Cognitive Networking with regards to NASA's Space Communication and Navigation Program

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Abstract — **This report describes Cognitive Networking and its application to NASA's Space Communication and Networking (SCaN) Program. This report clarifies the terminology and framework of cognitive networking and provides some examples of cognitive systems. It then provides a methodology for developing and deploying cognitive networking techniques and technologies. Finally, the report attempts to answer specific questions regarding how cognitive networking could benefit SCaN. It also describes SCaN's current and target networks and proposes places where cognition could be deployed**.

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1.0 EXECUTIVE SUMMARY

The goal of this one-year effort is to answer the following questions posed by NASA's Space Communications and Navigation (SCaN) Program concerning Cognitive Networking.

- What is cognitive networking? What are the future benefits for NASA? Which nodes would use cognitive networking? Would all nodes be equally cognitive? Could some nodes be non-cognitive?
- How would cognitive networking concepts fit into the SCaN network?
- How would the network learn and retain knowledge?
- Where does cognitive networking integrate into software-defined radios?
- What would the dialog between nodes be like and what type of information would be exchanged?
- How will loss or degradation of a node be handled?

What is cognitive networking? A cognitive network must include learning mechanisms. True learning requires that mistakes be made. Learning remains one of the challenges in artificial intelligence research. These tenets are examined as some incorrectly equate cognitive networks with rules-based dynamically adaptive networks.

What are the future benefits for NASA? A cognitive network can adapt to continuous changes rapidly, accurately, and automatically [Haigh11, Haigh12] The intelligent and judicious application of artificial intelligence to SCaN network systems would be expected to:

- Reduce network operating costs,
- Provide more dynamic, flexible user services,
- Increase performance and reliability, and
- Increase security and resiliency.

Only a cognitive network can be aware of its performance requirements, determine if these requirements are being met, and autonomously revise system configurations to better meet them. Defining performance expectations prior to integrating cognitive systems elements will help to further define the benefits from a SCaN operational perspective.

Which nodes would use cognitive networking? In order to fully evaluate the use of cognition in a networked system it is necessary to have a complete, detailed network diagram, operational procedures, security configurations, and network goals. Given the size and complexity of SCaN's integrated operations network, undertaking this analysis was determined to be beyond the scope of this activity. SCaN has invested in the development of Department of Defense Architecture framework (DODAF) documents for the current system (as is) view and target system (to be) views. These documents, coupled with the additional information listed above, will be extremely valuable to future efforts aimed at system automation. A well-architected and documented network greatly simplifies the infusion of cognition.

Would all nodes be equally cognitive? It is not necessary for all nodes to have the same level of cognition.

Could some nodes be non-cognitive? Yes.

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How would cognitive networking concept fit into the SCaN network? Given the size of SCaN's network(s) and varying operational conditions, automated artificial intelligence approaches have the potential to configure, manage and repair the SCaN network(s) faster and more efficiently than a human operations team [Haigh11, Haigh12].

How would the network learn and retain knowledge? It is assumed that intelligent agents (with local storage) will be integrated into the networked systems. The specifics on how these devices will be deployed will require additional design and operations information. The keys to understanding how the network will learn and retain knowledge are: 1) defining the measurement parameters that can and/or should be collected in each system; and, 2) determining which controls need to be made available for the cognitive machine to control and manipulate.

How does cognitive networking integrate into software defined radios? SDRs integrate and become a key element of the larger, cognitive network. The Software Defined Radio (SDR) must expose measurable parameters and dependencies and provide access to configuration controls. In this manner, the local cognitive engine will be able to manipulate the SDR to obtain the desired effect via continuous measurement and adaptation control.

What would dialog between nodes be like and what type of information would be exchanged? The first step is to identify the candidate system. The next step will be to determine if information exchanges will be between layers of a local system or between systems. The final step is to determine what information is required for exchange. Within a system, information may be exchanged via memory pointers of registers. Between systems, some standard application protocols may need to be developed or one may find commercial or open source software or standards that could be applied. Prototyping a subscale candidate system within the entire SCaN network infrastructure would probably be the most reasonable initial approach.

How will loss or degradation of a node be handled? One may be able to route around a node, reduce traffic through a node and/or repair the node once the problem has been identified. The solution will be largely dependent on the particular network or network section affected.

The questions posed by the SCaN program were very useful in capturing the overall or "big picture" view of cognitive networking and implications. However, for something as complex as the entire SCaN Network(s), additional questions need to be addressed:

- What does the network really look like?
- What are the limitations of the network?
- Where should automation be placed in the SCaN Network(s)?
- Where should one put autonomy?
- What gains will automation and autonomy provide SCaN?
- What is the potential cost/benefit that cognition provides?

The Way Forward

The next steps required to move Cognitive Networking forward follow below in order of operation:

- Develop a core cognitive networking research team focused on basic Artificial Intelligence[1] and Machine Learning as it applies to SCaN Networks. This is long-term research requiring at least a team of 4 or 5 full-time researchers.
- Define and analyze the current and future integrated SCaN network architecture including all machines, interfaces, and protocols used.
- Identify the system goals.
- Identify what parameters are exposed, what should be exposed as well as what controls are accessible (and what controls should be accessible).
- Identify measurement points that provide insight as to whether or not the system goals are being met.
- Automate a candidate system to gain a sufficient understanding of how that system interacts with others. Determine the AI methodologies that may improve system performance.
- Implement and deploy cognition into the automated system and measure performance to determine what gains have been obtained and at what cost.

Two reasonably bounded problems have been identified which may provide early benefit to the SCaN program are: 1) investigate the use of cognition toward scheduling and/or configuring of SCaN's major assets within either the Near Earth Network (NEN), the Space Network (SN), or the Deep Space Network (DSN); and, 2) apply cognition to point-to-point radio-links.

2.0 INTRODUCTION

The following report is the output to a one-year task given to the Networks and Architectures Branch at NASA Glenn Research Center by the NASA Space Communication and Navigation (SCaN). The goal of the task was to answer the following questions and put together a 5-year roadmap related to Cognitive Networking research.

1. What are the future benefits for NASA? Which nodes would use cognitive networking? Would all nodes be equally cognitive? Could some nodes be non-cognitive?
2. How would cognitive networking concept [Kliazovich] fit into the SCaN network?
3. How would the network learn and retain knowledge? Would does cognitive networking integrate into software-defined radios?
4. What would dialog between nodes be like and what type of information would be exchanged? How will loss or degradation of a node be handled?

Cognitive networking is an element of the NASA Office of Chief Technologist's (OCT) new Roadmap for Space

[1] The study and design of systems that perceive their environment and takes actions that maximize their probability of success.

Communications and Navigation (C&N) [Figure 1]. It supports OCT's desire for technology development and demonstrations that address NASA's Grand Challenges, one of which is to "unleash the power of machine intelligence". Cognitive networking technology also supports roadmap milestones for cognitive radios (2017), self-aware radios (2020), autonomous communications (2023) and cognitive networks (2025). From C&N Roadmap, Technology Area 5.5 (Integrated Technologies):

"Cognitive radios will be developed that will sense their environment, autonomously determine when there is a problem, attempt to fix it, and learn as they operate… …Develop a system in which each node is dynamically aware of the state and configuration of the other nodes. Today, most of the decisions in space communications and navigation are made on the ground. Communications and navigation subsystems on future missions should interpret information about their situation on their own, understand their options, and select the best means to communicate or navigate. For example, a node in such a network might be aware of the positions and trajectories of all other nodes, inferring this entirely through network communications and modeling."OCT_TA05, OCT_SRTP]

The aim of a Cognitive Networking Project would be the creation of a Cognitive Network through the incremental application of artificial intelligence to the current and future SCaN integrated network, which includes services as well as assets. The overall goal is the intelligent and judicious application of artificial intelligence to the system with the purpose of:

- Reducing network operating costs,
- Providing more dynamic, flexible user services,
- Increasing performance and reliability, and
- Increasing security and resiliency.

