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# Cognitive Communications and Networking Technology Infusion Study Report

*Eric J. Knoblock*
*Glenn Research Center, Cleveland, Ohio*

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*Glenn Research Center, Cleveland, Ohio*

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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# Cognitive Communications and Networking Technology Infusion Study Report

Eric J. Knoblock
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## Executive Summary

As the envisioned next-generation SCaN Network transitions into an end-to-end "system of systems" with new enabling capabilities, it is anticipated that the introduction of machine learning, artificial intelligence, and other cognitive strategies into the network infrastructure will result in increased mission science return, improved resource efficiencies, and increased autonomy and reliability. This enhanced set of cognitive capabilities will be implemented via a "space cloud" concept to achieve a service-oriented architecture with distributed cognition, de-centralized routing, and shared, on-orbit data processing. The enabling cognitive communications and networking capabilities that may facilitate the desired network enhancements are identified in this document, and the associated enablers of these capabilities, such as technologies and standards, are described in detail.

## 1.0 Introduction

### 1.1 Purpose

As NASA future mission plans continue to evolve, new technologies and capabilities will be introduced into the space communications architecture to accommodate the anticipated mission needs. The envisioned future architecture with new enabling technologies will transition into an end-to-end "system of systems" providing services to user missions communicating over various network elements, including relay and surface assets throughout the solar system.

The infusion of cognitive communications capabilities and technologies within the SCaN Network infrastructure is anticipated to offer increased mission science data return, enhanced automation, and increased efficiency. Through the incorporation of machine learning and other cognitive capabilities, the cognitive communications and networking efforts at NASA are striving to enhance the efficiency, autonomy, and reliability of the envisioned next-generation SCaN Network architecture. These potential advantages as well as the risks and complexities are currently under study using test platforms such as the SCaN Testbed (Refs. 1 and 2)

The purpose of this study is to identify cognitive communications and networking capabilities that may facilitate the desired network enhancements, and to identify the associated enablers of these capabilities, such as technologies, standards, and other constructs. The identified capability enablers are described in detail, including a general description, Maturity Level, current activities/research, and potential infusion points, in Section 3.0.

### 1.2 Scope

This document provides a cognitive communications and networking technology infusion assessment for NASA's communication and navigation infrastructure and anticipated user mission set for the time period ranging from the current operational capability to the envisioned next-generation architecture as defined to the year 2040.

## 1.3 Assumptions

This document assumes references to "technology" also include any capability enablers that would facilitate the SCaN program in achieving its desired capabilities for next generation services. Therefore, these capability enablers are assumed to include not only hardware implementations, but also software implementations, software constructs, and software algorithms, and technical standards.

## 1.4 Document Overview

This report is organized into the following sections:

- *Section 1.0*: Describes the purpose, scope, and assumptions of the report.
- *Section 2.0*: Provides an overview of the cognitive communications and networking vision and associated high-level capabilities.
- *Section 3.0*: Provides an assessment of relevant cognitive communications and networking technologies, standards, and other capability enablers. The section also describes the current activities, maturity level, and possible infusion points for each identified technology, standard, or other construct.
- *Section 4.0*: Provides a brief summary of the report.

# 2.0 Cognitive Communications Capabilities

A capability describes an ability that can be applied to achieve a desired outcome, and a capability model describes the complete set of capabilities that an organization requires to successfully fulfill its mission (Ref. 3). This section describes the desired cognitive communications and networking capabilities that would enable the SCaN Network to achieve its strategic vision. These capabilities can be mapped to enabling technologies, standards, and other constructs, as described in Section 3.0.

The cognitive communications and networking efforts at NASA strive to develop cognitive capabilities for increased mission science return, improved resource efficiencies, and increased autonomy and reliability of the SCaN next generation architecture through incorporation of machine learning, artificial intelligence, and other strategies. In order to achieve this enhanced set of capabilities, NASA researchers are striving to implement a "space cloud" concept, derived from the cloud computing paradigm, to achieve a service-oriented architecture with distributed cognition, de-centralized routing, and shared, on-orbit data processing. Figure 1 illustrates the notional "space cloud" concept.

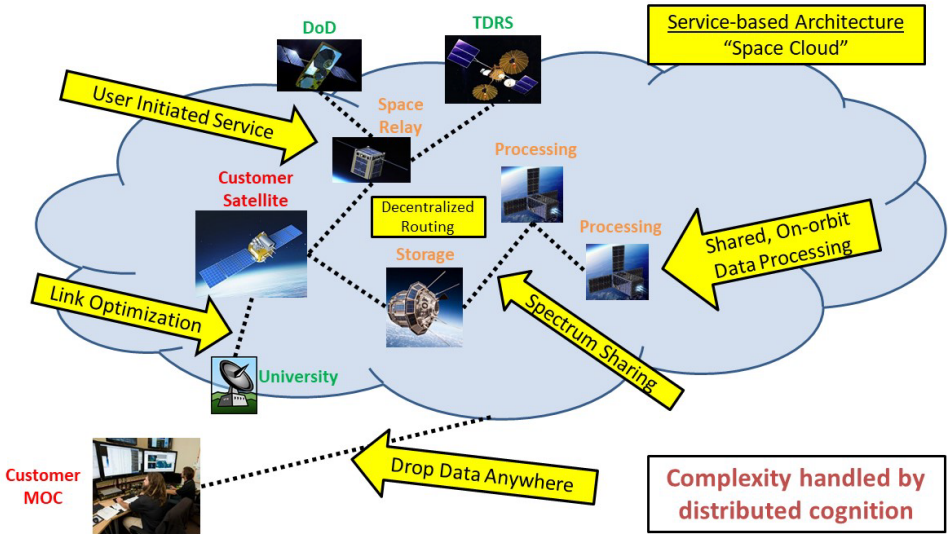


Figure 1.—Cognitive Communications "Space Cloud" Concept.

NASA also partners with industry and academia in the effort to develop and foster cognitive hardware capabilities, such as neuromorphic and memristor-based processors, for example, and to investigate various cognitive algorithms for use on network assets as well as on user mission platforms, including small SWaP-constrained platforms such as CubeSats (Ref. 4).

The envisioned cognitive communications capabilities can be generally categorized into cognitive links, cognitive networks, and cognitive systems and are described in the following sections (Ref. 2).

## 2.1 Cognitive Link Capabilities

The cognitive links capabilities focus on technologies, algorithms, and protocols applicable to the physical and data-link layers of the Open Systems Interconnect (OSI) protocol model. This includes efforts to maximize throughput and avoid spectrum interference, to cooperatively share spectrum with neighboring communications nodes, and to sense incoming signals for radio configuration. Link capabilities include (Ref. 4):

- *Interference Mitigation*: Automatically sense and avoid spectrum interference by changing frequency, bandwidth, and data rate, antenna pointing
- *Link Optimization*: Automatic reconfiguration of communications parameters (e.g., modulation, encoding, transmission power) based on observed channel conditions and user mission platform constraints via cognitive engine link controllers
- *Signal Characterization*: Also referred to as signal recognition, which uses signal processing mechanisms to recognize signal waveform parameters such as modulation scheme; this information can be used to facilitate system self-configuration and link acquisition even in the presence of noise or weak signals
- *Compensation for Nonlinear Effects*: Learned optimizing of communications parameters to compensate for nonlinearities due to the channel, amplifier, or propagation effects
- *Optimization of System Hand-Offs*: Seamless coordination of hand-off between radio frequency (RF) and free space optical (FSO) communications systems for a unified transport of user mission platform data

Various additional second-tier capabilities may be derived the aforementioned first-tier set. These include, among others:

- *Dynamic Spectrum Access*: A spectrum sharing paradigm that allows secondary users to access portions of unused spectrum or "white spaces" in the licensed spectrum bands
- *Cognitive Anti-Jamming*: Use of sensing techniques and machine learning algorithms to detect and avoid jamming from hostile sources

## 2.2 Cognitive Network Capabilities

The cognitive network capabilities focus on network-layer technologies and protocols in an effort to establish a decentralized, service-based network architecture with seamless integration of NASA and commercial service providers. These capabilities include (Ref. 4):

- *"Drop Data Anywhere"*: Use of Delay Tolerant Networking (DTN) and other mechanisms for distributed data fragmentation, storage and reassembly with support for both scheduled and opportunistic link types.
- *Intelligent Data Routing*: Use of protocols, artificial intelligence, requirements, network observations, policies and constraints to establish intelligent and adaptive data paths and network routing decisions through networks (Ref. 5).
- *Resilient Networking*: Improvement of environment awareness through a secure and decentralized computing and data analysis infrastructure (Ref. 6).

