Multiple Access Schemes for Lunar Missions

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Two years ago, the NASA Coding, Modulation, and Link Protocol (CMLP) study was completed. The study, led by the authors of this paper, recommended codes, modulation schemes, and desired attributes of link protocols for all space communication links in NASA's future space architecture. Portions of the NASA CMLP team were reassembled to resolve one open issue: the use of multiple access (MA) communication from the lunar surface. The CMLP-MA team analyzed and simulated two candidate multiple access schemes that were identified in the original CMLP study: Code Division MA (CDMA) and Frequency Division MA (FDMA) based on a bandwidth-efficient Continuous Phase Modulation (CPM) with a superimposed Pseudo-Noise (PN) ranging signal (CPM/PN). This paper summarizes the results of the analysis and simulation of the CMLP-MA study and describes the final recommendations.

Nomenclature

CCSDS	= Consultative Committee for Space Data Systems
CDMA	= Code Division Multiple Access
CEV	= Crew Exploration Vehicle
CMLP-MA	= Coding, Modulation, Link Protocol – Multiple Access
CPM	= Continuous Phase Modulation
DSN	= Deep Space Network
FDMA	= Frequency Division Multiple Access
FOM	= Figure of Merit
GMSK	= Gaussian-filtered Minimum Shift Keying
GSFC	= Goddard Space Flight Center
HDR	= High Data Rate
JPL	= Jet Propulsion Laboratory
LDR	= Low Data Rate
MA	= Multiple Access
MAI	= Multiple Access Interference
NEN	= Near-Earth Network
OQPSK	= Offset Quadrature Phase Shift Keying
PN	= Pseudo Noise
SCaN	= Space Communications and Navigation
SER	= Symbol Error Rate
TDRSS	= Tracking and Data Relay Satellite System
VLDR	= Very Low Data Rate

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I. Introduction

NASA's Space Communication and Navigation (SCaN) office chartered the Coding, Modulation, and Link Protocol – Multiple Access (CMLP-MA) study to recommend and justify multiple access (MA) communications and navigation schemes appropriate for exploration of the Earth's moon. Although tentative NASA budgets now call for the cancellation of the Constellation Program that would have made multiple orbiting and landed lunar assets a reality, the CMLP-MA study provides the best technical summary and recommendation for MA communications at the Moon and we trust it will be useful in planning future NASA missions and technology investments relating to lunar communications.

The CMLP-MA study is a follow-up to an earlier CMLP study [1] that recommended coding, modulation, and link protocols to be used in each of the links defined in the SCaN architecture. The earlier study identified two leading candidate MA schemes: (1) Code Division Multiple Access (CDMA) based on NASA's Space Network Tracking and Data Relay Satellite System (TDRSS) and emerging CDMA interference cancellation technology, and (2) a Frequency Division Multiple Access (FDMA) approach based on bandwidth-efficient data communications implemented via Continuous Phase Modulation (CPM)—e.g., Gaussian Minimal Shift Keying (GMSK) or filtered Offset Quadrature Phase Shift Keying (OQPSK)—with a superimposed Pseudo Noise ranging signal, designated variously as GMSK/PN and OQPSK/PN, or in general CPM/PN.

After extensive analysis and simulation of both approaches against a common set of standardized test scenarios (and some system-specific excursions), and following assessment of the schemes relative to the Figures of Merit (FOMs) developed in the earlier CMLP study, the CMLP-MA team made recommendations for the CDMA and FDMA approaches, each of which was viewed to be appropriate for applications within a defined parameter space.

This paper presents SCaN architecture, the need, scope and plan of the CMLP-MA study, the process used by the CMLP-MA Team, and a summary of the CMLP-MA recommendations.

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 (the Earth, our moon, and Mars) represent local networks supported by additional infrastructure elements such as communication and/or navigation relay satellites.

While the figure shows the three most frequently considered exploration regions, 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, which displays the architecture elements.

