Optimal Planning and Scheduling for a Mars Relay Communication Network

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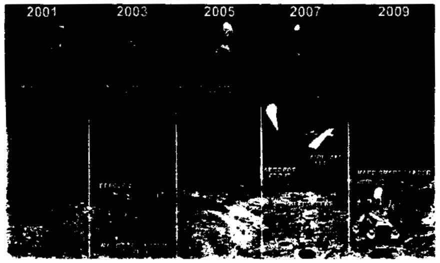

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Abstract-- Mars will be continuously explored this decade and beyond by many concurrent spacecrafts. At different time periods in the future, these missions are overlapped and previous studies indicate that during such periods existing deep space communication infrastructure cannot handle all Mars communication needs. There has been much coordination between various Mars projects and the Deep Space Network to ensure communication resources are effectively utilized so that valuable science and engineering data from Mars orbiters and landers can be accommodated. A plausible solution is to perform optimal resource allocation for the Mars relay communication network; a network consisting of multiple surface units and orbiters on Mars and the Deep Space Stations. Unlike direct-to-earth, a relay communication, either in real-time or store-and-forward, can increase network science data return, reduce surface unit's direct-to-earth communication demands, and enable communication even when the surface unit is not facing Earth. Our objective is to take advantage of the relay capability to plan and schedule the network communications efficiently subject to operational constraints.

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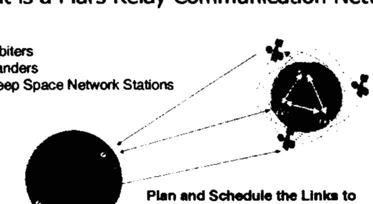
- M Landers
- N Deep Space Network Stations

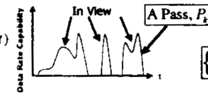


Plan and Schedule the Links to

- Maximize network throughput
- Minimize network tracking time
- Meet Operational/Spacecraft Constraints

Dynamic Network Links:

$R_{XMT,RCV}(t)$



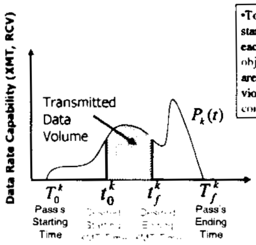
K Possible Passes

$$\{P_k \quad | \quad k = 1,2,\ldots K\}$$

- **Telecom resource ~ Supportable data rate (data rate capability) as a function of time between a transmitter and a receiver pair**
  - There are (LN + NM + LM) pairs
  - Data rate capability depends on time and spacecraft comm. parameters
  - Possible passes (in-view period) are generated by spacecraft trajectory and celestial dynamics simulations
- **(LN+NM+LM) data rate capability profiles (time-lines) are generated by simulation**
- **K passes are identified for planning**

Potentially interfering passes should be scheduled disjointly

Planning and Scheduling Challenges:



- To find the best possible start time and end time within each pass so that network objectives (network usage) are maximized without violating the operation constraints

$$X = \begin{bmatrix} t_o^1 \\ t_f^1 \\ \vdots \\ t_o^K \\ t_f^K \end{bmatrix}$$

Pre-Qualify Passes:

(C1) A qualified pass must be long enough (e.g. DSN>120 min; SE2ORB> 5 min)

$$T_f^k - T_0^k \geq T_{\min}$$

(C2) The data rate capability for each pass must exceed a certain performance threshold:

$$R^k_{XMT,RCV}(t) \geq R_{threshold}$$

(C3) Due to the limited onboard power constraint, the solar panels for the surface elements may need to be in the Sun's view in order to transmit or receive any data.

$$\theta^{Sun}_{Lander\,l}(t) \geq \Theta^{Sun}_{Lander\,l}$$

Operational Constraints (I):

(C4) If a pass is used, it must be at least longer than the required calibration/acquisition time

$$t_f^k - t_0^k \geq T^k_{\min}$$

(C5) If a pass is used, its communication time should not exceed the maximum allowable communicating time

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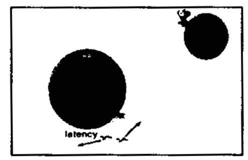
(C6) Network latency

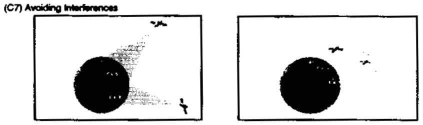
look-at-head latency value (how long is the wait before the next available contact) Λ_k

$$\text{Priority\_latency}_k = \exp(-\Lambda_k)$$



Operational Constraints (II):

