Modulation and Coding for NASA's New Space Communications Architecture

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With the release in 2006 of NASA's Space Communications and Navigation Architecture, the agency defined its vision for the future in these areas. The results reported in this paper help define the myriad communications links included in this architecture through the year 2030. While these results represent the work of multiple NASA Centers and some of the best experts in the Agency, this is only a first step toward developing international telecommunication link standards that will take the world into the next era of space exploration.

Nomenclature

BCH	=	Bose-Chaudhuri-Hochquenghem
CAT A	=	Category A Missions (< 2,000,000 km from Earth)
CAT B	=	Category B Missions (> 2,000,000 km from Earth)
CDMA	=	Code Division Multiple Access
DFE	=	Direct-From-Earth
DSSS	=	Direct-Sequence Spread-Spectrum
DTE	=	Direct-to-Earth
FDMA	=	Frequency Division Multiple Access
GMSK	=	Gaussian Mean Shift Keying
LDPC	=	Low Density Parity Check
LEO	=	Low Earth Orbit
OQPSK	=	Offset QPSK
PCM	=	Pulse Coded Modulation
PM	=	Phase Modulation
PN	=	Pseudo Noise
PSK	=	Phase Shift Keying
QAM	=	Quadrature Amplitude Modulation
QPSK	=	Quadrature PSK
r	=	Code Rate
R-S	=	Reed Solomon
SQPSK	=	Staggered QPSK
TT&C	=	Telemetry, Tracking, and Control

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I. Introduction

IN 2006, the National Aeronautics and Space Administration (NASA) presented its Space Communications and Navigation (SCaN) Architecture[i] that will carry the Agency forward and enable its exploration and science ventures through 2030. The SCaN architecture set forth a vision for the future that includes a vibrant infrastructure together with advances in spacecraft technology.

Recognizing a need to define this architecture in more detail, NASA formed the Coding, Modulation, and Link protocol (CMLP) Study Team. The CMLP study has examined all the links in the SCaN architecture and all the known modulation, coding, and multiple access schemes. The team defined figures of merit that reflect the user missions, operational infrastructure, technological maturity, and interoperability (both within NASA and with other US Agencies and international partners).

In the course of the CMLP Study, intermediate results and progress were shared with the Inter-Operability Advisory Group (IOAG)[ii] and the Consultative Committee for Space Data Systems (CCSDS)[iii] in order to both hone the technical results and ensure future international interoperability of space and ground systems.

After extensive analysis, the CMLP team has made recommendations to NASA[iv] for modulation and coding to be used on each SCaN link. For links where multiple access services will likely be required, the team has also recommended such schemes. Finally, although the CMLP Study was not responsible for recommending link protocols, favorable attributes of link protocols were recommended as appropriate. These attributes (including concepts such as retransmission and adaptive data rates) will be used in subsequent NASA studies to select link protocols for each link.

This paper presents the process used by the CMLP Team, a summary of the results, and a discussion of the programmatic ramifications of the results both at NASA and in the international community. It also outlines future work to be accomplished, including technology roadmapping, standards development, and systems planning for the SCaN infrastructure elements.

II. NASA's SCaN Architecture

The SCaN architecture is a long-term vision that connects NASA spacecraft across the solar system in a system as shown in Figure 1.

The dotted lines represent "long-haul" or "trunk" links between the Earth vicinity and spacecraft in deep space. The halos around targets of intense exploration (in this case, the Earth, our Moon, and Mars) represent local networks supported by additional infrastructure elements such as communication relay satellites.

While the figure shows three of these, different halos could also be deployed as needed to support new targets of interest.

Of course, there is much more to this architecture than this geometric view. This is indicated in Figure 2.