## 2.3 Cognitive System Capabilities

The cognitive systems capability strives to achieve system-wide cognition using an array of cognitive agents spanning multiple protocol layers. Cognitive systems capabilities can be generally categorized as follows (Ref. 4):

- *Self-Configuration*: Automatic configuration of communication parameters of network equipment, including ground stations, relays, etc.
- *Self-Optimization*: Monitoring of network parameters and communications environment to continually update parameters to ensure efficient network operations
- *Self-Healing*: The use of machine learning algorithms for autonomous monitoring of network performance for fault detection, fault classification, and fault recovery with minimal manual intervention

Various additional second-tier capabilities may be derived the aforementioned first-tier set. These include, among others:

- *Optimization of Spacecraft Configuration and Operation*: Use of learned behavior for optimal configuration and operation
- *Optimized Link Configurations*: Determination of optimal link configurations (e.g., ACM, interference and multipath mitigation, multiple access) based on a range of observed metrics including past performance and available resources for increase science data return while reducing complexity and burden
- *Optimized Network Asset and Resource Utilization*: Optimal use of relay satellites, ground stations, available spectrum, etc.
- *Automated and On-Demand Service Scheduling*: Allow spacecraft (or user mission ground systems) to request SCaN service(s) dynamically without human network operations personnel intervention (such as User Initiated Service capability) using intelligent mechanisms
- *Internetworked Data Transfer*: Facilitate communications capabilities across multinode, multihop relays and ground systems based on data characteristics and performance
- *Cooperative Relaying*: Nodes within a cluster use sensing techniques to discover and select other cooperating nodes for data sharing and relaying for enhanced communications capabilities
- *Cognitive Beamforming*: Selection of antenna array coefficients using machine learning algorithms for adjusting antenna array patterns to maintain link connectivity and avoid interference

# 3.0 Technology Assessments

The process by which the SCaN program infuses new technologies into its infrastructure is documented in the SCaN Technology Management Plan (SCaN-TMP) (Ref. 7). The process, in summary, includes technology identification; continuous development, demonstration, and viability evaluation; and ultimate infusion into the SCaN network infrastructure as well as applicable user mission platforms. Throughout the entire process, numerous SCaN Program and external entities are required for successful infusion. These entities, among others, include the SCaN Advanced Communications and Navigation Technologies Division, the SCaN Systems Engineering and Standards Division, the SCaN Network Services Division, and the relevant user mission community (Ref. 8).

This report refers to a technology's relative maturity level through TRLs, which are defined in the SCaN-TMP and summarized in Table 1. The relevant cognitive communications technologies are described in detail in the following sub-sections.

Within the 2015 NASA Technology Roadmaps, Technology Area (TA) 5 considers a wide range of required technologies and development areas for communications, navigation, and orbital debris tracking and characterization. Advancements in communications and networking technologies will enable

new mission concepts and facilitate the implementation of new capabilities for science and human exploration missions beyond Earth orbit. The Technology Area Breakdown Structure from the 2015 NASA Technology Roadmaps is shown in Figure 2.

The TAs within the structure that are supported by cognitive capabilities are highlighted in yellow and briefly described in Table 2.

TABLE 1.—NASA TECHNOLOGY READINESS LEVELS

| | |
|---|---|
| Technology Development at Early Levels of Readiness | |
| TRL 1 | Basic principles observed and reported |
| TRL 2 | Technology concept and/or application formulated |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof-of-concept |
| Technology Development and Demonstration in a Simulated Environment | |
| TRL 4 | Component and/or breadboard validation in laboratory environment |
| TRL 5 | Component and/or breadboard validation in a relevant environment |
| TRL 6 | System/sub-system model or prototype demonstration in a relevant environment (ground or space) |
| Technology Demonstration in a Qualified or Relevant Environment | |
| TRL 7 | System prototype demonstration in a space environment |
| TRL 8 | Actual system completed and "flight qualified" through test and demonstration (ground or space) |
| TRL 9 | Actual system "flight proven" through successful mission operations |

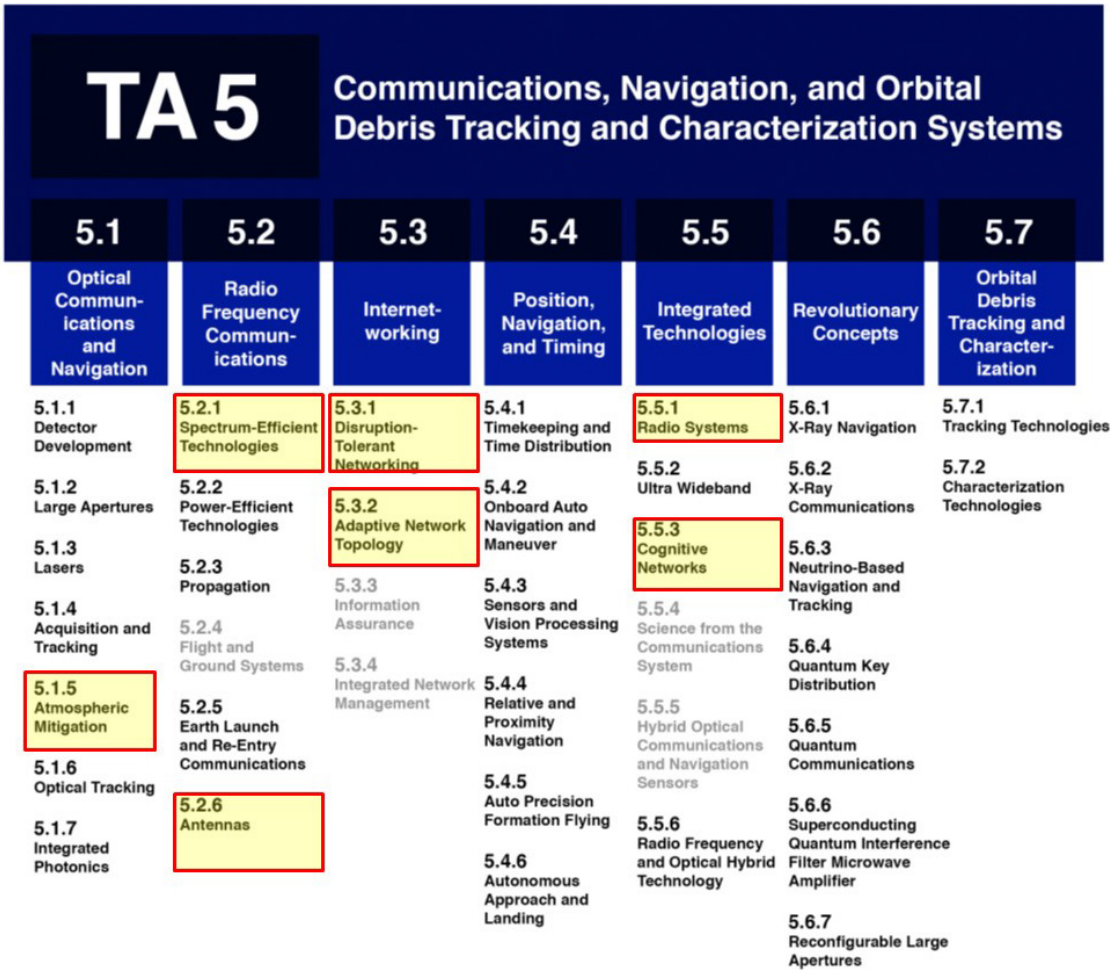


Figure 2.—NASA Technology Area 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems.

TABLE 2.—NASA TECHNOLOGY AREAS RELEVANT TO COGNITIVE COMMUNICATIONS AND NETWORKING

| Technology area | Description |
|---|---|
| 5.1.5 Atmospheric Mitigation | Includes measurement and modeling of the atmospheric channel. Cognitive links capabilities such as adaptive coding and modulation (ACM) can be used for mitigating atmospheric effects. |
| 5.2.1 Spectrum-Efficient Technologies | Includes mechanisms for more efficient use of allocated spectrum. Achieving this requires space-qualified modems, and space-qualified field programmable gate arrays (FPGAs), among others. Cognitive links capabilities such as RF interference mitigation, cooperative relaying, use of higher-order modulation schemes, amplifier nonlinearity compensation, and other techniques support this TA. |
| 5.2.3 Propagation | Includes measurement and modeling of the RF channel and associated techniques and technologies for mitigating the effects of RF impairments. Cognitive links capabilities such as ACM support this TA. |
| 5.2.6 Antennas | Includes flight and ground antennas providing high-efficiency large effective apertures with lower mass and accurate pointing. Cognitive beamforming techniques, based on acquired knowledge of the channel and surrounding communications nodes, support this TA. |
| 5.3.1 Disruption-Tolerant Networking | Includes networking techniques that facilitate data delivery across multiple links exhibited by periodic disruptions and/or long delays. Cognitive networking capabilities support this TA |
| 5.3.2 Adaptive Network Topology | Includes protocols and other mechanisms for optimization of data connectivity among elements. Cognitive networking capabilities such as adaptive/cognitive data routing support this TA. |
| 5.5.1 Radio Systems | Includes advances in RF communications, cognition, and space internetworking for increased performance and efficiency with a reduction in cost. Software-defined radios, for example, are considered within this TA for implementing cognitive functionality including the ability to autonomously sense and adapt to its environment to enhanced communications. |
| 5.5.3 Cognitive Networks | Includes technologies in which each communications nodes within a network are dynamically aware of its environment so that it may autonomously optimize its operational parameters in response to environmental considerations. Cognitive links, networks, and systems capabilities support this TA. |

## 3.1 Optical Communications and Navigation (TA 5.1)

Task Area 5.1 relates to technologies required to facilitate optical communications and navigation capabilities. Optical technologies offer the advantage of the virtually unconstrained bandwidth available in the optical spectrum.