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

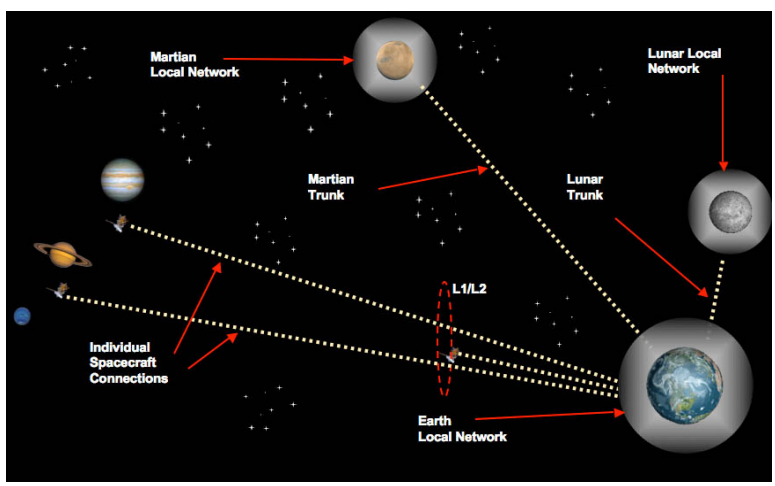

Figure 1. SCaN architecture overview.

The Earth-based Antenna Element is comprised of all of NASA's Earth-based communications and tracking assets and supporting systems. Today, NASA has a Near Earth Network (NEN) managed by Goddard Space Flight Center (GSFC) and consisting of assets that are optimized for supporting low Earth orbiting spacecraft, launches, and reentry/landings. NASA also operates the Deep Space Network (DSN) which has three near-equatorial sites spaced approximately equidistantly around the Earth, enabling at least one station to view a target in deep space at any time. DSN antennas are large and optimized for long-distance communication, typically beyond geosynchronous Earth orbit.

Even today, the NEN and DSN often co-support space missions. For example, the NEN 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.

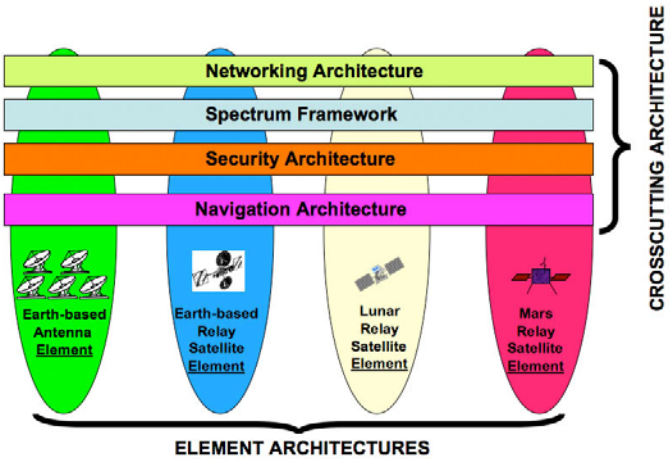

Figure 2. Cross-cutting elements of the architecture.

The Earth-based Relay Satellite Element consists of Geosynchronous Earth-orbiting communications relay satellites. Today, NASA has the Space Network (SN), comprising a set of TDRSs.

The Lunar Relay Satellite Element is a potential future capability comprising telecommunications and navigation relays in support of space missions in the lunar vicinity.

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 rovers and landers are returned via these orbiters. Furthermore, since the radio interfaces are defined as international standards (Consultative Committee for Space Data Systems Standards, or CCSDS), 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 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-MA Study

A. Need for the CMLP-MA Study

Good link designs are required for all the various links in the SCaN architecture–including those studied herein–for a number of reasons:

- Ensure adequate performance to meet anticipated mission requirements through 2030.
- Manage impacts (including cost) to the infrastructure elements.
- Manage impacts (including cost) to the space missions

- Ensure radiometrics are available as needed for navigation
- Determine required technology investments.
- Determine needs for any additional international standards.
- The last item is particularly important since NASA does not expect to fulfill its ambitions alone.

A significant gap in the SCaN Architecure was filled through the execution of the Coding, Modulation, and Link Protocol (CMLP) Study that concluded in 2008. The CMLP Study team recommended modulation types, coding schemes, and MA algorithms for nearly all of the SCaN Architecture. In addition, the team identified specific attributes of link protocols that should be pursued by NASA's networking teams. All the results are documented in the CMLP Final Report [1].

The code and modulation designs from the CMLP Report have been vetted in the international spacefaring community and are now firmly entrenched in the standards process. In addition, they are planks in the evolving SCaN development plans.

