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The Evolution of Future Mars Communications Architecture

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Abstract

The paper presents a Mars Communications Architecture, developed by a working group of the Interagency Operations Advisory Group (IOAG), chaired by the authors and including representatives from several space agencies. The architecture is defined as an incremental set of assets, capabilities and services spanning over two decades, until around 2040, aiming at supporting Mars exploration and science during the indicated time frame and beyond. It relies upon a down-selection of robust technical solutions from CCSDS, is fully compliant with ITU recommendations concerning utilization of radio frequency bands, and enables innovative technologies, like DTN and optical communications, enabling a leap step in performance for future missions, in terms of operability, data rates and navigation.
Keywords: (Mars, Communications, Relay, Interoperability)

Acronyms/Abbreviations
AOS: Advanced Orbiting System
ASI: Agenzia Spaziale Italiana
CCSDS: Consultative Committee for Space Data Systems
CDMA: Code-Division Multiple Access
CNES: Centre national d'études spatiales
DTN: Delay-Tolerant Networking
EIRP: Equivalent Isotropic Radiated Power
ESA: European Space Agency
EVA: Extravehicular Activity
FMCRL: Frequency, Modulation, Coding, Ranging, and Link Protocol
G/T: antenna gain over system temperature ratio
GMSK: Gaussian Minimum Shift Keying
IOAG: Interagency Operations Advisory Group
ISRO: Indian Space Research Organization
ITU: International Telecommunication Union
JAXA: Japan Aerospace Exploration Agency
LDPC: Low Density Parity Check
MBC-AWG: Mars and Beyond Communications Architecture Working Group
MSPA: Multiple-Spacecraft-Per-Antenna
NASA: National Aeronautics and Space Administration
PNT: Positioning, Navigation and Timing
SZM: Shielded Zone of the Moon
TT&C: Telemetry, Tracking and Command
UKSA: UK Space Agency
USLP: Unified Space Data Link Protocol

1. Introduction

In view of the large number of upcoming exploration and science missions to Mars and beyond, the IOAG tasked in early 2020 the Mars and Beyond Communications Architecture Working Group (MBC-AWG), made of representatives of IOAG member and observer agencies, to define a framework of communications architectures that would serve the IOAG member agencies (and their respective commercial partners), individually or collaboratively, to develop relevant communication assets for supporting all flying and future Mars missions, as well as other deep space missions, for the time frame 2020 - 2040. The overarching goal was to establish an architectural framework to facilitate interoperable communications among missions/assets at the network, data link, and physical layers as a minimum. In February 2022 the MBC-AWG, chaired by the authors and participated by representatives from ASI, CNES, CNSA, ESA, ISRO, JAXA, NASA and UKSA, delivered a first output focused of the Mars communications architecture with the understanding that any additional consideration for the "Beyond" part would be defined later, incrementally built upon the Mars case. The drivers taken into account in defining the architecture were: 1) the actual and anticipated communications needs, established through Agencies' missions survey; 2) the link to a general Moon-to-Mars exploration initiative, implying a strict coordination with similar results already developed for the Lunar environment; 3) the advancement of communications technology, with a shared vision of infusing "tipping point technologies" for supporting future scientific investigations and human and robotic exploration; 4) the adherence, as much as possible, to existing technical and regulatory frameworks like the Consultative Committee for Space Data Systems (CCSDS) and the ITU-R through the Space Frequency Coordination Group (SFCG); 5) the existing and planned new communication assets, capabilities, and services, at all space agencies and potential commercial providers, that were and will be relevant to Mars communications.

The present paper illustrates the process followed by the MBC-AWG in identifying the solutions, outlines the main features of the architectural framework, and underlines the challenges linked to reaching a technical and programmatic consensus within a fully international working group, considering the specificities of each participating agency, as well as their technical roadmaps and programmatic constrains. It is meant to be an executive summary of the main report [1] and is structured as follows: after the present introduction, the set of missions to Mars from the 2020s to the 2040s, and from the involved IOAG agencies, is presented in section 2, including a trend analysis based on the most important features and drivers of such missions. The following section 3 gives highlights about the communication system and capabilities employed by each Mars-faring agency to support their Mars missions. The section 4 is devoted to down-selecting standardized solutions, in terms of Frequency, Modulation, Coding, Ranging, and Link Protocol (FMCRL), from the large repertoire available in CCSDS, and also to identify potential gaps of CCSDS in specific areas deemed essential for the new architecture. In the same section key issues requiring further resolution are also presented, reflecting cases where different opinions across the various agencies could not be entirely resolved in the frame of the trade-off. The proposed Mars communications architecture is presented in section 5, based on trade-offs and elaborations reported in the previous sections. The architecture includes Mars Communications, Mars Relay Networks, Mars Surface Networks, involved Earth Networks, a preliminary PNT Architecture for Mars Communications and Cross Support Services, including Mars end-to-end network management. Conclusions are reported in section 6.

