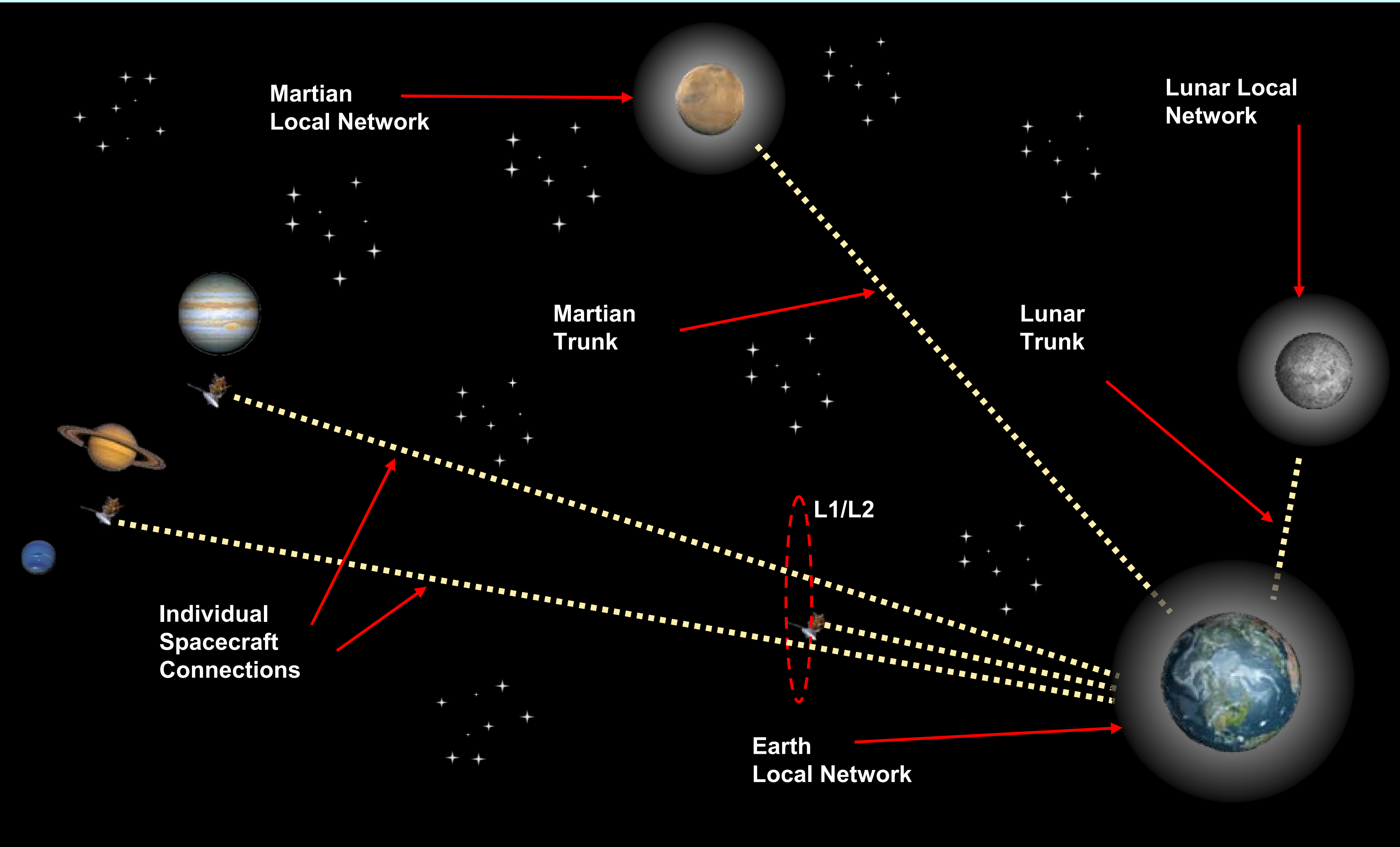
NASA/SCaN Coding, Modulation, and Link Protocol Study

Status Report to IOAG
June 2007

Agenda

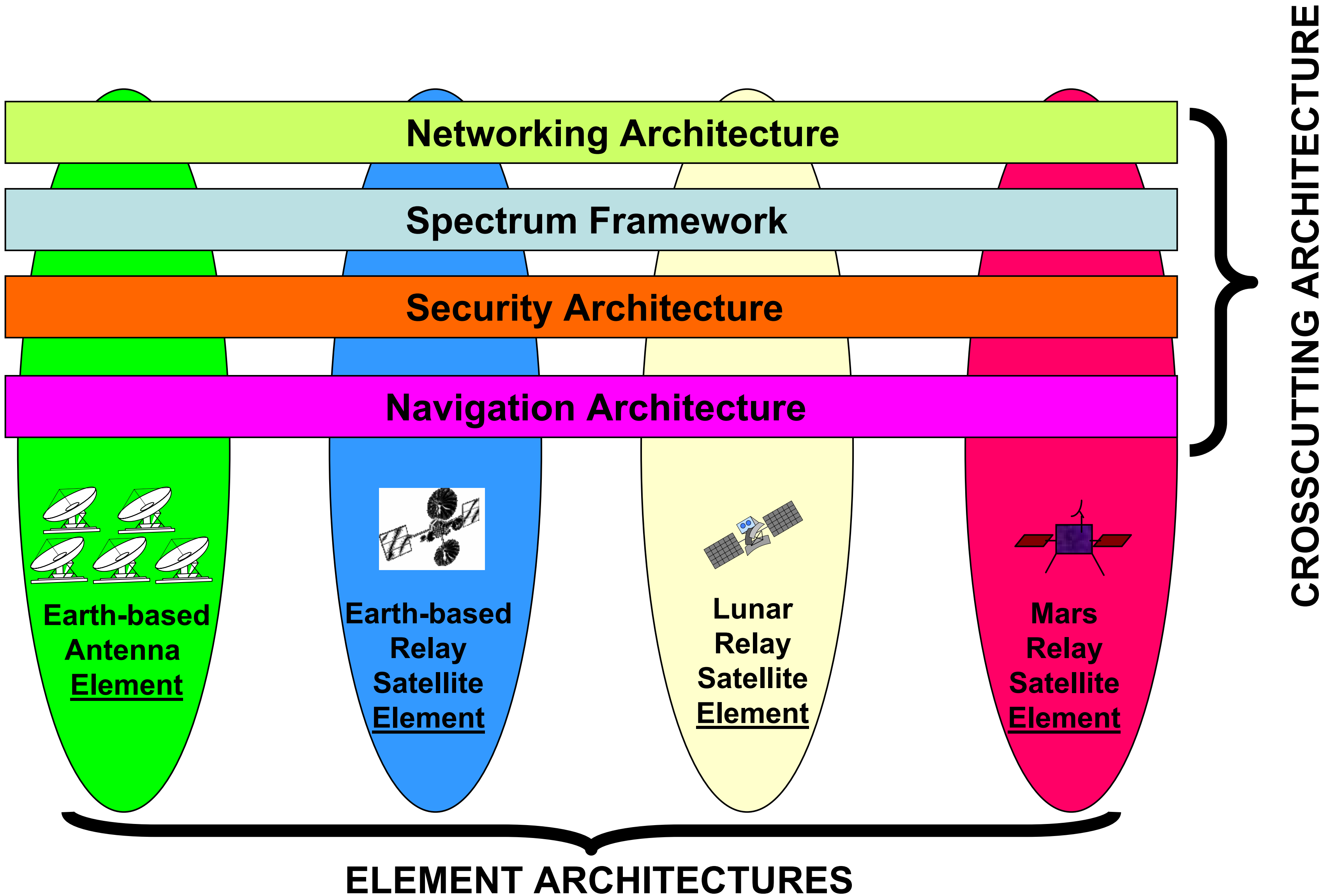
- Purpose/Scope of CMLP Study
- Process used in study
- Catalog of SCaN architecture Driving Links
- Catalogs of codes, modulations, multiple access (MA) schemes and link protocol (LP) attributes
- Figures of Merit (FOM)
- Link classification
- Recommended schemes for link classes
- Future work
- Summary

Top Level Space Comm & Navigation Architecture



National Aeronautics & Space Administration

Overall SCaN Architecture



A Hole in the Layers

- SCaN has defined a set of links across the Solar System
- SCaN has recommended spectrum for these links
- SCaN has recommended some networking protocols
- SCaN has NOT yet recommended how to implement the physical link up to the link layer protocols (i.e., coding, modulation,link protocol, etc.)
- This is problematic for several reasons
  - In the absence of overall guidance, missions may chose multiple directions, thereby costing more to develop and operate
  - There is no direction to the international standards community
  - There is no direction to SOMD to implement these links in the NASA comm/nav infrastructure
  - There is no guidance to NASA technology investors to develop needed spacecraft comm/nav systems

Purpose of the Study

- Plug this hole
- Recommend and justify link designs for the SCaN architecture
  - Defendable to naysayers
- Provide guidance
  - To NASA mission concept developers
  - To the builders of NASA's comm/nav infrastructure
  - To spacecraft technology developers
  - To the NASA Standards Program
- Identify key NASA comm/nav investments
- Engage international community

Scope

- Every link in the SCaN architecture through 2030
  - We exclude surface-to-surface links
- All reasonable coding, modulation, and multiple access schemes
  - We have applied common sense to narrow the study space
  - SCaN has acted as the approving authority for the elimination of schemes from specific link analyses
- We considered only certain properties of link protocols
  - We did not select specific protocols
  - We *DID* consider things that affect coding , modulation and link protocol)selection
    - Retransmission, Adaptive rate control …
- Radiometrics and Navigation considered
- Engaged outside experts to review and provide comments
- Maximized use of results from other NASA studies

Transition Planning

- The SCaN architecture represents a major change for NASA
  - Coding, modulation, multiple access, and link protocols may advance significantly beyond what current NASA systems support
  - CMLP is only one example of what will change
- Legacy systems will have to be supported until both spacecraft and ground systems complete transition
  - In some cases this will take many years
  - Spectrum (e.g., Cat A X-band), codes, modulations …
- This study will be one input to SCaN architecture transition plan
  - SCaN system roadmaps
  - Technology investment and infusion (end-to-end)
  - International standards development
  - Policies for new missions

Deliverables

- In June, we are delivering a draft final report that includes
  - A catalog of NASA's existing links with descriptions
  - A catalog of the SCaN links with (for each link)
    - A list of all the coding, modulation, protocol, and access schemes studied including evaluation according to a set of "figures of merit"(FOMs)
    - A small number of recommended coding, modulation, link protocol attributes, and multiple access schemes
- This is a summary of that report for the IOAG
  - We will gather feedback from all of you
- Final report to be released in late Summer 2007
  - Additional participation of international partners as defined at this meeting