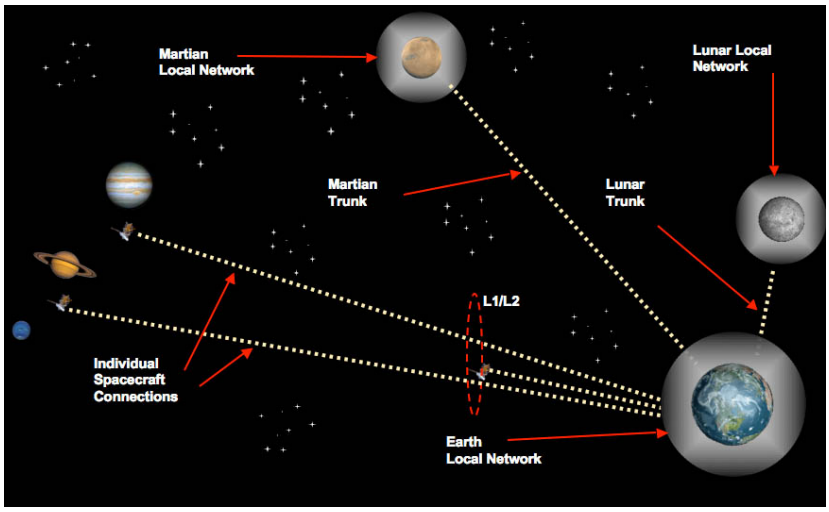


Figure 1: SCaN Architecture overview

The vertical ellipses represent physical NASA infrastructure elements. Each of these provides a set of coordinated services to NASA's space missions, enabling the missions to meet their objectives.

The Earth-based Antennas Element comprises all of NASA's Earth-based communications and tracking assets and supporting systems. Today, NASA has a Ground Network (GN) managed by GSFC and consisting of assets that are optimized for supporting low Earth orbiting spacecraft, launches, and reentry/landings. NASA also has the Deep Space Network (DSN) which has three near-equatorial sites spaced approximately equidistance around the Earth so

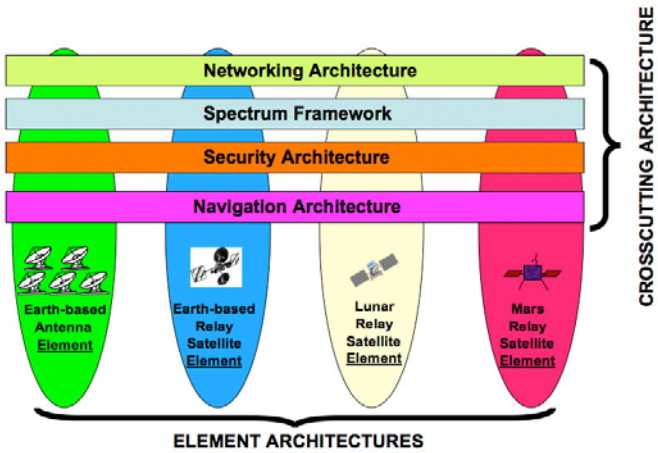


Figure 2: Cross-cutting elements of the architecture

that at least one will be able to view a target in deep space at any time. The DSN antennas are large and optimized for long-distance communication, typically beyond geosynchronous Earth orbit.

Even today, the GN and DSN often co-support space missions. For example, the GN might support the launch of a deep space mission, turning over support to the DSN as the spacecraft leaves the Earth vicinity. In the SCaN architectural vision, all the Earth-based Antenna Element assets will be capable of such cross-support as needed.

The Earth-based Relay Element consists of Geosynchronous Earth-orbiting communications relay satellites. Today, NASA has the Space Network (SN), which comprises a set of Tracking and Data Relay Satellites (TDRSs).

The Lunar Relay Satellite Element will comprise telecommunications and navigation relays in support of space missions in the lunar vicinity. NASA currently has no such assets, but will implement them when it makes sense according to its developing plans for lunar exploration.

The Mars Relay Satellite Element comprises relay satellites in orbit at Mars. Today, all NASA Mars orbiters are equipped with relay radios and, in fact, nearly all data from NASA's Mars Exploration Rovers is returned via these orbiters. Furthermore, since the radio interfaces are defined as international (Consultative Committee for Space Data Systems Standards, or CCSDS) standards, data may also be relayed through the European Space Agency's (ESA) Mars Express orbiter.

There are also four cross-cutting services shown in Figure 2.

The Networking Architecture provides the service-based interface between NASA's missions and the underlying physical elements. This concept is only partially deployed today. This will be the glue that holds the entire system together and allows for routine interoperability between the various elements with transparency to the missions.

