Design and Architecture of the Mars Relay Network Planning and Analysis Framework [1][2]

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Abstract— Prior Mars exploration studies indicate that the deployment of a Mars orbital infrastructure to support the telecommunications and navigation needs of the surface elements is essential to the success of the future Mars exploration missions. Efficient planning and scheduling of the communications between surface elements, orbiters, and Earth subjected to various constraints of deep space communications is a unique and challenging problem. In this paper we describe the design and architecture of the Mars Network planning and analysis framework that supports generation and validation of efficient planning and scheduling strategy. The goals are to minimize the transmitting time, minimize the delaying time, and/or maximize the network throughputs. The proposed framework would require (1) a client-server architecture to support interactive, batch, WEB, and distributed analysis and planning applications for the relay network analysis scheme, (2) a high-fidelity modeling and simulation environment that expresses link capabilities between spacecraft to spacecraft and spacecraft to Earth stations as time-varying resources, and spacecraft activities, link priority, Solar System dynamic events, the laws of orbital mechanics, and other limiting factors as spacecraft power and thermal constraints, (3) an optimization methodology that casts the resource and constraint models into a standard linear and nonlinear constrained optimization problem that lends itself to commercial off-the-shelf (COTS) planning and scheduling algorithms. Numerical studies for a sample Mars relay network of multiple surface elements and multiple orbiters, and multiple Earth stations are carried out to demonstrate the practicality of the design approach. The considered Mars relay network under our approach results in higher supportable data transmission rates, shorter communicating time, and thus a larger amount of telemetry data can be transmitted to Earth with a fixed set of surface elements and orbiters.

1. INTRODUCTION

Prior Mars exploration studies conclude that the deployment of a Mars orbital infrastructure to support the telecommunications and navigation needs of the surface elements is essential to the success of the future Mars exploration missions. Such Mars orbital infrastructure can provide the UHF relay capability that is a mission enabler for smaller mission elements since they cannot afford to communicate with Earth directly. For the larger mission elements, the UHF relay link can provide greatly enhanced data volume return. For all the missions, the orbiting infrastructure can offer larger surface coverage, improved fault tolerance, and enhanced navigation service. Starting in late 2003 timeframe, the twin Mars Exploration Rovers (MER) and the Beagle 2 will begin to share the UHF links offered by the orbital Mars Odyssey and MGS spacecraft. Future technology precursor missions and completed scout-class missions will rely more heavily on the relay capability of the Mars orbital infrastructure.

The planning and scheduling of the intercommunications between surface elements, orbiters, and Earth subjected to various constraints of deep space communications is a unique and challenging problem, and plays an important role in the efficient utilization of the Mars orbital infrastructure. Unlike a point-to-point communication link, a relay link consists of a concatenation of links, in which the data transfer mechanism can be either real-time or store-and-forward. In addition to topological relationship, time relationship between links becomes an important factor in the overall efficiency of data transfer. The

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performance and structural models, trajectory profile, and attitude profile of various communication assets, and the ephemeris and geometric properties of the celestial bodies that impact the performance and operation of the relay network. This architecture de-couples visualization, computation, and database functions to allow plug-and-play of various functions and extensions.

The modeling and simulation environment support three interactive types of modeling – link resource, spacecraft dynamic events, and operation constraints.

- Link resource refers to the statistical link performance between two communication elements (surface assets, orbiters, and Earth stations), which is modeled by the traditional point-to-point link analysis techniques in terms of the gains and losses along the communication path. From telecommunication viewpoint link resource is expressed as the supportable data rate as a function of time, or as the estimated data volume returned during a certain time span. From navigation viewpoint link resource is expressed as the time profiles of certain estimated signal-to-noise ratio quantities, which can be translated into the estimated accuracies of position, range, velocity, acceleration, and/or angular measurements of the communicating entities. Link analysis estimates these resources and performs trade-offs to configure the communication elements to achieve telecommunication and navigation objectives.