Plan and Status

	Task	Done	Explanation
Phase 1	Create catalog of existing NASA links	yes	
	Create catalog of SCaN links (w/ requirements)	yes	
	Create list of FOMs for evaluation	yes	
	Create list of coding, modulation, protocol, and access schemes for analysis	yes	
	Find all relevant, technically sound existing studies	yes?	
Phase 2	Define (and get NASA expert agreement) a list of schemes to evaluate for each link	yes	
	Do the analysis and evaluate the FOMs	part	Mars in-situ still to be completed
	Get agreement (with NASA experts) of FOM weighting for each link	part	Mars in-situ still to be completed
Phase 3	Create recommendations for each link	part	Mars in-situ, MA, and international engagement still to be completed
	Write draft final report	no	

National Aeronautics & Space Administration

Stakeholders

Space Communications CMLP Study

- NASA has many communities that have an interest in the results of this study
- Here is how the various US communities have participated thus far

Stakeholder	Team Member	NASA oversight	Internal review	External Review
SCaN		x	x	
Technologists	x		x	
Comm infrastrcuture engineers	x	x	x	
Spacecraft comm engineers	x			
Mission Directorates		x		
Constellation		x	x	
Other gov't, industry & academia				x

National Aeronautics & Space Administration

Reference Deep Space/Earth Links

Mission Type	Link type	Range (km)	Frequency (MHz)	Transmit Antenna	EIRP (dBW)	Receive Antenna	G/T (dB/K)	Data rate (kbps)	BER
Mars Lander or Orbiter	Safe Mode	400,000,000	7183	70m DSN	116	Low Gain	-31	0.0078125	1.00E-06
			8439	Low Gain	17	70m DSN	57	0.01	1.00E-03
Titan Orbiter	Operational	1,197,000,000	7183	34m DSN	110	6m	19	1000	1.00E-08
			8439	6m	72	70m DSN	57	600	1.00E-08
	High Rate	1,197,000,000	34316	34m DSN	122	6m	31	1000	1.00E-08
			32028	6m	90	70m DSN	62	10000	1.00E-08
Mars Relay Orbiter	Operational	400,000,000	7183	34m DSN	110	6m	19	6000	1.00E-08
			8439	6m	72	70m DSN	57	6000	1.00E-08
		58,000,000	7183	34m DSN	110	6m	19	20000	1.00E-08
			8439	6m	72	34m DSN	51	20000	1.00E-08
	High Rate	58,000,000	34316	34m DSN	112	6m	31	10000	1.00E-08
			32028	6m	90	34m DSN	56	500000	1.00E-08

Reference: High Capacity Communications from Martian Distances, A Report of the Space Communications Architecture Working Group (SCaN), March 2006

National Aeronautics & Space Administration

Ground Network Link Catalog

Mission	Link Characteristic	Orbit Regime	Launch Date	H/K Freq Band	H/K Data Rate	Science Freq Band	Science Data Rate	Latency	Uplink Band/Rate	Potential Support
Medium Class Explorer										
MIDEX-08	Distance	SEL1	2015	?	?	X-or Ka	213Kbps	Near R/T	X/4Kbps	GN, DSN, Other
JWST	Distance/Data Rate	SEL2	2013	S-Band	40Kbps	Ka-Band	24.5Mbps	Near R/T	S/16Kbps	GN, **DSN**
MIDEX-10	Distance/Data Rate	SEL2	2022	S-Band	16Kbps	Ka-Band	20Mbps		S/2-10Kbps	GN, DSN, Other
MIDEX-12	Distance/Data Rate	SEL2	2025	S-Band	32Kbps	Ka-Band	30Mbps		S/2-10Kbps	GN, DSN, Other
SNAP (JDEM)	Distance/Data Rate	SEL2	2021	X-Band	100Kbps	Ka-Band	150Mbps	Non R/T	X/100Kbps	GN, DSN
Earth System Science Pathfinder										
ESSP-07	High Data Rate	LEO	2014	S-Band	64Kbps	X-or Ka	300Mbps	Near R/T	S/1Kbps	GN, SN
ESSP-08	High Data Rate	LEO	2016	S-Band	64Kbps	X-or Ka	300Mbps	Near R/T	S/1Kbps	GN, SN, Other
ESSP-09	High Data Rate	LEO	2018	S-Band	64Kbps	Ka-Band	600Mbps	Near R/T	S/1Kbps	GN, SN, Other
ESSP-10	High Data Rate	LEO	2020	S-Band	128Kbps	Ka-Band	600Mbps	Near R/T	S/1Kbps	GN, SN, Other
ESSP-11	High Data Rate	LEO	2022	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	S/2Kbps	GN, SN, Other
ESSP-12	High Data Rate	LEO	2024	S-Band	1Mbps	Ka-Band	1 Gbps	Near R/T	S/2Kbps	GN, SN, Other
Earth Systematic Project										
SYSP-01	High Data Rate	LEO - P	2017	S-Band	128Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN
SYSP-02	High Data Rate	LEO - P	2019	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other
SYSP-03	High Data Rate	LEO - P	2021	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other
SYSP-04	High Data Rate	LEO - P	2023	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other
SYSP-05	High Data Rate	LEO - P	2025	S-Band	1Mbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other

National Aeronautics & Space Administration

Space Communications CMLP Study

Reference Space Network Links

Mission	Link Characteristic	Orbit Regime	Launch Date	H/K Freq Band	H/K Data Rate	Science Freq Band	Science Data Rate	Latency	Uplink Band/Rate	Potential Support
Earth System Science Pathfinder										
ESSP-07	High Data Rate	LEO	2014	S-Band	64Kbps	X-or Ka	300Mbps	Near R/T	S/1Kbps	GN, SN
ESSP-08	High Data Rate	LEO	2016	S-Band	64Kbps	X-or Ka	300Mbps	Near R/T	S/1Kbps	GN, SN, Other
ESSP-09	High Data Rate	LEO	2018	S-Band	64Kbps	Ka-Band	600Mbps	Near R/T	S/1Kbps	GN, SN, Other
ESSP-10	High Data Rate	LEO	2020	S-Band	128Kbps	Ka-Band	600Mbps	Near R/T	S/1Kbps	GN, SN, Other
ESSP-11	High Data Rate	LEO	2022	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	S/2Kbps	GN, SN, Other
ESSP-12	High Data Rate	LEO	2024	S-Band	1Mbps	Ka-Band	1 Gbps	Near R/T	S/2Kbps	GN, SN, Other
Earth Systematic Project										
SYSP-01	High Data Rate	LEO - P	2017	S-Band	128Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN
SYSP-02	High Data Rate	LEO - P	2019	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other
SYSP-03	High Data Rate	LEO - P	2021	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other
SYSP-04	High Data Rate	LEO - P	2023	S-Band	512Kbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other
SYSP-05	High Data Rate	LEO - P	2025	S-Band	1Mbps	Ka-Band	1Gbps	Near R/T	X/2Kbps	GN, SN, Other
Global Precipitation Mission										
GPM Core	SN Multiple Access	LEO	2013	S-Band	?	S-Band	300Kbps		S-Band	**SN**, GN
GPM CX	SN Multiple Access	LEO	2014	S-Band	?	S-Band	300Kbps		S-Band	**SN, GN**

TDRSS KSAR Upgrade Augmentation (TKUP-A) Project) will demonstrate 1Gbps+ data rates through TDRSS in 2007.

Driving Constellation Links

Mission Phase	Link type	Frequency Band	Transmit Antenna	Receive Antenna	Rate (kbps)	EIRP (dBW)	G/T (dBK)
Launch	Operational	S-Band	Low Gain	9.0m Dish	192	7.0	24.0
	High Rate	S-Band	Low Gain	9.0m Dish	20,000	7.0	24.0
Low Earth Orbit TDRSS Links	Operational	S-Band	TDRS-SA	Low Gain	72	46.3	-29.1
	Operational	S-Band	Low Gain	TDRS-SA	192	17.5	10.3
	High Rate	Ka-band	TDRS-SA	0.75m Dish	6,000	59.5	11.0
	High Rate	Ka-band	0.75m Dish	TDRS-SA	25,000	48.5	23.0
Rendezvous Links	Rendezvous	S-Band	Low Gain	Low Gain	192	-1.0	-30.8
	Rendezvous	S-Band	Low Gain	Low Gain	192	-4.2	-27.6
	Rendezvous	S-Band	Low Gain	Low Gain	6,000	-11.0	-30.8
	Rendezvous	S-Band	Low Gain	Low Gain	6,000	-14.2	-27.6
Lunar Relay Links	Operational	S-Band	1m Dish	Low Gain	72	35.9	-28.4
	Operational	S-Band	Low Gain	1m Dish	192	17.5	-2.1
	High Rate	Ka-band	1m Dish	0.75m Dish	6,000	46.7	11.0
	High Rate	Ka-band	0.75m Dish	1m Dish	25,000	48.5	18.0
Lunar Ground Links	Nominal	S-Band	34.0m Dish	Low Gain	72	98.1	-29.1
	Nominal	S-Band	Low Gain	34.0m Dish	192	17.5	32.9
	Nominal	S-Band	34.0m Dish	0.75m Dish	1,000	98.1	-9.1
	Nominal	S-Band	0.75m Dish	34.0m Dish	1,000	37.5	32.9
	High Rate	Ka-band	34m Dish	0.75m Dish	25,000	103.4	10.6
	High Rate	Ka-band	0.75m Dish	34m Dish	150,000	55.1	59.8

NOTE: these are **not** approved Constellation links. They should be considered **only** as representative for the purpose of this study.

