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Survey of Machine Learning Methods for Wideband Space Cognitive Antenna

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Introduction

- Cognitive Radios built on software defined radio (SDR) platforms are being developed and matured to address the problem of spectrum underutilization.
- Commercial technology investments are pushing the limits of reconfigurability, processing, and networking within the space communications architecture.
- As the development evolves to increasingly wideband capability, it is important to complement it with **advanced ultra-wideband antenna technology** for the future (e.g. support spectrum services for both commercial and defense frequency bands).
- The advent of **machine learning and cognition** provides an opportunity for this antenna of the future to not only react to adverse conditions, but learn to optimize its configuration for future scenarios within the complex, dynamic spacecraft environment i.e. become a **cognitive antenna.**

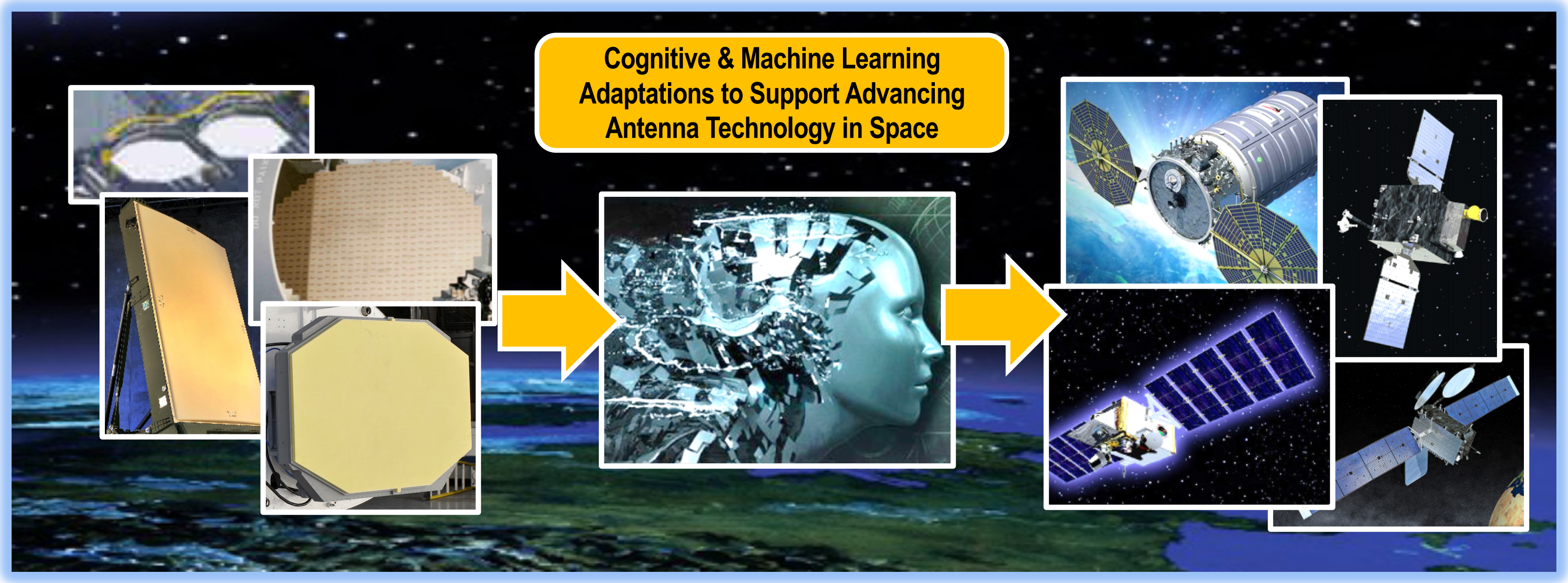
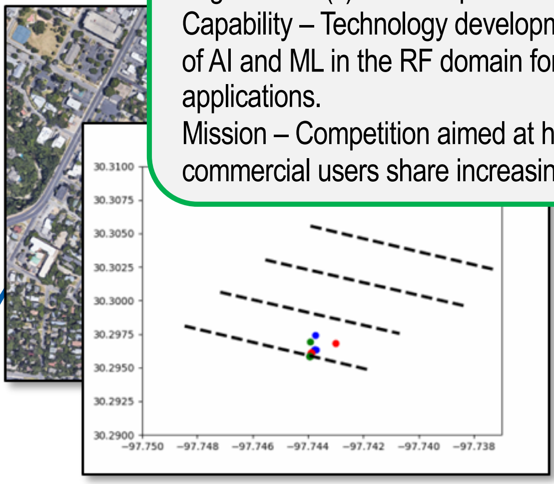