Although the CMLP team was able to make firm recommendations for codes and modulations for all of the links in the SCaN Architecture, there was insufficient time during the study to achieve a consensus recommendation on MA communication between the lunar environment and the Earth's surface. The team identified two leading candidates for this applications:

1. CDMA / Direct Sequence Spread Spectrum (DSSS) based on the TDRSS and emerging CDMA interference cancellation technology;
2. FDMA based on bandwidth-efficient data communications implemented via CPM—e.g., GMSK or filtered OQPSK—with a superimposed PN ranging signal, designated variously as GMSK/PN and OQPSK/PN, or in general CPM/PN.

The team viewed each of the two candidates as having certain advantages and disadvantages, leading to the lack of a final recommendation for these links. Instead, the team recommended further study of both options to resolve the remaining issues. Of primary interest for the CDMA approach was whether the legacy CDMA scheme would be sufficient to meet the needs of the SCaN architecture through 2030, and whether improvements involving multiple user interference cancellation would be necessary, practical, and well-performing. Of primary interest for the FDMA approach was whether the analytical predictions from the earlier CMLP study could be verified by simulation.

Since NASA was moving firmly ahead with plans for human lunar exploration including human lunar bases with multiple fixed and mobile elements, it was important to resolve these issues and make a clear recommendation. Hence NASA funded this CMLP-MA study in late 2008.

B. CMLP-MA Study Charter

The charter of the CMLP Multiple Access (CMLP-MA) study was to recommend and justify MA communications and navigation schemes appropriate for exploration of the Earth's moon. The CMLP-MA team was to:

- Study CDMA and FDMA approaches identified in the initial CMLP study in more detail, including analysis and simulation of SCaN Architecture scenarios, and recommend appropriate MA schemes for the exploration of the Earth's moon,
- Engage the international spacefaring community in order to capture good ideas, build advocacy for international standards, and build good will,

- Provide guidance on link designs to the builders of NASA's communications infrastructure, the developers of NASA's spacecraft technology, the developers of NASA's future mission concepts, and to the NASA Standards Program, and
- Identify key required NASA communications and navigation investments.

C. CMLP-MA Study Scope

Every link in the SCaN Architecture involving at least one lunar asset and one Earth asset is in the scope of the CMLP-MA Study, including any direct to Earth (DTE) and direct from Earth (DFE) links. Surface-to-surface lunar links and surface-to-relay links were not considered here, and the study also did not consider optical links.

The time frame for the links in the scope of the study is from 2013 through 2030. Links that become operational before 2013 are already defined and the study cannot influence their design. The Team chose the 2030 long-term cut-off date to both be consistent with the original SCAWG team work and to be able to include links to support humans beyond the Moon.

Communications and navigation are both within the study scope. We did not consider the use of specialized navigation systems (e.g. GPS or Galileo), which will certainly be appropriate in the Earth vicinity. Only situations where the radio link is required to provide both communications and navigation are within the scope. Both candidate schemes utilize a PN signal, modulated or unmodulated, to perform ranging.

The CMLP team, to avoid duplication of prior work, uses previous work by NASA or other experts in the areas of MA schemes, and link protocols, the only qualification being that the team viewed such prior work as technically sound.

D. CMLP-MA Study Plan

The study was originally to be conducted in two phases. Phase 1 involved analysis and software simulation, and Phase 2 involved a hardware implementation and demonstration.

In the analysis portion of Phase 1 the plan was to:

- Develop reference MA waveforms for each technique.
- Consider alternative MA waveforms varying modulation index, subcarrier frequency, PN code rate, etc.
- Consider alternative waveforms (e.g. pre-coding, square vs. half-sinusoidal chip shape, and sinusoidal vs. square wave subcarrier).
- Consider alternative receiver processing methods.
- Estimate the communications and ranging performance of each waveform both with and without interference.
- Establish metrics for comparison based on the FOMs.
- Rank the alternative MA techniques.

In the software simulations portion of Phase 1 the plan was to:

- For each waveform, write a single channel software transmitter emulator, followed by a software data receiver and a software ranging receiver.
- Connect the single-channel transmitter to the receiver through a software-simulated transmission channel to which software-generated noise can be added.
- Use the single channel software simulation to prove the viability of the waveform for simultaneous data communications and ranging and to make baseline performance measurements.
- Determine the effectiveness of the waveform in a MA environment, add software transmission channels to emulate the lunar MA scenarios to the first software transmission channel, and measure the effects on data and ranging reception of the first channel.
- Simulate telemetry performance in forward and return directions, and two-way ranging performance, including the effects of amplifier nonlinearities and all major sources of impairment.