2. Mars mission set – towards early 2040s

The Mars missions set was identified for all involved Agencies, summarised in Table 1 below. The key output of such survey was the idea that, over the two decades to be considered, the communications architecture will evolve according to an incremental path. Four reference time spans were identified: the one for currently flying missions; the one for missions under preparation with launch date until 2026; the future medium term for missions up to 2035 already heading to the establishment of a relay infrastructure and preparing for human exploration; and that for long term initiatives up to the 40s, which given the conceptual definition underway is aiming at fully supporting a sustained human exploration of Mars.

Table 1. Current and Potential Future Mars Missions. Colour code is as follows: grey for currently flying missions; green for future near-term missions; brown for future medium-term missions; white for future long-term missions. Significant changes occurred with respect to the content of the same table in [RD-1], partially reflected int the table, like for example the postponement and redefinition of ExoMars RSP, the re-definition of CNSA's Tianwen-2 which will no longer be a Mars mission (instead it will be an asteroid sample return mission plus a later comet rendezvous mission) and the introduction of Tianwen-3 which will be a Mars sample return mission.

Mission	Launch year	Agency	Mission type
Mars Odyssey	2001	NASA	Orbiter
Mars Express	2003	ESA	Orbiter
Mars Reconnaissance Orbiter (MRO)	2005	NASA	Orbiter
Mars Science Laboratory (MSL): Curiosity	2011	NASA	Rover
Mars Orbiter Mission-1 (MOM-1):	2013	ISRO	Orbiter
MAVEN	2013	NASA	Orbiter
ExoMars Trace Gas Orbiter (EDM-TGO)	2016	ESA	Orbiter, Lander
InSight	2018	NASA	Lander
Tianwen-1	2020	CNSA	Orbiter, Rover
Perseverance Rover	2020	NASA	Rover, Helicopter
Emirates Mars Mission (EMM)	2020	UAE Space	Orbiter
Tera-hertz Explorer-1 (TEREX-1)	2022	NICT	Small Lander
Mars Orbiter Mission-2 (MOM-2)	2024	ISRO	Orbiter
Tera-hertz Explorer-2 (TEREX-2)	2024	NICT	Orbiter
Martian Moon eXploration (MMX)	2024	JAXA	Phobos/Deimos sample return
Mars Micro Orbiter*	2024	NASA	Orbiter
Phobos-Grunt 2	2024	Roscosmos	Sample return
Mars Sample Fetch Rover	2026	ESA	Rover
Earth Return Orbiter	2026	ESA	Orbiter
Mars Sample Return Lander	2026	NASA	Lander, Mars Ascent Vehicle

Mission	Launch year	Agency	Mission type
Mars 2026 SmallSat*	2026	NASA	Orbiter
Mars SAR/ IceMapper*	2026	NASA, JAXA, CSA	Science Orbiter, Relay Orbiter
ExoMars RSP	2028	ESA	Rover, Surface Science Platform, carrier
Tianwen-3	2028	CNSA	Mars Sample Return Mission
Small Mars Science Orbiter*	2028	ESA	Orbiter
Mars Comms and Nav Infrastructure Network*♪	2031	ESA	Orbiter
Mars Icebreaker Life*	2033	NASA	Lander
Mars Short-Stay Mission - SEP1*	2033	NASA	Cargo deployment #1
Mars Long-Lived Weather Network Mission*	2033	ESA	Lander/Orbiter Network
Mars Ice Access and ISRU demo Mission*	2035	ESA	Lander
Mars Short-Stay Mission - SEP2*	2035	NASA	Cargo deployment #2
Mars Astrobiology Rover	2037	ESA	Rover
Mars Communication and Navigation Infrastructure Network Augmentation*♪	2037	ESA	Orbiter
Mars Short-Stay Mission - Lander*	2037	NASA	NEP Crew Lander staged for crew arrival
Mars Areostationary Relay 1*	2037	NASA	
Mars Short-Stay Mission - DSH*	2039	NASA	
Mars Short-Stay Mission - MAVBS*	2039	NASA	1st Human Mars Mission: DSH-Orion stack
Mars Short-Stay* Mission - CubeSats	2039	NASA	Mars Ascent Vehicle with Boost Stage
Human surface mission support	2041	ESA	
Mars Areostationary Relay 2*	2043	NASA	Lander/Rover

* Proposed mission or mission concept in planning.

