Mixed Integer Programming & Heuristic Scheduling for Space Communication Networks

Kar-Ming Cheung & Charles H. Lee
Jet Propulsion Laboratory
California Institute of Technology

2012 IEEE Aerospace Conference
Big Sky, Montana

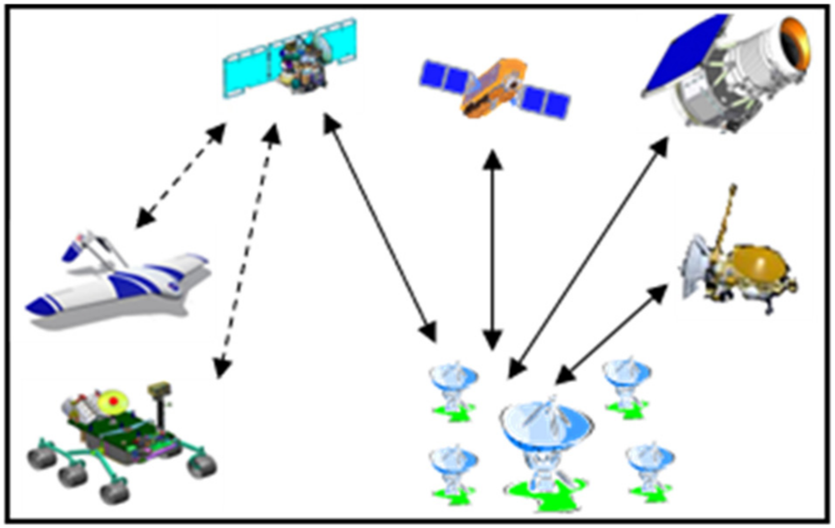
This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The research was supported by JPL's Research and Technology Development program.

Agenda

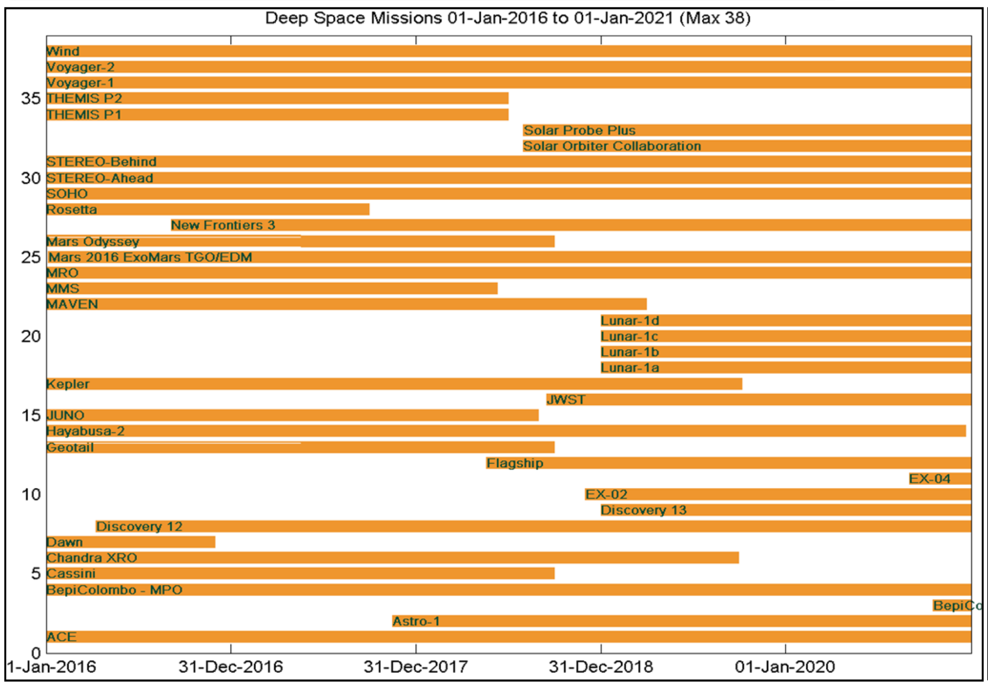
- **NETWORK MISSION SUPPORT**
- **NETWORK PLANNING APPROACH**
- **NETWORK OPTIMIZATION PROBLEM SETUP**
- **HEURISTIC OPTIMIZATION SCHEMES**
- **OPTIMAL COMMUNICATION SCENARIOS**
- **SUMMARY**