- Spacecraft dynamic events refer to the nominal and off-nominal spacecraft orientations and maneuvers performed by the communication elements that have direct and indirect impacts on the link. These events can be quiescent or dynamics. The two non-telecom factors that affect the link most are the range between the two communication elements and their corresponding antenna pointings. Quiescent events like cruise and science observation usually results in a relatively stable and predictable link performance. Dynamic (usually mission critical) events like launch, trajectory correction maneuver, spacecraft safing, and orbital insertion generally involved a rapid change in the range and antenna pointing of the communication elements, resulting in a wide swing of link performance in a short period of time. If trajectory and/or attitude information are already modeled and packaged in standard SPICE kernels, NAIF library can be used to compute the range and antenna off-boresight angles. In the event of an orbital mission, the spacecraft trajectory can be modeled using standard orbital propagation techniques likes the six orbital elements. Sometimes spacecraft attitude can also be modeled by simulating the spinning and coning of an orbiter's primary and secondary axes, and the orientation and tilt of a surface element.

- Operation constraints refer to the physical laws and geometric constraints, hardware limitations, mission requirements, mission priority, policy requirements, and other factors that restrict the availability and operation of a link. The in-view/out-of-view period between communication elements is governed by the laws of orbital mechanics and the shape and size of the celestial bodies in the solar system. Onboard data storage limits the amount of data to be transferred. Mission activities like instrument checkout and calibration mandate real-time communication at specific time. Mission priority imposes a biasing weight in the planning and scheduling of resource to service multiple spacecraft. Safety policy establishes a minimum elevation angle that affects the effective tracking time. Requirements on end-to-end data delivery latency depend on the criticality of the data. As shown in the subsequent sections, many of the above constraints are relationships between objects that can be formalized mathematically in the form of linear and non-linear systems of inequalities. Also the in-view/out-of-view periods between the communication elements reduce the continuous timeline into a finite set of possible contacts or passes within a given planning horizon.

The modeling of link resource, spacecraft dynamic events, and operation constraints provides an for example a one-week timeframe, there are K possible number of passes $\{P_k \mid k=1,2,\ldots K\}$ between all communicating entity pairs within the network; Each pass P_k represents the communicating window between a pair of transmitter and receiver, which could be from a surface element to an orbiter, or from a surface element to a ground station, or from an orbiter to a ground station. Associated with the pass P_k are its starting time T_0^k, end time T_f^k, transmitter XMT (lander or orbiter), receiver RCV (orbiter or DSN station), and the supportable data rate $R^k_{XMT.RCV}(t)$, which is valid only on $[T_0^k,\ T_f^k]$. If communication is scheduled for the pass P_k, the actual transmission starting (on) time and end (off) time are denoted by t_0^k and t_f^k respectively. Our goal is to determine the optimal pair of start and end time $\{[t_0^k,\ t_f^k] \mid T_0^k \le t_0^k \le t_f^k \le T_f^k\}$ for each pass P_k so that the total transmitting and delaying time are minimized while the network throughputs are maximized.

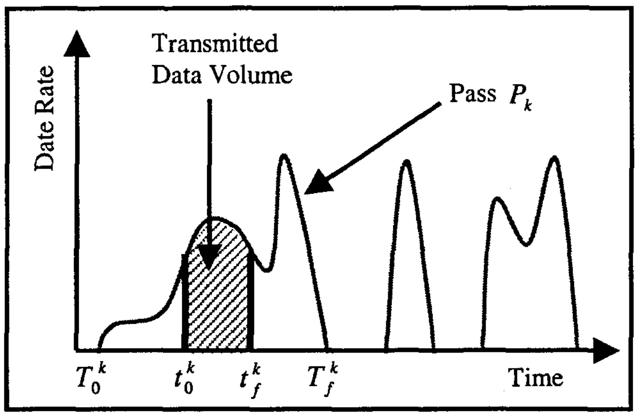

Figure 2 – Supportable Data Rate Sample During a Pass

We next discuss operational constraints and requirements for the Mars Relay network, which we assume in this paper. Our primary efforts are to eliminate unusable passes and refine the qualified ones. Selected candidates must satisfy the following set of constraints:

(a) Due to the limited onboard power constraint, the solar panels for the surface assets must be in the Sun's view in order to transmit or receive any data. Thus the passes whose transmitters are out of the Sun's view are removed.

(b) The supportable data rate for each pass must exceed a certain performance threshold:

$$R^k_{XMT.RCV}(t) \ge R_{threshold}\,. \tag{1}$$

In the event that the entire pass may not meet this requirement, only the portion that the supportable data rate is above the threshold is considered.