Image Sources: Northrop Grumman

Machine Learning Pedigree and Examples



Project – Spectrum Challenge
Organization(s) –Northrop Grumman
Capability – Technology development and integration of AI and ML in the RF domain for future DoD applications.
Mission – Competition aimed at helping military and commercial users share increasing less bandwidth.

AFRL

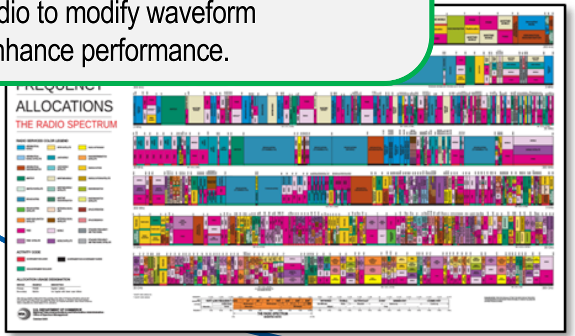
CMC

Project – Cognitive Mission Computer (CMC)
Organization – Northrop Grumman
Capability - Framework for Artificial General Intelligence with a repository of AI and machine learning algorithms

DARPA

SSC Shared Spectrum Company

Project – Spacecraft Cognitive Antenna Development Design Study
Organization(s) – SSC & Northrop Grumman
Capability – Cognitive antenna that can sense and transmit RF signals in the K- and Ka-band and cooperate with a radio to modify waveform characteristics to enhance performance.



RNC

Project – Resilient Network Controller (RNC)
Organization – Northrop Grumman
Capability - Adaptive, spectrum-aware, network management tool
Mission – Extends capability of Gateway Manager into heterogeneous network management