### 3.1.1 Atmospheric Mitigation (TA 5.1.5)

This section describes technologies relating to the atmospheric channel and its effects on optical propagation; more specifically for cognitive applications, this area captures technologies relating to mitigating atmospheric effects using link monitoring and adaptation schemes.

#### 3.1.1.1 Adaptive and Cognitive Modem for SmallSat Lasercom at High Data Rates

- *Description*: As part of a NASA SBIR effort, Fibertek, Inc., and a partner proposed to design, develop and demonstrate a SmallSat/CubeSat form-factor optical communication modem for space optical communication links (both space-to-ground and inter-satellite links) from LEO/MEO orbits. The design used a software-defined approach for optimizing link BER performance, and optimizes and extends protocols originally developed for RF/wireless fading channels to free-space-optical (FSO) modems. The objective of this program is to further optimize and validate cognitive algorithms and protocols for space optical links (Ref. 9).
- *Capabilities Supported*: Cognitive links
- *Maturity Level (start/end)*: TRL 3/5
- *Possible Infusion Points*: SmallSat/CubeSat (i.e., SWaP-constrained) platforms
- *Infusion Challenges*: TRL advancement

## 3.2 Radio Frequency Communications (TA 5.2)

Technology development for RF applications concentrates on more efficient use of constrained spectrum bands. Cognitive techniques offer the advantage of enhanced spectrum utilization via various mechanisms, such as interference management, as described in the following sub-sections.

### 3.2.1 Advanced Interference Management (TA 5.2.1.1)

Spectral bandwidth has become increasingly crowded, which drives the need for new and innovative ways to achieve spectrum efficiency enabling multiple wireless links to operate effectively in the same spectrum bands at the same time. Various mechanisms allow for reduced RF interference and advanced spectral efficiency including, for example, signaling strategies such as interference mitigation, and cooperative spectrum sharing. Technologies for advanced interference management are described in the follow sub-sections.

#### 3.2.1.1 Wideband Autonomous Cognitive Radios (WACR)

- *Description*: As part of a NASA SBIR effort, Wideband Autonomous Cognitive Radios (WACRs) are advanced radios with the ability to sense the state of its surrounding RF environment and optimize its operational parameters in response to the sensed state (Ref. 10). The design developed by Bluecom Systems and Consulting, LLC, consists of three modules: a cognitive engine, an SDR platform, and a reconfigurable RF front end.
- *Capabilities Supported*: Cognitive links, e.g., interference mitigation, cooperative spectrum sharing, cooperative relaying and beamforming
- *Current Activities*:
  - For Phase I STTR, Bluecom Systems developed a design for realizing a WACR and demonstrated the proof-of-concept operation in a hardware-in-the-loop simulation.
  - Phase II efforts focused on developing a prototype a STRS-compliant plug-n-play FPGA-based cognitive engine (referred to as the Radiobot 1.0), which can convert any suitably designed SDR into a WACR.
  - Researchers at Bluecom Systems and Consulting LLC, the University of New Mexico, and the NASA Glenn Research Center designed and developed a cognitive anti-jamming technique that was demonstrated on a satellite-to-ground link using the SCaN Testbed. The results of their experiments are described in (Ref. 11).
- *Potential Benefits*:
  - Enables autonomous and intelligent communication networks, including networked clusters of CubeSats
  - Enables commercial applications such as first-responder/emergency/public safety communications, autonomous systems and drones, and military communications
- *Maturity Level (start/end)*: TRL 2/4
- *Possible Infusion Points*: Clusters of networked CubeSats or other small platforms
- *Infusion Challenges*: TRL advancement, e.g., use of space-qualified FPGAs and other hardware

#### 3.2.1.2 Defense Advanced Research Projects Agency (DARPA)

- *Description*: DARPA sponsors various research initiates focusing on the development of cognitive radio-related technologies. Two of the more recent efforts are described below.
- *Capabilities Supported*: Cognitive links, e.g., interference mitigation, dynamic spectrum access
- *Recent Activities*:
  - *Radio Frequency Machine Learning Systems (RFMLS) (2017)*: Applies machine learning to the realm of RF. The intent is for an RF Machine Learning system to be able to sense and characterize the composition of the radio frequency spectrum (e.g., types and behaviors of signals). According to the RFMLS program manager, Paul Tilghman, “We want to be able to

understand and trust what is happening in the Internet of Things and to stand up an RF forensics capability to identify unique and peculiar signals amongst the proverbial cocktail party of signals out there." (Ref. 12)
    - *Spectrum Collaboration Challenge (SC2) (2016)*: The DARPA SC2 is a collaborative machine-learning competition to achieve enhanced spectral efficiency in the RF spectrum. SC2 competitors develop innovative, autonomous, and collaborative ways to achieve dynamic spectrum access. The challenge culminates in 2019 with a live event alongside "Mobile World Congress Americas, in Partnership with CTIA." (Ref. 13)
- *Potential Infusion Points*: Clusters of platforms contending for shared spectrum (e.g., planetary surface scenarios).
- *Infusion Challenges*: DARPA technology has not achieved production with no programs of record and limited numbers of units.

#### 3.2.1.3 Cognitive Radios in Commercial Industry

- *Description*: A cognitive radio market report provided the following assessment, summarized as follows (Ref. 14):
    - *Market Growth*: Global cognitive radio market is expected to grow from USD 3.45 Billion in 2017 to USD 7.44 Billion by 2022
    - *Growth Drivers*: Increasing adoption of the 5G technology and technological advancements in the wireless communication field
    - *Market Share*:
        - *Software Tools*: Expected to hold the largest market size during the forecast period. Software components are integrated with the radio hardware and are therefore an important component of the cognitive radio system
        - *Hardware*: Sub-divided into transmitter and receiver categories with the transmitter portion expected to hold the larger market size during the forecast period. Transmitters incorporate various functionalities that are primarily software-defined, which renders the operations software-driven
        - *Services*: Professional services are expected to be the largest contributor during the forecast period, mainly due to the complexity of operations and increasing deployment of the cognitive radio technology in the wireless domain
        - *Applications*: spectrum sensing is expected to hold the largest market size during the forecast period.
        - *End-Users*: Government and defense segment is expected to have the largest market size during the forecast period, mainly due to governments focusing on requirements of modern warfare and ensuring public safety and security.
        - *Global Regions*: North America, Europe, Asia Pacific (APAC), Middle East and Africa (MEA), and Latin America. North America is estimated to be the largest revenue-generating region during the forecast period.
- *Capabilities Supported*: Cognitive links, e.g., interference mitigation, dynamic spectrum access
- *Current Vendors*: The leading cognitive radio vendors are BAE Systems (London, UK), Raytheon Company (Massachusetts, U.S.), Thales Group (Paris, France), Rhode & Schwarz (Munich, Germany), Spectrum Signal Processing (Burnaby, Canada), xG Technology (Florida, U.S.), Nutaq (Quebec, Canada), Ettus Research (California, U.S.), Shared Spectrum Company (Virginia, U.S.), DataSoft (Arizona, U.S.), EpiSys Science (California, U.S.), and Kyynel (Oulu, Finland) (Ref. 14).
- *Infusion Challenges*: Security concerns, dynamic communication standards, and interoperability issues (Ref. 14).

