ride on NASA's HDTN bundle protocol or any other protocol stack that is used by the network. The cognitive control plane is instantiated using Heartbeats (HTBTs). CLAIRE is assisted by Wideband UHF-Ka Band RF Sensing that leverages advances in the Direct Digital Transceiver (DDTRX) technology. The Wideband RF Sensing is driven by statistical signal processing and machine learning algorithms. Interference is mitigated using Dynamic Spectrum Access (DSA). Finally, CLAIRE

addresses congestion using spectrum aware packet forwarding algorithm. CLAIRE provides an extensible protocol that allows passing of RF spectrum situational awareness, cross-layer sensing, delay tolerant networking and dynamic spectrum access information that can help with network optimization. Cross-Layer Sensing (CLS) and CLAIRE Decision Engine (CDE) enable spectrum and delay aware packet forwarding and Dynamic Spectrum Access during cases of severe interference.

Keywords- Cognitive Communications, Space Communications, Satellite Communications, Deep Space, Cognitive Control Plane, Cross Layer Sensing, Machine Learning, Decision Engine, Joint All Domain Command and Control (JADC2)



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I. LUNANET INTRODUCTION

During the next decade, NASA will launch a series of Artemis missions that will place new science instruments, vehicles, and astronauts on the Lunar surface. Unlike the previous Apollo missions, the objective is to develop a permanent Lunar presence on the Moon and to use the lessons learned in future missions to Mars. Communicating with the equipment and personnel on the Lunar surface presents unique challenges, for instance, from the Lunar South Pole, the Earth rises and sets over the horizon approximately every two weeks. Therefore, NASA is launching Gateway, a spacecraft that will orbit the Moon, providing surface radios with a connection to Earth—among many other capabilities. Additionally, Lunar relay satellites will likely supplement the relay capabilities of Gateway. This growing network of communication assets around the Moon, and the devices they serve (see Figure 1), presents new challenges and opportunities. To codify this future network, NASA has published specifications on what they’re calling LunaNet [1]. The communications links will consist of surface links, proximity links from the Moon’s surface to the orbital relays and direct-to-Earth (DTE) links from the orbital relays to the ground station. The communication links are likely to operate in many frequency bands. As an example, the proximity links will operate in the S-Band and the Ka-Band. The relay-to-relay links will operate in the Ka-Band, or they may be optical. The DTE links may operate in X-Band, Ka-Band or they may be optical. The Lunar surface network may consist of 4G/5G as well as Wi-Fi™ technologies. Hence, we believe that a wireless network optimization technology should be protocol and waveform agnostic and be able to operate in a heterogeneous multi-vendor ecosystem. The CLAIRE cognitive technology has been designed to be integrated with the LunaNet architecture and to enhance the basic services. The LunaNet specification describes the following services:

Networked Communications (COM): The networked communication services in LunaNet will enable users to transfer data to other nodes using addressable and routable data units. The primary COM services are real-time critical data transmission, data aggregation and transmission in a store-and-forward mode, and messaging. LunaNet user

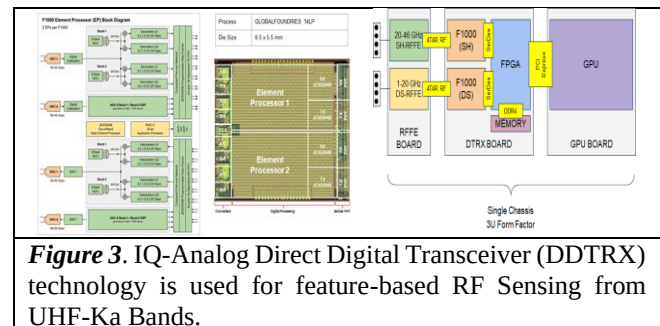
applications will be networked-based, using either Delay/Disruption Tolerant Networking (DTN) Bundle Protocol (BP) or Internet Protocol (IP). The standardized messaging services are expected to be utilized by applications such as service acquisition, PNT, and alerts. As shown in [2] Table 4, the implementation details of this messaging service are still “To Be Determined.” As such, a functional messaging implementation is utilized and described in this work to demonstrate the cognitive functionality that such services will enable.

Position, Navigation, and Timing (PNT): LunaNet is likely to provide PNT services for users on the Moon as well as for the proximity links. The PNT services will enable the users to determine the position and velocity of an orbiting or lunar surface-based asset using reference signals.