(c) To constitute a pass, the whole pass from start to finish must last longer than some minimal required time $T_{\min}$; otherwise it is not worth considering,

$$T_f^k - T_0^k \ge T_{\min} \qquad k=1,2,\ldots K\,. \tag{2}$$

(d) Communication in a pass can only start after some calibration and acquisition time τ_k during each pass,

$$C_{DV}(t_o^1, t_f^1, \ldots, t_o^K, t_f^K) = -\sum_{k=1}^{K} \sigma_k^{-1} \cdot DV_k \quad \text{where } \sigma_k \text{ is the priority score.} \tag{9}$$

(l) In addition, if the antenna resources are limited or expensive, then achieving link efficiency would require the communicating time to be as small as possible, so that more missions can be supported with the same resources. The corresponding minimizing criterion is

$$C_{TIME}(t_o^1, t_f^1, \ldots, t_o^K, t_f^K) = \sum_{k=1}^{K} \sigma_k^{-1} \cdot (t_f^k - t_0^k), \quad \text{where } \sigma_k \text{ is the priority score.} \tag{10}$$

(m) Finally, optimization criteria (9) and (10) can be imposed individually, interchangeably, or dually.

In summary, our scheduling optimization problem involves minimizing the cost functions in (9) and/or (10) subject to the communications and operational constraints (1)-(8).

4. Formulations for Operational and Communication Constraints

Optimizing the relay communication network requires the selection of the transmitting and receiving pairs as a function of time so that the objectives and constraints are satisfied. Equivalently, we seek for an optimal solution

$$X = \begin{bmatrix} t_o^1 & t_f^1 & \cdots & t_o^K & t_f^K \end{bmatrix}^T, \tag{11}$$

that optimizes the objective functions (9)-(10) and fulfills the constraints (1)-(8).

Let us next discuss all of the constraints and their corresponding mathematical formulations. First notice that the potential passes from our Mars relay network are screened a priori so that the considered passes must be long and strong enough, i.e. satisfy conditions (1)-(2) of the constraints (b)-(c). The calibration and acquisition time in constraint (3) for each transmission can be incorporated in the transmitted data volume. In other words, the data volume (7a) from the pass P_k is measured instead as,

$$DV_k = \int_{t_0^k + \tau_k}^{t_f^k} R_{XMT,RCV}^K(t)dt. \tag{12}$$

Consequently, conditions (3)-(5) can be translated into the following linear constraints

$$AX \le B, \quad \text{and} \quad L_B \le X \le U_B, \quad \text{where} \tag{13}$$

$$A = \begin{bmatrix} 1 & -1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & \vdots & \vdots \\ \vdots & \vdots & & & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 \end{bmatrix}_{K \times 2K}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad L_B = \begin{bmatrix} T_o^1 \\ T_o^1 \\ \vdots \\ T_o^K \\ T_o^K \end{bmatrix}, \quad U_B = \begin{bmatrix} T_f^1 \\ T_f^1 \\ \vdots \\ T_f^K \\ T_f^K \end{bmatrix}. \tag{14}$$

The rest of the constraints (6)-(8) are more complicated and nonlinear formulations are needed. Let us first consider a scenario in which several passes from a single lander are overlapped. Let there be a total of J incidents of overlapping passes among the K possible passes that we consider. We want our communicating time to be disjoined, namely satisfying constraint (6). Particularly we assume that at any time if a surface element possesses two overlapping passes, the communication time, if scheduled, should be done in the vicinity of the peak of the supportable data rate within the pass. That is, let us assume that the passes P_{k_1} and P_{k_2} are

Lander Number	Mars Longitude (deg)	Mars Latitude (deg)	Mars Altitude (km)	Horizon Mask Angle (deg)
1	175	-15	0	15
2	283	-9	0	15
3	354	-2	0	15
4	32	-43	0	15

Table 1: Location of the four Mars landing assets at J2000

Semi-major axis	Eccentricity	Inclin. Angle (deg)	Asc. Node (deg)	Arg. of Perigee (deg)	Time at Perigee
4084 km	0.010814	20	249	153	0
3772 km	0.011474	51	87	344	0
4052 km	0.009869	-89	292	317	0
4008 km	0.012156	53	336	251	0
3890 km	0.056136	26	46	110	0