#### 3.2.1.4 European Defence Agency (EDA) Cognitive Radio Efforts

- *Description*: The CapTech Communication Information Systems and Networks (CapTech Information) fosters innovations for military communication systems with the objective of enhancing capabilities in the "Command and Inform" knowledge domain (Ref. 15). CapTech support areas include communication systems from devices to networks; information systems from data acquisition and processing to fusion and presentation; ubiquitous mobile, ad-hoc and networked computing; semantic technologies; smart and efficient communications; management of information at large scale (e.g., for wireless sensor networks); user-friendly presentation of information and controls; and Common System Interoperability including multilayer information gateways.
- *Current Activities*: Cognitive Radio for Dynamic Spectrum Management (CORASMA) is a recently completed project under CapTech. CORASMA focused on the rationale and needs for using CRs as way to optimize spectral efficiency. Among other goals, the project proposed a system-level dynamic spectrum management solution, including considerations for spectrum policies, rules of collaboration, and concepts of operations.
- *Maturity Level*: The work of CapTech is generally in TRL ranges from 2 to 6, with occasional advanced TRLs as well.
- *Infusion Challenges*: TRL advancement; transition of technologies from military to satellite domain

#### 3.2.1.5 Cognitive Radio Scenarios for Satellite Communications (CoRaSat)

- *Description*: CoRaSat was a European Commission 7th Framework Programme (FP7) project funded under the Information and Communications Technologies (ICT) Call 8. CoRaSat focused on investigating cognitive radio techniques for spectrum sharing in the satellite domain. Outcomes of the study intended to drive the definition of strategic roadmaps for industry stakeholders, European Institutions, and governmental entities. FP7 was the European Union's (EU's) primary effort for research funding in Europe from 2007 to 2013 (Ref. 16).
- *Capabilities Supported*: Cognitive links, e.g., interference mitigation, dynamic spectrum access
- *Activities*: CoRaSat identified and investigated cognitive radio scenarios suitable for satellite communications; the study investigated Ka, Ku, C, and S bands, and identified challenges associated with the applicability of cognitive radio, e.g., market/business, regulatory, standards, and technologies (Ref. 17).
- *Maturity Level*: TRL 1-3
- *Infusion Challenges*: No activity since 2013

#### 3.2.1.6 IEEE 802.22 (Wireless Regional Area Networks) Standard

- *Description*: IEEE 802.22 is a set of standards for Wireless Regional Area Networks (WRANs) where cognitive radio technologies are used for exploiting white spaces in the television spectrum (54 to 862 MHz) on a noninterfering basis with the primary users. This allows for the provision of broadband wireless access services to rural environments.
- *Capabilities Supported*: Dynamic spectrum access via white space detection
- *Current Activities*: The IEEE 802.22, the Working Group on Wireless Regional Area Networks is developing a wide variety of standards to enable spectrum sharing
- *Potential Benefits*: Leveraging of commercial investments and advancements for application to NASA networks and missions
- *Maturity Level*: Active standard
- *Possible Infusion Points*: User mission scenarios involving multiple assets contending for shared spectrum access (e.g., multiple planetary surface assets; cluster of small satellites)
- *Infusion Challenges*: Transition from terrestrial wireless domain to satellite domain

#### 3.2.1.7 IEEE 1900.4 (Radio Resource Management) Standard

- *Description*: IEEE 1900.4 is set of standards that addresses radio resource management and reconfiguration management in wireless networks utilizing multiple radio access technologies; these standards apply for both fixed and dynamic spectrum access frameworks (Ref. 19).
- *Capabilities Supported*: Cognitive links capabilities
- *Current Activities*: Current active 1900.4 standards include:
  - 1900.4-2009—IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks
  - 1900.4.1-2013—IEEE Standard for Interfaces and Protocols Enabling Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Networks
  - 1900.4a-2011—IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks Amendment 1: Architecture and Interfaces for Dynamic Spectrum Access Networks in White Space Frequency Bands
- *Potential Benefits*: Resource optimization, distributed decision-making
- *Maturity Level*: Active standard
- *Possible Infusion Points*: Ground and space systems
- *Infusion Challenges*: Transition from terrestrial wireless domain to satellite domain

### 3.2.2 Propagation (TA 5.2.3)

This technology area focuses on signal propagation through space and atmospheres; however, the development of innovative ways to better utilize information derived from measurements of atmospheric and other fading conditions allows for the development and use of cognitive and adaptive techniques to enhance link performance and spectral efficiency. The following sections describe various mechanisms for measuring and optimizing communications links.

#### 3.2.2.1 Adaptive Coding and Modulation (ACM)

- *Description*: ACM provides for adjustments of modulation, coding and other waveform parameters in response to observed link conditions.
- *Capabilities Supported*: Cognitive links
- *Current Activities*:
  - *Digital Video Broadcasting–Satellite–Second Generation (DVB–S2)*: NASA experiments of DVB-S2 over satellite using ACM have been demonstrated and shown improvements in system throughput. The experiment consisted of a direct-to-Earth link from the SCaN Testbed on the International Space Station (ISS). Software Defined Radios (SDRs) loaded with the DVB-S2 waveforms transmitted data to the ground system, and a decision algorithm selected the most appropriate modulation and encoding (MODCOD) scheme based on the channel conditions. The selected MODCOD information was relayed back to the SDR via a low-rate binary phase-shift keying (BPSK) feedback link. Results of the experiment demonstrated a more than 4 dB improvement in user information throughput over standard Constant Coding and Modulation (CCM) waveforms (Ref. 20).
  - *IEEE 802.11 and 802.16*: ACM is also used in wireless communications, including the IEEE 802.11 (Wi-Fi), IEEE 802.16 (WiMAX) standards and others. The use of ACM allows wireless technologies to optimize throughput, yielding higher throughput over long distances. The selection of modulation/coding is made according to a channel quality feedback indictor is used, where downlink channel quality can be assessed by the mobile and then forwarded to the base station, and/or the base station can estimate the quality of the forward channel based on signals received by mobile users (Ref. 21).

- *Potential Benefits*: Improvements in system throughput
- *Maturity Level*: Active standards
- *Possible Infusion Points*: User mission platforms with processing power capable of implementing ACM functionality
- *Infusion Challenges*:
  - SWaP-constrained user platforms may not have sufficient resources to implement ACM
  - ACM requires channel observations, typically sent to the transmitting source via a feedback link

#### 3.2.2.2 Cognitive Distortion-Resilient Communications

- *Description*: DeepSig Inc., has developed and demonstrated the use of deep learning techniques to train channel encoder/decoders to compensate for channel effects and hardware nonlinearities; this machine learning-based radio technology was applied to NASA's space-to-space and space-to-ground communications links under government contract # 80GRC017C0048 (Ref. 22).
- *Capabilities Supported*: Cognitive links
- *Accomplishments*: Deliverables made by DeepSig, Inc., to NASA:
  - Monthly program status updates: brief status of the efforts conducted during the prior month along with program expenditures
  - Two OmniPHY runtime licenses and the waveform or waveforms developed during the program; this enables NASA to continue to use and evaluated the waveform or waveforms developed under this program
  - Final report: detailed results of the program
- *Potential Benefits*: Ability to quickly learn new physical channel characteristics; optimized communications parameters for complex and dynamic channels; facilitates use of new classes of physical layers
- *Maturity Level*: TRL 2/3
- *Possible Infusion Points*: Any physical channel (e.g., Relay-Ground, Relay-Relay, etc.)
- *Infusion Challenges*: Implementation of space-side signal decoder; feedback mechanism for Global Loss Optimizer

### 3.2.3 Antennas (TA 5.2.6)

Development of antenna technologies allows for enhanced efficiency and pointing capabilities. Cognitive beamforming and antenna pointing technologies allow for interference mitigation, cognitive anti-jamming, and consequently more efficient use of available spectrum.

#### 3.2.3.1 Cognitive Antenna Beamforming/Arraying/Steering

- *Description*: Cognitive beamforming and antenna steering allows for interference mitigation in that the antenna boresight can be directed as needed based on observed conditions and decisions made by the cognitive engine.
- *Capabilities Supported*: Cognitive links
- *Current Activities*:
  - Tethers Unlimited, Inc. offers a COBRA gimbal, which is a low SWaP, high precision gimbal with 3 degrees of freedom and suitable for cognitive applications such as interference mitigation via antenna pointing (TRL 9) (Ref. 23).
  - Cognitive beamforming selects of antenna array coefficients based on machine-learning algorithms, where a cognitive engine uses a knowledge base of previously store actions/responses, and applies decisions for optimal link performance. A survey of cognitive beamforming techniques is provided in Reference 24.
- *Potential Benefits*: Enhanced operational throughput and robustness
- *Possible Infusion Points*: Space and ground-based assets

## 3.3 Internetworking (TA 5.3)

As space communications scenarios evolve away from simple point-to-point links and carefully planned and scheduled link operations, there is a developing need for enhanced networking capabilities (such as disruption tolerant networking) that facilitate communications across diverse multihope network scenarios with dynamic scheduling capabilities.

### 3.3.1 Disruption-Tolerant Networking (TA 5.3.1)

The use of conventional Internet protocols used by terrestrial applications are not ideally suited for the intermittent and long-latency links that are characteristic of interplanetary network distances. The DTN concept, however, uses store-and-forward techniques to compensate for intermittent and long-latency link connectivity, and makes use of the Bundle Protocol (BP), which functions as an overlay between the network applications and the underlying communications protocols of the network nodes. BP has been demonstrated in a number of ground-based and space-based experiments, including various experiments on the International Space Station (ISS). The use of DTN also has potential application in military operations where transmission and reception of vital information can be achieved despite the intermittency and dynamic nature of the communications links (Ref. 25).