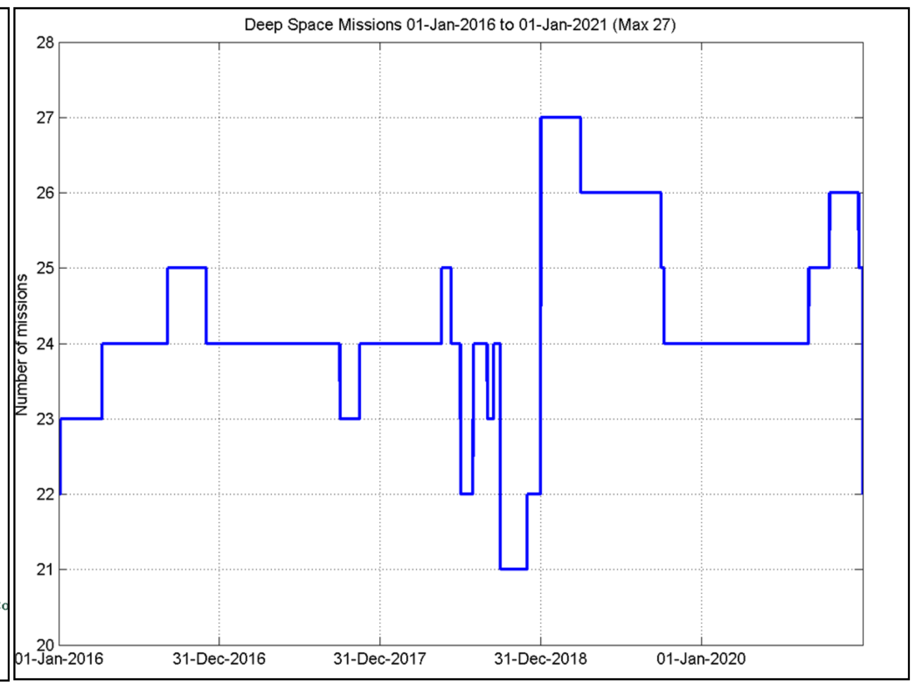
Sample DSN Support Timeline

(2016-2021)