The Spectrum Framework defines the spectral allocations to the various links in the architecture. This is crucial to the reliable performance of the entire system. Spectral constraints ensure that all missions will have a clear signal path, unencumbered by natural or artificial interference and protected from encroachment by future users of the radio spectrum.

There is a current spectrum framework in place for NASA missions. The architectural vision requires further development of the framework to define new areas of exploration (such as the Moon) and relays.

The Security Framework will provide the necessary protection of human and robotic assets in space. This becomes more critical as humans once more venture beyond low Earth orbit.

The Navigation Architecture provides the radiometric information needed for mission operators to determine spacecraft position and trajectory. It also provides the entire system with uniform time synchronization.

III. The CMLP Study

A. Study Scope

The CMLP Study was chartered by NASA's Space Communication and Navigation (SCaN) office to fill in some technical detail to the SCaN Architecture. In particular, the CMLP study team was to recommend coding, modulation, link protocol attributes, and multiple access communication schemes to be used in each of the links defined in the architecture. The time frame was from today through the year 2030.

Surface-to-surface links were excluded from the study. These are mostly Earth terrestrial links and planned links on the surface of the Moon.

Only radio links were considered. Although the SCaN architecture included consideration of optical communications, any practical operational use is far enough in the future, and too loosely defined, to permit any meaningful recommendations at this time.

The CMLP team only considered link protocols to the extent that they have a significant impact on the choice of codes, modulations, and multiple access schemes. Another SCaN team is chartered with recommending actual link protocols. That team will use these recommendations on link protocol attributes as one of their inputs.

B. Study Process

The process used by the CMLP Study Team is shown in Figure 3. The CMLP team developed a catalog of links in the SCaN architecture through the year 2030 together with whatever is currently known about the eventual communications requirements of the corresponding missions. The team next created catalogs of all known and reasonable codes, modulations, link protocol attributes, and multiple access schemes. These catalogs, which were reviewed by a set of non-NASA US experts, formed the set from which subsequent down-selections were accomplished.

A set of "figures of merit" (FOMs) was developed to reflect performance, cost, and other constraints that would bias selection of the best schemes on a link. The FOMs were reviewed both by the outside US experts and by the SCaN Space Communications Architecture Working Group (SCAWG). The list of FOMs is shown in Table 1.

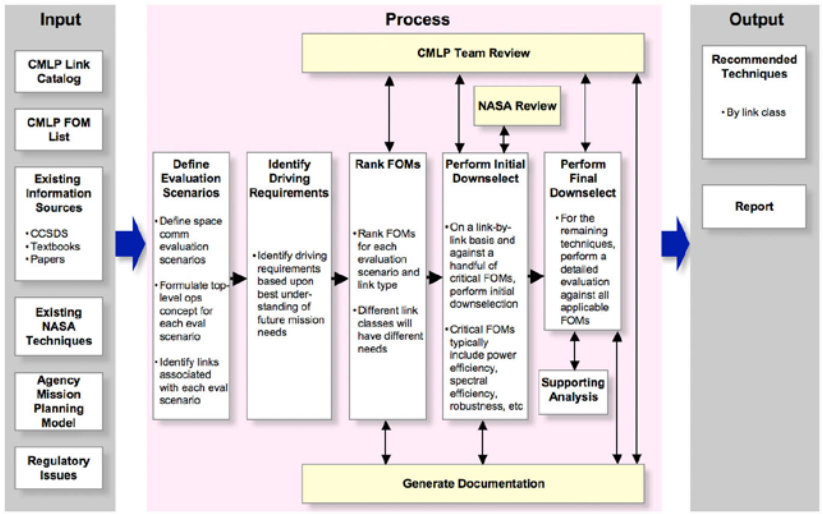


Figure 3: CMLP Study Process

The links in the SCaN architecture were classified into a smaller number of distinct "representative" links in order to reduce the amount of analysis needed. For each of these link classes, the CMLP team performed an initial down-select based on very high-level considerations. The resulting set of "reasonable" options for each link class was reviewed by a set of internal NASA experts.