#### 3.3.1.1 Delay (or Disruption) Tolerant Networking (DTN)

- *Description*: Delay Tolerant Networking (DTN) is a set of standardized mechanisms and protocols to facilitate data communications in the presence of long delays and/or intermittent connectivity. The DTN suite consists primarily of the Bundle Protocol (BP) and the Licklider Transmission Protocol (LTP); both the Consultative Committee for Space Data Systems (CCSDS) and the Internet Engineering Task Force (IETF) have active working groups defining and refining the DTN mechanism standards (Refs. 26 and 27).
- *Capabilities Supported*: Cognitive networking, e.g., adaptive data routing, “Drop data anywhere”, et al.
- *Current Activities*:
  - The SCaN Systems Engineering and Standards Division has initiated a DTN infusion study for the SCaN Networks and user missions has been initiated with HEOMD and SMD co-leading the study with the support of subject matter experts (SMEs). The study team is developing a plan for incorporating DTN into both ground and flight segments of NASA infrastructure and user missions (Ref. 28). SCaN has developed a plan to infuse DTN into its constituent networks into multiple phases: Initial Operating Capability, Expanded Operating Capability, and Infusion of full DTN capabilities; the science mission community is currently in the process of formulating their requirements and approach to DTN infusion.
  - The CCSDS Space Internetworking Services (SIS) Area is working to address the communications services and protocols to support end-to-end communications for network topologies spanning multiple heterogeneous physical and link layer technologies, and the Delay Tolerant Networking Working Group is specifying the protocols needed to implement the Solar System Internetwork (SSI) concept (Ref. 26).
  - The IETF Delay/Disruption Tolerant Network Working Group (DTNWG) is currently working to update the base specifications in light of multiple independent implementations and recently identified new use cases (Ref. 27).
- *Potential Benefits*: The use of DTN and other network routing mechanisms can be used collectively to provide a cognitive networking capability.

- *Maturity Level*:
  - CCSDS Bundle Protocol Specification Recommended Standard (i.e., "Blue Book"); released in September 2015 (Ref. 29)
  - CCSDS Licklider Transmission Protocol Specification Recommended Standard; released in May 2015 (Ref. 30)
- *Possible Infusion Points*: Both ground and flight segments of NASA infrastructure and supported user missions, as described by the DTN study group; significant operational use is forecasted to begin in the early 2020s.
- *Infusion Challenges*:
  - Multiple independent implementations exist for these technologies and multiple deployments in space and terrestrial environments; a consensus on the issues should be addressed with the specifications updated accordingly.
  - Cost to infuse DTN capabilities into multiple disparate communications networks poses a challenge; SCaN is looking to reduce the scope and cost of implementation (Ref. 28).

### 3.3.2 Adaptive Network Topology (TA 5.3.2)

With the introduction of constellations of CubeSats, planetary surface networks, and other future scenarios, there is an increasing need for advanced routing capabilities with cognitive algorithms to facilitate efficient data exchange and spectrum efficiency across multihop networks with changing topologies. Resilient networking and cognitive gateways are two emerging approaches that offer increased network-layer cognition for enhanced network performance.

#### 3.3.2.1 Blockchain Technology

- *Description*: Blockchain is a distributed electronic ledger technology that creates an unchangeable digital record or "block" of transactions among disparate users, and each digital record is time-stamped and linked to the previous one. The technology allows either an open or controlled set of users to participate in the electronic ledger (Ref. 31). This effort was supported as part the Early Career Faculty (ECF) component of the Space Technology Research Grants Program.
- *Capabilities Supported*: Resilient networking
- *Current Activities*: The Resilient Networking and Computing Paradigm (RNCP) efforts conducted by the University of Akron proposes the use of blockchain technology to allow unmanned deep space platforms to "think" on their own and make decisions for automatic detection and avoidance of potentially harmful debris (Ref. 6).
  - Ethereum blockchain technology will be exploited to develop a decentralized, secure, and cognitive networking and computing infrastructure for deep space exploration
  - Develop technology that can recognize environmental threats and avoid them, as well as complete a number of tasks automatically
- *Potential Benefits*:
  - Allow spacecraft to complete more tasks and collect more data
  - Allow scientists more time to analyze that information since the spacecraft will anticipate and respond to environmental threats more autonomously
  - Support secure, decentralized processing among network nodes, resulting in a more responsive, resilient, and scalable network
- *Maturity Level*: TRL 2/3
- *Possible Infusion Points*:
  - Deep space user platforms
  - User platforms that require minimal supervision from ground personnel
- *Infusion Challenges*: TRL advancement, e.g., implementation of blockchain computing capabilities on SWaP-constrained platforms

#### 3.3.2.2 Cognitive Gateways

- *Description*: Cognitive gateways (CG) makes use of system and network requirements, observations, policies, and constraints in an effort to identify viable data paths and forward data objects using cognitive reasoning capabilities (Ref. 5). This effort was supported as part the Early Career Faculty (ECF) component of the Space Technology Research Grants Program.
- *Capabilities Supported*: Cognitive networking, e.g., adaptive data routing, "Drop data anywhere", et al.
- *Current Applications/Research*: Adaptive Data Routing with Cognitive Gateways (Ref. 5)
  - Artificial learning using a modified reservoir of spiking neural networks
  - Spike firings are used to encode data network decisions
  - Evaluation of a prototype on an emulated space-earth testbed and through realistic simulations
- *Potential Benefits*:
  - Significant improvements to the reliability, performance, and asset efficiency of space communication networks.
  - Low-power and small footprint implementation with cognitive processors.
  - Integrates multiple communication technologies: cognitive radio, delay-tolerant networks, free-space optical, and conventional systems.
  - Advance core knowledge of cognitive networking applied to the context of NASA missions, which involve harsh communication environments and the use of mixed network technologies.
  - Main innovation: New computational framework that exploits the brain-like computational power of spiking neural network models for autonomous decision-making in space-earth data networking
- *Maturity Level*: TRL 2/3
- *Possible Infusion Points*:
  - Ground stations and other terrestrial-based network nodes
  - Possible implementation on space-based assets using neuromorphic chips or other technologies suitable for SWaP-constrained platforms
- *Infusion Challenges*: TRL advancement, e.g., implementation of routing capabilities on SWaP-constrained platforms

## 3.4 Integrated Technologies (TA 5.5)

This TA integrates technologies from other areas with the goal of reduced SWaP and enhanced autonomy. Reconfigurable systems include software defined radios and neuromorphic computing platforms, which allow for implementation of cognitive algorithms.

### 3.4.1 Reconfigurable Systems (TA 5.5.1.1)

#### 3.4.1.1 Software Defined Radios

Software Defined Radios (SDRs) are digital radios capable of adaptive reconfiguration of the radio hardware in response to software command functions. SDRs implement the much of the radio functionality, including waveform synthesis, in the digital domain (using technologies such as field programmable gate arrays [FPGAs]) to allow for enhanced configuration and flexibility of the radio operations (Ref. 32). Cognitive radios (CRs) are implemented on SDR platforms and use cognitive algorithms for intelligent adaptation and control (Ref. 33). This allows for more autonomous operation, and future missions can benefit from increased autonomy and reduced dependence on manual control (Ref. 34).

With advancements in microelectronics functionality, packaging, and ability to withstand harsh space environments, SDR SWaP will be reduced. This can be achieved with advancements in radio frequency integrated circuits (RFICs), the use of metal-semiconductor field effect transistors (MESFETs), for

example, with wide operational temperature ranges, and other methods (Ref. 34). While future SDRs may become more size-constrained and power efficient, current SDR implementations may not be suitable for resource-constrained user platforms such as CubeSats, balloons, and sounding rockets. Neuromorphic computing offers the ability implement cognitive engine capabilities on SWaP-constrained platforms, as described in Section 3.4.1.2.

SDRs are considered mission critical since they instantiate the cognitive communications functionality. Therefore, sufficient verification and validation testing is necessary to alleviate significant risk. To reduce this risk, cognitive functions should be evaluated on a ground Avionics/SDR system before deployment to the flight system [Boeing/McGiffin]. Furthermore, cognitive engines implemented on SDRs require realistic training data, possibly derived from actual recorded telemetry, to properly train the cognitive algorithms for effective use in operations (Ref. 35).

The following sub-sections describe SDR platforms that are aligned with the needs of the SCaN network infrastructure.