3.0 Cognitive Networking

Researching various articles, books and papers on cognitive networking, it is apparent that the term "Cognitive" is a new technology buzzword. "Cognitive" is "game-changing". Interestingly, even within chapters of the same book on Cognitive Networking, the definition varies greatly [Mahmound]. However, when consulting the noted recognized experts in the field, there is a common aspect: "Cognitive Networks include artificial intelligence (AI) and machine learning." In order to ground ourselves we need to first define what Cognitive Networking "is" and "is not".

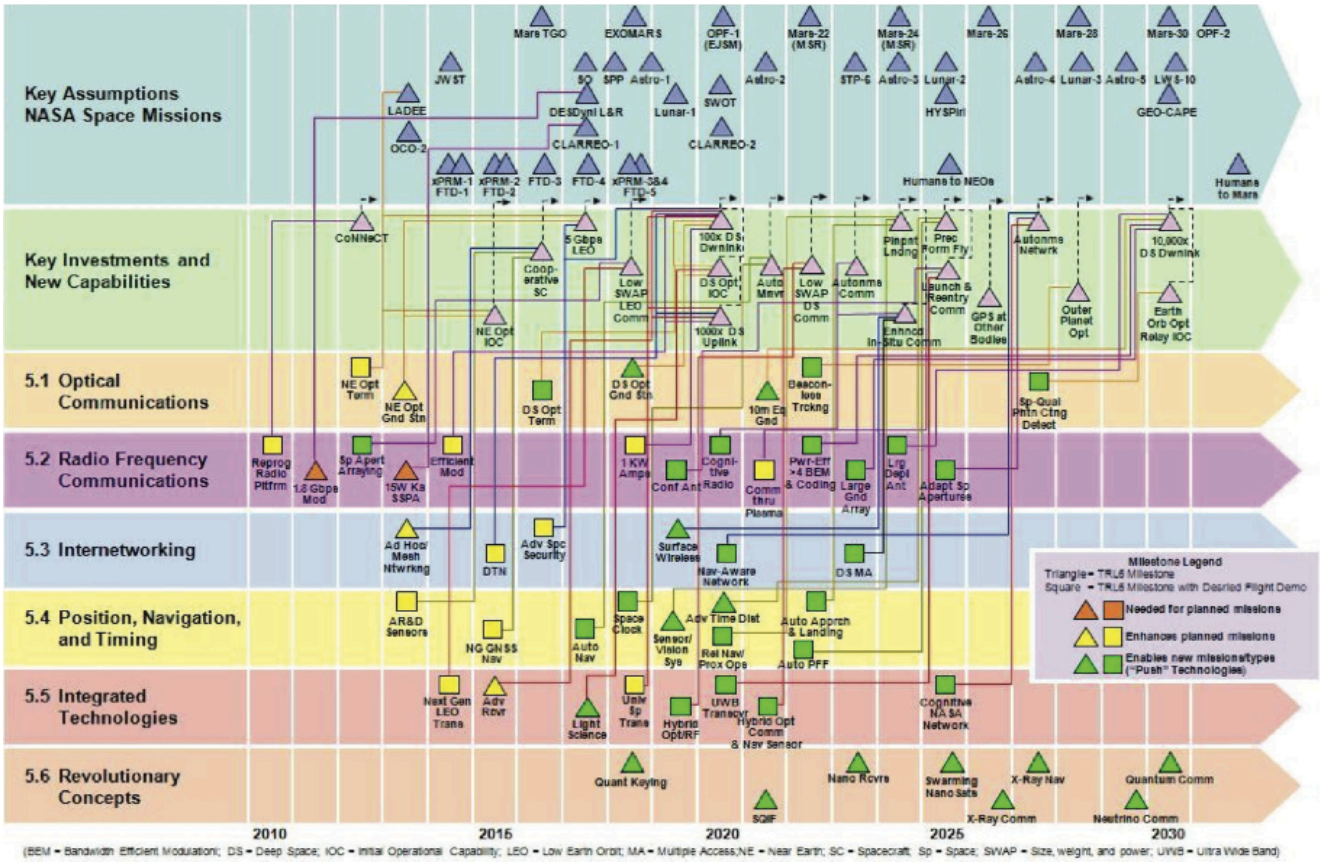

Figure 1 - NASA Space Communication Roadmap

3.1 What is Cognitive Networking?

The two descriptions that we feel best define cognitive networking are from R. W. Thomas el al [Thomas].

"In a cognitive network, the collection of elements that make up the network observes network conditions and then, using prior knowledge gained from previous interactions with the network, plans, decides and acts on this information. Cognitive networks are different from other "intelligent" communication technologies because these actions are taken with respect to the end-to-end goals of a data flow. In addition to the cognitive aspects of the network, a specification language is needed to translate the user's end-to-end goals into a form understandable by the cognitive process. The cognitive network also depends on a Software Adaptable Network that has both an external interface accessible to the cognitive network and network status sensors. These devices are used to provide control and feedback."

"A cognitive network has a cognitive process that can perceive current network conditions, and then plan, decide and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals."

A cognitive network is guided by network end-to-end goals and policies. It can reason and learn to improve overall system performance. It uses experience to create novel rules and actions. It takes advantage of unpredicted events. It can predict events and act accordingly. It allows new knowledge to be inferred from experience and resolves problems with the appropriate solution (rules-based or machine learning).

A cognitive network could enable networks to: reconfigure network and radio operating parameters; monitor, diagnose and repair system level anomalies; and, provide autonomous security mechanisms such as detecting and isolating network intruders. There is an important caveat to consider. It is imperative to remember, that a cognitive network learns and true learning requires that mistakes be made. Learning remains one of the challenges in artificial intelligence research.

3.2 What Cognitive Networking is not.

A cognitive network is not simply a collection of cognitive/adaptive radios; but is, instead, a complex integrated end-to-end system including, but no limited to: radios, routers, scheduling systems, antennas, protocols, and applications.

Adding confusion, the terms oftware Defined Radio (SDR) and Cognitive Radio are often used interchangeably – incorrectly so. An SDR is a radio that puts much of the radio functionality, including waveform synthesis and perhaps intermediate frequency (IF) and Radio frequency (RF), into the digital domain using technologies such as field programmable gate arrays (FPGAs). This allows for great flexibility and re-programmability of the operation.

A Cognitive radio goes one step further by incorporating an cognitive engine (designed to emulate key human cognitive elements such as learning, motivation and reasoning). A Cognitive Radio then utilizes the reprogramability and reconfiguration aspects of the SDR to adapt the radio to perceived changes in the operating environment as well as the system goals. The cognitive radio maintains situational awareness (through feedback) and makes behavior choices from the feedback and external inputs. It then monitors and measures the performance in order to learn how better to adapt.