Table 2: Six orbital elements the five Mars orbiters at J2000

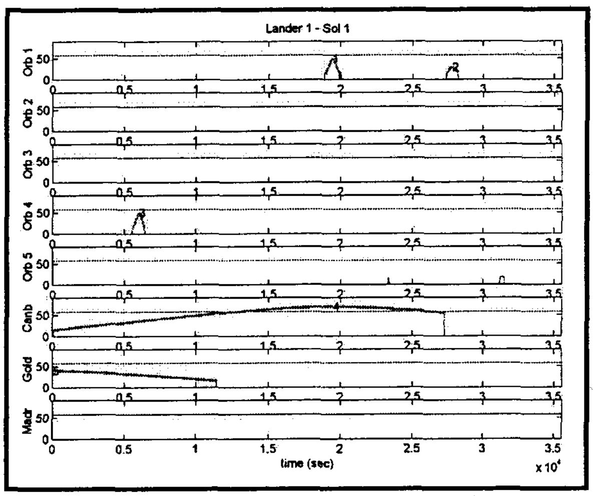

Figure 3. Supportable data rates between Lander 1 and five orbiters and the DSN stations

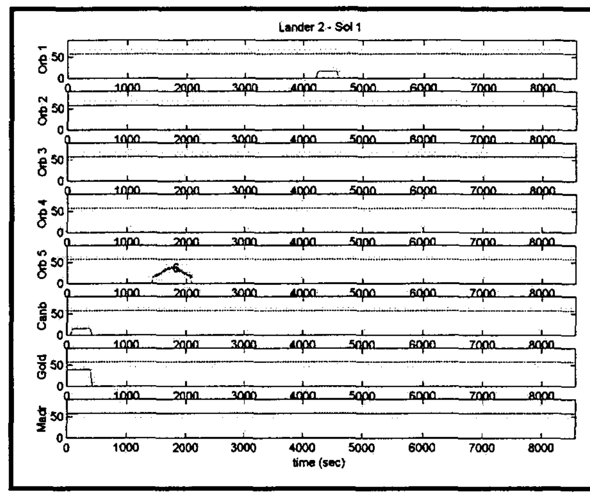

Figure 4. Supportable data rates between Lander 2 and five orbiters and the DSN stations

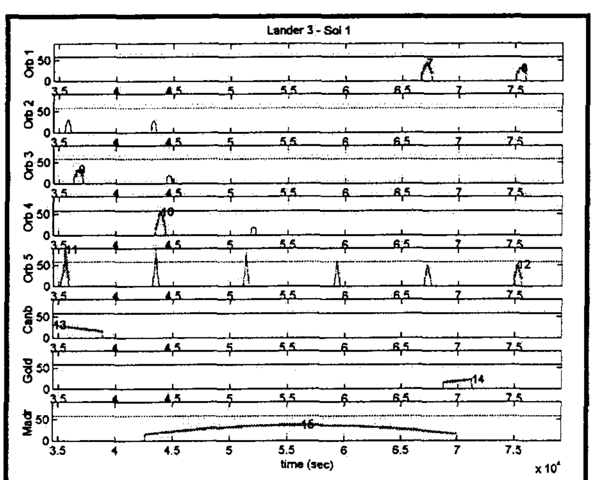

Figure 5. Supportable data rates between Lander 3 and five orbiters and the DSN stations

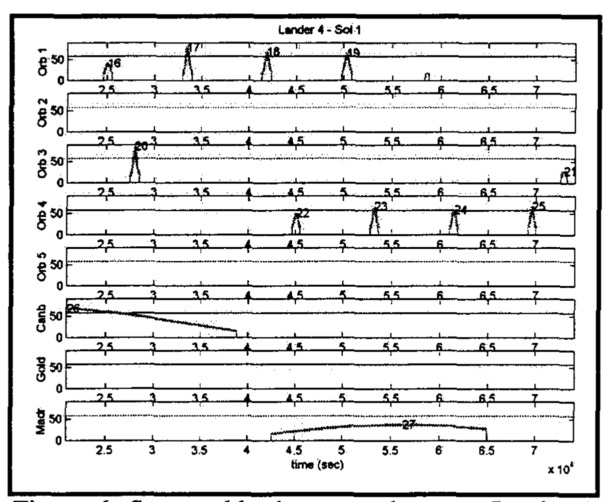

Figure 6. Supportable data rates between Lander 4 and five orbiters and the DSN stations

$\omega = 1$ in equation (18). Constraints (13)-(16) are imposed, while, by assuming that the storage onboard the orbiters are capable of storing and forwarding received data, the constraint (17) is satisfied automatically. Scheduling for orbiters to Earth communication is assumed to be direct following the allowable passes in Figure 7. Namely, we assume that when there is a need for an orbiter to communicate, a DSN station is available. Otherwise, optimization can be employed following our previous work in [1]. Information for the passes and the optimized solution are displayed in Table 3.