#### 3.4.1.2 OpenSWIFT

- *Description*: The SWIFT software defined radio is a SWaP-C (space, weight, power, and cost) efficient RF communications, signal processing, and general computing platform enabling on-orbit reprogrammability and flexibility for space missions within NASA's STRS framework (Refs. 36 and 37).
- *Current Activities*: Tethers Unlimited, Inc., is researching and developing cognitive radio solutions, within the STRS framework, using the OpenSWIFT platform (Ref. 4).
- *Cognitive Capabilities Supported*:
  - Spacecraft antenna auto-tracking for near-earth constellation cross links
  - Interference mitigation
  - Spectral mapping
  - Cooperative waveform and rate selection for quality of service assurance
- *Potential Benefits*: Reduced mission planning and mission implementation costs by providing a standardized, robust, hardware and software platform that can dynamically adjust to a rapidly changing space communications environment through the use of machine learning techniques, such as neural networks, genetic algorithms, and reinforced learning.
- *Maturity Level (start/end)*: TRL 3/5 (Ref. 38)
- *Possible Infusion Points*:
  - User mission flight terminals
  - Platforms for new technology development and testing
- *Infusion Challenges*: May not be suitable for highly SWaP-constrained platforms, such as CubeSats

#### 3.4.1.3 Advanced Radio for Cognitive Communication (ARCC)

- *Description*: ARCC is a reconfigurable, STRS-compliant SDR used for cognitive experiments compatible with SN and NEN ground stations.
- *Capabilities Supported*: Cognitive algorithms
- *Current Activities*: Installed and verified operations at White Sands Complex in June 2018.
- *Potential Benefits*: Allows for demonstration of cognitive communication experiments in a relevant environment
- *Maturity Level*: TRL 5
- *Possible Infusion Points*: SN and NEN ground stations
- *Infusion Challenges*: None identified (TBR)

#### 3.4.1.4 Space Telecommunications Radio System (STRS)

- *Description*: The STRS standard defines an open architecture for software-defined radios, and provides a common, consistent framework to abstract the application software from the radio platform hardware. This enables the reuse of application software across diverse SDR platforms. STRS supports both legacy capabilities as well as advanced waveforms (Ref. 39).
- *Capabilities Supported*: Cognitive algorithms on STRS-compliant SDRs
- *Current Activities*: The SCaN Testbed has three STRS-compliant SDRs provided by government and industry partners:
  - *General Dynamics (GD)*: Capable of S-band communications; leverages developments of the TDRSS fourth-generation transponder
  - *Jet Propulsion Laboratory (JPL)*: Capable of S-band communications and GPS L-band navigation in a receive-only configuration; leverages developments of the Electra radio
  - *Harris Corporation (HC)*: Capable of Ka-band communications
- *Potential Benefits*: Reduce cost and risk of using complex reconfigurable and reprogrammable radio systems across NASA missions.
- *Maturity Level*: NASA-STD-4009 (active standard)
- *Possible Infusion Points*: Ground and space-based SDRs
- *Infusion Challenges*: None identified (TBR)

#### 3.4.1.5 Neuromorphic Computing

Neuromorphic computing refers to a non-von Neumann computing architecture that utilizes analog and digital electronic circuits to mimic the architectures present in the biological nervous system. Neuromorphic systems exhibit increased energy efficiency, execution speed, and robustness over traditional computing architectures, and can provide complex pattern recognition capabilities for SWaP-constrained applications (Ref. 40).

#### 3.4.1.6 Neuromemristor (NASA Collaboration with Oakridge National Laboratories)

- *Description*: Neuromemristive systems are a subclass of neuromorphic computing systems that focus on the use of memristors to implement neuroplasticity (Ref. 41).
- *Cognitive Capabilities Supported*: Cognitive algorithms on SWaP-constrained platforms
- *Current Activities*: Oak Ridge National Laboratories is developing a neuromorphic chip that uses a mixed-signal approach for implementing neural networks with spiking events. The use of nano-scale memristive devices saves both area and power in the system (Ref. 42).
- *Potential Benefits*:
  - Demonstrate the efficiency gains of neuromorphic systems for implementing cognitive algorithms, as well as examine the reliability and performance of memristive materials in space (Ref. 4)
  - This effort would place SCaN at the forefront of emerging neuromorphic technology, as this would be the first known flight test of a neuromorphic processor (Ref. 4)
- *Maturity Level*: TRL 2/3
- *Possible Infusion Points*: User mission platforms, CubeSats, and other SWaP-constrained platforms
- *Infusion Challenges*: TRL advancement, e.g., space qualification of neuromorphic chips

#### 3.4.1.7 DynapSEL (NASA Collaboration with the University of Zurich)

- *Description*: DynapSEL is a five-core fully-asynchronous mixed-signal spiking neural network chip with an on-chip learning capabilities, i.e., spike-timing-dependent plasticity (STDP).
- *Cognitive Capabilities Supported*: Cognitive algorithms on SWaP-constrained platforms

- *Current Activities*:
  - NASA is collaborating with Professor Giacomo Indiveri from the Institute of Neuroinformatics at the University of Zurich, Switzerland (Ref. 4), and a DynapSEL chip to be used by NASA researchers with a prototype anticipated by summer 2018
  - NASA was provided with the NCSBrian2 library, which models the neuron and synapses of the DynapSEL hardware; Tutorials show the neuron and synapse behavior
  - The Dynap-se (cxQuad) chip contains 1,024 neurons, 4 nonplastic cores, but does not support online learning
- *Potential Benefits*: Demonstrate the efficiency gains for implementing cognitive algorithms
- *Maturity Level*: TRL 2/3
- *Possible Infusion Points*: User mission platforms, CubeSats, and other SWaP-constrained platforms
- *Infusion Challenges*: TRL advancement, e.g., space qualification of neuromorphic chips

#### 3.4.1.8 IBM TrueNorth Processor

- *Description*: Inspired by the brain's structure, the IBM TrueNorth chip is an efficient, scalable, and flexible non–von Neumann architecture that leverages contemporary silicon technology. The TrueNorth project began as part of the DARPA SyNAPSE project in 2008, and as the project has evolved, IBM has increased the number of neurons per system from 256 to 64 million (Refs. 43 and 44).
- *Cognitive Capabilities Supported*: Cognitive algorithms on SWaP-constrained platforms
- *Current Activity*: In 2017, IBM collaborated with the U.S. Air Force Research Lab to improve its TrueNorth line of chips and develop a 64-chip array, consisting of four boards, each with 16 chips (Ref. 44).
- *Potential Benefits*: The architecture is suited to power-constrained applications that use complex neural networks in real time, such as, for example, multiobject detection and classification.
- *Maturity Level*: The technology is still immature in that applications are still limited. IBM envisions TrueNorth to be eventually introduced into constrained applications like mobile phones, self-driving cars, satellites and unmanned aerial vehicles (UAVs) (Ref. 44).
- *Possible Infusion Points*: User mission platforms, CubeSats, and other SWaP-constrained platforms
- *Infusion Challenges*: Technology is not space qualified; although IBM may eventually pursue space applications, as stated previously.

#### 3.4.1.9 Intel Loihi Processor

- *Description*: A novel self-learning neuromorphic chip that mimics brain functions by learning based on various modes of feedback from the environment (Ref. 45).
- *Cognitive Capabilities Supported*: Cognitive algorithms on SWaP-constrained platforms
- *Current Activity*: Intel has produced the Loihi test chip
- *Potential Benefits*:
  - Loihi test chip offers on-chip learning and combines training and inference on a single chip
  - Demonstrated learning at a rate that is a 1 million times improvement compared with other typical spiking neural nets
  - Compared to technologies such as convolutional neural networks and deep learning neural networks, the Loihi test chip uses many fewer resources on the same task
- *Maturity Level*: The technology is still immature in that applications are still limited
- *Possible Infusion Points*: User mission platforms, CubeSats, and other SWaP-constrained platforms
- *Infusion Challenges*: TRL advancement, e.g., space qualification

#### 3.4.1.10 Neuromorphic Processors for Next Generation Systems

- *Description*: As part of the NASA SBIR program, Bascom Hunter Technologies, Inc., is investigating photonic integrated circuit (PIC) platforms, which when combined with non von-Neumann processing architectures, results in Neuromorphic Photonics resulting increases in both processing speed and energy efficiency (Ref. 46).
- *Capabilities Supported*: Cognitive engine
- *Potential Benefits*: Enhanced processing speed and energy efficiency over traditional computing architectures
- *Maturity Level (start/end)*: TRL 3/4
- *Possible Infusion Points*: SWaP-constrained platforms; applications involving navigation, long-range communications, RF signal processors, and other systems used for spacecraft control.
- *Infusion Challenges*: TRL advancement

#### 3.4.1.11 Low-Power, Ultra-Fast Deep Learning Neuromorphic Chip for Unmanned Aircraft Systems

- *Description*: The use of Deep Neural Networks (DNN) have allowed for advances in machine learning applications such as object recognition, decision making, and speech recognition, for example. However, real-time DNN operation remains in a challenge in that the required computational power can only be realized energy-inefficient systems like GPUs. As part of a NASA SBIR, Mentium Technologies, Inc. is working to advance technology in the area of Machine Learning hardware accelerators, particularly Deep Learning Hardware Accelerators.
- *Capabilities Supported*: Cognitive Engine
- *Potential Benefits*: Real-time situational awareness for cognitive applications
- *Maturity Level (start/end)*: TRL 3/6
- *Possible Infusion Points*: Ground and space-based platforms requiring cognitive capabilities
- *Infusion Challenges*: Technology is focused on aerial applications; transition to the space domain would require space qualification

### 3.4.2 Automated Intelligent Network Systems (TA 5.5.3.1)

This section refers to technologies that enable system nodes to be dynamically aware of the state and configuration of its environment to facilitate autonomous and optimized operations. Described below are various constructs that contribute to this TA.