Phase 2 was to convert the software simulations to FPGA designs. The objectives were to

- Develop and test forward link CPM/PN software simulations.
- Verify CPM/PN operation though one-way hardware simulations.
- Develop and conduct two-ways tests with CPM/PN waveform on radio equivalent to the JPL CoNNeCT radio
- Plan flight demonstration using CoNNeCT.

Phase 2 was canceled because of complications in funding, schedule, personnel, and a redistribution of responsibility within NASA.

E. CMLP-MA Study Process

The original CMLP study followed the process shown in Figure 3 to arrive at its recommendations. The MA portion of the CMLP study completed the definition of evalution scenarios, identification of driving requirements, establishment and prioritization of FOMs, and an initial down-selection of candidate MA schemes.

In the present CMLP-MA study, we study the two remaining candidate schemes in much more detail, verify compliance with international spectrum mask standards, and analyze and simulate the telemetry and ranging performance in the presence of multiple interfering users. Several scenarios of interest were analyzed and simulated and reviewed by CMLP-MA team members.

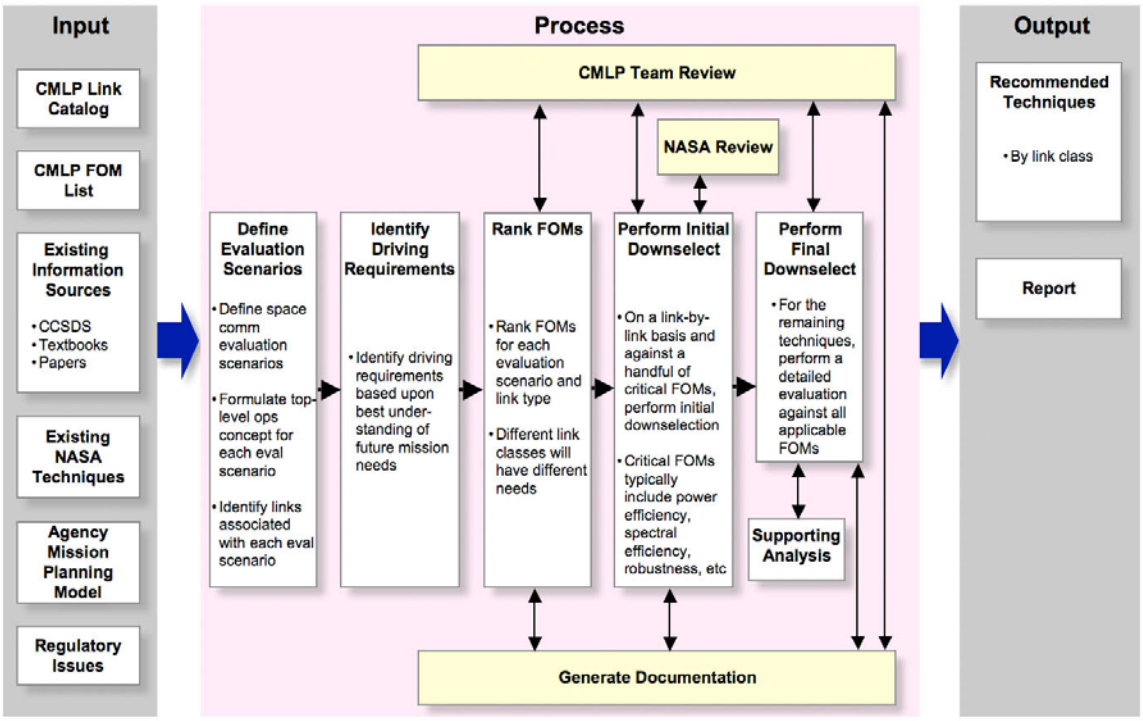

Figure 3. The CMLP-MA process.

IV. Results

The CMLP-MA team recommends use of CDMA for certain application profiles, and FDMA for others. In summary, CDMA is recommended when higher ranging accuracy is needed, higher telemetry losses are tolerated, and relatively fewer users (and no users at encoded symbol rates exceeding 600 Ksps) are present; and FDMA is recommended when higher telemetry performance is needed, lower ranging accuracy is tolerated, and a relatively larger number of users (or any > 600 Ksps users) are present. Several additional restrictions apply to each approach, and the full recommendation is spelled out in more detail in the application profiles below.