It should be noted that having a radio that performs Dynamic Spectrum Access (DSA) does not necessarily make it a cognitive radio. DSA can be performed via some rules-based or central control-based system. Only if learning is involved does the radio become cognitive. In the same manner, having a network of radios that use cross-layer communications does not make it a cognitive network. "Cognitive networks are likely to employ cross-layer optimizations and act simultaneously on parameters belonging to multiple layers in the protocol stack. However, cognitive networks are more than cross-layer design." [Thomas]

It has been argued by some that network routers are cognitive and that the TCP protocol is cognitive. Both have memory and sense their environment to infer global situational awareness that provides an input to fixed algorithms to adapt the routing or transmission to the perceived conditions. Is this learning? Perhaps. However, given the same sequence of input conditions (albeit difficult to do in networking) one will always receive the same output. In other words, the algorithms and weighting of parameters within those algorithms is fixed. Thus, we argue that a group of routers running routing protocols and routing algorithms is not a cognitive network and that the TCP protocol is not cognitive. Rather, we view these along the lines of reflexes. For example, when a child touches something hot, their reflexes make them pull their hand away. The learning process (cognition) is what happens over a much longer timeframe. Eventually the child will feel the heat radiating from an object and learn via some reasoning process that that touching a hot object is painful and causes damage (and thus is an undesirable action). For a routing protocol to be cognitive, the weighting within the algorithms or the algorithms themselves will need to autonomously adapt to environmental conditions. Work is ongoing in this area; in particular, mobile ad hoc networking has been the subject of much research [DLEP, modemPLA]. One way that the TCP protocol could become cognitive is if the actual TCP algorithm (for which there are many) would adapt per information flow or via an ability to sense the network characteristics and determine which TCP algorithm best suits those conditions such as using more aggressive congestion control (or no congestion control), depending on the current situation (deployment environment).

3.3 Examples of Cognition

The following two examples of cognitive systems have been chosen to show the complexity involved in what are relatively simple bounded problems. The entirety of cognitive networking is nearly unbounded. Thus, initial progress must be confined to subsets of the entire network in order to understand the system well enough to infuse cognition.

The first example is of machine learning from "Resilient Machines Through Continuous Self-Modeling" [Bongard]. Here, we strive to provide an understanding of what cognition is and what it takes to learn. In this example, the goal of the simple machine is to move forward. "The legged robot learned how to move forward based on only 16 brief self-directed interactions with its environment. These interactions were unrelated to the task of locomotion, driven only by the objective of disambiguating competing internal models." This machine uses actuation-sensation relationships to indirectly infer its own structure, and it then uses this self-model to generate forward locomotion. A short video is available that shows the experiments. It can be found at:

http://ccsl.mae.cornell.edu/research/selfmodels/videos/resilient_720x480.wmv

Note: Learning is not perfect and that many mistakes and trials are necessary before a reasonably good result is obtained. The important items that this research shows are that a cognitive system using 16 simple self-directed interactions performed quite well whereas "Without internal models, robotic systems can autonomously synthesize increasingly complex behaviors or recover from damage through physical trial and error, but this requires hundreds or thousands of tests on the physical machine and is generally too slow, energetically costly, or risky."

The second example illustrates how a biological system learns and how multiple biological systems interact to reach a desired "Goal". Note, there must be some "Goal" for which the entire system is attempting to reach. In this example, the goal is to get the puppy to go to its mat. The link below is to a video that illustrates this in the first 6 minutes of the video2:

http://www.thedogtrainingsecret.com/the-first-step/

Note the amount of feedback required for training. The goal of the controlling system, the trainer, is to get the subsystem (the puppy) to perform at its optimum. In this case, to get the dog to behave according to the trainers desires – specifically to "go to the mat."

It is imperative that the controller understands the behavior of the subsystem in order to provide proper stimuli to train the subsystem and obtain the desired outcome. In this case, the subsystem is the puppy and the stimuli are attention (or lack thereof) and food (treats).

The algorithms are very simple.

Subsystem (Puppy's) Algorithms:

- I am a pack animal. I want to be accepted as part of the pack. I hate being ignored. I will consider receiving attention as a measure of goodness.
- I like treats. I will consider receiving a treat as a measure of goodness

Controller's (Trainer's) Algorithms:

- Give dog treat when dog makes appropriate progress toward goal (sit on mat on command). Note, as the dog progresses towards the final goal, what is considered progress is modified – i.e. a weighted algorithm.
- Ignore dog if it performs inappropriate behavior (barking, nipping, etcetera).
- Having the wrong set of algorithms will make the system go unstable or end up with unintended results. For example: people often wonder why they cannot stop their dog from jumping on people or nipping or barking.

Unintended People Algorithms:

- If the puppy (or mature dog) jumps up on people or nips, than push back on them get excited and say NO.
- If the puppy continues, get more excited and push back more.

Unbeknownst to the person they are rewarding negative behavior. The problem with these algorithms is that the dog really does not understand the word "No". The dog thinks the person is playing with him because the person is giving him attention by pushing back and getting excited. The dog thinks, "Obviously the person is having fun because are excited and playing with me." The end result is the dog has trained the person to play with him by jumping up and nipping at them. The system has gone unstable.

Although neither example has direct application to the SCaN problem set, they do help to illustrate how cognitive systems interact with their environment. In a similar way, it is anticipated that future cognitive SCaN systems will interact with their environment and apply "lessons learned" to achieve a goal.

3.4 Learning

Learning requires time, memory and feedback. Learning requires that mistakes be made. Learning occurs on a much longer time scale than simple algorithms such as rules-based adaptation. One can use a cognitive system to determine algorithms and the weights that may be applied to the algorithms, thus combining the best of cognition with the best of automation and rules-base algorithms.

3.5 Why Cognition is Needed

Even simple networks can be surprisingly complex. The intricate interactions between subsystems and nodes are

[2] This is not intended to be an endorsement of the product. Rather, the video illustrates simple cognition and interaction between controller system (the trainer) and a subsystem (the dog)

difficult to model. The scale can be massive. For example, in an SDR network used in BBN's Adaptive Dynamic Radio Open-Source Intelligent Team (ADROIT) project, individual nodes had approximately 600 observable parameters as well as 400 controllable parameters. However, to minimize system complexity, the system did not expose all of the parameters, the highest was approximately 100 parameters of which 30 were controllable [Haigh08]. Because of the complexity of large networked systems, poorly understood interactions among parameters, complex temporal feedback loops and the inability to obtain full situational awareness (due to latency, constrained communications and rapid decision cycles) use of artificial intelligence (AI) and cognitive engines for network management are imperative. Human network engineers simply cannot handle this level of complexity. Modern network theory suggests that the underlying connectivity of a complex network has such a strong impact of its behavior that no approach to complex systems can succeed unless it exploits the network topology [Barbasi]. Again, human network engineers cannot handle this level of complexity.

3.6 Cultural Issues

There are a number of significant cultural issues that have to be overcome in order for Cognition and AI to be deployed in networks. Networking engineers may be reluctant to allow an outside autonomous controller to operate the network. However, for AI to realize its full potential, AI must be allowed to control the system. Thus, "failsafe" mechanisms must be developed and deployed to sense runaway conditions and prevent further performance declines or catastrophic failures. Also, traditional networking has very clear boundaries between "networks" and "applications", whereas cognitive networking blurs those boundaries. The networking engineer may be uncomfortable with this due to the complexity and their inability to accurately model and predict performance. Cognitive networking and AI need this blurring of boundaries in order to obtain full system benefit [Haigh08].