♪ A ground station, network, or relay orbiter.

The analysis of the mission set shown in Table 1 led to few important observations relevant to the Mars communications architecture:

- The significant increase in mission launches: according to the above February 2022 snapshot, there would be about 15 missions with 22 spacecraft to be launched during this coming decade, i.e., 2022 – early 2030s. As compared to the last decade, i.e., 2010 – 2020, when 9 missions with 15 spacecraft were launched, this represents a remarkable increase.
- Science missions will continue to dominate the Mars exploration activities until late 2030s when the set of robotic precursor missions for human Mars exploration will begin to roll out.
- The trend toward Mars surface exploration: at least 7 missions have been planned to deploy a lander, a rover, or both during the next decade. In comparison, there were only 4 in the last decade. Sample return as a new type of Mars science missions seems to contribute to the trend.
- Inter-agency cross support: the decade-old practice of leveraging the services provided by other space agency's communication assets will be carried forward into the next decade almost by all 15 new Mars missions.
- The advancement of new technology through Mars exploration: predictably, the wave of Mars missions will spur many "tipping point technologies" to be infused for supporting the scientific investigations and human exploration.
- The emerging Mars relay orbiters: when implemented, a communications and navigation infrastructure would reduce the cost and risk of future Mars missions and increase the return on investment, as measured by vastly greater data return. It would provide reliable, near-continuous support to surface and in-orbit users, providing essential capacity for the next decade that scales toward a human and robotic missions thereafter.

3. Mars communications – current and future as envisioned by individual space agencies

After the identification of the Mars mission set, the key preparatory step of the MBC-AWG was to report, from each participating agency, about their current ground and on-board capability and projected technology which will be relevant to Mars exploration. The purpose of such survey was twofold: first, most importantly, to tighten any notional architectural consideration to actual capabilities and technology roadmaps; second, to increase the engagement of each Agency into the IOAG initiative, by ensuring adequate treatment of Agency's specific information and ideas. A comprehensive set of Agencies' on-board and ground capabilities is reported in [1] which cannot be reproduced here, except for the radio frequencies employed by the various Earth network assets as summarized in Table 2. This table addresses the availability of substantial resources at X-Band and Ka-Band, with uplink, downlink and tracking performance commensurate to the needs of complex deep space missions at Mars interplanetary distance and beyond.