The application profiles are primarily categorized by:

User encoded symbol rates. Three data symbol rate regimes are considered: very low data rate (VLDR) refers to rates up to about 50 ksps, low data rate (LDR) to rates up to about 400 ksps, and high data rate (HDR) to rates as high as 2 Msps. This captures the data rates preliminarily planned for CEV, namely, forward rates of 36 Ksps (VLDR) and 144 Ksps (LDR), and return rates of 48 Ksps (VLDR) and 384 Ksps (LDR).

Number of users. This refers to the inherent capacity of the approach to support multiple user channels in accordance with established success criteria (error rates, spectral containment, etc.) Although specific capacity studies for the two formats were not performed, the test scenarios are sufficiently stressful to identify differences between the alternatives in number of supportable users.

Telemetry performance. This is measured as the symbol SNR Es/N0 required to achieve a symbol error rate (SER) of 0.1 in the presence of MAI. (SER = 0.1 can correspond to a user bit-error-rate as low as 10-8 after error-correction).

Ranging performance. This is defined as the two-way coherent ranging accuracy, measured on a one standard deviation (1-σ) basis, counting only the contributions to ranging error due to thermal noise and mutual interference among the user signals. Error sources such as calibration error or ground instrumentation error are excluded.

F. CDMA recommendation

CDMA is the recommended MA scheme for applications having the attributes shown in Table F.

Table IV.1: MA attributes for which CDMA is recommended.

Scenario	Number of simultaneously active users	Required E_s/N_0 to achieve SER = 0.1 (db)	Allowable ranging error (1- σ) (m), 5 Hz PN bandwidth
Only VLDR users	≤ 48	≥ 0.8	≥ 1.28
Only LDR users	≤ 9	≥ 1.2	≥ 0.67
VLDR and LDR users	≤ 14 (7+7)	≥ 1.6 (VLDR) ≥ 0.8 (LDR)	≥ 1.2 (VLDR) ≥ 0.52 (LDR)

This recommendation is limited to those applications for which all of the following statements are true:

1. Each LDR user has the resources to either (1) implement all-users interference cancellation prior to symbol detection, or (2) tolerate an additional telemetry loss of up to 2.3 dB (depending on the scenario) if interference cancellation is not used.
2. Interference cancellation, if employed, is compatible with the latency requirements for telemetry data (e.g., for voice channels or critical events), and with response times, data outage tolerance, and mission complexity requirements in dynamic MA scenarios (users joining and leaving the session).
3. The links contain no unpredicted fading, shadowing, or multipath with a time constant less than 2.6 seconds (the lunar feedback time for power control).
4. The encoded symbol rate is limited to 300 Ksps for each I-channel and Q-channel (600 Ksps total).

G. FDMA recommendation

FDMA is the recommended MA scheme for applications having the attributes shown in Table G.

Table IV.2: MA attributes for which FDMA is recommended.

Scenario	Number of simultaneously active users	Required E_s/N_0 to achieve SER = 0.1 (db)	Allowable ranging error (1- σ) (m), 5 Hz PN bandwidth
Only VLDR users	≤ 59	≥ 0.4	≥ 2.06
Only LDR users	≤ 11	≥ 0.5	≥ 1.01
VLDR and LDR users	≤ 20 (10+10)	≥ 0.5	≥ 2.55 (VLDR) ≥ 0.77 (LDR)
VLDR, LDR, and HDR users	≤ 9 (4+3+2)	≥ 0.5	≥ 1.14 (VLDR) ≥ 0.40 (LDR)

This recommendation is limited to those applications for which the following statement is true:

1. Each user transceiver has the resources to implement both bandwidth-efficient CPM (e.g., GMSK or filtered OQPSK) and PN ranging as described in Section 4.2, and the corresponding demodulation and range determination capability.
2. The overall technological maturity of such implementation is compatible with mission requirements.
3. In dynamic MA scenarios (users joining and leaving the session), the method of dynamic frequency assignment is compatible with mission complexity and latency requirements.

V. Conclusions and Next Steps

Acknowledgments

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[1] Les Deutsch, Frank Stocklin, *Coding, Modulation, and Link Protocol (CMLP) Study Report,* NASA SCaN, January 10, 2008.