4.0 METHODOLOGY

4.1 OODA Loop

A reasonable place to begin understanding a methodology for developing cognitive systems is to understand the OODA loop [Figure 2]. OODA is an acronym for Observe, Orient, Decide, and Act. The OODA loop is attributed to Colonel John R. Boyd who developed it as in information strategy concept for information warfare [Boyd]. This is a process often applied at the strategic level in military operations as well as to understand commercial operations and learning processes. The diagram shows that all decisions are based on observations of the evolving situation. The Observed information (inputs) must be processed to Orient the system prior to making a Decision and Acting upon that decision. The Actions cause the situation to change, which, in turn, alters the inputs that are used to reorient the system. Thus there are continuous adjustments being made based on actions taken. Note, this loop does not show any learning mechanism.

4.2 Cognitive Cycle

The Cognitive Cycle (later know as the OOPDAL Loop) [Figure 3] was introduced by John Mitola in his 2000 Dissertation, "Cognitive Radio An Integrated Agent Architecture for Software Defined Radio." [Mitola2000]. OOPDAL is an acronym that stands for Observe, Orient, Plan, Decide, Act and Learn. The OOPDAL loop builds off the OODA loop and adds an aspect of planning and learning. Although originally used to describe a cognitive radio architecture, this is an open architecture framework for integrating agent-based control, natural language processing, and machine learning technology into a variety of systems (including cognitive networks). "Cognitive radio (or system) is a goal-driven framework in which the radio (or system) autonomously observes its environment, infers context, assesses alternatives, generates plans, supervises services, and learns from its mistakes." [Mitola1999]

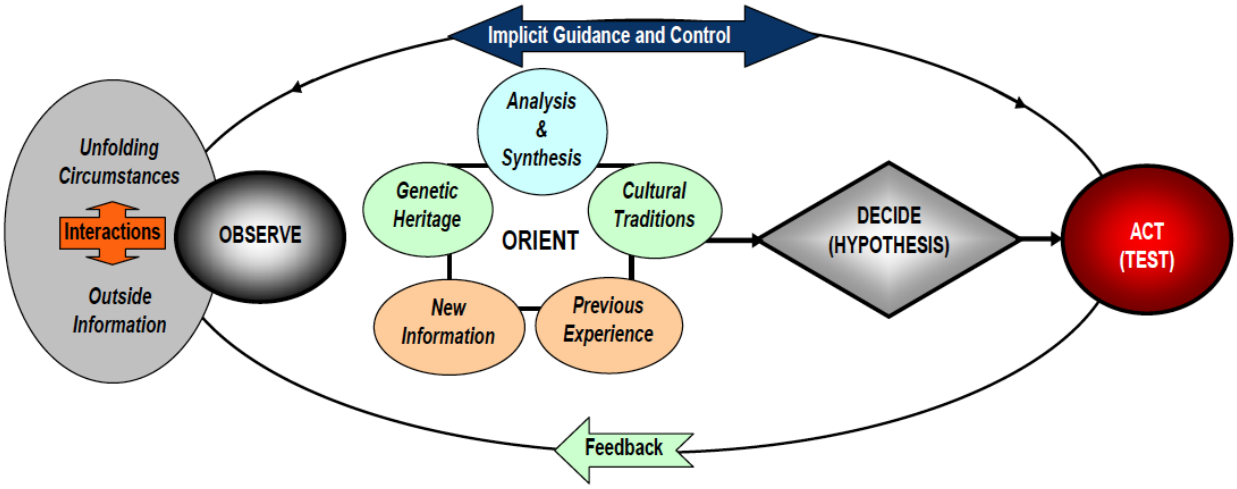

Figure 2 - OODP Loop (source - Dr. Thomas A. Lifvendahl)

During the Observation Phase, inputs are received both externally and internally to provide situational awareness. That information is analyzed in order to assess the situation (i.e. Orient, or obtain situational awareness). Once the system is Oriented, it enters the Planning Phase where goals are set depending on the situation and a variety of plans and schedules are made. During the Decision Phase, a plan is selected and the necessary system resources are allocated to achieve the plan. The Acting phase is where the plan is implemented. Within this outer loop is the Learning Phase. Learning receives inputs from the Observations, Plans and Decisions. Learning requires continuous feedback including the ability to analyze inputs (measure results) and correlate those with the previous plans and decision and assess how close the system came to reaching its goals. This information is then used to modify the system inputs and plans in order to converge on the set goals.

4.3 Approach

Before we can attempt to apply cognition to a network or system, one must thoroughly understand the system and subsystems and establish the goal or goals of the system. One needs to understand what they want the system to accomplish (it may be useful to also understand why). Thus, one needs a Concept of Operations (CONOPS). In addition, a detailed network architecture needs to be developed to the level of addressing, wiring, radios and configuration parameters. Preferably that would include all machines, interfaces and protocols. This is of primary importance because characterizing the underlying network structure is required for understanding the system. Since it may be difficult to obtain this level of detail, one strategy can be to obtain sufficient detail to identify a critical portion of the network and then go back and obtain the remaining detail at a later date (e.g. machines, interfaces, protocols, addressing, wiring, radios and configuration parameters).

Two critical elements are required to develop a cognitive network. The first is the ability to have sufficient self-awareness and situational awareness (Observe) to determine whether or not goals are being met and if one is converging on or diverging from those goals (Orient). The second is to be able to provide inputs into the system to make appropriate adjustments to the network such that the goals are obtained within some bounds (Plan and Decide). Thus, we need to identify what parameters are exposed, what should be exposed, as well as what controls are accessible and what controls should be accessible.

Since a network is such a complex entity with many intricate interactions and observable parameters, it can be difficult to understand what to observe (and what to ignore) in order to ascertain whether or not goals are being met within appropriate bounds. The use of data mining, the process that attempts to discover patterns in large data sets, is essential to distill down the number of potential observables to a manageable set. An example of this occurred in GRC's "Secure, Network-Centric Operations of a Space-Based