Other Driving Links

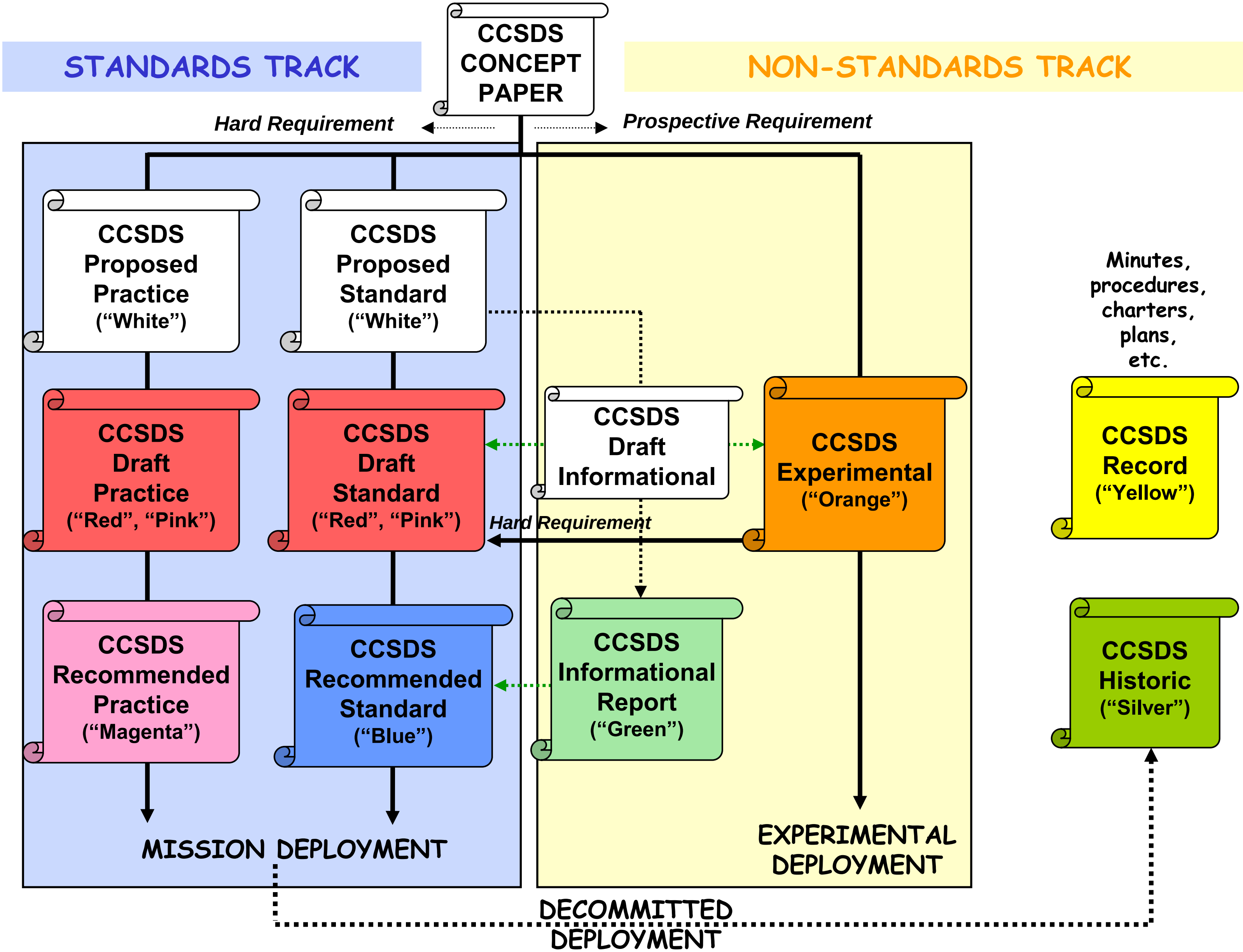
Still to come:

- Mars in-situ
  - Expect much commonality with lunar in-situ

Modulations: Introduction

- **Goal:** ***recommend appropriate modulations for emerging space mission scenarios through 2030***
- **Key points of comparison:**
  - **Spectral efficiency, particularly at S-band and X-band**
    - **> 1 bit/s/Hz will be needed for some links**
  - **Power efficiency**
    - **Comparing *uncoded* modulation performance allows us to make modulation choices before having to consider which code to use**
    - **Constant envelope modulations preferred – avoids distortion and need for amplifier back off**
  - **Complexity**
    - **Space receivers have limitations; ground receivers can be more complex**
    - **Modulation performance reported for Optimal, Integrate & Dump, and COTS receivers**
  - **Standardization,**
    - **Prefer modulations compliant with CCSDS and SFCG specifications**
  - **Maturity – mission heritage, existing infrastructure support**

CCSDS Products



CCSDS Standards Track

The Standards Track has two branches:

- documents that are intended to be "Recommended Standards" (CCSDS 'Blue Books'), and;
- documents that are intended to be "Recommended Practices" (CCSDS 'Magenta Books').

The principal difference between these two branches is that:

- Recommended Standards are precise, prescriptive and/or normative specifications that define interfaces, protocols, or other controlling standards at a sufficient level of technical detail that they can be directly implemented and used for space mission interoperability and cross support.
- Recommended Practices are more general in nature and capture "best" or "state of the art" recommendations for applying standards or standardized processes. They differ from "Informational" documents in that they do provide controlling guidance, rather than purely descriptive material.

The Non-Standards Track includes CCSDS Experimental (Orange Book)

- The "Experimental" designation typically denotes a specification that is part of some research or development effort. Its funding and other associated resources are normally independently provided by the organization that initiates the work, so the CCSDS role is limited to one of periodic review and publication. Experimental work may be based on soft or "prospective" requirements, i.e., it may be looking into the future and may intend to demonstrate technical feasibility in anticipation of a "hard" requirement that has not yet emerged. This designation therefore allows the work to progress roughly to the equivalent technical status of a "Draft Standard" without being actually on the Standards Track and therefore consuming large amounts of CCSDS resources. Experimental work may be rapidly transferred onto the Standards Track if a hard requirement emerges, thus shortening the response time in satisfying the new customer.

National Aeronautics & Space Administration

Modulations: Catalog

Modulation ID	Shaping/Filter Type	Receiver Type
BPSK	Unfiltered	Optimum
BPSK	Unfiltered	COTS
BPSK	SRRC (roll-off factor=1)	Optimum
BPSK	SRRC (roll-off factor=0.5)	Optimum
BPSK	SRRC (roll-off factor=0.2)	Optimum
BPSK	Manchester-coding (Bi-phase)	Optimum
Binary DPSK	Unfiltered	Optimum
Duobinary		Optimum
PCM/PSK/PN		Optimum
MSK (h=0.5)	Unfiltered	Trellis
Precoded GMSK(h=0.5)	Gaussian (BT_b=0.5)	Trellis
Precoded GMSK(h=0.5)	Gaussian (BT_b=0.5)	COTS
Precoded GMSK(h=0.5)	Gaussian (BT_b=0.5)	I&D
Precoded GMSK(h=0.5)	Gaussian (BT_b=0.25)	Optimum
Precoded GMSK(h=0.5)	Gaussian (BT_b=0.25)	COTS
Precoded GMSK(h=0.5)	Gaussian (BT_b=0.25)	I&D
GMSK (h=0.5)	Gaussian (BT_b=0.3)	Trellis
GMSK (h=0.5)	Gaussian (BT_b=0.3)	I&D
QPSK	Unfiltered	Optimum
Quaternary DPSK	Unfiltered	Optimum
pi/4-DQPSK	Unfiltered	Optimum
OQPSK (SQPSK)	Unfiltered	Optimum
OQPSK (SQPSK)	Unfiltered	COTS
OQPSK (SQPSK)	SRRC (roll-off factor=1)	Optimum
OQPSK (SQPSK)	SRRC (roll-off factor=1)	I&D
OQPSK (SQPSK)	SRRC (roll-off factor=0.5)	Trellis
OQPSK (SQPSK)	SRRC (roll-off factor=0.5)	COTS
OQPSK (SQPSK)	SRRC (roll-off factor=0.5)	I&D
OQPSK (SQPSK)	SRRC (roll-off factor=0.2)	Trellis
OQPSK (SQPSK)	SRRC (roll-off factor=0.2)	I&D
OQPSK/PM	Butterworth 6th order	I&D
OQPSK/PM	Bessel 6th order	I&D
FQPSK-B		Trellis
FQPSK-B		I&D
SOQPSK-A		Trellis

Modulation ID	Shaping/Filter Type	Receiver Type
SOQPSK-A		I&D
SOQPSK-B		Trellis
SOQPSK-B		I&D
8-PSK	Unfiltered	Optimum
8-PSK	SRRC (roll-off factor=1)	Optimum
8-PSK	SRRC (roll-off factor=0.5)	Optimum
8-PSK	SRRC (roll-off factor=0.35)	Optimum
16-PSK	Unfiltered	Optimum
16-PSK	SRRC (roll-off factor=0.5)	Optimum
16-PSK	SRRC (roll-off factor=0.35)	Optimum
16-QAM (rectangular)	Unfiltered	Optimum
16-QAM (rectangular)	SRRC (roll-off factor=0.5)	Optimum
16-QAM (rectangular)	SRRC (roll-off factor=0.35)	Optimum
16-APSK (12-4)	Unfiltered	Optimum
16-APSK (12-4)	SRRC (roll-off factor=0.5)	Optimum
16-APSK (12-4)	SRRC (roll-off factor=0.35)	Optimum
32-PSK	Unfiltered	Optimum
32-PSK	SRRC (roll-off factor=0.5)	Optimum
32-PSK	SRRC (roll-off factor=0.35)	Optimum
32-QAM (cross)	Unfiltered	Optimum
32-QAM (cross)	SRRC (roll-off factor=0.5)	Optimum
32-QAM (cross)	SRRC (roll-off factor=0.35)	Optimum
32-APSK (16/12/4)	Unfiltered	Optimum
32-APSK (16/12/4)	SRRC (roll-off factor=0.5)	Optimum
32-APSK (16/12/4)	SRRC (roll-off factor=0.35)	Optimum
64-QAM (rectangular)	Unfiltered	Optimum
64-QAM (rectangular)	SRRC (roll-off factor=0.5)	Optimum
64-QAM (rectangular)	SRRC (roll-off factor=0.35)	Optimum
64-APSK(28/20/12/4)	Unfiltered	Optimum
64-APSK(28/20/12/4)	SRRC (roll-off factor=0.5)	Optimum
64-APSK(28/20/12/4)	SRRC (roll-off factor=0.35)	Optimum
128-QAM (cross)	Unfiltered	Optimum
Binary FSK	Unfiltered	Optimum
OFDM/BPSK	Unfiltered	Optimum
OFDM/QPSK	Unfiltered	Optimum

Blue = CCSDS Blue Book Standard   Orange = CCSDS Orange Book Specification   Green = Infrastructure support

Codes: Introduction

- **Goal:** ***recommend appropriate codes for emerging space mission scenarios through 2030***
- **Key points of comparison:**
  - **Power efficiency**
    - **Required Eb/N0 to achieve a target error rate**
  - **Complexity (encoding and decoding)**
    - **Space receivers have limitations; ground receivers can be more complex**
  - **Standardization**
    - **Prefer codes compliant with CCSDS specifications**
  - **Maturity – mission heritage, existing infrastructure support**