#### 3.4.2.1 Software Defined Networking (SDN)

- *Description*: Software-Defined Networking (SDN) is an approach to network management that separates the network control aspects (i.e., the control plane) from the data forwarding aspects (i.e., the data plane) for enhanced user experience (Ref. 47).
- *Capabilities Supported*: Cognitive system capabilities
- *Current Activities*: NASA has demonstrated the User-Initiated Service (UIS) capability with the Space Network. In this demonstration, a user mission platform sent service requests and received network responses through a dedicated control signaling plane implemented via the TDRSS satellites. Requested services were provided through single access high-rate links, which are considered part of the data plane. Follow-on efforts will focus on demonstrating the UIS concept for the Near Earth Network (Ref. 48).
- *Potential Benefits*:
    - Allows for centralized network management where necessary adjustments can be accomplished from a single access point
    - Provides for reduced operating costs and other expenses by virtualizing the control planes and minimizing the need for manual configuration updates from trained specialists

- Allows administrators to evenly distribute security information throughout the network across multiple sites
- *Maturity Level*: Terrestrial networks are currently applying SDN concepts
- *Possible Infusion Points*: SN and NEN ground assets
- *Infusion Challenges*: In some cases, such as implementation on NEN ground stations, additional hardware may be required (such as omni-directional antennas) to allow for more readily available control plane connectivity.

#### 3.4.2.2 Cognitive Algorithms (Machine Learning)

- *Description*: A cognitive system perceives its environment, classifies its observations into categorizes (i.e., establish a base of knowledge), performs reasoning, and make use of acquired knowledge to enact appropriate decisions based on its operational objectives. Many learning algorithms are applicable to cognitive systems (such as hidden Markov models, genetic algorithms, and neural networks), where the overall intent is the use of an objective function to optimize parameters of its application. ML algorithms can be generally categorized as unsupervised, supervised, and reinforcement, which can be applied based on the operational environment.
  - *Unsupervised Learning*: Unsupervised algorithms infer knowledge of its environment from acquired observational data that has not been labeled or classified. Additionally, there are no feedback mechanisms within this learning category, and the response of such algorithms cannot easily be evaluated due to lack of an available baseline for comparison.
  - *Supervised Learning*: In this case, the system has labeled training data available, which it uses to produce an inferred function that maps input data to a desired output value. This allows the learning algorithm to strategize an approach to responding to new inputs in a way that is reasonable based on its acquired experience.
  - *Reinforcement Learning*: In this method, algorithms take actions in an environment with the intent on maximizing the "reward" derived from the actions taken. Reinforcement learning can use both trial-and-error and delayed reward approaches to exploring its environment. As the name suggests, in the trial-and-error approach, the cognitive system has no prior knowledge of its environment and makes decisions in an effort to explore and learn about its environment. The delayed reward approach involves positive or negative feedback based on the selected actions, and the system works toward achievement of maximum reward while exploring its environment.
- *Capabilities Supported*: Cognitive engine
- *Current Activities (Ref. 49)*:
  - Projections indicate that Machine Learning will become ubiquitous by 2020 with companies such as IBM, NVIDIA, Intel, and ARM competing to retool the computer industry for machine learning workloads over the next few years.
  - Algorithm designers are working to create faster, more efficient, and more accurate training techniques to improve speech and image recognition, image tagging, data analytics and others.
  - Deep-learning and low-precision inference are current "hot topics"
- *Potential Benefits*: Machine Learning is the essence of the cognitive engine, which enables the systems to function in an intelligent manner.
- *Maturity Level*: Advancements in Machine Learning and Artificial Intelligence techniques and algorithms are continuing to evolve
- *Possible Infusion Points*: Space and ground systems
- *Infusion Challenges*:
  - Limitations on computing capabilities (e.g., massive parallelism, distributed processing, real-time processing) to execute cognitive algorithms, particularly on SWaP-constrained platforms
  - Limitation of available training data to tune the cognitive algorithms

#### 3.4.2.3 Self-Organizing Network (SON) Concept

- *Description*: The Self-Organizing Network (SON) concept is defined as an adaptive, scalable, and autonomous network that can independently decide when and how to execute desired actions based on continuous observation of its operating environment. SONs are able to learn based on previous actions and improve its overall performance. The SON concept can be divided into three categories: self-configuration, self-optimization and self-healing; these are commonly referred to as self-x functions (Ref. 50).
- *Capabilities Supported*: Cognitive system capabilities
- *Current Activities*: SON functionality and behavior has been defined and specified in mobile industry recommendations produced by organizations including the 3rd Generation Partnership Project (3GPP) and Next Generation Mobile Networks (NGMN)
- *Potential Benefits*:
  - Introduces intelligence and autonomous adaptability into cellular networks
  - Reduction of capital and operational expenditures and enhanced network performance in terms of network capacity, coverage, offered services, user experience, etc.
  - Improved spectral efficiency and simplified network management of next-generation wireless systems
- *Maturity Level*: Terrestrial cellular and wireless networks are incrementally applying the SON concepts
- *Possible Infusion Points*: Ground and space systems to achieve increased autonomy and system-wide cognition
- *Infusion Challenges*:
  - Implementation of SON requires a significant investment by the operator since functionality must be deployed throughout the network to achieve the desired benefits.
  - Research and development for SON functionality has been entirely devoted to serve the terrestrial wireless/cellular community; therefore, significant development (e.g., space qualification) may be required to benefit the satellite communications domain

# 4.0 Summary

The cognitive communications and networking efforts at NASA strive to develop cognitive capabilities for increased mission science return, improved resource efficiencies, and increased autonomy and reliability of the SCaN next generation architecture through incorporation of machine learning, artificial intelligence, and other strategies. This report provided an assessment of relevant cognitive communications and networking technologies, standards, and capability enablers that facilitate the achievement of enhanced cognition for the next generation architecture. As the SCaN strategic vision and user mission plans continue to evolve, this report should be updated to incorporate the latest developments in technology and standards to facilitate achievement of the enhanced capabilities.

# References


1. R.C. Reinhart, J.S. Schier, D.J. Israel, W. Tai, P.E. Liebrecht, and S.A. Townes, "Enabling Future Science and Human Exploration with NASA's Next Generation near Earth and Deep Space Communications and Navigation Architecture," in *68th International Astronautical Congress (IAC)*, Aedlaide, Australia, 2017.
2. J. Briones, "Artificial Intelligence - The Future of Space Communications," in *1st NESC Integrated Multi Technical Discipline Space Engineering Workshop*, Hampton, VA, 2018.
3. J. Scott, "Putting Business Capabilties to Work," 15 January 2014. [Online]. Available: https://www.omg.org/news/member-news/OMG-Putting-Cap-To-Work.pdf.