Finally, the team performed detailed analysis on the remaining options for each link class with respect to the FOMs. Although all FOMs were considered for all links, the relative importance of the FOMs was customized to the link type. For example, "latency" was less important for links from outer planets spacecraft than for links from Earth orbiters.

a. Supports legacy missions
b. Spectrum utilization
c. Power efficiency
d. Infrastructure burden
e. Alignment with international standards
f. Provide radiometrics for navigation
g. Robustness
h. Latency
i. Technology maturity
j. Capacity (number of simultaneous links)

Table 1: Figures of Merit (FOMs)

IV. Results

Table 2, Table 3, and Table 4 provide an overview of the recommended coding, modulation, multiple access, and link protocol techniques. It should be noted that legacy modulation and coding techniques are recommended. While these legacy techniques may not be as powerful as other recommended techniques, they are, however, deeply embedded in the current infrastructure and will probably remain in use for some time. A notional transition plan is provided in Section V that will shows an evolution but it is of course very subject to available funding and should be considered in that context.

Although the team has recommended TDRSS-style CDMA as the multiple access scheme for the Earth relay scenario, we were not able to come up with a single recommendation for the lunar direct-to-Earth scenario. All but two of the candidate schemes were eliminated – but both the CDMA or GMSK/PN schemes remain as possible recommendations. There were two obstacles to deciding on a single recommendation.

Network Parameter	Recommended Technique	Typical Application
Coding	CCSDS turbo codes (r = 1/6, 1/4, 1/3)	• For low data rate, severely power-constrained links or links which have little spectral containment requirements • Typical application may be a small Mars surface platform with DTE/DFE link
	CCSDS AR4JA LDPC codes (r = 1/2, 2/3, 4/5)	• Code family with general applicability to most links • Envisioned future replacement to traditional convolutional and concatenated codes • Offers superior coding gain over traditional codes
	CCSDS C2 LDPC code (r = 7/8)	• For links which are power-constrained and spectrum-constrained • Typical application may be high data rate CAT A missions
	Convolutional codes	• Mid-Transition: General applicability to most links except spectrum-constrained links • Post-Transition: For severely latency-constrained links only • Offers superior heritage and reliability • Typical application may be a LEO mission's TT&C link and the high rate science link
	Legacy Reed-Solomon, BCH	• R-S and BCH have general applicability to most links, especially as outer codes • Need for an outer code is diminished with planned migration to LDPC codes as noted above • Typical application may be a mission which launches prior to the demonstrated operational readiness of LDPC-capable NASA infrastructure
	Uncoded	• For links which are not power-constrained • Although a mission may not be power constrained, consideration should be given to use of a code because of the benefits to power flux density and resiliency to distortions • Typical application may be an X-band LEO mission downlinking at a very high data rate to the NASA GN

Table 2: Recommended Coding Schemes

First, although CDMA works just fine in the nearer-term lunar scenarios, there may be cases in the further term where CDMA as it is currently configured may be over-whelmed. There are several possible solutions to this, such as obtaining additional bandwidth, using polarization diversity, and interference mitigation.

Second, although the GMSK/PN scheme may be more attractive when there are large numbers of channels, it is less technically mature and would require further work to bring it to the desired maturity level.

Since both schemes work in the near-term, the team proposes that NASA do to the additional technical work on the GMSK/PN scheme and reach a consensus on this within two years. If this time frame were too late (e.g. NASA's Constellation Program is driving things faster than that) then we would have to recommend CDMA with the

Network Parameter	Recommended Technique	Typical Application
Modulation	PCM/PSK/PM, PCM/PM	For links to/from NASA ground infrastructure in which the residual carrier signal structure is the de facto mode of operation (e.g., the NASA GN) • For low power links which cannot reliably ensure carrier lock with a suppressed carrier signal structure • Typical application may be a LEO mission's S-band TT&C link to the GN
	OQPSK/PM	• General applicability to most links except very high data rate links (where Trellis receivers and space-qualified digital modulators may not be practical) • Typical application may be spectrum-constrained S-band TT&C links via the SN or DFE/DTE
	Precoded GMSK	
	OQPSK (SQPSK)	• For very high data rate links in which filtered OQPSK/PM and Precoded GMSK hardware may not be feasible • Typical application may be ultra-high data rate science data link via the SN 650 MHz Ka-band channel
	8-PSK and 16-QAM	• 8PSK is recommended for links which are so severely spectrally constrained that 4PSK is not feasible • 16QAM is recommended for Category B missions which are so severely constrained that 4PSK and 8PSK are not feasible • Typical 8PSK application may be ultra-high data rate science data link via the SN 225 MHz Ku-band channel

Table 3: Recommended Modulation Schemes

understanding that this could change in the out years.