Source: NG RAIN Summit

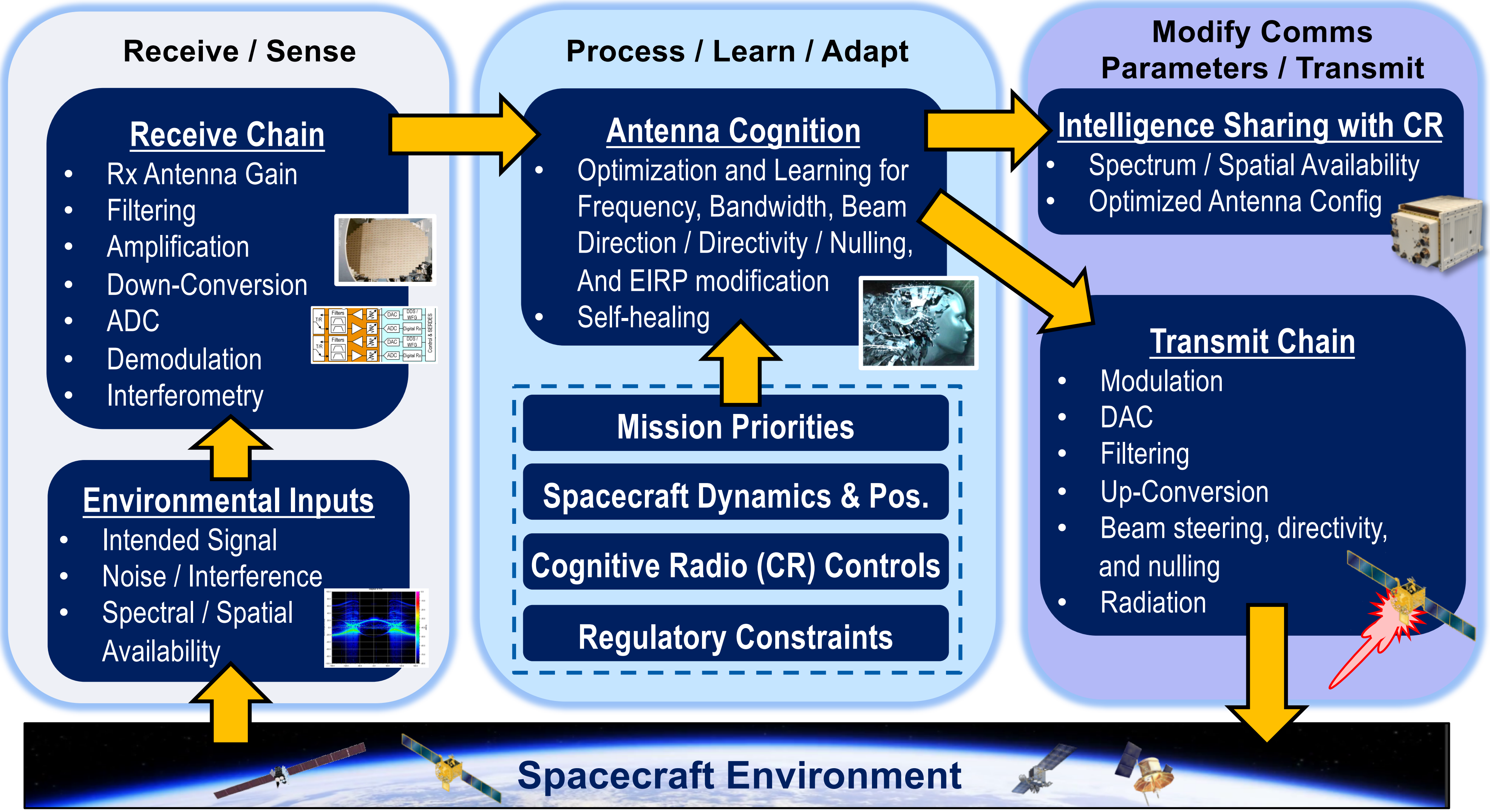
Image Sources: Northrop Grumman

Cognitive Antenna Motivation

- ***Cognitive Radio (CR):*** Defined as a radio with the ability to change its transmitter parameters based on interaction with the environment in which it operates, Source: Federal Communications Commission (FCC).
- ***Cognitive Antenna (CA):*** Defined as an environmentally perceptive antenna that can dynamically allocate bandwidth and / or adjust beam direction and directivity (beamwidth), EIRP, provide beam nulling, etc. to optimize spectral, spatial and temporal resources to complement cognitive radio technology, Source: National Aeronautics and Space Administration (NASA).

No.	Category	System Goals
1	Frequency	The Cognitive Antenna shall operate anywhere from 18 GHz to 33 GHz.
2	Bandwidth	The Cognitive Antenna shall have an adjustable bandwidth from 10 MHz to 200 MHz.
3	Beamwidth	The Cognitive Antenna shall support an arbitrary beamwidth for variable data rates.
4	Coverage	The Cognitive Antenna shall provide Hemispherical coverage.
5	Beams	The Cognitive Antenna shall support at least four (4) independent beams.
6	EIRP	The Cognitive Antenna shall support variable EIRP dependent on use case applications.
7	Nulling	The Cognitive Antenna shall provide directional nulling to minimize interference.
8	Power	The Cognitive Antenna shall support low power per channel, e.g. <500 mW where feasible.
9	Interoperability	The Cognitive Antenna shall be interactive with a Cognitive Radio.