Table 2. A dashboard view of Earth network assets for Mars mission support

Agency	Antenna Aperture	Location	Uplink (EIRP)		Downlink (G/T)		Remarks
			X-band	Ka-band	X-band	Ka-band	
ASI	64m	Sardinia	>112 dBW	>112 dBW	>56.5 dB/K*	Plan TBD	Newly upgraded, performance TBC
CNSA	66m	Jiamusi	>108.3 dBW	Plan TBD	>53.3 dB/K	Plan TBD	
	35m	Kashi	>104 dBW	Plan TBD	>49 dB/K	>56 dB/K	
	35m	Neuquen	>104 dBW	Plan TBD	>50.2 dB/K	>56 dB/K	
	70m	Tianjing	No plan	No plan	55 dB/K	No plan	
ESA	35m	New Norcia	107 dBW	Plan TBD	55.5 dB/K	Planned 63 dB/K	Two antennas at New Norcia and Malargüe (TBC), by end of 2025 and 2029 respectively. Enhancement of Malargüe Ka-band EIRP planned by 2025
	35m	Cebreros	108 dBW	Plan TBD	55.5 dB/K	63 dB/K	
	35m	Malargüe	107 dBW	Current: >94.7dBW Planned: >101.7dBW	55.5 dB/K	63 dB/K	
ISRO	32m	Bylalu	98 dBW	Plan TBD	47.0 dB/K	Plan TBD	
JAXA	54m	Misasa	>142.6 dBm	Plan TBD	>53.3 dB/K	>59.3 dB/K	New antenna
	34m	Uchinoura	>138.7 dBm	Plan TBD	>47.7 dB/K	Plan TBD	
NASA	34m	Goldstone	>110 dBW (20 kW)	Planned for 2025	>54.2 dB/K	>61.1 dB/K (45°EL)	3x34m BWG now. 4th by 2026
	34m	Canberra	>110 dBW (20 kW)	Planned for 2026	>54.2 dB/K	>61.1 dB/K (45°EL)	3x34m BWG now. 4th by 2028
	34m	Madrid	>110 dBW	Planned for 2028	>54.2 dB/K	>61.1 dB/K	4x34 BWG now
	70m	Goldstone	>116 dBW	No plan	>61.5 dB/K	No plan	
	70m	Canberra	>116 dBW	No plan	>61.5 dB/K	No plan	
	70m	Madrid	>116 dBW (20 kW)	No plan	>61.5 dB/K	No plan	
	34m HEF	Goldstone	>110 dBW (20 kW)	No plan	53.2 dB/K	No plan	
UKSA	32m	Goonhilly	>95 dBW	Plan TBD	>45 dB/K	Plan TBD	Newly upgraded
	30m	Goonhilly	No plan	No plan	55 dB/K	No plan	Newly upgraded, performance TBC
Roscosmos	70m	Yevpatoria	Data TBD	Plan TBD	Data TBD	Plan TBD	
	64m	Bear Lakes	Data TBD	Plan TBD	58.5 dB/K	Plan TBD	
	64m	Kalyazin	113.5 dBW	Plan TBD	58.2 dB/K	Plan TBD	
	64m	Ussuriisk	Data TBD	Plan TBD	Data TBD	Plan TBD	

* for ASI – The value refers to the present provisional downlink configuration to be updated

The following Fig. 1 shows sample apertures from the above collection, with diameters ranging between 32 and 54m.

Fig. 1. Ground antennas of IAOG agencies suitable for Mars missions, starting from top left and clockwise: ESA Malargüe 35m antenna, ISRO IDSN-32 antenna, JAXA Misasa 54m antenna, Goonhilly's 32m antenna, NASA DSS-26 34m antenna, ASI-INAF 54m radio telescope/deep space antenna and CNSA Neuquen 35m

4. Frequency, modulation, coding ranging, and link protocol

The third step was the crucial down-selection of Frequency Bands, Modulation, Coding and Data Link Protocols. Even though regulative frameworks and standards exist to help missions' managers in defining the communications solutions, the number of options is often too large to ensure maximum level of interoperability. The principles followed in the down selection are reported in the following table 3, accompanied by supporting examples from the main report [1]. A detailed and comprehensive list of down selected solution is indeed available in the section 4 of the above quoted report.

Some issues remain to be completely resolved within the working group, even though none of them prevented a consensus to be reached on the final down-selection. They are listed below, whereas their detailed discussion, as well as the potential way forward, is addressed in the main report [1].

- Selection of a unique frequency bands pair for high rate communications at RF
- Mars in SZM of the Moon
- Coexistence of residual carrier and suppressed carrier modulations
- Coexistence of GMSK and O-QPSK
- Need of variable coding and modulation
- Need of MFSK modulation
- Coexistence of S-Band and X-Band for proximity links
- Need of O3K complementing PPM for cross-links or proximity links
- Need of AOS on top of USLP
- Coexistence of LDPC and turbo codes
- Need of Ku-Band for proximity links
- Adequacy of current CDMA CCSDS blue book for Mars region
- Use of telemetry ranging
- Potential use of PCM/PM/NRZ-L modulation
- Departure from Reed Solomon/convolutional codes towards LDPC

Table 3. Principle followed for down-selection of Frequency Bands, Modulation, Coding and Data Link Protocols