(C7) Avoiding Interferences

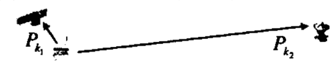


Identify all possible RFI using geometric means and optimal schedule should be interference-free

(C8) Starting and ending time constraints

$$T_0^k \leq t_0^k \leq t_f^k \leq T_f^k$$

(C9) One2One communication constraints (Solar Power)



Operational Constraints (III):

(C10) Total data volume throughputs from a spacecraft must meet or exceed its requirement.

$$\sum_{\substack{k=1 \\ P_k \text{ rec'ved from } SC_i}}^{K} DV_k \geq RDV_i \qquad DV_k = \int_{t_0^k}^{t_f^k} R^k_{XMT,RCV}(t)\,dt$$

(C11) Priority is assigned to each pass depending on its phase and criticality

σ_k Priority of the pass

(C12) Onboard storage constraint

Given a schedule $[\,t_o^1,\ t_f^1,\ \cdots\ t_o^K,\ t_f^K\,]$

$$S_{Orbiter_n}([\,t_o^1,\ t_f^1,\ \cdots\ t_o^K,\ t_f^K\,],t) \leq C_{Orbiter_n}$$

Nonlinear Constrained Optimization:

Mission priority & latency (C6, C11)

MINIMIZE

$$C(X) = \omega_{DV}\,C_{DV}(X) + \omega_T\,C_{TIME}(X)$$

Objective 1: Max. data vol. Objective 2: Min. track time

SUBJECT TO ...

$$AX \leq B \qquad L_B \leq X \leq U_B \qquad [\vec{G}_1(\vec{X}); \vec{G}_2(\vec{X}); \vec{G}_3(\vec{X}); \vec{G}_4(\vec{X})]^T \leq \vec{0}$$

ω_{DV} and ω_T are the weights

$$C_{TIME}(t_o^1, t_f^1, \ldots, t_o^K, t_f^K) = \sum_{k=1}^{K} \sigma_k^{-1} \cdot (t_f^k - t_0^k),$$

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XMT Power limitation (C7)

$$A = \begin{bmatrix} -1 & 1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & \vdots & \vdots \\ \vdots & \vdots & & & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & -1 & 1 \\ 1 & -1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & \vdots & \vdots \\ \vdots & \vdots & & & \ddots & 0 & 0 \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 \end{bmatrix}_{2K\times 2K} \quad B = \begin{bmatrix} T^1_{\max} \\ T^2_{\max} \\ \vdots \\ T^K_{\max} \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad U_B = \begin{bmatrix} T_f^1 \\ T_f^1 \\ \vdots \\ T_f^K \\ T_f^K \end{bmatrix} \quad L_B = \begin{bmatrix} T_o^1 \\ T_o^1 \\ \vdots \\ T_o^K \\ T_o^K \end{bmatrix}$$

Start/End time (C8)

$$G_1^j(\vec{X}) = [\min(t_f^{k_1}, t_f^{k_2}) - \max(t_0^{k_1}, t_0^{k_2})]$$

Ensure non-overlapping passes (C9)

$$G_2^k(\vec{X}) = (t_f^k > t_0^k)[T^k_{\min} - (t_f^k - t_0^k)]$$

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$$G_4^m(\vec{X}) = RDV_m - \sum_{\substack{k=1 \\ P_k \text{ involves } SC_m}}^{K} DV_k \quad m = 1,\ldots,L+N.$$

Ensure meeting required data volume requirement (C10)

Considered Mars Relay Communication Network

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- Four Orbiters (Odyssey, Express, MRO, Premier)
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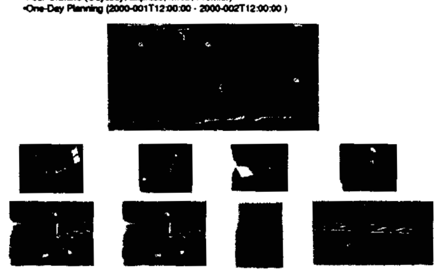