Detection and Information (DET): LunaNet detection and information services provide alerts and other critical information to users. This is used to enhance situational awareness of the users which may include astronauts, rovers, and other assets on the lunar surface. DET service will also alert the users of potentially dangerous solar activity. These alerts may be enabled using smartphones that use Wi-Fi™ and a 4G network that is planned to be deployed on the lunar surface. LunaNet detection and information services will also include a lunar search and rescue capability, or LunaSAR.

Science Services (SCI): The SCI services will enable various researchers to conduct measurements and experiments. Some other uses of the SCI service include radio astronomy enabled by the radio telescope on the lunar surface.

II. CLAIRE CONCEPT



CLAIRE provides spectrum and network situational awareness to the LunaNet architecture to enable link-layer selection and optimization to maximize the data flow based on the desired Quality of Service (QoS) requirements for NASA’s SCI, NET, DET and PNT services. CLAIRE cognitive control plane is instantiated as an APP so that it can ride on NASA’s DTN Bundle Protocol or any other protocol stack that is used by the network as shown in Figure 2. Also, this architecture may be applied to any other future deep space missions since changes may be made easily. CLAIRE provides an extensible protocol that allows exchange of RF spectrum situational awareness, CLS, buffer backlog and other Dynamic Spectrum Access (DSA) information that can help with network optimization. The CLS and CDE enable

spectrum and delay aware packet forwarding and DSA during cases of severe interference. CLAIRE packet forwarding maps each service packet to an appropriate band and channel (e. g. UHF, X-Band, Ka-Band etc.). CLAIRE cognitive control plane is enabled by feature-based multi-band RF sensing that is driven by advances in Direct Digital Transceiver (DDTRX) technology shown in **Figure 3**. The RF sensing algorithms consists of Cyclostationary Signal Processing (CSP) techniques combined with Machine Learning (ML), to detect and characterize various interference types. CLAIRE adds autonomy, optimization and self-configuration to a deep space network that may suffer from large delays, interference, and service disruptions. CLAIRE ensures that important packets are delivered to the destination, hence avoiding congestion due to un-necessary traffic. CLAIRE also enables future network function virtualization and network slicing, which will take NASA from link optimization to network optimization to create compartmentalization of requests and services. The underlying need for CLAIRE is to reduce both the mission and network operator burden while providing complete control to the Mission Manager to configure the network based on the current posture and policies.

III. COGNITIVE CONTROL PLANE ENABLED BY CLAIRE APP

To enable a cognitive control plane, without making any modification to the existing NASA SCaN architecture and protocol stack, we proposed an innovative CLAIRE Appliqué (APP) that rides on top of the protocol stack as shown in **Figure 2 and 4**. Advantages of our design include: 1. No changes needed to the existing NASA SCaN protocol stack. CLAIRE rides on top of it as an application layer protocol, 2. APP based approach allows continuous addition, deletion and modification of capabilities through Convergence Layers (CLA) and Application Programming Interfaces (APIs), 3. APP based approach allows future Network Function Virtualization (NFV) of the space communications architecture which allows the NASA mission managers to

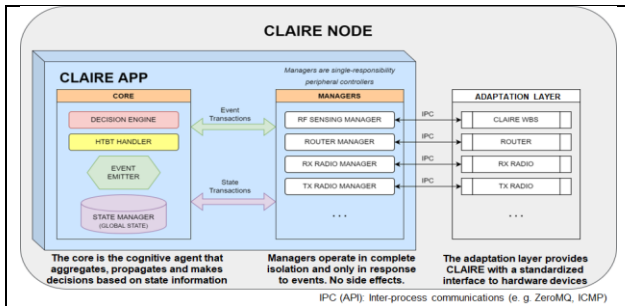


Figure 4. Architecture of the CLAIRE APP consisting of Core, Managers and Adaptation Layer

focus on the core missions and less on network configuration, 4. APP-layer protocol, and messaging may be dynamically tailored to the communications overheads to keep the network efficiencies high. CLAIRE exchanges the Heartbeat



Figure 5. Wideband RF sensing User Interface - Signal processing flow consisting of spectrum segmentation, statistical signal processing, CSP and ML based detection and characterization, Channel Quality Estimation (CQE).

messages to develop spectrum and network situational awareness which then allows the CLAIRE Decision Engine (CDE) to make intelligent routing decisions. Spectrum awareness consists of obtaining noise and interference statistics for every channel. It also consists of detecting and characterizing the signals to verify their spectrum assignments or interference. Cross-layer awareness consists of obtaining Physical (PHY) and Medium Access Control (MAC) Layer information such as Received Signal Strength Indicator (RSSI), Signal to Interference plus Noise Ratio (SINR), Packet Error Rate (PER) and Header Checksum information. Finally, the Network Layer statistics consist of position, topology, buffer backlog and routes.