Principle	Examples from [1]
Adherence to SFCG frequency allocations and CCSDS recommendations	7145 – 7190 MHz, 34.2 – 34.7 GHz for Earth to Mars links 8400 – 8450 MHz, 31.8 – 32.3 GHz for Mars to Earth links 22.55 –23.55 GHz, 25.5 – 27.5 GHz for cross-links (orbiter to orbiter) 435 – 450 MHz, 2025 – 2110 MHz for proximity TT&C links (orbit to Mars surface/low orbit) 7190 – 7235MHz, 22.55 – 23.55 GHz for proximity TT&C links (orbit to Mars surface/low orbit) 390 – 405 MHz, 2200 – 2300 MHz for proximity TT&C links (Mars surface/low orbit to orbit) 8450 – 8550MHz, 25.5 – 27.5 for proximity TT&C links (Mars surface/low orbit to orbit) 2483.5-2500 MHz for accurate PNT Several allocations for Mars surface communications, yet to be streamlined
Preferred use of bandwidth efficient modulations	GMSK, filtered OQPSK, CCSDS VCM (DVB-S2, SCCC, or LDPC) employed for several links, all selected according to applicable CCSDS blue books referenced in [1].
Adoption of Low Density Parity Check (LDPC) and Turbo codes with a wide set of coding rates	LDPC adopted for all links, with coding rates 1/2, 2/3, 4/5, 7/8, Turbo codes adopted for link with Earth, with coding rates 1/2, 1/3, 1/4, 1/6 Full coverage of either power constrained or bandwidth constrained link scenarios
Adoption of the Unified Space Data Link Protocol (USLP)	USLP adopted uniformly through all the links, i.e. the various link types (long haul space-Earth, relay, and surface links) and directions (forward, return, and cross links)
Re-use of solutions across different links from the Earth-Mars to the local Mars region.	Ensured e.g. by adoption of the above mentioned bandwidth efficient modulations, LDPC, and USLP
Re-use of solutions from the Lunar region into a Moon-to-Mars communications roadmap	Large overlap with solutions reported in [3] for all links scenarios
Extensive use of Ka-Band uplink (34.2 –34.7 GHz)	Ka-Band uplink is proposed beyond its current use for radio science, as a potential attractive TT&C solution due to the larger immunity to solar plasma effects than X-band
Inclusion of optical communications for all spacelinks	1030 nm, 1064.15 nm, 1070 nm wavelengths for Earth to Mars links 1530.33 nm – 1567.13 nm wavelengths for Mars to Earth links, cross-links and proximity links Adoption of OOK, SC-PPM in terms of modulation and coding for links with Earth, RS for cross-links

5. Description of Mars communications architecture

The Mars communications architecture will evolve through the next two decades, over four distinct, but overlapping eras for the missions:

- Current Flying Missions: Present
- Future Near-Term Missions: Starting 2022 launch
- Future Mid-Term Missions: Starting 2026 launch
- Future Long-Term Missions: Starting 2037 launch

The Fig. 2 below illustrates the mission eras and the overall complexion of driving missions in each era.

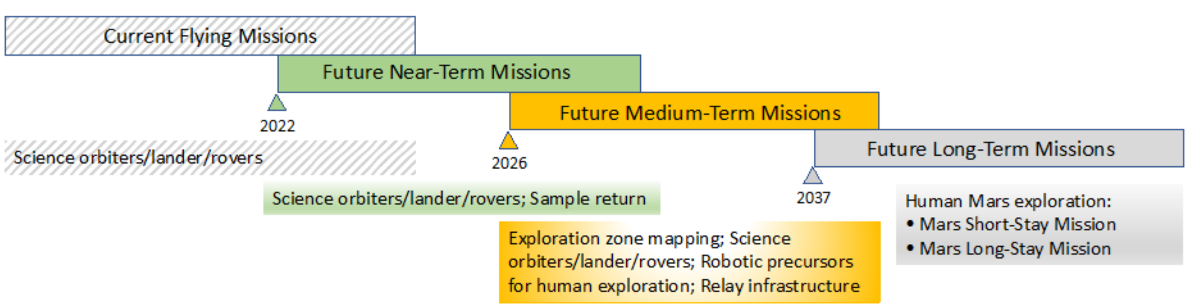

Fig. 2. mission eras and the overall complexion of driving missions in each era

In order to illustrate and summarize the architecture transformation, Fig. 3 shows the growth of data rates/data volumes, and some new functional capabilities (albeit only a select few).