Space Communications CMLP Study

Catalog of Codes 1

	Code ID	Type	Rate (r)	Info length (k)
1	Uncoded	Uncoded	1	1
2	CC(3,1/2)	Convolutional	0.5	1022
3	CC(5,1/2)	Convolutional	0.5	1020
4	CC(7,1/2), delay=5 bits, Q=inf	Convolutional	0.5	Inf
5	CC(7,1/2), delay=10 bits, Q=inf	Convolutional	0.5	Inf
6	CC(7,1/2), delay=15 bits, Q=inf	Convolutional	0.5	Inf
7	CC(7,1/2), delay=30 bits, Q=inf	Convolutional	0.5	Inf
8	CC(7,1/2), delay=60 bits, Q=inf	Convolutional	0.5	1784
9	CC(7,1/2), delay=60 bits, Q=inf	Convolutional	0.5	3568
10	CC(7,1/2), delay=60 bits, Q=inf	Convolutional	0.5	8920
11	CC(7,1/2), delay=60 bits, Q=inf	Convolutional	0.5	16384
12	CC(7,1/2), delay=60 bits, Q=inf	Convolutional	0.5	Inf
13	CC(7,1/2), delay=inf, hard dec.	Convolutional	0.5	Inf
14	CC(7,1/2), delay=inf, Q=3	Convolutional	0.5	Inf
15	CC(7,1/2), delay=inf, Q=8	Convolutional	0.5	Inf
16	CC(7,1/2), delay=inf, Q=inf	Convolutional	0.5	Inf
17	CC(7,2/3), delay=60 bits, Q=inf	Convolutional	0.67	8920
18	CC(7,2/3), delay=120 bits, Q=inf	Convolutional	0.66	1024
19	CC(7,3/4), delay=60 bits, Q=inf	Convolutional	0.75	8920
20	CC(7,3/4), delay=120 bits, Q=inf	Convolutional	0.75	1024
21	CC(7,5/6), delay=60 bits, Q=inf	Convolutional	0.83	8920
22	CC(7,5/6), delay=120 bits, Q=inf	Convolutional	0.83	1024
23	CC(7,7/8), delay=60 bits, Q=inf	Convolutional	0.88	8920
24	CC(7,7/8), delay=120 bits, Q=inf	Convolutional	0.87	1024
25	CC(9,1/2), delay=45?, Q=inf	Convolutional	0.5	63
26	CC(9,1/2)	Convolutional	0.5	1016
27	CC(9,1/2)	Convolutional	0.5	4088
28	CC(15,1/4)	Convolutional	0.25	1010
29	CC(15,1/6)	Convolutional	0.16	1010
30	RS(255,223)	Reed-Solomon	0.87	1784

	Code ID	Type	Rate (r)	Info length (k)
31	RS(255,239)	Reed-Solomon	0.94	1912
32	RS(252,220)	Reed-Solomon	0.87	1760
33	RS(255,223)+(7,1/2), I=1	Concatenated	0.44	1784
34	RS(255,223)+(7,1/2), I=2	Concatenated	0.44	3568
35	RS(255,223)+(7,1/2), I=3	Concatenated	0.44	5352
36	RS(255,223)+(7,1/2), I=4	Concatenated	0.44	7136
37	RS(255,223)+(7,1/2), I=5	Concatenated	0.44	8920
38	RS(255,223)+(7,1/2), I=8	Concatenated	0.44	14272
39	RS(255,223)+(7,1/2), I=16	Concatenated	0.44	28544
40	RS(255,239)+(7,1/2), I=1	Concatenated	0.47	1912
41	RS(255,239)+(7,1/2), I=2	Concatenated	0.47	3824
42	RS(255,239)+(7,1/2), I=3	Concatenated	0.47	5736
43	RS(255,239)+(7,1/2), I=4	Concatenated	0.47	7648
44	RS(255,239)+(7,1/2), I=5	Concatenated	0.47	9560
45	RS(255,239)+(7,1/2), I=8	Concatenated	0.47	15296
46	RS(255,239)+(7,1/2), I=16	Concatenated	0.47	30592
47	RS(255,223)+(7,1/2), I=5	Concatenated	0.47	4780
48	RS(255,223)+(7,2/3), I=5	Concatenated	0.62	6373
49	RS(255,223)+(7,3/4), I=5	Concatenated	0.7	7170
50	RS(255,223)+(7,5/6), I=5	Concatenated	0.78	7966
51	RS(255,223)+(7,7/8), I=5	Concatenated	0.82	8365
52	RS(255,239)+(7,1/2), I=5	Concatenated	0.47	4780
53	RS(255,239)+(7,2/3), I=5	Concatenated	0.62	6373
54	RS(255,239)+(7,3/4), I=5	Concatenated	0.7	7170
55	RS(255,239)+(7,5/6), I=5	Concatenated	0.78	7966
56	RS(255,239)+(7,7/8), I=5	Concatenated	0.82	8365
57	Turbo(1784,1/6)	Turbo	0.17	1784
58	Turbo(1784,1/4)	Turbo	0.25	1784
59	Turbo(1784,1/3)	Turbo	0.33	1784
60	Turbo(1784,1/2)	Turbo	0.5	1784

Blue = CCSDS Blue Book Standard   Orange = CCSDS Orange Book Specification   Green = Infrastructure support

Catalog of Codes 2

	Code ID	Type	Rate (r)	Info length (k)		Code ID	Type	Rate (r)	Info length (k)
61	Turbo(3568,1/6)	Turbo	0.17	3568	91	TPC(64,57)^2	Turbo Product	0.79	3249
62	Turbo(3568,1/4)	Turbo	0.25	3568	92	TPC(53,46)x(51,44)	Turbo Product	0.75	2024
63	Turbo(3568,1/3)	Turbo	0.33	3568	93	TPC(39,32)^2	Turbo Product	0.67	1024
64	Turbo(3568,1/2)	Turbo	0.5	3568	94	TPC(32,26)^2	Turbo Product	0.66	676
65	Turbo(7136,1/6)	Turbo	0.17	7136	95	TPC(19,13)^2	Turbo Product	0.47	169
66	Turbo(7136,1/4)	Turbo	0.25	7136	96	TPC(32,26)x(32,26)x(4,3)	Turbo Product	0.5	2028
67	Turbo(7136,1/3)	Turbo	0.33	7136	97	TPC(32,26)x(32,26)x(16,11)	Turbo Product	0.45	7436
68	Turbo(7136,1/2)	Turbo	0.5	7136	98	TPC(16,11)x(16,11)x(16,11)	Turbo Product	0.32	1331
69	Turbo(8920,1/6)	Turbo	0.17	8920	99	TPC(S16xH64^2)	Turbo Product	0.74	48735
70	Turbo(8920,1/4)	Turbo	0.25	8920	100	TPC(H64xH32xS32)	Turbo Product	0.7	45942
71	Turbo(8920,1/3)	Turbo	0.33	8920	101	TPC(H64xH32^2)	Turbo Product	0.59	38532
72	Turbo(8920,1/2)	Turbo	0.5	8920	102	TPC(H16xH64^2)	Turbo Product	0.55	35739
73	Turbo(16384,1/6)	Turbo	0.17	16384	103	TPC(S4xH16xH32^2)	Turbo Product		
74	Turbo(16384,1/4)	Turbo	0.25	16384	104	TPC(H16^4)	Turbo Product		
75	Turbo(16384,1/3)	Turbo	0.33	16384	105	TPC(S16xH32^2)	Turbo Product	0.62	10140
76	Turbo(16384,1/2)	Turbo	0.5	16384	106	BCH-LDPC(16200,1/4)	BCH-LDPC	0.19	3072
77	BCH-SEC(63,56)	BCH	0.89	56	107	BCH-LDPC(16200,1/3)	BCH-LDPC	0.32	5232
78	BCH-TED(63,56)	BCH	0.89	56	108	BCH-LDPC(16200,2/5)	BCH-LDPC	0.39	6312
79	AR4JA(64,1/2)	LDPC	0.5	64	109	BCH-LDPC(16200,1/2)	BCH-LDPC	0.43	7032
80	AR4JA(1024,1/2)	LDPC	0.5	1024	110	BCH-LDPC(16200,3/5)	BCH-LDPC	0.59	9552
81	AR4JA(1024,2/3)	LDPC	0.67	1024	111	BCH-LDPC(16200,2/3)	BCH-LDPC	0.66	10632
82	AR4JA(1024,4/5)	LDPC	0.8	1024	112	BCH-LDPC(16200,3/4)	BCH-LDPC	0.72	11712
83	AR4JA(4096,1/2)	LDPC	0.5	4096	113	BCH-LDPC(16200,4/5)	BCH-LDPC	0.77	12432
84	AR4JA(4096,2/3)	LDPC	0.67	4096	114	BCH-LDPC(16200,5/6)	BCH-LDPC	0.81	13152
85	AR4JA(4096,4/5)	LDPC	0.8	4096	115	BCH-LDPC(16200,8/9)	BCH-LDPC	0.88	14232
86	AR4JA(16384,1/2)	LDPC	0.5	16384	116	BCH-LDPC(64800,1/4)	BCH-LDPC	0.25	16008
87	AR4JA(16384,2/3)	LDPC	0.67	16384	117	BCH-LDPC(64800,1/3)	BCH-LDPC	0.19	12408
88	AR4JA(16384,4/5)	LDPC	0.8	16384	118	BCH-LDPC(64800,2/5)	BCH-LDPC	0.4	25728
89	C2, 50 iterations	LDPC	0.87	7136	119	BCH-LDPC(64800,1/2)	BCH-LDPC	0.5	32208
90	TPC(128,120)^2	Turbo Product	0.88	14400	120	BCH-LDPC(64800,3/5)	BCH-LDPC	0.6	38688

Blue = CCSDS Blue Book Standard   Orange = CCSDS Orange Book Specification   Green = Infrastructure support