IV. WIDE-BAND RF SENSING

NASA LunaNet links are likely to operate in many frequency bands ranging from UHF to Ka Band. The links will work in a Frequency Division Duplex (FDD) regime. Some of the challenges involving links that span the distance from the Moon to the Earth include: 1. Large propagation delays (> 1 second), 2. Solar flares which may disrupt Comms, 3. Interference on the Earth, 4. Mis-configured radios and interference in space, 5. Remote monitoring the network health. To obtain the situational awareness for Challenges 2 – 5, RF sensing is extremely important.

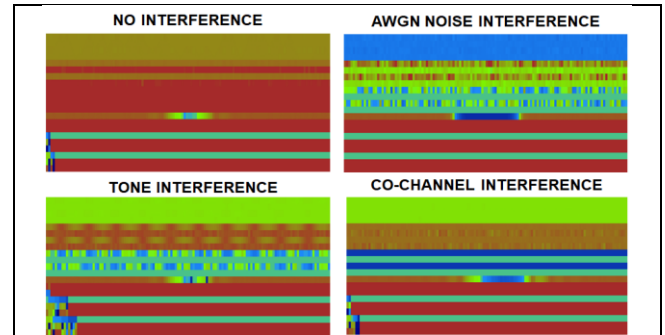


Figure 6. CSP and cross-layer features are applied to a Deep Convolutional Neural Network (DCNN) engine to detect several different types of interference.

RF Sensing Hardware: An important aspect of RF sensing is to be able to have a low Size Weight and Power (SWAP) hardware that is capable of sensing UHF to Ka Bands. CLAIRE multi-band RF sensing systems is powered by the latest advances in the DDTRX Technology from IQ-Analog, as shown in **Figure 3 and 10**, which allows complete frequency coverage from UHF to the Ka Band. Given the challenging nature of being able to operate across the spectrum, our selection of DDTRX Technology makes sense and is important for low-SWAP implementation for spectrum situational awareness. The monolithic Antenna Processor Unit (APU) F1000 from IQ-Analog addresses over 20-GHz of instantaneous bandwidth with both transmit and receive capabilities. The F1000 APU receiver is comprised of four channels of synchronous sampling 8-bit 64-Gsps ADCs/DACs each coupled to 2 independent band processors performing digital mixing coupled with variable rate digital down conversion. This allows Instantaneous Bandwidths (IBW) from 78.125 MHz to 1.25 GHz over UHF to Ku Bands. By using simple COTS parts, and an additional F1000, we can create a low-SWAP system that is able to scan all the necessary bands from UHF to Ka, and all the channels for the LunaNet architecture.

RF Sensing Algorithms: Spectrum sensing has been widely used in cognitive radio [4-6] systems. The primary algorithm that is used to determine the Cyclostationary property of the signals is given by the well-known equation (1) below that represents the cyclic periodogram, for the signal $x(t)$,

$$\hat{I}_{xx}^{\alpha}(T, f) = \frac{1}{N} X_T \left(t, f + \frac{\alpha}{2} \right) X_T^* \left(t, f - \frac{\alpha}{2} \right) \quad (1)$$

where t is the time, T is the sensing time, f is the frequency, α is the Cycle Frequency, X refers to the Discrete-Fourier Transform (DFT) signal $x(t)$ in the frequency domain. The cyclic periodogram, when averaged over many data records, produces an estimate of the Spectral Correlation Function (SCF) which has (f, α) support that resembles a diamond. We compute both the non-Conjugate as well as the Conjugate statistics which are then provided to the Machine Learning module to detect and characterize signals and interference.