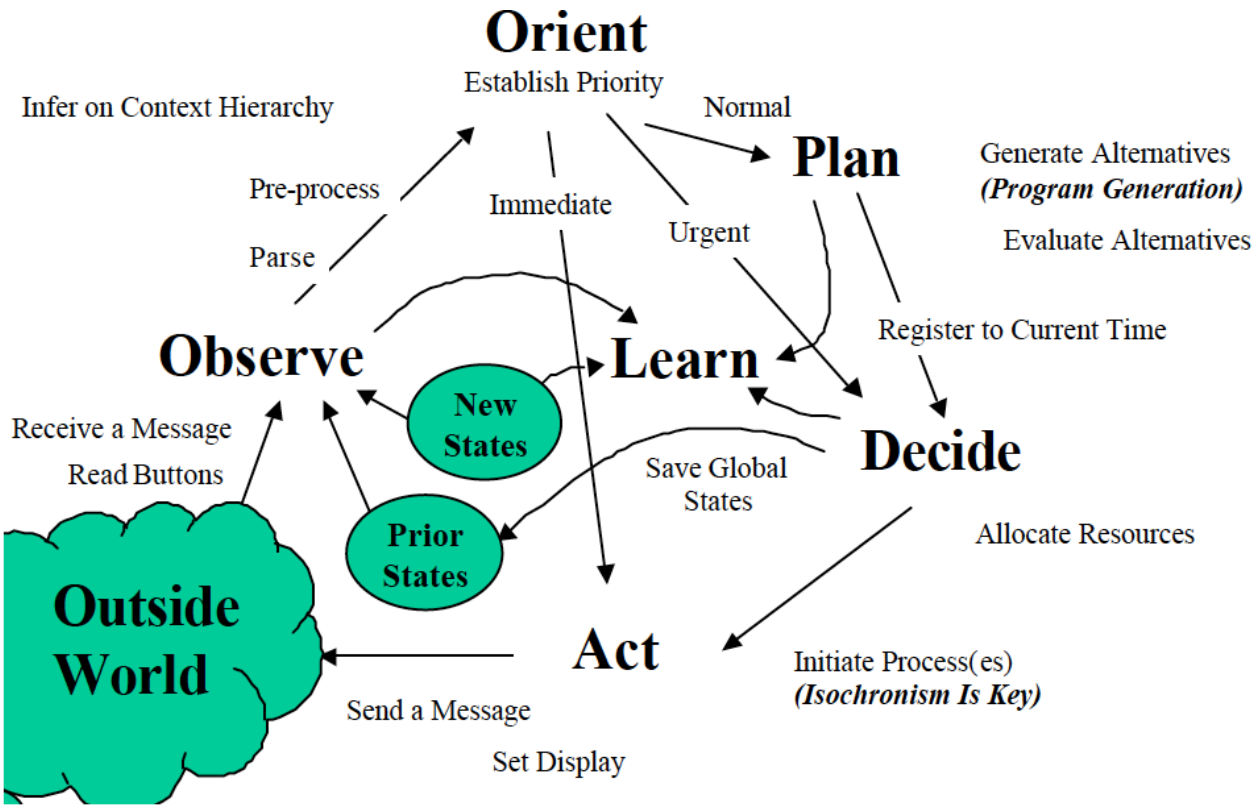

Figure 3 – Cognitive Cycle (source - Joseph Mitola III, *Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio*, PhD Thesis, Royal Institute of Technology (KTH), 2000)

Asset" mobile networking experiments [Ivancic2005]. In this experiment, a commercial router was deployed on a low-earth orbiting spacecraft. Multiple ground stations were used from various service providers with most of the assets under the control of each of the service providers. Interestingly, none of the ground assets were controlled by NASA (with the exception of the home-agent routers, located at Glenn Research Center). During the experiment, test engineers had access to hundreds of observable parameters including router statistics, modem parameters and RF equipment parameters (e.g. steering, transmitter ON, modem lock, modulation and coding formats, packet counts, frame counts). After numerous tests, trials and tribulations, it was determined that only two parameters had to be monitored to indicate everything was operational (i.e. goal was met). The first parameter was mobile network registration in the mobile-ip home agent. Additionally, if the system was not operational, observing the data communication equipment (DCE) line in the ground station router would indicate if the RF chain was operational or not. Thus, 100s of observables where distilled down to two manageable observables.

Once we understand which SCaN network system parameters are useful to observe and what inputs are available, we can begin to automate a portion of the SCaN network system. Currently SCaN's ground networks are largely statically configured. Initially, dynamic, rules-based algorithms may be deployed to gain a sufficient understanding of how various subsystems interact. By instrumenting the system and measuring performance we can obtain sufficient information to help determine which AI methodologies to deploy that may improve system performance. Most likely a rules-based system would be followed by supervised learning system to gain experience and confidence in the cognitive system. This would be followed by a fully autonomous unsupervised learning system. Finally, once we implement and deploy the AI cognitive system (and measure the performance) we can determine what gains have been obtained over simple automation and at what cost.

5.0 NASA's SCaN Network

"The SCaN Network is the sum of NASA's space Communication and Navigation (C&N) infrastructures that are managed and operated by the SCaN Program, regardless of the evolutionary phase of the network. The SCaN Network is mainly composed of the three networks: the Space Network (SN), Deep Space Network (DSN), and Near Earth Network (NEN). User missions typically negotiate services according to their mission requirements with the individual network, or set of networks that can provide them.

The NASA space communications infrastructure as a whole offers an extensive repertoire of capabilities, including launch/tracking range support, early orbit tracking, routine user mission services, data relay, emergency support, and science services (e.g., radar science). SCaN provides services to user mission platforms at locations ranging from the surface of the Earth to deep space.

The SCaN Network provides services to user mission ground systems and user mission platforms. The standard ground end point for delivery of service is typically at the user mission operations center (MOC), and the end point in space is the user mission platform." [SRD].

Note: SCaN's current and future architectures are described in the Architecture Development Document [ADD], which provides a high-level overview.

5.1 SCaN Goals

Since SCaN's systems do not currently utilize cognition, none of the current SCaN documentation has been written in such a way as to describe what the SCaN Goals are with regards to cognitive networking [SDR, ADD]. This leads to three key unanswered questions: 1) What goals should be set for a cognitive network system? 2) What should the network measure? and, 3) What metrics should be used to determine if the goals are being met? With no formal document to draw upon, we will assume some generic goals and comment on implementation at an abstract level. The generic goals that could be addressed include:

- Reducing operations costs
- Providing more dynamic, more flexible user services
- Increasing system performance (i.e. increase information throughput – goodput)
- Improving system reliability
- Increasing system security
- Increasing system asset utilization

5.1.1 Reducing Operations Costs

It is generally agreed that in order to reduce the cost of operations one must reduce labor costs. There may be some savings in better utilization of hardware, buildings, utilities, etcetera; but they tend to be insignificant relative to the cost of labor. One way to reduce labor is to simplify the architecture and automate processes. Note, a simplified, well thought out architecture will be easier to automate, more reliable, and require much less manpower to operate than one that requires constant manual configuration. Applying cognition to automation may further reduce operations costs; however, that reduction is likely to be much less than the reduction associated with simply automating systems.

Applying cognition to reduce the cost of labor is certainly an interesting problem for a cognitive system; but one that is more related to general business than computer networking. One would have to instrument the system in a manner to enable measurement of costs relative to stimuli. The needed observables would probably be obtained from the business system database and would include labor and utilities to name a few. Determining the stimuli would be quite interesting. Control parameters could include such things as wage increases, days off, flexible work schedules or free lunches. This is not a new idea. Numerous papers exist on the topic.

5.1.2 Provide more dynamic, more flexible user services

Providing more dynamic, more flexible user services is another goal. This is a scheduling problem – how best to discover which assets are available under a certain set of conditions and schedule those assets to meet the demands of the user. Depending on the customer requirements, this may be in conflict with 5.1.1, Reducing Operations Costs. Various users will most assuredly have different demands that are also in conflict with each other. In that case the network can provide more flexibility by enabling the procurement of third party services to increase capacity. That will also mean that SCaN should assess which facilities and services it should keep and which it should outsource. Unfortunately, it is unclear how a system would be instrumented to determine whether or not the goal is being met (what observables and stimuli are available?) This topic is a major study unto itself and is probably too broad and ambiguous a goal as currently stated.

4.1.3Increasing System Performance
(Increase information throughput – goodput)

Increasing performance is certainly a goal that can be measured – particularly if performance is defined as increasing information throughput (goodput[3]). In addition, there are numerous controls that can be adjusted to effect goodput such as scheduling of assets combined with storage, and manipulating radio parameters (e.g. modulation, coding, transmission power, transmission rate, etc…). This can be done within portions of the network so as to put bounds on the problem. Simply working within the bounds of the point-to-point radio link may provide significant performance improvements. The degree that cognition will add to simple rules-based algorithms is most likely dependent on specific deployment scenarios, which could be modeled and implemented in simulations and in a laboratory environment for relatively low cost. Instrumentation and controls should be readily identifiable for this bounded system.

5.1.4 Improving System reliability

A cognitive system has the potential to improve reliability because a cognitive system has to have very good local situational awareness and most likely has additional regional situational awareness (and perhaps some global situational awareness). Thus, a cognitive system may be able to autonomously self-repair or autonomously sense a failure within the network or route around that failure. Others have demonstrated this such as BBN in their ANDROIT project [Haigh11].