Network Parameter	Recommended Technique	Typical Application
Multiple Access (Earth)	CDMA DSSS	For SN forward or return S-band multiple access, use CDMA with spread spectrum PN codes through a multiple access phased array antenna
	FDMA	For SN forward or return Ku- or Ka-band multiple access, use an FDMA-type scheme using scheduled services through multiple single access antennas with unique frequency slots and/or spatial separation for each user
	FDMA	For GN S-/X- or Ka-Band multiple access, use scheduled services through multiple ground antennas which themselves employ multiple frequency bands
Multiple Access (Moon)	CDMA DSSS or FDMA GMSK/PN	For lunar DTE/DFE GT forward or return S-Band multiple access, use CDMA with spread spectrum PN codes or GMSK with PN code ranging through a ground antenna which provides multiple access RECOMMENDATION UNDER STUDY
	CDMA DSSS or FDMA GMSK/PN	For Lunar Relay Satellite forward or return S-band multiple access, use CDMA with spread spectrum PN codes or GMSK with PN code ranging through a multiple access relay antenna RECOMMENDATION UNDER STUDY
	FDMA	For lunar DTE/DFE GT forward or return Ka-Band multiple access, use scheduled services through ground antennas which provide multiple access
	FDMA	For Lunar Relay Satellite forward or return Ka-Band multiple access, use scheduled services through a multiple access relay antenna

Table 4: Recommended Multiple Access Schemes

V. Notional NASA Transition Plan

One immediate concern is the planning for possible upgrades in SCaN's communications networks; the GN, SN, and DSN. Three main factors will influence when a new modulation, coding, multiple access, or link protocol scheme will be introduced into the SCaN facilities:

1) Technology maturity of the scheme
2) Need by the customer missions
3) Availability of funds

The team as part of the FOM analysis considered the technology maturity of the various schemes.

Customer need was based on our understanding of the Agency Mission Planning Model and various analyses of future mission concepts.

We have made no assumptions on the availability of funds: rather we assume the funds will be available when they are needed to respond to the first two items. This is an important assumption and the schedules need to be viewed in light of this.

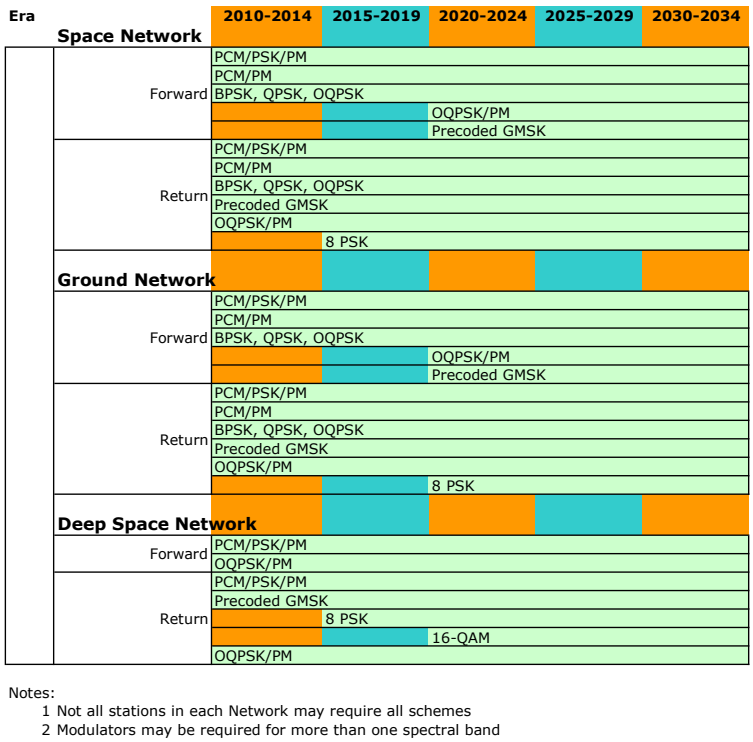
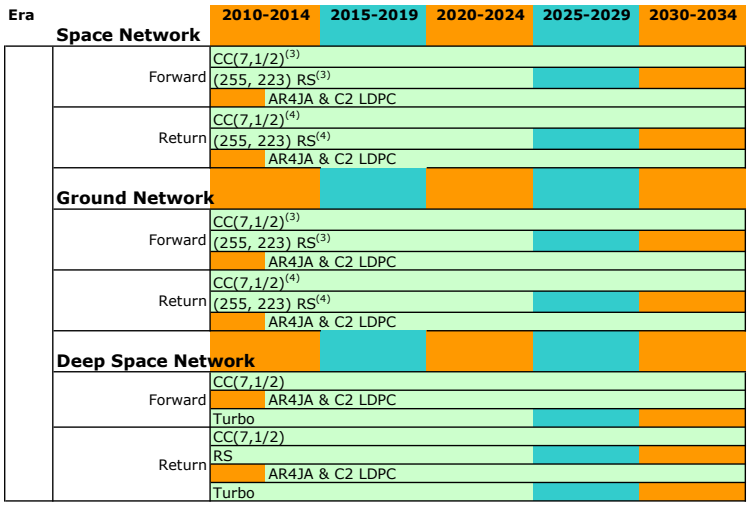