National Aeronautics & Space Administration

Space Communications CMLP Study

Catalog of Codes 3

	Code ID	Type	Rate (r)	Info length (k)
121	BCH-LDPC(64800,2/3)	BCH-LDPC	0.66	43040
122	BCH-LDPC(64800,3/4)	BCH-LDPC	0.73	47408
123	BCH-LDPC(64800,4/5)	BCH-LDPC	0.8	51648
124	BCH-LDPC(64800,5/6)	BCH-LDPC	0.83	53840
125	BCH-LDPC(64800,8/9)	BCH-LDPC	0.89	57472
126	BCH-LDPC(64800,9/10)	BCH-LDPC	0.9	58192
127	Flarion- low threshold	LDPC	0.5	4096
128	Flarion- low floor	LDPC	0.5	4096
129	LDPC(432,3/4) 802.16e	LDPC	0.75	432
130	LDPC(1008,3/4) 802.16e	LDPC	0.75	1008
131	LDPC(1728,3/4) 802.16e	LDPC	0.75	1728
132	LDPC(1/2) 802.16e	LDPC	0.5	
133	LDPC(2/3) 802.16e	LDPC	0.67	
134	LDPC(5/6) 802.16e	LDPC	0.83	
135	(3,4,7)LPDC(64)	LDPC	0.5	64
136	(3,4,7)LPDC(128)	LDPC	0.5	128
137	(3,4,7)LPDC(256)	LDPC	0.5	256
138	LDPC 802.11n	LDPC		
139	F-LDPC (4096, _)	LDPC	0.5	4096
140	F-LDPC (4096, 2/3)	LDPC	0.67	4096
141	F-LDPC (4096, 4/5)	LDPC	0.8	4096
142	F-LDPC (4096, 8/9)	LDPC	0.89	4096
143	F-LDPC (4096, 16/17)	LDPC	0.94	4096
144	F-LDPC (8192, _)	LDPC	0.5	8192
145	F-LDPC (8192, 2/3)	LDPC	0.67	8192
146	F-LDPC (8192, 4/5)	LDPC	0.8	8192
147	F-LDPC (8192, 8/9)	LDPC	0.89	8192
148	F-LDPC (8192, 16/17)	LDPC	0.94	8192
149	F-LDPC(16k, _)	LDPC	0.5	16384
150	F-LDPC(16k, 2/3)	LDPC	0.67	16384

	Code ID	Type	Rate (r)	Info length (k)
151	F-LDPC(16k, 4/5)	LDPC	0.8	16384
152	F-LDPC(16k, 8/9)	LDPC	0.89	16384
153	F-LDPC(16k, 16/17)	LDPC	0.94	16384
154	(3,1/2)+acc.	SCCC		
155	CRC-32	CRC		
156	CRC-96	CRC		
157	CRC-128	CRC		
158	CRC-192	CRC		
159	CRC-16-CCITT	CRC		
160	CRC-16-IBM	CRC		
161	CRC-16-IEEE	CRC		
162	SCCC(k=428,1/3)	SCCC	0.33	428
163	SCCC(k=428,5/6)	SCCC	0.83	428
164	SCCC(k=428,9/10)	SCCC	0.9	428
165	SCCC(n=16384,1/3)	SCCC	0.33	5461
166	SCCC(n=16384,5/6)	SCCC	0.83	13653
167	SCCC(n=16384,9/10)	SCCC	0.9	14745

Blue = CCSDS Blue Book Standard   Orange = CCSDS Orange Book Specification   Green = Infrastructure support

Multiple Access Techniques

- Developed descriptions of legacy, variations on legacy, and new multiple access techniques for support of simultaneous communications and tracking
- Simultaneous support to multiple assets has been achieved by use of:
  - Communications & Tracking Network Resources
    - Multiple ground stations or data relay satellites
    - Multiple antennas at a ground station or on a data relay satellite
  - Antenna/Spectrum Resources
    - Multiple frequency bands on a ground station or data relay satellite antenna
    - Multiple frequencies in a frequency band – by assignment of unique frequencies to users
    - Multiple users at a frequency
      - Assignment of user-unique spectrum spreading codes or time slots
      - Multi-beam or phased array antennas for spatial segregation of users
  - Service Multiplexing
    - Multiple simultaneous services to a user – Command and telemetry communications (emergency, operational, mission) data and radiometric tracking data (range & Doppler)

National Aeronautics & Space Administration

Multiple Access Catalog

Space Communications CMLP Study

MA Type	Implementation / Description
Time Shared	Scheduled-based time sharing approach
FDMA	General – Frequency Division Multiple Access
FDMA	Orthogonal Frequency Division Multiplexing (OFDM)
FDMA	Wavelength Division Multiple Access (WDMA)
DAMA	Demand Assignment Multiple Access
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
CDMA/DSSS	Traditional – Direct Sequence Spread Spectrum (Used by TDRSS)
CDMA/DSSS	Constant Envelope
CDMA/FHSS	Frequency Hopped Spread Spectrum (FHSS)
CDMA/DS/FHSS	Direct Sequence/FHSS
Random Access	Pure ALOHA
Random Access	Slotted ALOHA
Random Access	Carrier Sense MA (CSMA)
Random Access	CSMA/CA – with Collision Avoidance
Random Access	CSMA/CD – with Collision Detection
Random Access	Multiple Access with Collision Avoidance (MACA)
Random Access	Reservation ALOHA
Random Access	Packet Reservation MA (PRMA)
Hybrid	FDMA/CDMA (Used by TDRSS)
Hybrid	Time CDMA (TCDMA)
Hybrid	Time Division Frequency Hopping (TDFH)
Other	Time Hopping – Pulse Position Modulation (TH-PPM)

Blue = CCSDS Blue Book Standard   Orange = CCSDS Orange Book Specification   Green = Infrastructure support

National Aeronautics & Space Administration

Space Communications CMLP Study

Catalog of Link Protocol Functions

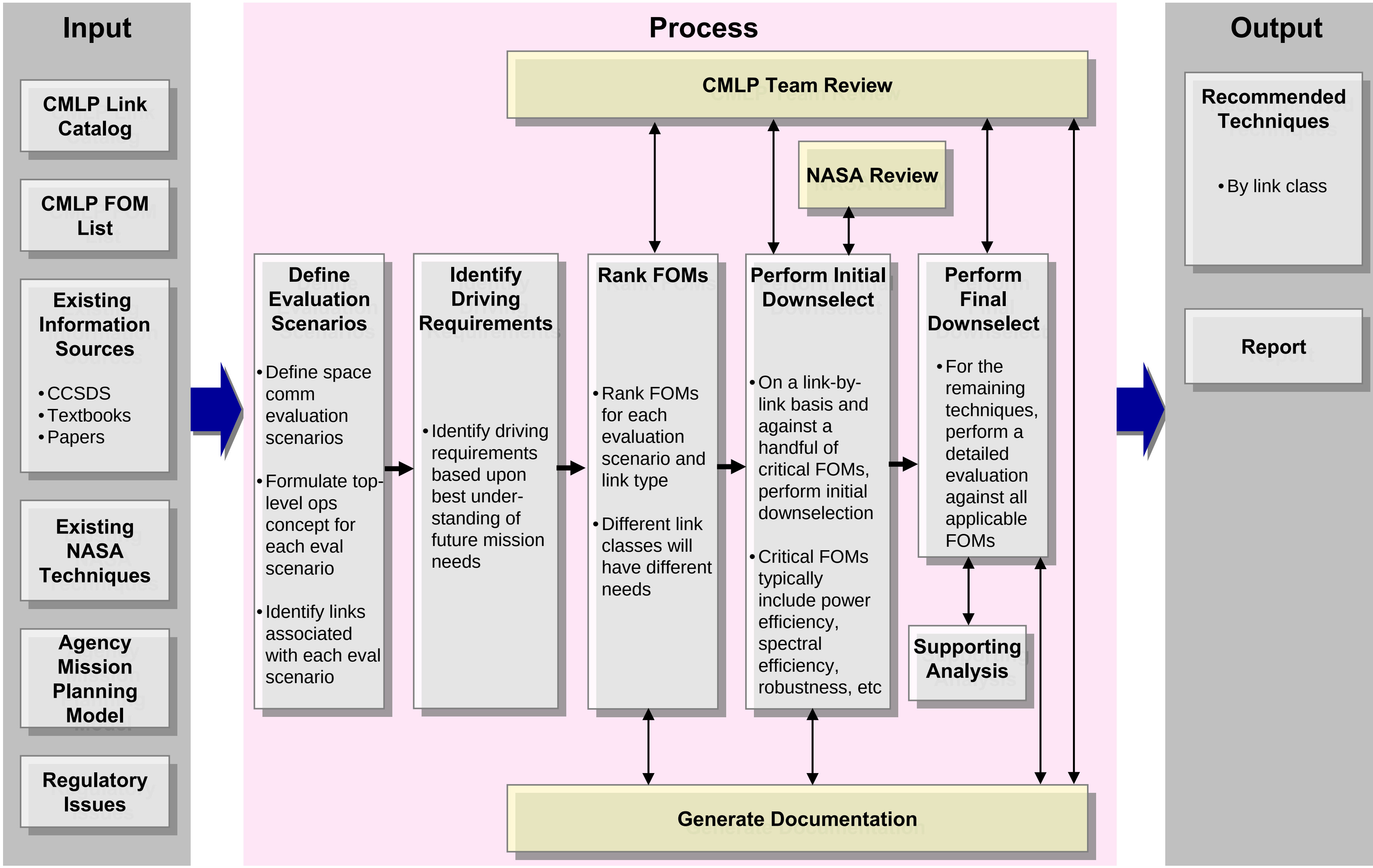
- Data Transfer
  - Transfer variable-sized data units (SDUs) over serial links
  - Recognize data units and length at receiver
  - Provide Segmentation and Reassembly
  - Provide fill data when required by Physical Layer; synchronization
  - Provide Link Layer encapsulation and addressing
  - Provide compatibility with multiple network layer protocols (IPv4, IPv6, and legacy network layers)
  - Minimize overhead (impact on throughput/utilization)
  - Minimize impact on coding and lower layers
- Reliability and Quality of Service (QoS)
  - Support class of service capability at Link Layer
    - Prioritization
  - Provide strong error detection capability at Link Layer
  - Support rich Link Layer metrics for accountability
- Channel Access and Usage
  - Operate over a shared channel
    - Virtual Channels
    - Medium Access Control (MAC)
  - Provide link establishment (hailing)
  - Provide channel management and link adaptation
- Link Layer Security

Figures Of Merit (FOMs)

a. Supports legacy missions (time span, percent of features)
b. Spectrum utilization
c. Power efficiency ($P_T/(RN_0)$ to get required performance)
d. User burden (Percent cost increase)
e. Infrastructure burden (Percent cost increase)
f. Alignment with international standards (Probability of alignment)
g. Provide radiometrics for navigation (Accommodation % cost increase)
h. Robustness
i. Latency (seconds)
j. Technology maturity (TRL)
k. Capacity (aggregate BPS)