4. J. Briones, D. Chelmins, D. Mortensen, G. Clark, J. Downey and R. Roche, “Cognitive Communications Project Mid-Year Review 2018,” Cleveland, 2018.
5. R. Lent, “Adaptive Data Routing with Cognitive Gateways,” 2017. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/strg_ecf17_lent_adaptive_data_routing_with_cognitive_gateways.pdf.
6. The University of Akron, “Researcher and NASA work to help spacecraft avoid floating debris,” 8 February 2018. [Online]. Available: https://www.uakron.edu/im/news/researcher-and-nasa-work-to-help-spacecraft-avoid-floating-debris/. [Accessed 26 June 2018].
7. SCaN, “SCaN Technology Management Plan,” NASA, Washington DC, 2014.
8. NASA, “NASA - Technology Infusion,” 2010. [Online]. Available: https://www.nasa.gov/offices/ipp/centers/kennedy/technology_infusion/index.html.
9. NASA SBIR, “Adaptive and Cognitive Modem for SmallSat Lasercom at High Data Rates,” Fibertek, Inc., 19 April 2017. [Online]. Available: https://sbir.nasa.gov/SBIR/abstracts/17/sbir/phase1/SBIR-17-1-Z8.02-8495.html. [Accessed 13 November 2018].
10. SBIR, “Wideband Autonomous Cognitive Radios for Networked Satellites Communications,” 2017. [Online]. Available: https://www.sbir.gov/sbirsearch/detail/1217741.
11. S.K. Jayaweera, S. Feng, D. Mortensen, A. Holland, M. Piasecki, M. Evans and C. Christodoulou, “Cognitive Anti-jamming Satellite-to-Ground Communications on NASA’s SCaN Testbed,” in *Wireless Innovation Forum*, Melbourne, 2018.
12. DARPA, “The Radio Frequency Spectrum + Machine Learning = A New Wave in Radio Technology,” 11 August 2916. [Online]. Available: https://www.darpa.mil/news-events/2017-08-11a. [Accessed 13 November 2018].
13. DARPA, “The Spectrum Collaboration Challenge,” 5 November 2018. [Online]. Available: https://spectrumcollaborationchallenge.com/. [Accessed 13 November 2018].
14. Markets and Markets, “Cognitive Radio Market by Component (Software Tools, Hardware, and Services), Application (Spectrum Sensing, Spectrum Analysis, Spectrum Allocation, Location Tracking, and Cognitive Routing), End-User, and Region - Global Forecast to 2022,” January 2018. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/cognitive-radio-market-219954724.html. [Accessed 13 November 2018].
15. European Defence Agency, “CapTech Information,” 27 June 2017. [Online]. Available: https://www.eda.europa.eu/what-we-do/activities/activities-search/captech-information. [Accessed 13 November 2018].
16. University of Luxembourg, “CoRaSat - Cognitive Radio for Satellite Communication,” 2018. [Online]. Available: https://wwwfr.uni.lu/snt/research/sigcom/projects/corasat_cognitive_radio_for_satellite_communication. [Accessed 14 November 2018].
17. K. Liolis, “Cognitive radio scenarios for satellite communications: The CoRaSat approach,” in *2013 Future Network & Mobile Summit*, Lisboa, 2013.
18. IEEE 802.22 Working Group, “IEEE 802.22 Working Group on Wireless Regional Area Networks,” 2014. [Online]. Available: http://www.ieee802.org/22/.
19. IEEE Standards Association, “DYSPAN-P1900.4 - Architecture and Enablers for Optimised Radio & Spectrum resource usage,” IEEE, 2018. [Online]. Available: https://standards.ieee.org/develop/wg/DYSPAN-P1900.4.html. [Accessed 18 July 2018].
20. J.A. Downey, D.J. Mortensen, M.A. Evans, J.C. Briones, and N. Tollis, “Adaptive Coding and Modulation Experiment with NASA’s Space Communications and Navigation Testbed,” in *International Communications Satellite Systems Conference*, 2016.
21. S.W. Ho, “Adaptive Modulation (QPSK, QAM),” Intel, 2004. [Online]. Available: http://ecee.colorado.edu/~ecen4242/marko/WiMax/WiMax/adaptivemodulation.pdf. [Accessed 15 November 2018].
22. DeepSig Inc., “Advancing Next Generation Satellite Communications Systems,” 3 October 2017. [Online]. Available: https://www.deepsig.io/news/2018/6/14/advancing-next-generation-satellite-communications-systems. [Accessed 2 April 2019].

23. Tethers Unlimited, Inc., "COBRA Brochure," 2018. [Online]. Available: http://www.tethers.com/SpecSheets/Brochure_COBRA.pdf. [Accessed 15 November 2018].
24. B.P. Murray and A.I. Zaghloul, "A survey of cognitive beamforming techniques," in *United States National Committee of URSI National Radio Science Meeting*, Boulder, 2014.
25. E. Knoblock and A. Madanyake, "Assessment of Cognitive Communications Interest Areas for NASA Needs and Benefits," NASA Technical Reports Server, Cleveland, 2017.
26. "CCSDS Space Internetworking Services Area (SIS)," CCSDS, [Online]. Available: https://cwe.ccsds.org/sis/default.aspx. [Accessed 19 July 2018].
27. IETF, "Delay/Disruption Tolerant Networking," IETF, [Online]. Available: https://datatracker.ietf.org/wg/dtn/about/. [Accessed 19 July 2018].
28. SCaN Systems Engineering and Standards Division, "DTN Implementation Status," SCaN Program Technical Forum, Washington DC, 2018.
29. CCSDS, "CCSDS Bundle Protocol Specification," September 2015. [Online]. Available: https://public.ccsds.org/Pubs/734x2b1.pdf. [Accessed 19 July 2018].
30. CCSDS, "Licklider Transmission Protocol for CCSDS," May 2015. [Online]. Available: https://public.ccsds.org/Pubs/734x1b1.pdf. [Accessed 19 July 2018].
31. L. Mearian, "What is blockchain? The most disruptive tech in decades," 31 May 2018. [Online]. Available: https://www.computerworld.com/article/3191077/security/what-is-blockchain-the-most-disruptive-tech-in-decades.html.
32. W. Ivancic, P. Paulsen, K. Vaden and D. Ponchak, "Cognitive Networking With Regards to NASA's Space Communication and Navigation Program," NASA NTRS Report Number: NASA/TM-2013-216585, E-18775, GRC-E-DAA-TN6016 , Cleveland, 2013.
33. B. Vermeire, E. Venosa, J. Patin, N. Nicholson, E. Block, E. Tarver, S. Efthyvoulos and C. Alakija, "Design of a Novel Software Defined-Near Earth Space Transceiver for Simultaneous Ka-band and S-band Communications," in *International Communications Satellite Systems Conference (ICSSC)*, Cleveland, 2016.
34. NASA Office of the Chief Technologist, "NASA Technology Roadmaps TA 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems," 2015. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf. [Accessed 17 July 2018].
35. T.H. Rogge, "Cognitive Communication State of Practice Study," Boeing Research & Technology, 2016.
36. Tethers Unlimited, Inc., "OpenSWIFT-SDR for STRS - Quarterly Report #3," 2017.
37. SBIR, "OpenSWIFT-SDR for STRS," 2017. [Online]. Available: https://www.sbir.gov/sbirsearch/detail/1425793.
38. NASA SBIR, "OpenSWIFT-SDR for STRS," 7 March 2017. [Online]. Available: https://sbir.nasa.gov/SBIR/abstracts/16/sbir/phase2/SBIR-16-2-H9.02-7583.html.
39. NASA Glenn Research Center, "Space Telecommunications Radio System (STRS)," 2016. [Online]. Available: https://strs.grc.nasa.gov/.
40. C. Deboy, E. Birrane, D. Copeland, D. Jablonski, S. Jones, and R. Nichols, "Cognitive Communications State of Practice Study," Johns Hopkins University Applied Physics Laboratory, 2016.
41. D. Kudithipudi, "Towards Intelligent Computing with Neuromemristive Circuits and Systems," NICE Workshop, 2014.
42. C. Gangotree, M.M. Adnan, A. Wyer, R. Weiss, C. Schuman and G. Rose, "Memristive Mixed-Signal Neuromorphic Systems: Energy-Efficient Learning at the Circuit-Level," *IEEE Journal on Emergin and Selected Topics in Circuits and Systems,* pp. 125–136, 2018.
43. P.A. Merolla, J.V. Arthur, R. Alvarez-Icaza, A.S. Cassidy, J. Sawada, F. Akopyan, B.L. Jackson, N. Imam, C. Guo, Y. Nakamura, B. Brezzo, I. Vo, S.K. Esser, R. Appuswamy, B. Taba, A. Amir, M.D. Flickner, W.P. Risk, R. Manohar and Mod, "A Million Spiking-Neuron Integrated Circuit with a Scalable Communication Network and Interface," Science, 2014.

44. J. Mannes, “IBM is working with the Air Force Research Lab on a TrueNorth 64-chip array,” 23 June 2017. [Online]. Available: https://techcrunch.com/2017/06/23/truenorth/. [Accessed 18 July 2018].
45. M. Davies and et al., “Loihi: A Neuromorphic Manycore Processor with On-Chip Learning,” *IEEE Micro,* pp. 82–99, January-February 2018.
46. NASA SBIR, “Neuromorphic Processors for Next Generation System,” 25 May 2018. [Online]. Available: https://sbir.nasa.gov/SBIR/abstracts/18/sbir/phase1/SBIR-18-1-H9.05-1079.html. [Accessed 14 November 2018].
47. K. Benzekki, A.E. Fergougui and A.E. Elalaoui, “Software-defined Networking (SDN): A Survey,” *Security and Communication Networks.*
48. D. Mortensen, C. Roberts, and R. Reinhart, “Automated Spacecraft Communications Service Demonstration Using NASA’s SCaN Testbed,” in *AIAA SpaceOps Conference*, Marseille, 2018.
49. R. Farber, “State-Of-The-Art Machine Learning Algorithms and How They Are Affected by Near-Term Technology Trends,” in *HPC Knowledge Meeting 17*, San Sebastian, 2017.
50. P.V. Klaine, M. Ali Imran, O. Onireti and R.D. Souza, “A Survey of Machine Learning Techniques Applied,” in *IEEE COMMUNICATIONS SURVEYS & TUTORIALS*, 2017.
51. D. Chelmins, J. Briones, D. Mortensen, J. Downey, J. Downey, and R. Roche, “Cognitive Communications 2016 Year-end Review,” 2016.