Cognitive Mission Workflow



Receive / Sense

Receive Chain
- Rx Antenna Gain
- Filtering
- Amplification
- Down-Conversion
- ADC
- Demodulation
- Interferometry

Environmental Inputs
- Intended Signal
- Noise / Interference
- Spectral / Spatial Availability

Process / Learn / Adapt

Antenna Cognition
- Optimization and Learning for Frequency, Bandwidth, Beam Direction / Directivity / Nulling, And EIRP modification
- Self-healing

Mission Priorities

Spacecraft Dynamics & Pos.

Cognitive Radio (CR) Controls

Regulatory Constraints

Modify Comms Parameters / Transmit

Intelligence Sharing with CR
- Spectrum / Spatial Availability
- Optimized Antenna Config

Transmit Chain
- Modulation
- DAC
- Filtering
- Up-Conversion
- Beam steering, directivity, and nulling
- Radiation

Spacecraft Environment

Cognitive Antenna mission is to adapt to / learn from the environment and dynamically adjust its parameters to improve end-to-end communications performance.

Image Sources: Northrop Grumman

Example Interference Mitigation Scenario with Cognitive Antenna

① ISS transmits science data to Near Earth Relay (NER) for forwarding to NASA SCaN gateway.

② NER receives ISS science data with sufficient link margin for healthy comms.

③ Interferer begins transmitting within NER Rx channel / Rx beam disrupting ISS ←→ NER comms and impairing NASA data collection efforts.

④ NER cognitive antenna senses / characterizes interference and optimizes antenna parameters for ISS ←→ NER link while providing beam nulling in direction of interferer. Cognitive antenna learns to implement optimal configuration for future flybys of interferer and other similar interferers.

⑤ NASA mission experiences improved science data collection rates.

Legend

↔ NER Uplink / Downlink

↔ Interference

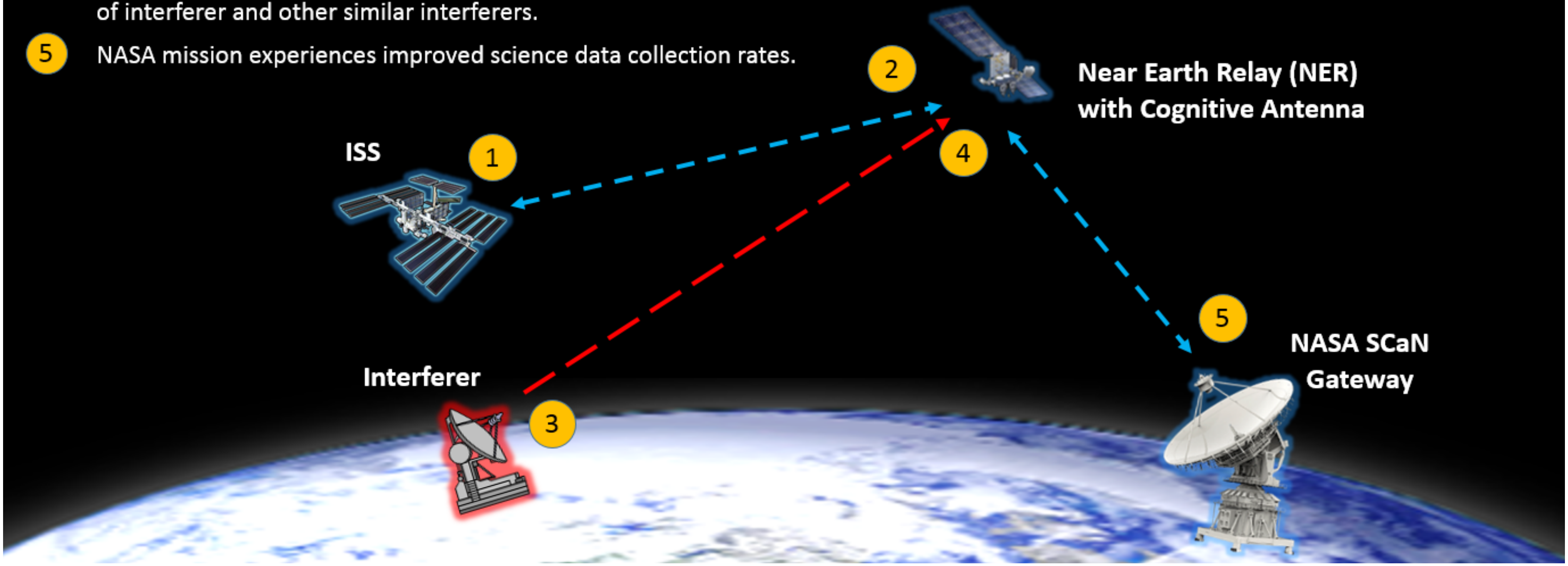
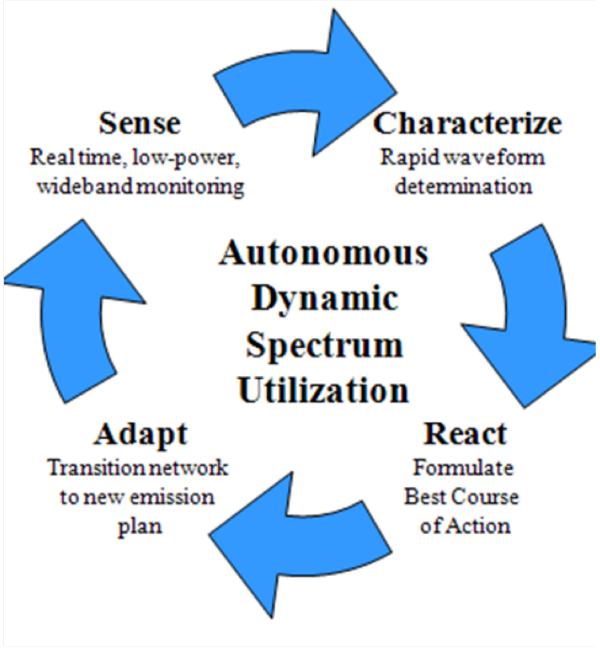