Pass P_k	From	To	Priority σ_k	Overlapped With Pass	T_o^k	t_o^k	t_f^k	T_f^k
1	Lander 1	Orbiter 1	1	4	18930	18931	18931	19920
2	Lander 1	Orbiter 1	1	None	27420	27420	28170	28170
3	Lander 1	Orbiter 4	1	4, 5	5610	5610	5610	6420
4	Lander 1	Canberra	1	3, 5	120	5610	27270	27270
5	Lander 1	Goldstone	1	3, 4	30	30	5610	11430
6	Lander 2	Orbiter 5	1	None	1470	1470	2100	2100
7	Lander 3	Orbiter 1	1	15	66660	66660	67560	67560
8	Lander 3	Orbiter 1	1	12	75090	75502	75900	75900
9	Lander 3	Orbiter 3	1	13	36330	36330	37080	37080
10	Lander 3	Orbiter 4	1	15	43470	43470	44219	44340
11	Lander 3	Orbiter 5	1	13	35190	35190	35850	35850
12	Lander 3	Orbiter 5	1	8	74910	74910	75502	75570
13	Lander 3	Canberra	1	9, 11	34530	34530	35190	38880
14	Lander 3	Goldstone	1	15	68730	68730	71220	71220
15	Lander 3	Madrid	1	7, 10, 14	42630	44219	66660	69900
16	Lander 4	Orbiter 1	1	26	24690	25530	25530	25530
17	Lander 4	Orbiter 1	1	26	32970	32970	33960	33960
18	Lander 4	Orbiter 1	1	None	41400	41400	42390	42390
19	Lander 4	Orbiter 1	1	27	49800	49800	50790	50790
20	Lander 4	Orbiter 3	1	26	27510	27510	28470	28470
21	Lander 4	Orbiter 3	1	None	72630	72630	73290	73290
22	Lander 4	Orbiter 4	1	27	44700	44700	45480	45480
23	Lander 4	Orbiter 4	1	27	52830	52830	53572	53640
24	Lander 4	Orbiter 4	1	27	61020	61020	61830	61830
25	Lander 4	Orbiter 4	1	None	69210	69210	69990	69990
26	Lander 4	Canberra	1	16, 17, 20	20970	20970	25530	38880
27	Lander 4	Madrid	1	19, 22, 23, 24	42630	53572	61020	64950

Table 3: Optimized on-off time versus allowable time.

Remarkable achievements can be summarized as:

1. The optimal solution yields the largest total transmitting data volume from the surface elements. For example, the optimization process chooses to sacrifice pass number 1, which in return yield more transmitting data volume from pass number 4.

[4] Pedro Ramon Escobal, *Methods of Orbit Determination*, Florida: Krieger, 1976.

[5] Tom Logsdon, *Orbital Mechanics – Theory and Applications*, New York: John Wiley & Sons, 1998.

[6] R.H. Tung, *Telecom Forecaster Predictor and Unified Telecom Predictor (TFP/UTP) V2.1 User's Guide*, JPL D-21499, February 21, 2002.

BIOGRAPHIES

Dr. Kar-Ming Cheung *is a Technical Group Supervisor in the Communications Systems Research Section (331) at JPL. His group provides telecom analysis support for JPL missions, and develops the operational telecom analysis and predict generation tools for current and future JPL missions and the DSN. He received NASA's Exceptional Service Medal for his work on Galileo's onboard image compression scheme. He was the Manager of the Network Signal Processing Work Area of NASA's Deep Space Network (DSN) Technology Program. He has authored or co-authored 6 journal papers and over 20 conference papers in the areas of error-correction coding, data compression, image processing, and telecom system operations. Since 1987 he has been with JPL where he is involved in research, development, production, operation, and management of advanced channel coding, source coding, synchronization, image restoration, and link analysis schemes. He got his B.S.E.E. degree from the University of Michigan, Ann Arbor in 1984, his M.S. degree and Ph.D. degree from California Institute of Technology in 1985 and 1987 respectively.*

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