Figure 5 shows the Wideband RF sensing User Interface which provides the channelization of radios, the Power Spectral Density (PSD), Non-Conjugate and Conjugate CSP

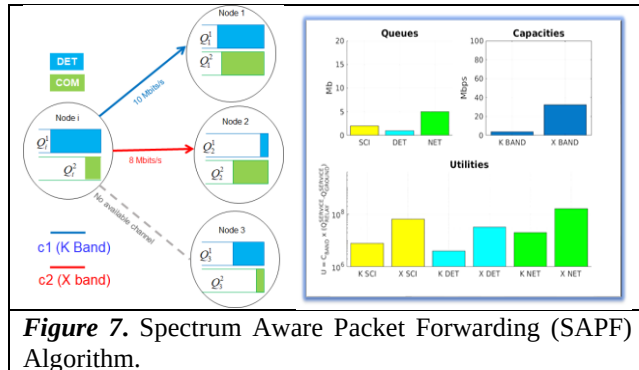


Figure 7. Spectrum Aware Packet Forwarding (SAPF) Algorithm.

statistics, detection and characterization of spurs, tones, or

interference, and finally the channel quality estimate (CQE). The CQE is used to predict the backup channel to orchestrate DSA in case of the onset of interference. **Figure 6** shows how the generated CSP and cross-layer features are applied to the DCNN engine to detect several different types of interference.

V. SPECTRUM AWARE PACKET FORWARDING

A key objective of the CLAIRE App is to provide Spectrum-Aware Packet Forwarding (SAPF), to enable link closures and operations even in adverse conditions to meet service level guarantees (QoS). The chosen forwarding algorithm needs to provide an optimum hop, while keeping in mind the heterogeneous service (COM, SCI, DET) needs, finite number of channels that are available, potential buffer backlog and interference situations. Our aim is to enable autonomous configuration, adaptation, and recovery of the network. In fact, our formulated algorithm, which aims to maximize the Utility, as a function of both capacity and differential buffer backlog, is a good fit for this mission.

We considered several alternative strategies with different trade-offs in terms of sophistication of the decision-making algorithms, complexity, and communication overhead, starting from simple heuristics, and adding DCNN based decision making. We eventually selected an algorithmic strategy that builds on our previous work [7] while extending

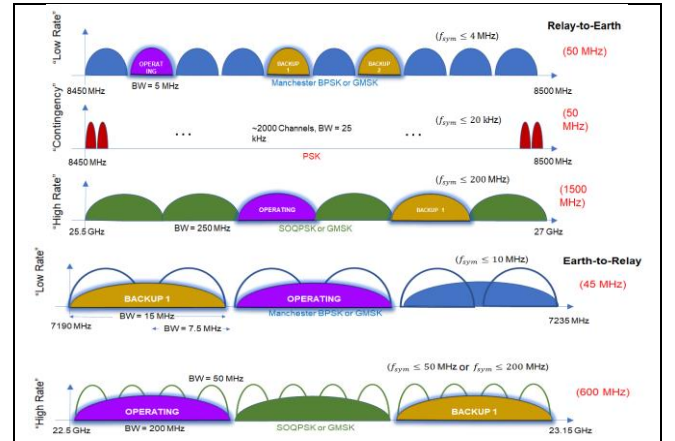


Figure 8. Possible frequency channelization of the radios from relay to Earth and Earth to relays. Figures show notional allocation of channels as Operational and Backup.

the framework and specializing it to the unique characteristics of space missions. We developed the SAFPF framework based on deterministic non-linear optimization.

The algorithmic framework results in localized, distributed, and real-time decision strategies that select the best next hop, relay node, and transmission interface while maximizing the link capacity.

The distributed algorithm is executed at each backlogged Node i , which will dynamically and independently 1. Select the best next hop j , and 2. Perform spectrum allocation

(which interface w to use, and at what power P) based on local queue and spectrum occupancy information collected on the common control channel. Note – future enhancement of this algorithm includes substituting power for adaptive modulation and coding. This local optimization problem consists of maximizing the spectrum utility,

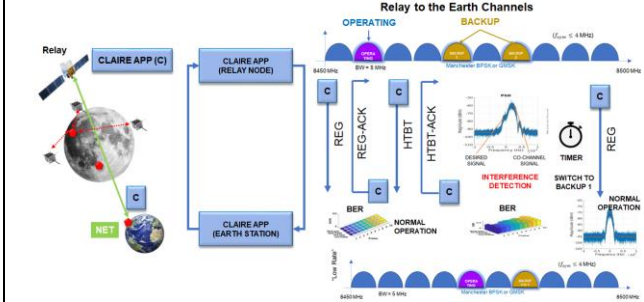


Figure 9. Dynamic Spectrum Access Orchestration using Heartbeat (HTBT) Messages via the CLAIRE Cognitive Control Plane.