National Aeronautics & Space Administration

General Downselect Process



Link Classification for Coding & Modulation Selection

- **Uplink considered independently of downlink**
  - Downlink (ground) receiver & decoder can be complex
  - Uplink (spacecraft) receiver & decoder must be relatively simple
- **Deep Space Link Classes**
  - X-band low rate, power limited
  - High rate X-band; Bandwidth limits vs. symbol rate
    - (SFCG rec. 23-1)
  - High rate Ka-band
- **Near Earth Link Classes**
  - S-band
  - X-Band
  - Ka-band

GN and SN Modulation Downselect Example

S-Band

Link Name	Link Description: Link Type	Link Description: Data Rate	Remaining Modulations after First Stage Downselect[1,2]: Modulation ID	Remaining Modulations after First Stage Downselect[1,2]: Shaping/Filter Type	First Stage Downselect Process (Eliminate modulations which underperform on certain critical FOMs)	Second Stage Downselect Process (Rank remaining 1st stage modulations relative to each other): Supports Legacy Missions	Spectrum Util. (in nonlinear channel)	Power Efficiency	User Burden	Infrastructure Burden	Alignment with Int'l Stds	Robustness	Latency	Technology Maturity	Score (w/ FOM weighting lower = better)	Remaining Modulations after Second Stage Downselect[1,2] (Eliminate clear underperformers): Modulation ID	Shaping/Filter Type
S-band	Operational Forward	² 60 kbps	Precoded GMSK (h = 0.5)	Gaussian (BT_b = 0.5)	- Req'd Eb/No at 1E-5 BER <= 11.0 dB - Req'd bandwidth (considering all potential applicable codes) <= 6 MHz (standard S-band allocation) - Spectral efficiency >= 0.95 using 99% bw (i.e., meet the NTIA out-of-band emission mask) - High hardware maturity required (i.e., keep forward operational link simple and low risk; no trellis receiver possible) - Special exceptions to this process have been made for modulations which help ensure carr acq at low C/No, i.e., PCM/PSK/PM and PCM/PM/NRZ - Although not recommended here, differential PSK modulations should be considered in cases where a low-complexity, high-reliability link design is required - this safety is at the expense of worse BER performance relative to modulations recommended by the downselection process	7	1	4	3	1	1	1	1	3	10.2	OQPSK/PM	Butterworth 6th order
			OQPSK (SQPSK)	SRRC (roll-off factor = 1.0)		3	5	1	3	1	7	4	1	3	11.4		
				SRRC (roll-off factor = 0.5)		4	4	2	3	1	1	4	1	3	10.6		
			OQPSK/PM	Butterworth 6th order		5	2	2	3	1	1	1	1	3	**8.3**		
				Bessel 6th order		6	3	4	3	1	1	1	1	3	11.0		
			PCM/PSK/PM	TBD		1	6	6	1	1	1	6	1	1	14.0		
			PCM/PM/NRZ	TBD		1	6	6	1	1	1	6	1	1	14.0		
	Operational Return	² 60 kbps	Precoded GMSK (h = 0.5)	Gaussian (BT_b = 0.5)	- Req'd Eb/No at 1E-5 BER <= 11.0 dB - Req'd bandwidth (considering all potential applicable codes) <= 6 MHz (standard S-band allocation) - Spectral efficiency >= 0.95 using 99% bw and assuming a rate 1/2 code (i.e., meet the NTIA out-of-band emission mask) - Medium or high hardware maturity required (i.e., keep return operational link relatively simple and low risk) - Special exceptions to this process have been made for modulations which help ensure carr acq at low C/No, i.e., PCM/PSK/PM and PCM/PM/NRZ - Although not recommended here, differential PSK modulations should be considered in cases where a low-complexity, high-reliability link design is required - this safety is at the expense of worse BER performance relative to modulations recommended by the downselection process	8	6	1	3	3	1	1	1	3	**10.6**	Precoded GMSK (h = 0.5) OQPSK/PM	Gaussian (BT_b = 0.5) Butterworth 6th order
				Gaussian (BT_b = 0.25)		9	3	1	3	9	1	1	1	3	11.3		
			GMSK (h = 0.5)	Gaussian (BT_b = 0.3)		13	4	1	3	13	1	1	1	3	13.9		
			OQPSK (SQPSK)	SRRC (roll-off factor = 1.0)		3	11	1	3	3	12	9	1	3	18.8		
				SRRC (roll-off factor = 0.5)		4	10	1	3	3	1	9	1	3	15.8		
				SRRC (roll-off factor = 0.2)		7	9	1	3	3	12	9	1	10	22.1		
			OQPSK/PM	Butterworth 6th order		5	7	1	3	3	1	1	1	3	**10.5**		
				Bessel 6th order		6	8	1	3	3	1	1	1	3	11.2		
			FQPSK-B	Defined by modulation		12	4	1	13	9	1	1	1	10	20.9		
			SOQPSK-A	Defined by modulation		10	1	1	11	9	1	1	1	10	18.0		
			SOQPSK-B	Defined by modulation		11	2	1	11	9	1	1	1	10	18.7		
			PCM/PSK/PM	TBD		1	12	12	1	1	1	12	1	1	26.0		
			PCM/PM/NRZ	TBD		1	12	12	1	1	1	12	1	1	26.0		
	Operational / Science Return	> 60 kbps	Precoded GMSK (h = 0.5)	Gaussian (BT_b = 0.5)	- Req'd Eb/No at 1E-5 BER <= 11.0 dB - Req'd bandwidth (considering all potential applicable codes) <= 6 MHz (standard S-band allocation) - Spectral efficiency >= 0.95 using 99% bw and assuming a rate 1/2 code (i.e., meet the NTIA out-of-band emission mask) - Medium or high hardware maturity required	6	6	1	1	1	1	1	1	1	**7.5**	Precoded GMSK (h = 0.5) OQPSK/PM	Gaussian (BT_b = 0.5) Butterworth 6th order
				Gaussian (BT_b = 0.25)		7	3	1	1	7	1	1	1	1	8.2		
			GMSK (h = 0.5)	Gaussian (BT_b = 0.3)		11	4	1	1	11	1	1	1	1	10.8		
			OQPSK (SQPSK)	SRRC (roll-off factor = 1.0)		1	11	1	1	1	10	9	1	1	15.2		
				SRRC (roll-off factor = 0.5)		2	10	1	1	1	1	9	1	1	12.7		
				SRRC (roll-off factor = 0.2)		5	9	1	1	1	10	9	1	8	18.5		
			OQPSK/PM	Butterworth 6th order		3	7	1	1	1	1	1	1	1	**7.4**		
				Bessel 6th order		4	8	1	1	1	1	1	1	1	8.1		
			FQPSK-B	Defined by modulation		10	4	1	11	7	1	1	1	8	17.8		
			SOQPSK-A	Defined by modulation		8	1	1	9	7	1	1	1	8	14.9		
			SOQPSK-B	Defined by modulation		9	2	1	9	7	1	1	1	8	15.6		

Category A Recommendations: Legacy Modulations

- **Following are the current modulation techniques that are part of the existing SN and GN and are expected to be utilized for some time in the future:**
  - **Filtered QPSK for GN* and SN forward and return links**
  - **Filtered OQPSK for GN* and SN forward and return links**
  - **Filtered BPSK for GN* and SN forward and return links**
  - **PCM/PSK/PM for GN and forward SN links**
  - **PCM/PM for GN and forward SN links**

* Not all GN stations support this modulation

National Aeronautics & Space Administration

Space Communications CMLP Study

Category A Recommendations: New Modulations

Link Description			Recommended Modulation[2, 3]		Comments
Direction	**Band**	**Data Rate[1]**	**Modulation ID**	**Shaping/Filter Type**	
Forward	S-band	^{2} 6 Mbps	OQPSK/PM[4]	Butterworth 6th order (BTs = 1.0)	- S-band maximum channel BW: 6 MHz - X-band maximum channel BW: 10 MHz - CCSDS compliant
	X-band	^{2} 10 Mbps			
Return	S-band	^{2} 5 Mbps	Precoded GMSK (h = 0.5) OQPSK/PM[4]	Gaussian (BT_b = 0.5) Butterworth 6th order (BTs=1)	- Maximum channel BW: 6 MHz - GMSK (BT_b=0.5) is technically not CCSDS compliant for Cat A
		6 Mbps	OQPSK/PM[4]	Butterworth 6th order (BTs=1)	
		20 Mb/sec	OQPSK/PM[4]	Butterworth 6th order (BTs=1)	- Constellation launch - Maximum channel BW: 10 MHz - CCSDS compliant
	X-band	^{2} 10 Mbps SRS ^{2} 12 5 Mbps EES	Precoded GMSK (h = 0.5) OQPSK/PM[4]	Gaussian (BT_b = 0.5) Butterworth 6th order (BTs=1)	- Maximum channel BW: 10 MHz SRS, 300 MHz EES - GMSK (BT_b=0.5) is technically not CCSDS compliant for Cat A
		> 240 Mbps ^{2} 30 0 Mbps	8PSK	SRRC (roll-off factor = 0.5) SRRC (roll-off factor = 0.35)	
	Ka-band	^{2} 55 0 Mbps	Precoded GMSK (h = 0.5) OQPSK/PM[4]	Gaussian (BT_b = 0.5) Butterworth 6th order (BTs=1)	- Maximum channel BW: 650 MHz - Only OQPSK/PM BTs = 1 CCSDS compliant
		600 Mbps	OQPSK/PM[4]	Butterworth 6th order (BTs=1)	
		> 650 Mbps ^{2} 100 0 Mbps	OQPSK (SQPSK)	SRRC (roll-off factor = 0.2)	

SRRC = Square Root Raised Cosine

Notes:
1. Only data rate ranges that have relevance to future Category A missions considered.
2. Modulation recommendations formulated excluding consideration of multiple access technique and ranging technique. If certain multiple access and ranging techniques are ultimately recommended for the types of links described here, the modulation recommendations provided here may need to be modified.

. Return link modulation recommendations based upon the assumption of a trellis receiver detection method. If the trellis receiver cannot be used, recommendation of these modulation types may be withdrawn.

4. Baseband filtered OQPSK with linear Phase Modulator (OQPSK/PM). Fully suppressed carrier, constant envelope modulation technique. This is not a subcarrier modulation.