5.1.5 Improving System Security

Cognitive engines have been applied to pattern recognition as well as anomaly detection. Both of these are used in intrusion detection systems (IDS). Furthermore, one can deploy distributed intrusion detection agents where each minimal agent can monitor its own reasoning and reconfigure parts of itself dynamically. Each agent makes a decision on whether a network object is acting according to its behavior specification, which is based on the security policy. These same reflective operations are provided between agents. Thus the management of the whole system is distributed and mutual [Kennedy].

Debar devotes an entire chapter to intrusion detection in cognitive networks [Mahmound]. Here three OODA loops run concurrently on three operational planes: the Policy plane, the Management plane, and the Network (Device) plane. Each plane exchanges information with the lower and higher planes. The Policy plane represents interactions between the network and its operators. The Policy plane is built around the security policies and business objectives and associated legal and technical constraints. The Management plane takes polices and analyzes and segments the policies according to enforcement capabilities and requirements. The Network plane receives policies from the management plane as configuration files.

5.1.6 Increasing Asset Utilization

Increasing asset utilization is most likely best accomplished by improving scheduling of the asset or assets. This is a fairly bounded problem with measurable outputs and realizable controls on inputs. Thus, deploying cognitive engines to perform this task is quite reasonable.

Scheduling activities are carried out in the numerous domains of industry including production scheduling, personnel and transportation. Scheduling is a particularly complex activity. From the point of view of the mathematical theory of complexity, it is considered an NP-Difficult problem[4]. Within scheduling, many experts have noted that up to 90% of this time is devoted to the identification of the relevant constraints, with only 10% spent on building the schedule. Thus, it is extremely important to be able to identify relative constraints. Furthermore, schedulers often seek "satisfactory" performance rather than optimal results as this provides a greater degree of freedom and allows schedulers to perform well, even in very complex situations with often-conflicting objectives (constraints). Also, the number of variables that have to be controlled is, in fact, not a very good indication of complexity. This is because the more resources available, the greater degrees of freedom that exist [Cegarra].

Applying cognitive engines to scheduling has great promise due to the numerous degrees of freedom available, the imprecise measure of "goodness" and the ability to terminate the solution once a "satisfactory" result has been obtained.

[3] Goodput is useful information throughput and does not include protocol overhead, coding, or retransmission.

[4] NP refers to "nondeterministic polynomial time." NP is one of the most fundamental complexity classes in computational theory.

5.2 SCaN's Current Architecture.

In SCaN's current architecture, known as Phase 0, SCaN is an equipment interface provider, not an Internet Service Provider (ISP) or even a Network Service Provider [Figure 4]. Under Phase 0, SCaN manages radios, ground stations, and the Earth Based Relay Element (EBRE) also known as the Tracking and Data Relay Satellite System (TDRSS). Missions use SCaN as a pass through. The mission controls all addressing of mission assets. In fact, this is the basis for current CCSDS datalink protocols [CCSDS135]. As such, there is no unique or global addressing understood by intermediate points and no easy way to route end-to-end (everything has to be manually configured). The system is extremely limited since addressing is mission unique and forwarding is manually configured albeit perhaps with scripts; thus, it is difficult to put cognition into the communication path (except, perhaps, within the radios themselves).

It is also important to note that the CCSDS Space Packet Protocol has no global addressing scheme making it difficult to automate routing. Rather, it is switchable at the data-link layer with forwarding tables that need to be manually configured. Thus, when the Space Packet Protocol is used for end-to-end routing, Space Packets are usually transferred with a Space Link Extension (SLE) Service in the ground subnetwork (SLE enables extension of the datalink between spacecraft and mission operation by effectively encapsulating the datalink into Internet Protocol packets and routing over the Internet).

Having a well-architected network will greatly simplify infusion of cognition. As stated in the Space Internetworking study, "There is no existing SCaN capability or network infrastructure to support Space Internetworking (SI). Since users do not see SI implementations or plans for implementation, their confidence that SI capability will work as advertised is reduced. Lack of SI infrastructure also reduces future user confidence that the SI capabilities will be available when they are needed to support future missions. However, the Space Network Ground Segment Sustainment (SGSS) project is holding requirements to implement IP over Advanced Orbiting System Encapsulation (AOS/ENCAP) and High-Level Data Link Control (HDLC) for forward and return links – requirements that can be leveraged for implementation of SI." [SI] [5]

5.3 SCaN's Target Architecture.

SCaN's target architecture was established in SI study during cycle 3 of the level-2 Program Systems Engineering (PSE) set of architecture studies. The focus was on establishing a reference design for implementing the Disruption Tolerant Networking (DTN) and Internet Protocol (IP) data flow capabilities internal to the network elements [Figure 4, Architecture 2]. This approach essentially covers forward and return data flows within network elements over DTN/IP. The point of the reference design was to provide meaningful information to the Goddard and JPL contractors that do the SN/NEN/DSN engineering in order for those groups to provide cost estimates. It was not the intention that Architecture 2 to be a

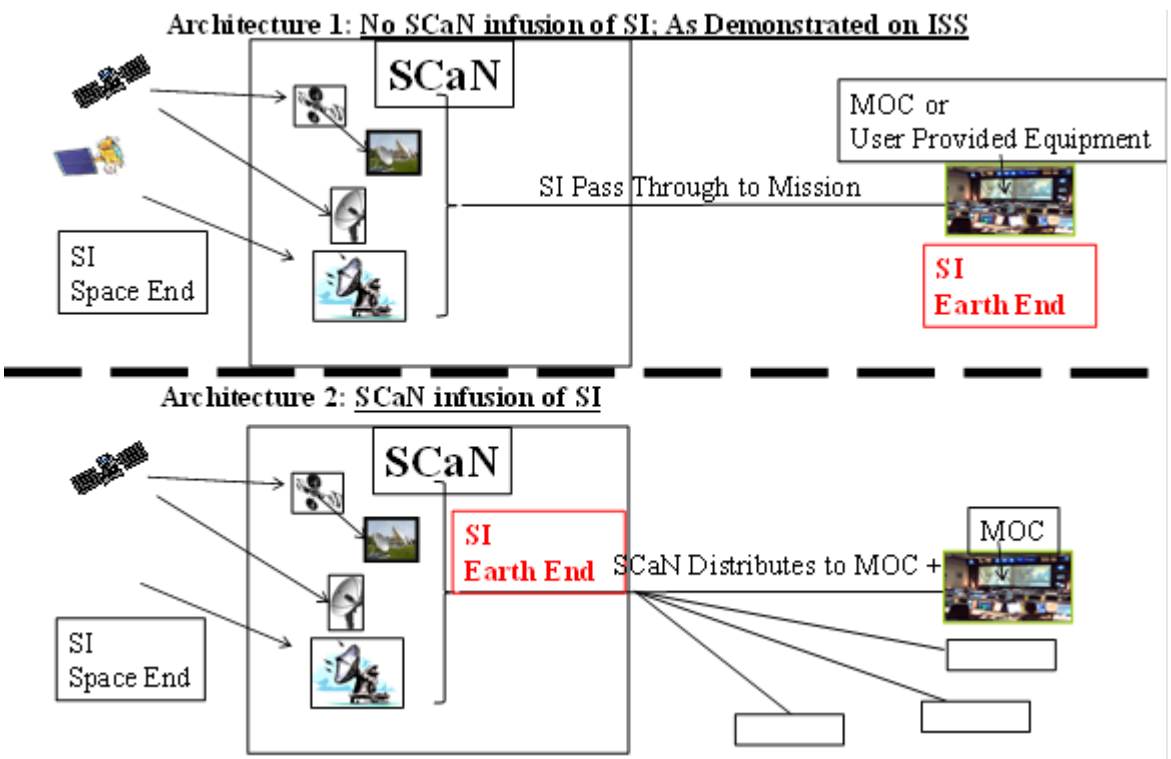

Figure 4 - SCaN Architecture

[5] Recent discussions with technical reviewers indicate that the HDLC requirement may be removed from SGSS.

prescriptive design of what to build, but rather a basis for establishing system costing data.