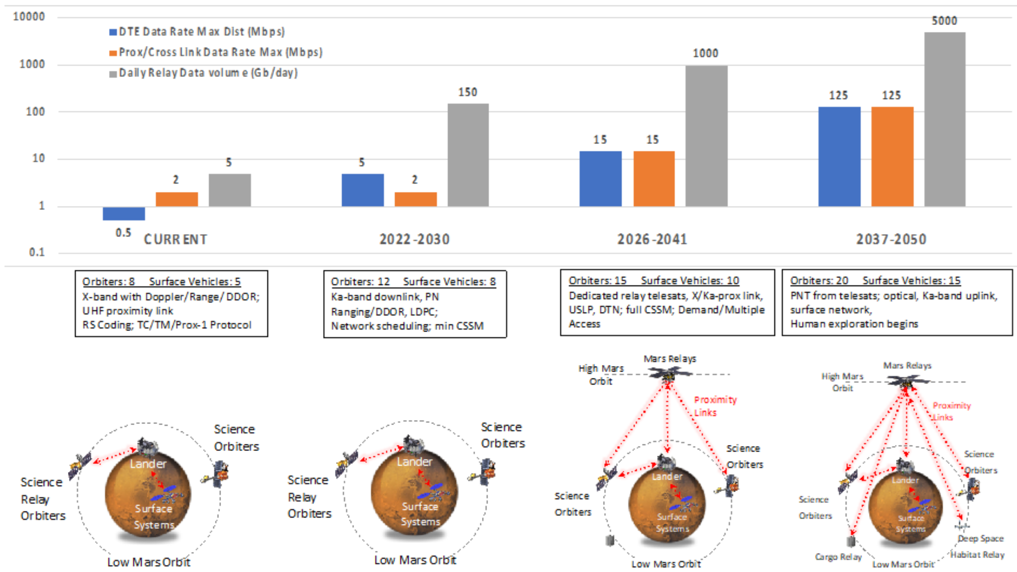

Fig. 3. Evolution of Mars communications architecture – data rate, data volume, mission count and networking

Whereas the main report [1] details the evolution of the Mars communications architecture for all above four eras, this paper presents the main features of only the long term solution, visualised in Fig. 4. Such architecture is based upon the following main features:

- the establishment of robust Mars Relay and Mars surface networks, the including a) a constellation of relay satellites; (b) the deployment of the telecommunications payload on the Deep Space Habitats (DSH) and Cargo Relay; (c) the establishment of crosslinks to interconnect the dedicated relay satellites, the DSH, and the Cargo Relay and (d) a full-fledged Mars surface network enabling vicinity wireless communications between the various landed elements including astronaut's hand-held/body-mounted devices.
- full space internetworking, enabling true end-to-end network protocol, network-wide addressing schemes, provision for different classes of data, and common, fully automated, accountable, data delivery;
- Disruption/Delay Tolerant Networking (DTN) network management, to orchestrate in a coherent and efficient manner the multitude of Mars missions, the combination of relay orbiters, surface network hub(s), and Earth stations, ultimately providing fully integrated, interoperable services;
- availability of high-rate solutions for links with Earth and at Mars, both in RF and optical, to be selected based on latency/availability requirements;
- establishment of Link Layer and Network Layer Security, offering to increasingly interconnected relay orbiters, surface vehicles and Earth stations an integrated approach to address both the security concerns traditionally faced by Earth networks and users' mission operations systems, and those in Mars environment;
- availability of new relay services in addition to data delivery service: time service, in-situ tracking and navigation, services which may be crucial to some crewed activities;
- multiple access to proximity link, i.e. an access mode which allows multiple user vehicles to have shared access to a physical link at the "same time", indeed a key attribute of the relay services;
- user vehicle-initiated service initiation mode, allowing a user to autonomously request a service from the relay network, another important attribute of the Mars relay services;
- single beam sharing and arraying configurations for Earth antennas, with multiple-spacecraft-per-antenna (MSPA) configurations to support up to 4 missions simultaneously by a single antenna, hence reducing the demands on Earth antennas;
- Use of optical for direct-to-Earth links and cross-links (and potentially for proximity links as well), providing, in addition to Ka-Band, solutions for high-volume and high-rate data return;
- hot, stand-by contingency links, primarily to ensure safety of crew members;

- inclusion of commercial relay services, primarily to build and operate the Mars relay architecture, offering relay services on fee-for-service basis, functioning very much like a commercial terrestrial network