$$(w, P, j) = \operatorname{argmax}(U_{ij}) \quad (2)$$

$$U_{ij} = c_{ij}(w, P, j)(Q_i^{S_{ij}} - Q_j^{S_{ij}}) \quad (3)$$

where $c_{ij}(w, P, j)$ represents the capacity of link (ij) for a given choice of interface w , power P , and next hop j , while $Q_i^{S_{ij}}$ indicates the queue backlog for session S_{ij} , i.e., the session with maximum differential backlog. The expression to be maximized represents the product between the achievable data rate (given by the link capacity under spectrum sharing and power budget constraints) and the differential backlog of the session with the highest backlog (i.e., the traffic sessions with maximum difference in the queue backlog between source and destination).

The expression to be maximized represents the product between the achievable data rate (given by the link capacity)

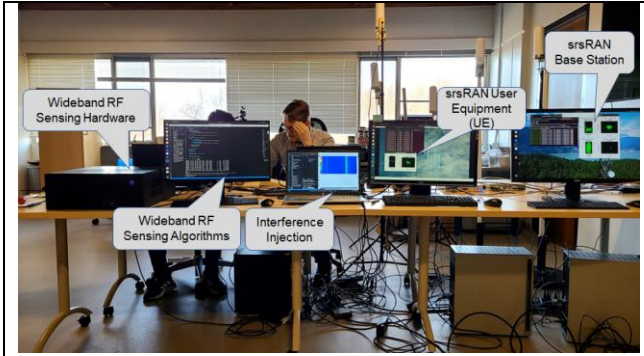


Figure 10. CLAIRE Testbed demonstrating capabilities over srsRAN (4G) network.

and the differential buffer backlog. By maximizing the expression above based on the current dynamic spectrum, queuing conditions, the node will choose 1. Which packet is allocated to which band 2. Spectrum/channel allocation, and 3. Power boosting to maximize the channel capacity.

A CLAIRE APP packet forwarding decision involves a choice of packet (of either NET, DET, or SCI service) and a choice of link. The choice of link includes the destination node (ground station, relay, or lunar surface node), the band of transmission (UHF, X, or K), and then the channel within that band. Consider a decision from a relay with line-of-sight to a single Earth ground station. In this case, the choice of destination node is fixed. Suppose also that the packet type and transmission band are fixed. What remains is to choose the channel, which is determined by optimizing the capacity according to the Shannon Capacity Theorem $C(f) = w \log_2(1 + \text{SINR}(f))$. In general, the CLAIRE APP will evaluate all channels on all bands and calculate the capacity of each channel, which maps each band to a maximal possible capacity. Suppose now the band, channel, Source, i , and Destination j , are fixed. What remains is to choose the packet type to transmit. This is done by choosing the maximal differential buffer backlog over all possible packet types S : $Bi,j = (Q_i^{S_{ij}} - Q_j^{S_{ij}})$. When transmitting to a ground station, it is assumed that the buffer backlog is '0' since Earth is expected to have a good high-speed connectivity. So, we choose the service with the largest queue at the source node. The CLAIRE APP will combine all factors into its packet forwarding decision by jointly considering the Destination, Band and Channel, and Service (SCI, DET, COM, PNT) and choosing the link with the greatest Utility. In **Figure 7**, we show an example of the decision process for a link from a relay to a ground station where the destination is chosen but the choice of band and service needs to be selected. Each band, (X and K), have a time varying capacity based on channel and noise fluctuations. Each service queue will also vary in time. While the K Band has higher capacity in general, it is potentially less reliable. In this instance represented by the Figure, the X band has higher Capacity, and the COM service has the highest backlog. From this we compute all six Utility values and select the largest one, which is to transmit a COM packet on the X band. The routing decision process is decided locally by using information about other nodes passed through control plane messages. The advantage of the Utility function approach is that it can be potentially modified to consider other needs in the network. For instance, the feasible link network topology varies in accordance with the celestial mechanics governing the nodes of the network, which means there will sometimes be a substantial delay in the routing process. The Utility function could contain a factor based on geometries that takes this into account.