Image Sources: Northrop Grumman, CATSATs Overview. 2019. NASA

Advanced Autonomous Dynamic Spectrum Access (DSA)

- **DSA:** A spectrum sharing approach that provides **real-time** conditional access to spectrum that would otherwise be unavailable
- Conditional access is based on spectrum policy constraints and local spectrum utilization to minimize cross-system interference
- DSA technology enables radios to share **multiple frequency bands** without interfering with legacy and otherwise protected systems
- Frequency adaptation maintains and restores network topology in **dynamic spectrum conditions**
- Decentralized, autonomous, follows commander's intent and spectrum manager's policy



Sense
Real time, low-power, wideband monitoring

Characterize
Rapid waveform determination

Autonomous Dynamic Spectrum Utilization

React
Formulate Best Course of Action

Adapt
Transition network to new emission plan

SSC's DSA provides autonomous decentralized operations for greatly increased network survivability.

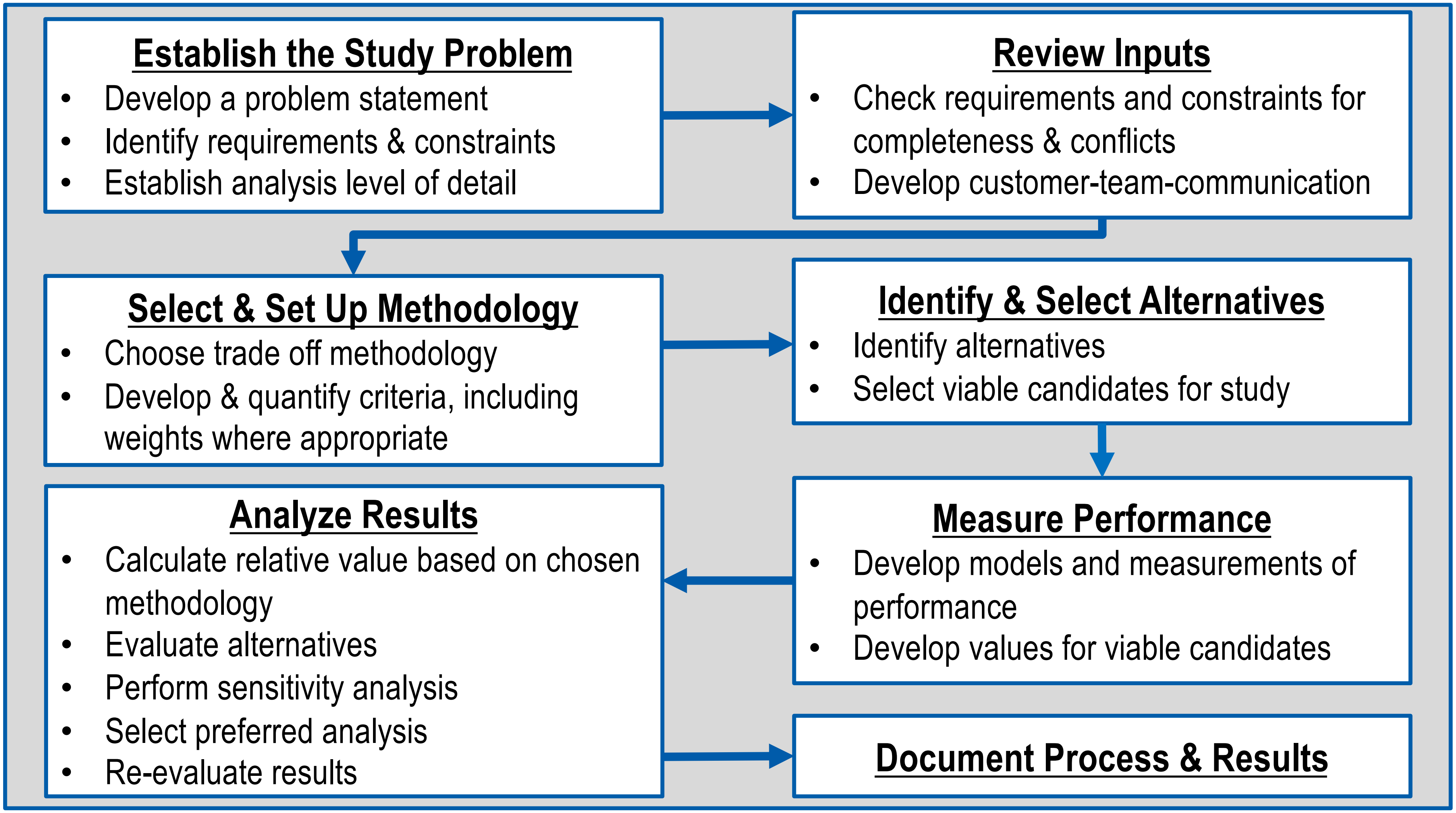
Image Sources: Shared Spectrum Company

State-of-the-Art Survey – Exploring Potential Algorithm Implementations for the Cognitive Antenna

Algorithm	Description	Applicability to Cognitive Antenna
Bayesian Learning	Updates beliefs about elements in the system based on observations	Estimation of other secondary user activity in a repeated auction for spectrum access[1]
Hidden Markov Model (HMM)	A process of deriving a model of states, observations probabilities, and state transitions	Prediction in spectrum sensing, decision, sharing, and mobility[2]
Support Vector Machines (SVM)	A classifier that learns given a function (separation shape) or kernel enabling classification of complicated data spaces	Signal identification[3], protocol identification[4]
Multilayer Perceptron Neural Network	Learns non-linear transformation of inputs to produce outputs with real values, classifications, or action selections	Beamforming capability driven by neural network elements[5];
Convolutional Neural Network	Neural network performing the same set of operations (e.g. filters) over all elements in an array	Indoor localization[6]; direction of arrival estimation[7]; proposed: receive processing for an AESA where local signal deviation and dynamics may indicate informative environmental effects
Recurrent Neural Network e.g. Long Short Term Memory (LSTM)	Prior states enable learning and processing of temporal patterns	Proposed: Training neural network receive beamformer / nulling parameter selection given prior spatial-temporal signal and using SINR for reinforcement
Reinforcement Learning (Q-Learning)	Estimate system state and policy for parameter / action selection given the estimated state; learn using positive and negative reinforcement	

State-of-the-art cognitive communications algorithms provide a vast trade space for Cognitive Antenna selection.