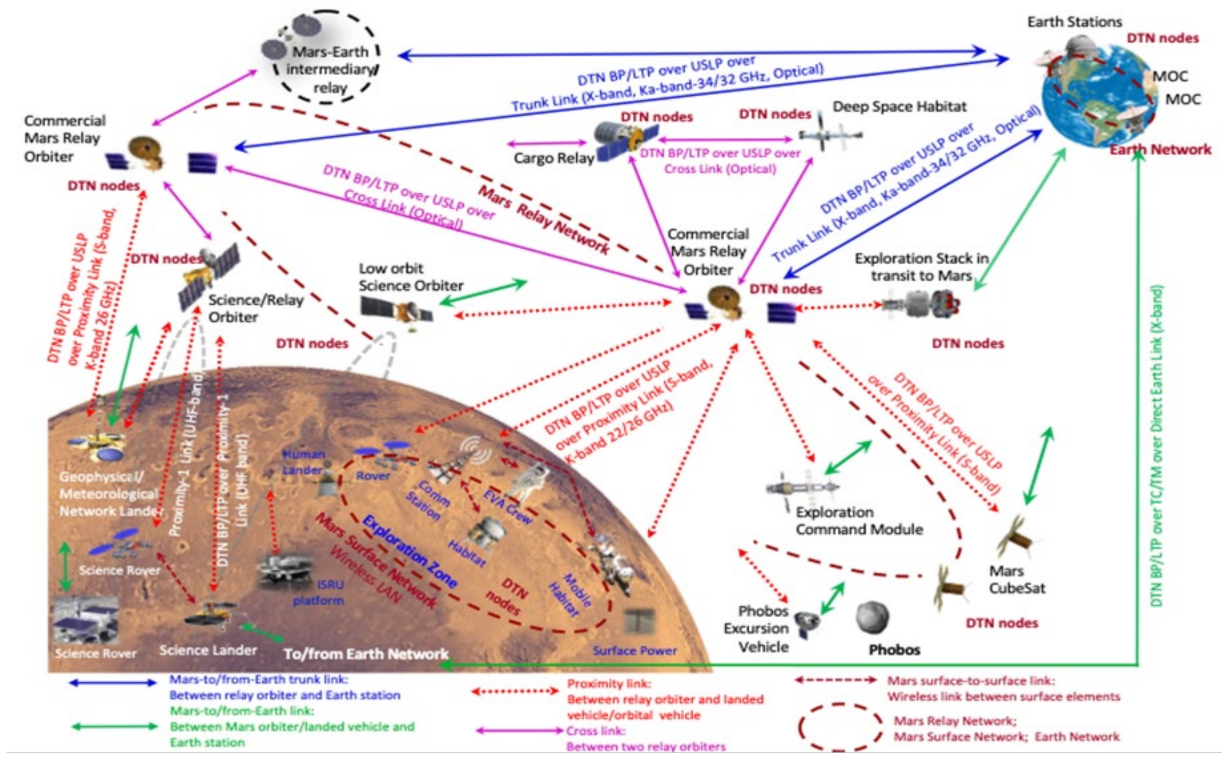

Fig. 4 Mars Communications Architecture – Future Long-Term Mission Era

For supporting the human Mars exploration, the long term architecture of Fig. 4 will feature the full-grown Mars relay network, Mars surface network and a set of more capable Earth networks. As such, it will evolve into a more encompassing end-to-end space internet than the previous eras. In addition to the data transfer at the space internetworking layer, the Mars network management capabilities, in terms of service management and network control, will be infused to operate network assets provided by the collaborating space agencies and commercial service providers. Closely coupled with the Mars network management is the network security. The proposed network security architecture features the trusted certificate authority that will be used as part of access management, authentication, and encryption of data using an asymmetric, public key, infrastructure. It requires that trusted identities are assigned to all user elements, as well as to all service providing elements, e.g., relay orbiters, DTN routers, surface communications hub, Earth stations. To cater to the increased data throughputs, the 34 GHz Ka-band (uplink) and 32 GHz Ka-band (downlink) as well as optical communications at 1030 – 1070 nm (uplink) and 1530 – 1567 nm (downlink), are applied to form the trunk links between Earth and Mars. As the complement to the trunk link, the high-rate proximity link using the 22 GHz K-band for forward link and 26 GHz band for return link is recommended.