Figure 4:Notional modulation infusion plan for SN, GN, and DSN



Notes:
1 Not all stations in each Network may require all schemes
2 Coders (encoders and decoders) are assumed to be capable of coding family of code parameters
3 Currently supported by NASA SN and GN as pass-through data (i.e., customer performs encoding)
4 Currently supported by NASA SN and GN equipment (R-S decoding not supported for all SN and GN service modes)

Figure 5: Notional coding infusion plan for SN, GN, and DSN

With these assumptions, Figure 4 shows a notional infusion plan for modulation schemes. The 2010-2014 column exhibits the current capability. The various new CMLP-recommended modulation schemes are shown appearing when needed. The legacy schemes disappear when they are no longer needed.

It is important to note that not all nodes in these networks (e.g. DSN or GN antennas) will require every modulation scheme. Also, distinct modulation systems may be required for different frequency bands within the networks.

However, most modulation systems available today offer a wide range of formats so the number of distinct systems may be much smaller than might be indicated by the Figure.

Figure 5 shows a similar infusion schedule for coding schemes. Once again, not all nodes will need all these codes. It is assumed that each coder will be capable of processing a variety of codes within a related family. Hence, for example, the LDPC coder will be able to handle all the recommended LDPC codes.

VI. Conclusions and Next Steps

The NASA CMLP study team has examined all the links in the NASA Space Communications and Navigation Architecture. For each link, the team has recommended a small set of modulation, coding, and (as appropriate) multiple access schemes. In addition, the team has recommended attributes that should be included in the selection of link protocols to use with these links (on a single-hop basis.)

The team had a great deal of support from NASA Headquarters and from all the appropriate NASA centers. The technical work was reviewed at important junctures during the study and, in fact, has resulted in a number of soon-to-be-submitted technical papers describing new technical results.

The study, in addition to providing valuable guidance to the NASA SCaN office and to the international space communications community, has been a great opportunity to share ideas between NASA centers.

A. Future Work

Now that the internal NASA team has completed its work on codes and modulations, it is time to redouble our discussions and development with the international space community in these areas. The goal will be an international plan to move forward with link standards and developments. The plan will be coordinated among international partners as well as among space and ground facilities.

The choice of a recommended multiple access scheme for the lunar scenarios, however, requires additional work. We recommend that NASA continue work in this area as our lunar plans continue to become more solid.

SCaN has embarked on an effort to update NASA's roadmaps for technologies that support communications and navigation. The CMLP results will provide guidance for several of these roadmaps, including software-defined radios, spacecraft antennas, navigation, and power amplifiers.

Finally, SCaN has implemented a high-level System Planning function for communications and navigation for NASA. The CMLP results will serve as guidance to this group as NASA moves forward in its implementation of the SCaN Architecture.

Acknowledgments

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