One requirement presented in the report drove the network architecture design and severely restricts any true networking. That requirement is "No changes at the customer interface on the space link or Mission Operations Center (MOC) sides [SI]." This implies a continued use of end-to-end CCCSD datalink protocols from MOC to Spacecraft and may preclude properly architecting IP and/or DTN networking. Unfortunately this approach results in the SI model being a "bolt-on" solution, rather than a reworking of the system. As such, it is challenging to show anything but a dramatic cost and complexity increase over the existing architecture.

Also indicated in the report is that Integrated Network Management (INM) and Integrated Service Execution (ISE) were not included in the study's technical or cost data. There were also services that an Internet Service Provider (ISP) would normally provide that were not considered. Such services include: network management, address pool management, time services (Network Time Protocol - NTP), name resolution services (Domain Name Server -DNS), routing (static or dynamic/protocols), security administration (Access Control Lists - ACLs, firewalls, Network Intrusion Detection System - NIDS, etc.) Network Management, routing, data prioritization, DTN, and security; areas where cognitive networking is likely to help.

5.4 Request for Information (RFI)

NASA Glenn Research Center issued a Request for Information (RFI) on February 15th, 2012 seeking information related to "cognitive networking" technologies related to:

- Biologically inspired networking, autonomic networking, and adaptive networking.
- The application of machine learning and distributed reasoning to network systems.
- Cross-layer design and optimization.
- Dynamic security and intrusion detection.

Responders were asked to address two key area central to our understanding: 1) the application of artificial intelligence to network systems; and, 2) quantifying the effects of added complexity to existing SCaN network systems. In particular, some of the key questions were:

- In what sense are cognitive networks truly "intelligent"? Is it possible to establish a methodology for quantifying the intelligence of these networks?
- Can cognitive networks have a strategy for establishing initial network security parameters and later dynamically modify that strategy after recognizing attempts to disrupt or suppress the data flows in these networks (or gain access to sensitive information)?
- Can cognitive networks be developed that create, process, share, and interpret system information that spans multiple layers of the OSI model?
- Quantification of the computational requirements for cognitive networks. Can cognitive network technologies be reasonably accommodated by existing systems (including both ground and flight systems)?
- To what extent can cognitive networking tools be used to dynamically allocate system resources or provide automated scheduling of resources?
- How does the introduction of cognitive network technologies impact the modeling and simulation of integrated systems? Will new modeling and simulation tools need to be developed?
- What metrics can be applied (or need to be developed) to be able to quantify the performance gains (or losses) associated with the addition of cognitive networking technologies?

Input was received from several different groups including industry and academia. There was consensus in a number of areas:

- NASA can benefit from further automation of its systems.
- Use of cross-layer communications (Layer-2 triggers) can also be used to improve system performance (throughput) and reduce data loss.
- Cognition, applying learning processing to integrated systems, can provide benefits, with a key caveat: Fast acting processes (millisecond response times or faster) will likely have a difficult time converging with cognition and may be best handled with reconfigurable algorithms whose inputs are controlled by cognitive processes.

5.5 Application of Cognitive Networking to SCaN's Networks

As has been shown in 4.2 and 4.3, SCaN's current and target architectures have very little automated networking. As such, deployment of cognition within the SCaN Network will be difficult as cognition is generally infused by adding intelligence to automation. There are two areas where cognition may be deployed early on: the scheduling of assets and point-to-point radio communications.

5.5.1 Scheduling

NASA's Deep Space Network (DSN) consists of three deep-space communications facilities placed approximately 120 degrees apart around the world: at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. It supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe. The network also supports selected Earth-orbiting missions [DSN]. The mission user committee performs early scheduling. Current tools can generate schedule and identify conflicts, but cannot resolve conflicts. The active scheduling is tightly tied to operational support and is predictive due to latency. For the DSN, network scheduling and network asset scheduling are automated over long time horizons, as this is the nature of deep space operations.

"The Space Network consists of a Space Segment composed of the Tracking and Data Relay Satellite System (TDRSS) and a Ground Segment that includes the White Sands Complex (WSC) and the Guam Remote Ground Terminal (GRGT). ..… The Space Network is operated 24x7, 365 days per year. Operations on the network run above 99.5% proficiency every month." [SN] The Space Network (SN) is highly automated with IT-facilitated early scheduling, which can identify conflicts. Network assets are scheduled by software including resolution of conflicts. There is active scheduling with some situational awareness of network configuration and automated configuration & control. There is also capability for real-time decisions on TDRSS operations including real-time reconfiguration and flexible start/stop capability.

"The NEN provides services to a wide variety of mission customers with missions in low-earth orbits (LEO), geosynchronous orbits (GEO), highly elliptical orbits, Lagrange orbits, Lunar orbits, Lunar surface and transfer, sub-orbital and launch trajectories, at multiple frequency bands through all phases of a mission's lifetime." [NEN] The Near Earth Network (NEN) consists of NASA owned ground stations and commercial assets. NASA provides a significant portion of its space communications services by contracting commercial ground station providers to support NASA missions. The NASA portion of the NEN is mostly manual scheduling with intensive early scheduling. There is also manual active schedule integration for NASA and commercial assets and manual data entry for some network equipment scheduling with semi-automated network asset configuration and control via scripting. The commercial portion of the NEN is highly automated within the commercial entity.

It is evident that scheduling of asset is a major concern to SCaN and the automation has been put into place for each of the major radio networks: DSN, SN and NEN. However, for a number of reasons, these various scheduling systems are not integrated. For example, the DSN has very long time profiles with planning occurring years in advance whereas the NEN and SN may include much more near-term and opportunistic scheduling. Some gain may be possible by integrating the systems or by adding cognition.

In order to add cognitive engines to the scheduling system, one must be able to gain knowledge of the improvements (or reductions) in operations via system monitoring; and use those metrics to adjust inputs. One must also identify the goals of the scheduling system such as reduced overall operations costs or increased science. Tuning controls need to be identified that allow the scheduler to autonomously modify schedules or, more likely, use assisted learning to suggest modifications to a human scheduler – at least initially. By monitoring the systems, one may find that users are scheduling assets more often than needed or perhaps at time slots where another could operate more efficiently (or at times that may be more convenient for the human operations and research groups). By charging different prices for different operations times (prime time, etc.) one may provide additional degrees of freedom to the cognitive scheduler. The cognitive scheduler may even suggest the optimal costing model.

5.5.2 Cognitive Radio

Unlike many military tactical radio networks or commercial Wi-Fi radio systems, which are point-to-multipoint or broadcast, NASA's current deployed radio systems are basis point-to-point links. There is little or no layer-2 routing or switching taking place and very little adaptation. Nearly everything is preconfigured via mission operations. Possibly, the most sophisticated radios that NASA currently deploys are those using the Proximity-1 protocol, all others use predefined configuration settings.