Blue = CCSDS Blue Book Standard | Orange = CCSDS Orange Book Specification | Green = Infrastructure support

Category A New Modulations: Details

- **Baseband-Filtered OQPSK/PM**
  - Fully suppressed carrier, Constant envelop modulation technique
  - Good power efficiency regardless of data detection method
    - Outperforms GMSK when a Trellis receiver is not available
  - Good spectral efficiency even in a nonlinear channel
    - Outperforms standard filtered OQPSK in a nonlinear channel
    - Similar performance as GMSK
  - Fully compatible with existing customer and SN receiver hardware
  - Aligned with international standards

- **Precoded GMSK (h=0.5, BT_b=0.5)**
  - Constant envelop modulation technique
  - Good power efficiency when used with a Trellis receiver
    - Performance consistent with unfiltered BPSK when a Trellis receiver is used
  - Good spectral efficiency even in a nonlinear channel
    - Outperforms standard filtered OQPSK in a nonlinear channel
    - Slightly outperforms OQPSK/PM
  - Fully compatible with existing customer and SN receiver hardware
  - Aligned with international standards
    - Technically, international standards recommend BT_b=0.25

Category B Modulation Recommendations

Link Description			Recommended Modulation		Comments
Direction	Band	Symbol Rate	Modulation ID	Shaping/Filter Type	
Forward (Uplink)	X-band	Low rate	PCM/PSK/PM	Unfiltered	Enables large residual carrier, which is needed to coherently demodulate very weak signals
	X-band	High rate	OQPSK/PM	Butterworth 6^{th} order	Constant envelope; simple integrate & dump receiver
	Ka-band	All rates			
Return (Downlink)	X-band*	<180 ksps Mars, else <360 ksps	PCM/PSK/PM	Unfiltered	Enables large residual carrier, which is needed to coherently demodulate very weak signals
		<6 Msps Mars, else <9 Msps	Precoded GMSK (h = 0.5)	SRRC (roll-off factor = 0.5)	Best bandwidth efficiency with minimum E_b/N_o
		<18 Msps Mars, else <27 Msps	8-PSK	SRRC (roll-off factor = 0.35)	Best spectrum efficiency for modulation order 8
		<24 Msps Mars	16-QAM (TBR)	SRRC (roll-off factor=0.35)	Minimum E_b/N_o for modulation order 16
	Ka-band	All rates	Precoded GMSK (h = 0.5)	Gaussian (BT_b = 0.5)	Best bandwidth efficiency with minimum E_b/N_o

* X-band downlink symbol rate limits based on SFCG Recommendation 23-1, Efficient Spectrum Utilisation for Space Research Service, Deep Space (Category B) in the Space-to-Earth Link.

Blue = CCSDS Blue Book Standard   Orange = CCSDS Orange Book Specification   Green = Infrastructure support

Codes: Category A Recommendations

Link Description				Recommended Codes			Comments
Direction	Band	BW (MHz)	Data Rate (Mbps)	Code ID	Rate	Input length	
Forward (Uplink)	S-band	6	< 0.001	CC(7,1/2)	½	< 1000	CC offers best latency Š use when realtime operation needed at < 1 kbps
			0.001 to 3	AR4JA LDPC	½	1024 to 16384	Best coding gain; lower complexity and error floor than r=1/2 turbo
			3 to 4.8	AR4JA LDPC	2/3, 4/5	1024 to 16384	
			> 4.8	C2 LDPC	0.87	7136	High bandwidth efficiency; better coding gain than RS-only
	X-band	50	< 25	AR4JA LDPC	½	1024 to 16384	
Return (Downlink)	S-band	6	< 0.001	CC(7,1/2)	½	< 1000	
			0.001 to 3	AR4JA LDPC	½	1024 to 16384	
			3 to 4.8	AR4JA LDPC	2/3, 4/5	1024 to 16384	
			> 4.8	C2 LDPC	0.87	7136	
	S-band (launch)	20	16 to 22	AR4JA LDPC	½	1024 to 16384	
	X-band	50	< 50	Turbo	1/6, 1/4, 1/3, 1/2	8920	Best coding gain for rates < ½
			50 to 150	AR4JA & C2 LDPC	0.5 to 0.87	1024 to 16384	
	Ka-band	650	< 300	Turbo	1/6, 1/4, 1/3, 1/2	8920	
			300 to 650	AR4JA & C2 LDPC	1/2 to .87	1024 to 16384	

Blue = CCSDS Blue Book Standard Orange = CCSDS Orange Book Specification

Codes: Category B Recommendations

Link Description				Recommended Codes			Comments
Direction	Band	BW (MHz)	Data Rate (Mbps)	Code ID	Rate	Input length	
Forward (Uplink)	X-band	50	< 0.001	CC(7,1/2)	½	< 1000	CC offers best latency Š use when realtime operation needed at < 1 kbps
			0.001 to 40	AR4JA LDPC	1/2, 2/3, 4/5	1024 to 16384	Best coding gain at r=1/2; lower complexity & error floor than r=1/2 turbo
			0.001 to 15	Turbo	1/6, 1/4, 1/3	1784 to 8920	Can use when additional coding gain needed, and UER not an issue
			> 40	C2 LDPC	0.87	7136	High bandwidth efficiency; better coding gain than RS-only
	Ka-band	500	All	AR4JA LDPC	½	1024 to 16384	
				Turbo	1/6, 1/4, 1/3	1784 to 8920	Can use when additional coding gain needed, and UER not an issue
Return (Downlink)	X-band	50	< 50	Turbo	1/6, 1/4, 1/3, 1/2	8920	Best coding gain for rates < ½
			50 to 150	AR4JA & C2 LDPC	0.5 to 0.87	1024 to 16384	
	Ka-band	500	< 300	Turbo	1/6, 1/4, 1/3, 1/2	8920	
			300 to 500	AR4JA & C2 LDPC	1/2 to .87	1024 to 16384	

Blue = CCSDS Blue Book Standard Orange = CCSDS Orange Book Specification

Codes: Recommendation Summary

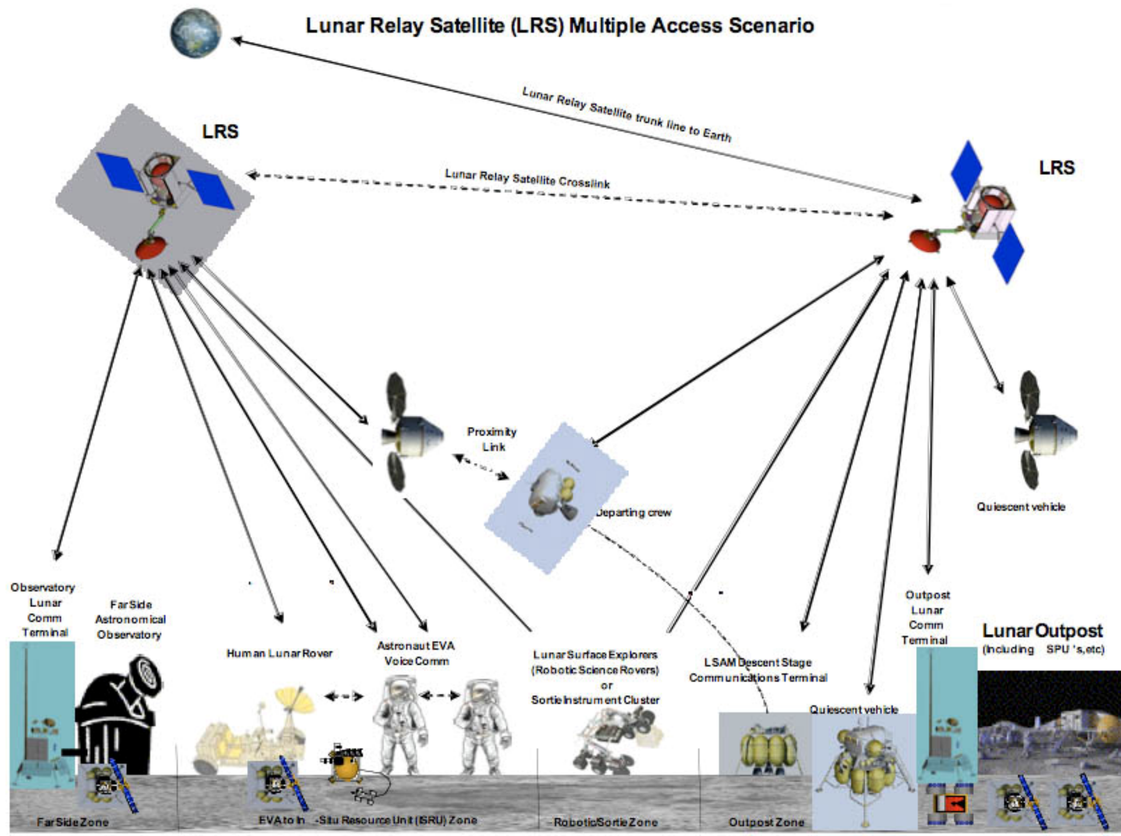
- All recommended codes are in existing CCSDS blue and orange books
- Summary of recommendations:
  - CCSDS turbo codes (r = 1/6, 1/4, 1/3): for low code rate applications
  - CCSDS AR4JA codes (r = 1/2, 2/3, 4/5): for higher rate applications
  - C2 code (r = 0.87): for bandwidth constrained links
  - CC: for low data-rate, real-time links; complexity-limited applications; and legacy systems
  - Uncoded operation can be used when link SNR is sufficient
    - Recommendations in table assume coding gain is needed or useful
  - Legacy CC, RS+CC, BCH, and turbo codes will continue to be used
    - In the near-term, because of flight heritage and infrastructure support
    - In the long-term, for CC, because of excellent latency performance

Navigation Summary

- Links subject to SFCG 23-1 bandwidth limitations (Cat. B X-band RTN Mars and other deep space) become incompatible with extant tracking signals at high symbol rates:
  - Sequential tone ranging
  - PN ranging
- The CMLP team is investigating novel methods to combine wideband tracking signals with highly bandwidth-efficient modulation (GMSK) for bandwidth-limited channels
- Example signal: GMSK comm + PN subcarrier
- Goals being pursued (and achieved) for Mars X-band RTN
  - Data symbol rates up 6-7 Msps
  - PN chip rate ~ 1 MHz
  - Constant envelope
  - Minimal SNR impact to GMSK comm
  - Adequate tracking SNR
  - Adequate spectral separation of comm and tracking signal
  - SFCG 23-1 compliance by parameter choices: data symbol rate; subcarrier modulation index; subcarrier frequency; PN chip rate

MA Evaluation Scenarios

- **Identified five MA applications in architecture**
  - Near Earth Relay
  - Lunar DTE/DFE
  - Lunar Relay
  - Mars DTE/DFE
  - Mars Relay
- **Developed scenarios for each for downselection of MA techniques**
  - Example: evaluation scenario considered in the MA downselect for lunar environment