Currently no surface-to-surface communications exist as part of a defined Mars mission architecture. However It is expected that, during the Long-term Missions era, crewed activities on Mars surface will rely on surface-to-surface communications at an unprecedented level. As motivated by an analysis for a Mars Short-stay Surface Mission, reported in [1] and reference therein, videos will the single largest driver to the communications involving EVA crew, local mobility vehicles, science packages, public affairs cameras, in-situ sensor platforms, landers and cargo pallets. These elements could return and receive data via the relay proximity links using their respective communication terminals. A Mars surface network would feature one or two communication hubs that provide the essential function of multiplexing surface traffic (destined to Earth or relay orbiters) onto the proximity links with a Mars relay network. The surface hubs also de-multiplex data (originated on Earth or relay orbiters) from the Mars relay network and distribute the data to the surface elements over the Mars surface network.

Figure 5 shows a conceptual representation of the architecture for the Mars surface network.

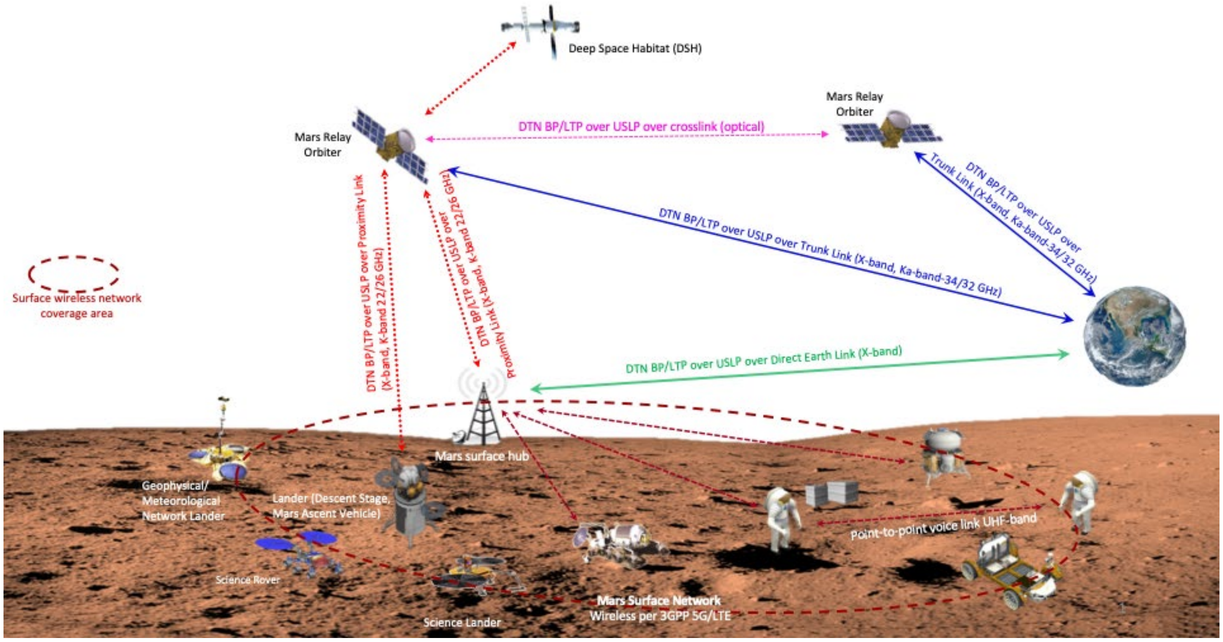

Fig. 5 Conceptual architecture for the Mars surface network.

6. Conclusions

The IOAG communications architecture presented in [1] and summarised in the previous section is a coherent and complete input for Mars missions to identify interoperable solutions. It largely relies on consolidated standards and regulatory frameworks, however with a strong down-selection aiming at maximising interoperability. It also relies on infusion of new technologies, especially for the long-term Missions Era. Even though it cannot replace detailed specifications, to be formulated by missions based upon their specific requirements, it will accommodate a high level of commonality in terms of communication to enable cross-support for mutual benefit and the gradual build-up of a Mars communication infrastructure, reflecting a shared principle and wisdom, that Mars Exploration will be a collective effort of humankind, across different countries, national and international agencies and commercial operators.

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References

In the following only the sources directly referenced within this paper are reported, with the understanding that the main report [1] contains the reference to the several publications, journals and standards used to compile it.

[1] The Future Mars Communications Architecture, Report of the Interagency Operations Advisory Group, 22/2/2021, available at https://www.ioag.org/SitePages/Home.aspx, in the " Reports" section.
[2] SFCG 22-1R4 Frequency Assignment Guidelines for Communications in the Mars region, 10 December, 2021
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