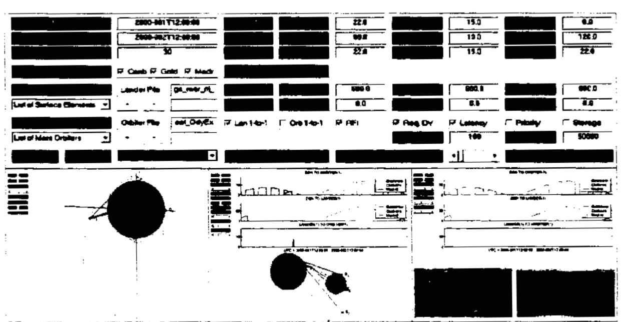

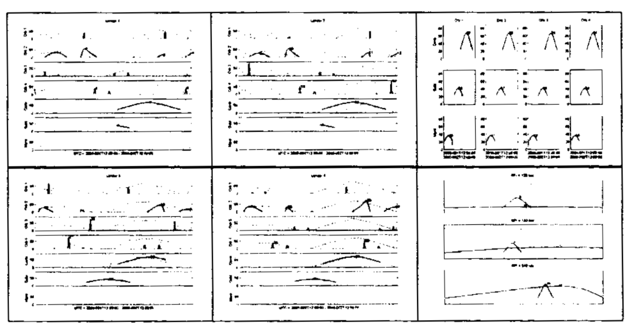

Summary:

Our work in achieving optimal planning and scheduling for the relay communication network include:

(i) Modeling and simulating the overall end-to-end network link capabilities as time-varying resources by incorporating spacecraft dynamics, telecom configurations and other limiting factors such as planet occultation, weather, etc.;

(ii) Developing mathematical formulations to describe the actual operational constraints such as lander's local Sun angle restriction, time for acquisition and calibration, lander and orbiter one-to-one communication, return science data volume requirement, onboard storage capacity, network latency, radio frequency interference, mission priority, etc;

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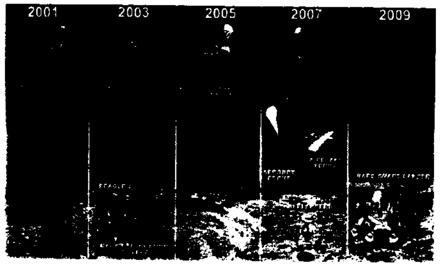

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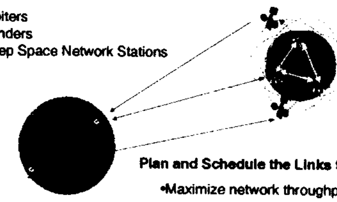

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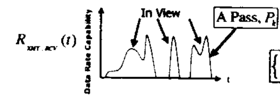

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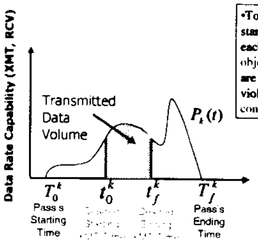

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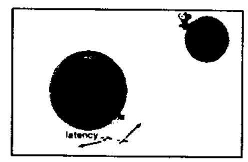

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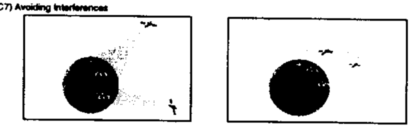

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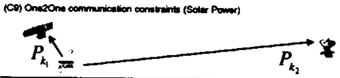

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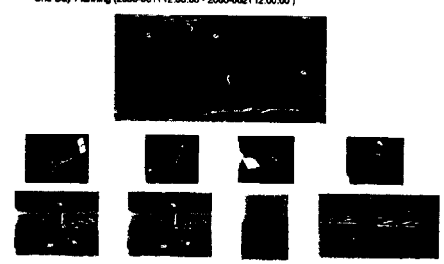

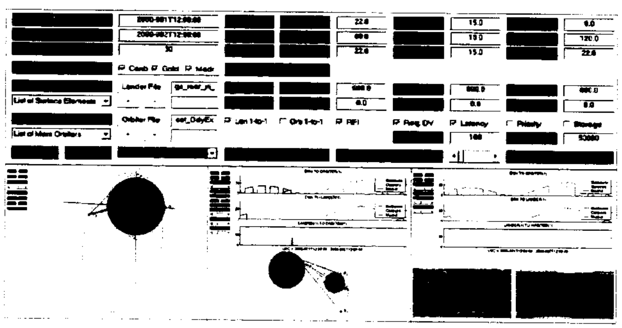

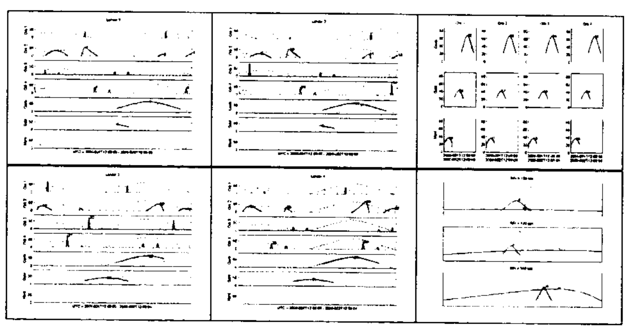

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