VI. DYNAMIC SPECTRUM ACCESS

As we discussed in Section III, the function of the CLAIRE APP is to establish the cognitive control plane that allows information exchange enabling network optimization. The cognitive control plane network synchronization starts with exchange of Registration (HTBT-REG) and Registration Acknowledgement (HTBT-ACK) messages between the two

adjacent nodes. Once they are registered with each other, they then start exchanging periodic (say every 4 seconds) Heartbeat (HTBT) and Heartbeat ACK (HTBT-ACK) Messages. In case of severe interference requiring rapid channel switch, a.k.a. DSA, we have embedded special fields inside the HTBT to alert the Transmit Node that a channel switch may be required. This may also happen in case of critical events such as descent or docking which may need urgent command and control information to be passed to the neighboring nodes, or to the mission control center. All these messages are extensible and designed to have **low overhead (less than 1%)**. Each HTBT contains: 1. Message (MSG) Header, 2. MSG-ID, 3. Node-IP-Address, 4. Position, 5. Session ID, 6. Operating Channel, 7. Backup Channel, 8. Band, 9. For each Channel - RSSI, SINR, Noise Floors, etc.

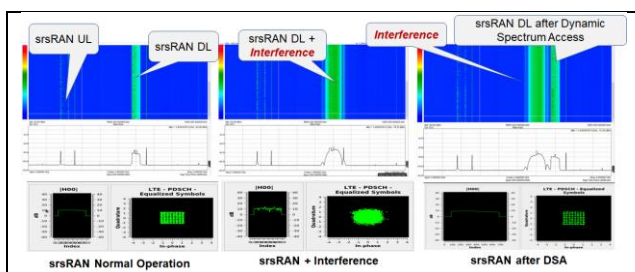


Figure 11. Dynamic Spectrum Access Orchestration using Heartbeat (HTBT) Messages using CLAIRE Cognitive Control and Wideband RF Sensing demonstrated over srsRAN (4G) network.

The cognitive control plane may also be used to fulfil other missions that NASA may have by extending these Messages.

Note, that all the Communications Links that will be used for the Moon and space missions are Frequency Division Duplex (FDD) in the network architecture which makes things slightly more complicated than if it was Time Division Duplexing (TDD). **Figure 8.** shows a potential frequency channelization of the radios from relay to the Earth and Earth to the relays. Figures show notional allocation of channels as Operating and Backup. This means that any link statistics or sensing information on the ground station must be returned to the relay, on the channels in a different band. This loop of forward in one band and return on another band makes orchestration of DSA slightly more challenging when the system encounters interference. In addition, long links, from Earth to relays cause further delays. We demonstrate the CLAIRE capability including the Wideband RF Sensing on srsRAN radio network as shown in **Figure 10. Figures 9 and 11.**, demonstrate the orchestration of DSA. It shows how the CLAIRE APPs on the relay nodes and the Earth ground station register with each other to create a connection. This is followed by periodic HTBT and HTBT-ACK messages which, among other things, contain RF sensing information, radio statistics and optimal Backup channel information, used when the current Operating channel experiences interference. CLAIRE APPs monitor these statistics to check the health of the wireless links. The candidate Backup channels for each

band is periodically updated. This is also based on the NASA policies, in case certain channels are prohibited from being used. If the Radios at the Earth ground station experience sustained period of interference, then this is conveyed to the CLAIRE APP on the Relay. The HTBT-ACK contains information about worsening SINR statistics, Header Checksums not converging and hence, worsening BER/PERs, higher RSSI etc. The CLAIRE APP on the Relay monitors the interference statistics for a certain time (Timer), before switching to the Backup Channel as shown in the **Figures 9 and 11.** The radios then send out HTBT-REG Message on the new Operating channel and logically synchronize to each other. The Timer can be adjusted based on the system response that is desired.

CONCLUSIONS

In this paper, we presented the architectural construct and capabilities of the CLAIRE System, which provides value-added service to the LunaNet. CLAIRE provides a cognitive control plane, spectrum / buffer aware packet forwarding, wide-band RF sensing, interference mitigation and congestion control. CLAIRE can operate on any radio or network which may include 4G / 5G, Wi-Fi, SATCOM as well as legacy radios that may be used for the Lunar Mission. These capabilities make the LunaNet operation autonomous, robust, and resilient. The CLAIRE construct is highly applicable to upcoming Department of Defense Joint All Domain Command and Control (JADC2) thrust.

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