Multiple Access Downselect Criteria

- **Capacity must be sufficient to meet link/network scenario data rate and simultaneous user requirements**
- **Capacity/efficiency must remain sufficient to meet link/network scenario data rate and simultaneous user requirements in a high latency environment**
- **Spectral efficiency must be such that anticipated spectral allocations are sufficient to enable full link/network scenario support**
- **User burden must be low**
- **Technology maturity must be medium to high**

Operational Link MA Downselect (S-, X-band)

Link	Remaining MA Schemes	Initial Downselect Comments
Forward (Point-to-Multipoint)	CDMA FDMA TDM FDMA/CDMA FDMA/TDM TCDMA TDFH	• Random access techniques are incompatible with point-to-multipoint links - time-shared approach eliminated due to inability to meet simultaneous users requirement dictated by link/network scenario - DAMA eliminated due to the effect of large latency on network efficiency - TH-PPM eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users as well as stringent user position accuracy requirements
Return (Multipoint-to-Point)	FDMA CDMA FDMA/CDMA	- Random access techniques eliminated due to the effect of large latency on network efficiency - TDMA eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users - TH-PPM eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users as well as stringent user position accuracy requirements - Time-shared approach eliminated due to inability to meet simultaneous users requirement dictated by link/network scenario - DAMA eliminated due to the effect of large latency on network efficiency - Hybrid techniques FDMA/TDMA, TCDMA and TDFH eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users

National Aeronautics & Space Administration

High Rate Link MA Downselect (Ka-Band)

Space Communications CMLP Study

Link	Remaining MA Schemes	Initial Downselect Comments
Forward (Point-to-Multipoint)	FDMA TDM FDMA/TDM	- Random access techniques are incompatible with point-to-multipoint links - Time-shared approach eliminated due to inability to meet simultaneous users requirement dictated by link/network scenario - DAMA eliminated due to the effect of large latency on network efficiency - CDMA eliminated due to excessive bandwidth expansion on high rate links and expected high hardware complexity for extreme chip rates - TH-PPM eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users as well as stringent user position accuracy requirements
Return (Multipoint-to-Point)	FDMA	- Random access techniques eliminated due to the effect of large latency on network efficiency - TDMA eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users - TH-PPM eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users as well as stringent user position accuracy requirements - Time-shared approach eliminated due to inability to meet simultaneous users requirement dictated by link/network scenario - DAMA eliminated due to the effect of large latency on network efficiency - Hybrid techniqes FDMA/TDMA, TCDMA and TDFH eliminated due to the difficulty in establishing and maintaining strict time synchronization among the system and users - CDMA eliminated due to excessive bandwidth expansion on high rate links and expected high hardware complexity for extreme chip rates - FDMA/CDMA eliminated due to expected high hardware complexity

MA Selection Rationale

- CDMA and FDMA systems operate efficiently in a high latency environment, whereas, random access systems become very inefficient in such environments
  - Scenarios where random access techniques would have been considered, such as lunar surface communications, were not within the scope of this study
- CDMA and FDMA systems do not require strict time synchronization across a widely distributed system, whereas, TDMA and some other MA techniques do require such synchronization
- CDMA and FDMA systems can be designed to support the necessary number of simultaneous users, whereas, time-shared systems cannot support simultaneous users

Slide continued on next page

MA Selection Rationale (cont'd)

- CDMA and FDMA systems do not require user hardware to support burst data rates, whereas, TDMA does
- CDMA and FDMA are mature space technologies, whereas, random access techniques are not mature space technologies
- CDMA and FDMA are supported access techniques of the SN, GN and DSN (FDMA), whereas, TDMA and other access techniques are not supported

Link Protocol Study

- Identified Link Protocol functions that may be applied to space communications links
  - Some functions are more suited for shorter-range links, and many require two-way communications
- Identified Link Protocol relationships with lower layers affecting trades
- Link Protocol scope is "one-hop" as compared to the protocols considered by the SCaN Network Architecture Team (NAT) that were "multi-hop" or end-to-end (e.g., IP). Full consideration Link Protocols and higher layers has not yet been fully treated.
- The down-selection of the Link Protocols has therefore not been completed

Link Protocol Lower-Layer Interactions

- Link Layer Retransmission vs. Frame Error Rate
  - May operate with higher Frame Error Rate and overcome with retransmissions
  - Within certain operational regimes, can result in performance gain
- Other considerations of Link Layer impacts on lower layer
  - Virtual Channels vs. physical channels
    - VCs offer greater efficiency, ease/flexibility of bandwidth management
    - VCs require some overhead (header bits, processing)
  - Quality of Service (QoS)
    - Ability to differentiate prioritized traffic types allows data rate to be adjusted accordingly and increase total volume delivered
  - Link Layer Services
    - Provide services of data accountability, metadata (e.g. timestamp, s/c ID), handling of data grouped as user has offered (vs. bitstream)
    - 10% overhead vs. 0.4 dB link margin

Future Work

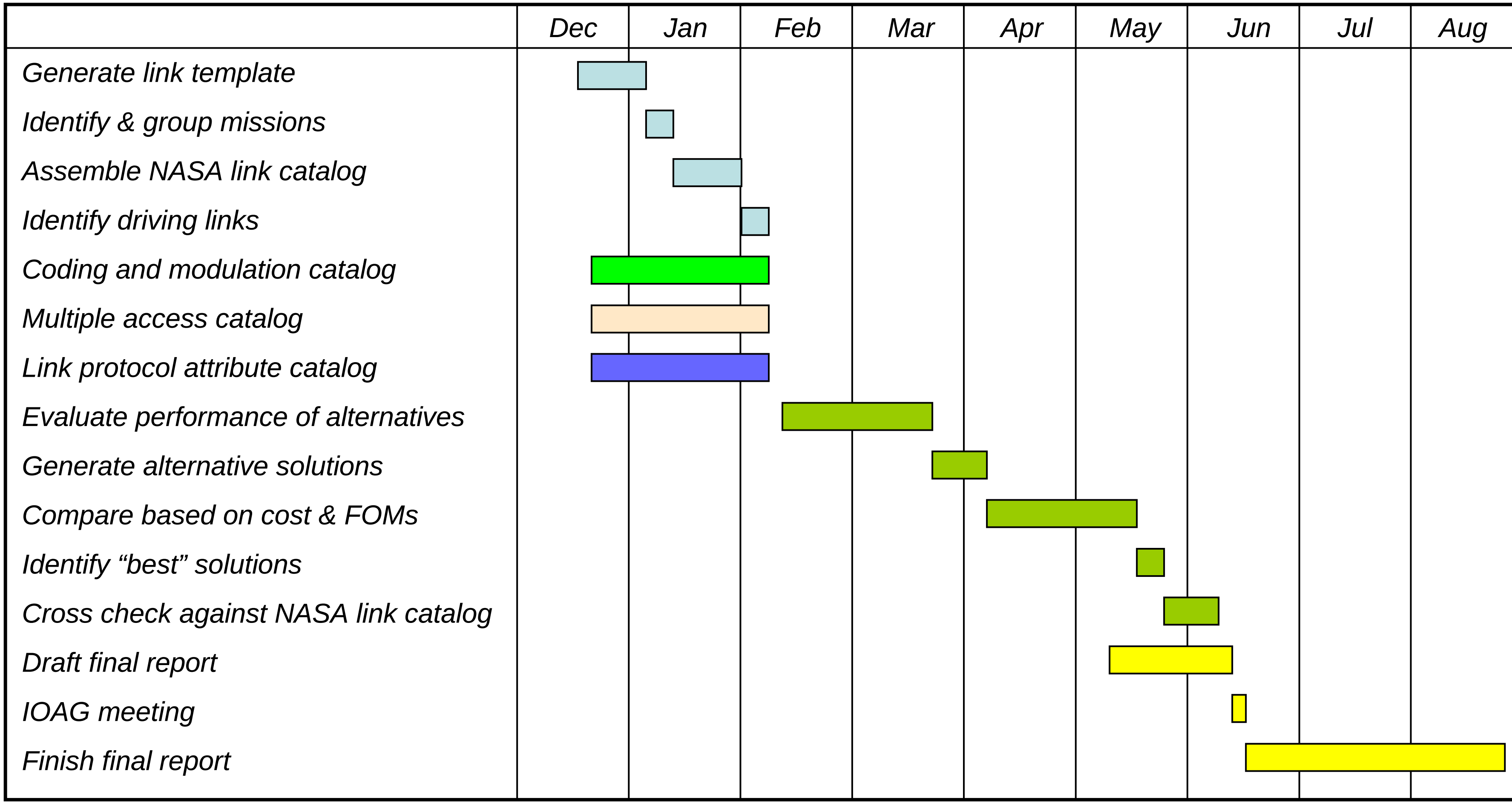
- Collect and respond to IOAG comments
  - Engage existing international fora for selected issues
- Complete analysis and formulate recommendations
  - Mars in-situ links
  - Multiple access
- Write draft final report
- Review within NASA and international partners
- Publish final report
- Post report work:
  - Merge results into SCaN roadmaps and technology strategy
    - Develop NASA transition plan
  - Engage standards community to do further analytical work and create any required new standards

Summary

- Successfully brought CMLP study to this point
- Need to incorporate IOAG comments/thoughts/ suggestions
- Need to complete technical work leading to recommendations for each link type in the architecture
- Work on final draft report to begin this month
- Resolution for new MA standards effort
- Resolution for new surface-to-surface link study

Backup

CMLP Study Master Schedule



National Aeronautics &
Space Administration

Space Communications CMLP Study

Team

- Les Deutsch and Frank Stocklin, co-leads
- Monty Andro (GRC)
- Dan Brandel (HQ)
- Loren Clare (JPL)
- Dariush Divsalar (JPL)
- Sam Dolinar (JPL)
- Pat Eblen (NASA HQ)
- Wai Fong (GSFC)
- Jay Gao (JPL)
- Jon Hamkins (JPL)
- Dave Israel (GSFC)
- Dennis Lee (JPL)
- Peter Militch
- Bob Nelson
- Gary Noreen (Cx)
- Richard Orr (Sa-Tel)
- Fabrizio Pollara (JPL)
- Tudor Stoenescu (JPL)
- Scott Sands (GRC)
- Victor Sank (GSFC)
- Len Schuchman (Sa-Tel)
- John Wesdock (GSFC)
- Dave Zillig (GSFC)

Subteam Leads:

Systems Engineering:	Gary Noreen
Coding and Modulation:	Jon Hamkins
Multiple Access:	Dave Zillig
Link Protocols:	Loren Clare