Trade Space Evaluation Process



Establish the Study Problem

- Develop a problem statement
- Identify requirements & constraints
- Establish analysis level of detail

Review Inputs

- Check requirements and constraints for completeness & conflicts
- Develop customer-team-communication

Select & Set Up Methodology

- Choose trade off methodology
- Develop & quantify criteria, including weights where appropriate

Identify & Select Alternatives

- Identify alternatives
- Select viable candidates for study

Measure Performance

- Develop models and measurements of performance
- Develop values for viable candidates

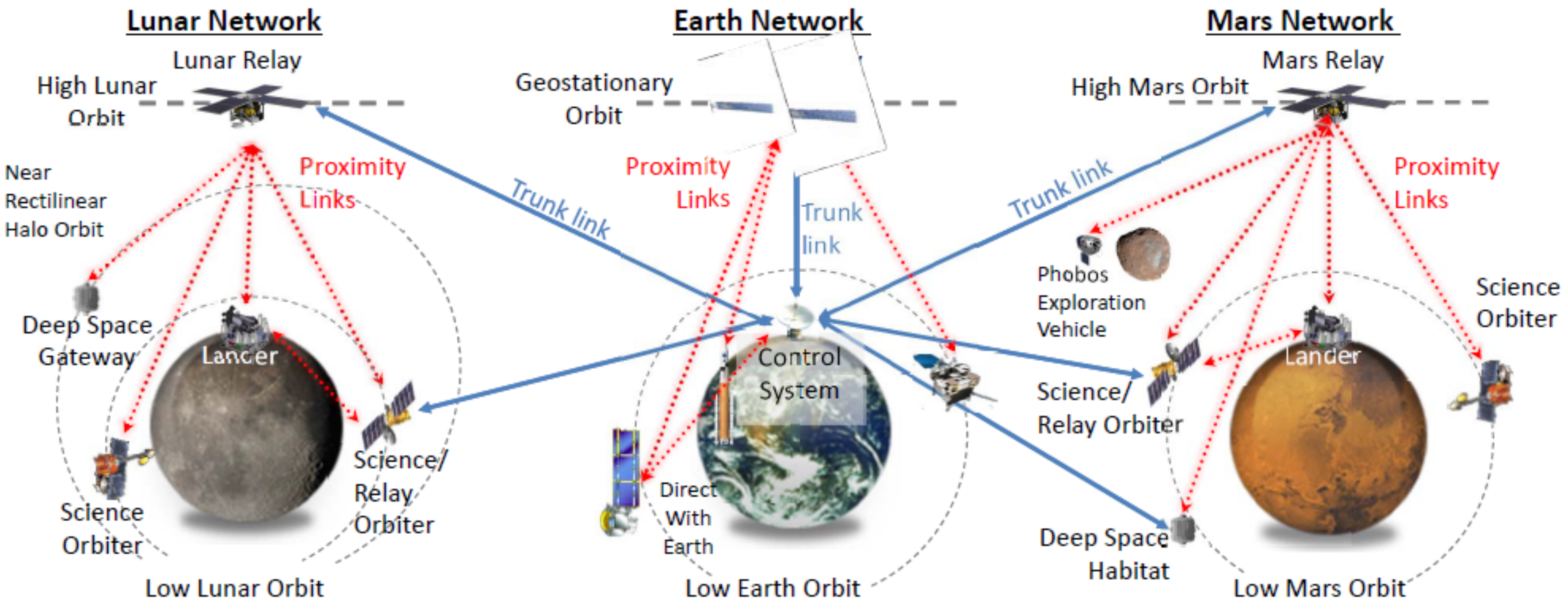
Analyze Results

- Calculate relative value based on chosen methodology
- Evaluate alternatives
- Perform sensitivity analysis
- Select preferred analysis
- Re-evaluate results

Document Process & Results

Through an agile, proven-trade evaluation process and utilization of internal engineering expertise, we will determine the feasibility of a Cognitive Antenna that meets / exceeds NASA's goals.