The Proximity-1 protocol controls and manages data interchange across the communications link. Proiximity-1 enables the automated selection of communications frequencies, data rates, modulation, coding, and link directionality (full duplex, half duplex, and simplex). The key items are a Hailing channel and the Communication Operations Procedure for Proximity links (COP-P). Hailing is a persistent activity used to establish a Proximity link by a caller to a responder in either full or half duplex. (It does not apply to simplex operation. Note: It is the responsibility of the caller to use the correctly pre-determined coding, modulation, and data rate in this process. Once communications via hailing is established, both nodes follow their respective operations plans move off the hailing channel and on to an agreed upon working channel The COP-P includes both the Frame Acceptance and Reporting Mechanism for Proximity links (FARM-P), for Sequence Controlled service carried out within the receiver in the Proximity-1 link and the Frame Operation Procedure for Proximity (FOP-P) links for ordering the output frames form Sequence Controlled service carried out in the transmitter in the Proximity-1 link [CCSDS210].

To date, Proximity-1 has performed dynamic configuration control based on rules. Most recently the Mars Science Laboratory (MLS) demonstrated Adaptive Data Rate (ADR) data return technology by monitoring the signal strength between the Mars Relay Orbiter (MRO) and MSL (a.k.a. Curiosity) and then adapting the rover's data transmission rate to maximize the throughput [ADR]. There currently are no known deployments that have incorporated a learning system (cognition) into the radios. However, this is a reasonable place to investigate use of cognition if computational resources are available to handle the additional processing. The Proximity-1 protocol could certainly be used by the cognitive process to implement the negotiations between systems.

Rules-based adaptive algorithms may be quite useful in improving performance of point-to-point radio links and Proximity-1 may be an effective protocol to use to negotiate radio configurations for all forms of point-to-point radios, not just rover-relay communications as is done by Mars missions. However, Proximity-1 possesses a number of CCSDS properties that need to be reconsidered (such as CCSDS specified identifiers). These identifiers are mission controlled and mission specific, properties that are undesirable characteristics for generic network deployment.

The next steps that need to be taken for development of a cognitive radio technology are to:

- Expose meaningful measurable radio parameters to the network controller
- Provide inputs to the radio to allow the network controller to adjust radio parameters
- Define the system goals that are to be obtained
- Perform data mining to determine what parameters provide the greatest gain and under what conditions
- Automate the radios with rules-base algorithms
- Add a cognitive engine and determine if the additional computation and complexity justifies the improvement in performance

This should be initially performed in a terrestrial testbed where one can easily control environmental parameters and instrument the systems. Only after thoroughly understanding the problem and solution space should such a system be considered for flight-testing as the cost and effectiveness of terrestrial testing is orders of magnitude better than restrictive space-flight tests. These results will provide input to software defined radio implementations and should serve as a guide for what parameters and controls should be made available in a Space Telecommunications Radio System (STRS) architecture.

5.6 Recommendations for SCaN Cognitive Networking Research

This study concentrates on Cognitive Networking for NASA's SCaN Program. However, rather that immediately investigating Cognitive Networking, it may be more appropriate to first automate SCaN's systems in a more generic sense through the use of Dynamic Adaptive Networking (DAN). DAN includes simple automation, rules-base algorithms, cross-layer communications as well as, when appropriate, application of learning systems (cognition). Systems automation alone will likely allow SCaN to realize significant savings related to manpower reductions in operation while improving overall system performance and reliability. Once the systems have been fully automated, cognitive processes can then be evaluated and integrated into the automated systems.

A core cognitive networking research team should be formed and focused on basic Artificial Intelligence and Machine Learning as it applies to SCaN Networks. This is long-term research requiring at least a small team of 4 or 5 full-time researchers.

A detailed network architecture should be developed. This activity is a natural extension of the existing systems engineering that is ongoing. The detailed architecture should include all machines, interfaces and protocols with sufficient detail to identify: addressing, wiring, radios and configuration parameters. Minimally, this detail is needed for the portion of the network that one would incorporate cognition into. This detail is also required to gain a full understanding of how future systems will interact. From this information and the system goals, one can identify: what parameters are exposed and what parameters should be exposed as well as what controls are accessible and what controls should be accessible.

With the above information one should be able automate the system and strategically measure performance. This will allow SCaN to determine what inputs should be controlled and provide insight as to whether or not the system goals are being met.

The next step is to move from automation to cognition – adding a learning system.

Two reasonable, bounded problems that may provide the greatest payoff to SCaN early on, are to investigate use of cognitive networking toward the problem of scheduling SCaN's major assets within the Near Earth Network (NEN), the Space Network (SN), and the Deep Space Network (DSN) or to simply concentrate on automated point-to-point cognitive radio performance monitoring and autonomous reconfiguration.

6.0 SUMMARY

This report clarifies the terminology and framework of cognitive networking and provides some examples of cognitive systems. It then provides a methodology for developing and deploying cognitive networking techniques and technologies. The report attempts to answer specific questions regarding how cognitive networking could benefit SCaN and describes SCaNs current and target networks and proposes places where cognition could be deployed. Finally SCaN should consider opening up the spectrum of solutions for automating their networks by incorporating all aspects of Dynamic Adaptive Networking of which cognitive networking is a subset.

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BIOGRAPHIES

William Ivancic *has over twenty-nine years experience in network and system engineering for communication applications, communication networking research, state-of-the-art digital, analog and RF hardware design and testing. He currently is a senior research engineer at NASA's Glenn Research Center. His work areas include network centric technologies for space, aeronautics and terrestrial systems. He has lead research efforts to deploy commercial-off-the-shelf (COTS) technology into NASA missions. Of particular interest is large scale, secure deployment of mobile networks including mobile-ip and mobile router technology. Mr. Ivancic's recent areas of research include: high-speed reliable data transport protocols, store-carry-and-forward protocols, and adaptive dynamic networking including cognitive networking.*

Mr. Ivancic is also principle of Syzygy Engineering, a small consulting company specializing in communications systems and networking as well as advanced technology risk assessment. Mr. Ivancic is currently performing research and development on Identity-based security and key and policy management and distribution for tactical networks - particularly mobile networks.

Phil Paulsen *Phillip E. Paulsen is a certified NASA Project Manager with over 21 years of experience in the design and development of space flight systems. His past projects include the solar array wing and rotary joint for the International Space Station, a TDRSS-compliant telemetry system for Atlas and Titan expendable launch vehicles (ELVs), and a satellite vehicle destruct system for Titan. He was the lead engineer for the EOS-AM1 mission (on Atlas) and he served as the Tracking and Data Acquisition Manager (TDAM) for all intermediate and large class NASA ELV missions. He also served from as an executive member of the multi-agency Network Control Group (NCG) that was tasked with the coordination of worldwide telemetry assets. Currently, he has fielded a miniature Cisco router on board a satellite in Low Earth Orbit (CLEO) that is remotely controlled over the open Internet by a Virtual Mission Operations Center (VMOC). Mr. Paulsen is also managing the development of secure, mobile, network centric systems, and a UAS-based, delay tolerant network (DTN).*

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Karl R. Vaden *joined the NASA Glenn Research Center in 1989. His early work was primarily focused on the research and design of travel-wave tube amplifiers for deep space communications, with an emphasis on multistage depressed collectors. He was also involved in the computational modeling of various devices and components, including THz meta-materials, photonic and electromagnetic band-gap structures, waveguide power combiners and microwave antenna for RF fuel gauging systems to be used with fuel tanks in low-gravity environments. From 2008 to 2011, he was the NASA Research Agreements Manager for the Hypersonics Project of the Aeronautics Research Mission Directorate. His current research interests include cognitive networking and communications for unmanned aircraft systems in the national airspace system.*