Vision for the Future - Next Generation SCaN Architecture



- While the Near Earth Network (NEN) is the primary focus of this feasibility study, Lunar and Mars architectures are also of high interest for a cognitive antenna application and will be explored.
- The benefits of autonomous communications optimization and learning extends beyond our planet and has the potential to greatly enhance mission resilience and overall performance.

Image Source: Next Gen SCaN Architecture. 2018. NASA

Summary

- As cognitive radio technology becomes more prominent in the space communications domain, it is imperative that a complementary **ultra-wideband cognitive antenna** is developed.

- Northrop Grumman and Shared Spectrum Company are developing the hardware and cognitive architecture of a K / Ka-band cognitive antenna to ascertain its feasibility within the next-gen NASA SCaN architecture.

- The conclusions of this study will determine whether there is an opportunity to develop and implement a **cognitive antenna technology demonstrator.**

Cognitive and machine learning algorithms will be critical for future space based systems to optimize communications in complex, dynamic environments.

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Abstract

- With the emergence of more complex space systems, there is a strong need to optimize network and data link capacities that will work in concert with cognitive radios to manage the spectrum effectively. A cognitive antenna for this matter will be an environmentally aware antenna that can manage bandwidth, beam direction and directivity, equivalent isotropically radiated power (EIRP), and nulling to improve spectral, spatial, and temporal resources and complement cognitive radio technology. We propose to survey different artificial intelligence and machine learning techniques for the purposes of aggregating data from various sources (e.g. cognitive radio, environment, instrumentation, etc.) that can be utilized to facilitate smart decisions about how to configure a complex phased array to ensure threshold link performance is achieved. Furthermore, we will explore where the cognition controlling algorithms should reside within the highly integrated space system to yield higher communications performance benefits.

Author Biographies

Samuel Vineyard received his B.S. in Electrical Engineering at the University of California, San Diego (UCSD) in 2017 with an emphasis on Machine Learning. He is currently a Systems Engineer for the Communications and Signals and Intelligence (Comms & SIGINT) Operational Unit (OU) at Northrop Grumman. His work has focused on developing advanced low Technology Readiness Level (TRL) communications and networking systems for applications spanning across ground, air, underwater, and space domains. He consistently supports Comms and SIGINT OU proposals for next generation military systems.

Suzanna LaMar received her B.S. in Electrical Engineering at the University of San Diego, CA in 2001. She received her M.S. in Electrical Engineering with an emphasis in Signal and Image Processing at the University of California, San Diego (UCSD) in 2006. She is currently the Chief Engineer for the Communications and Signals and Intelligence (Comms & SIGINT) Operational Unit (OU) at Northrop Grumman supporting early technology developments and maturation. She has extensive experience in radio frequency engineering and network communications where her work has concentrated on research and development projects for advanced military systems. Suzanna LaMar is an Northrop Grumman Technical Fellow.

Todd Gillette received his B.S. in Engineering and B.A. in Computer Science at Swarthmore College in 2003. He received his Ph.D. in Neuroscience from George Mason University in 2015 with a focus on informatics applied to neuronal morphology. Todd recently graduated the Northrop Grumman Future Technical Leader (FTL) program, having provided systems engineering support on the F-35 CNI and Comms & SIGINT OU proposals and IRAD, and is now heading to Baltimore to apply machine learning and cognitive approaches with CIMS and Advanced Intelligent Systems (AIS). Todd is a certified INCOSE ASEP.