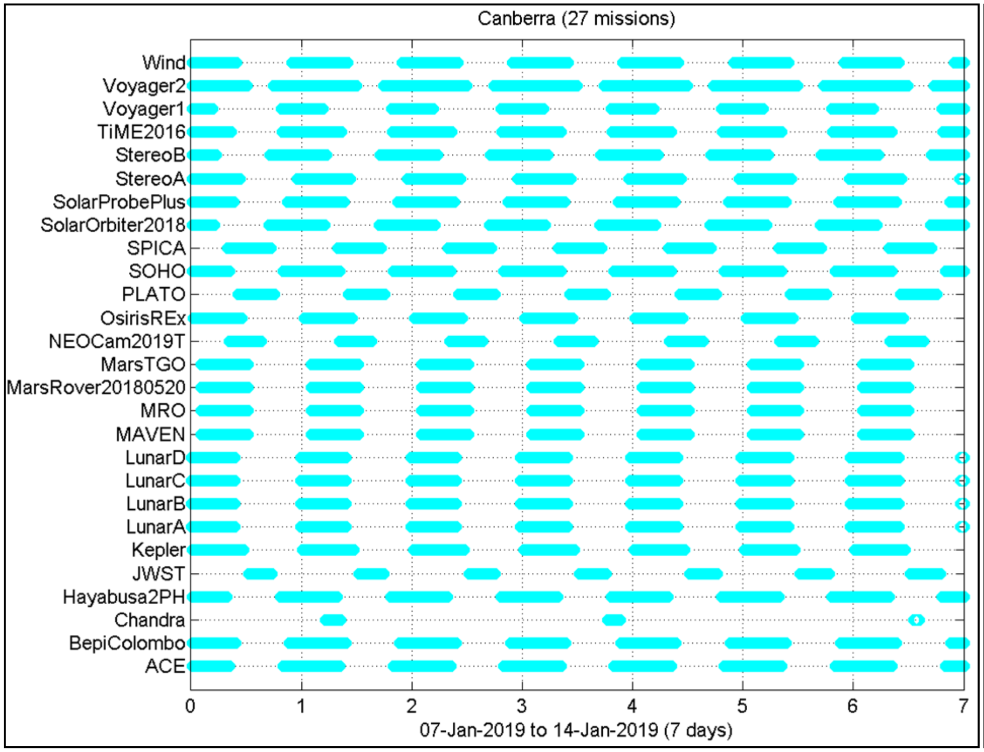


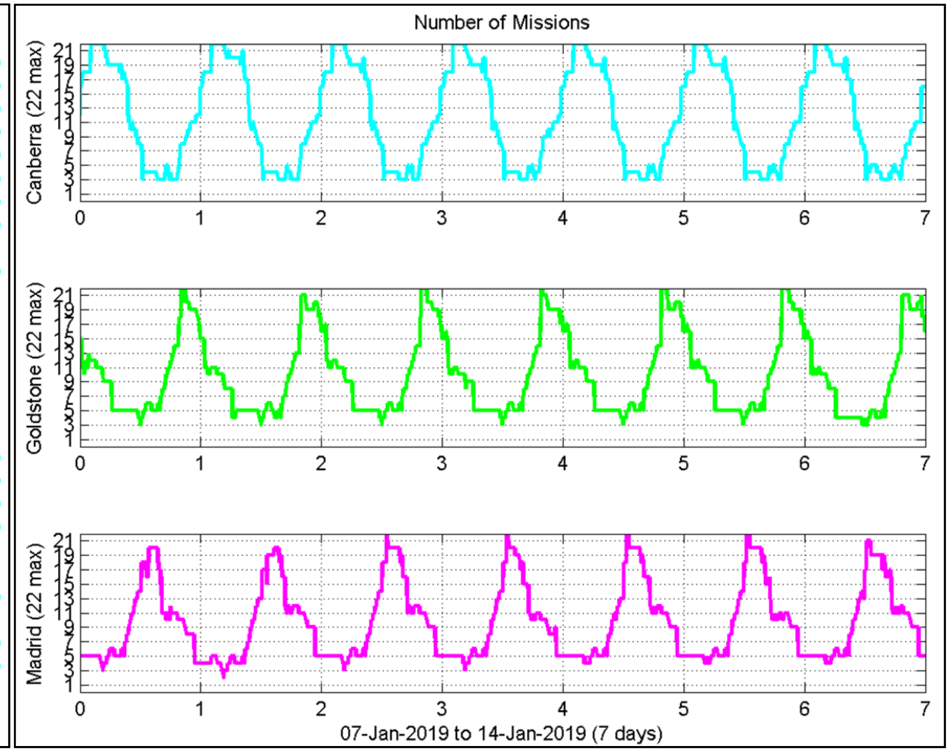
- Deep Space Network
(DSN Primary sites @ Canberra, Goldstone, and Madrid)
- Deep Space Missions (S, X, Ka Bands)
- Planetary Surface Assets (UHF Relay, X-Band DTE)
- Planned missions for the time period
- Different phases, activities, criticalities, priorities
- Multiple-body missions
- Peaked period @ beginning of 2019 (27 missions)
- This is where we focus our scheduling attention





Network Supportability



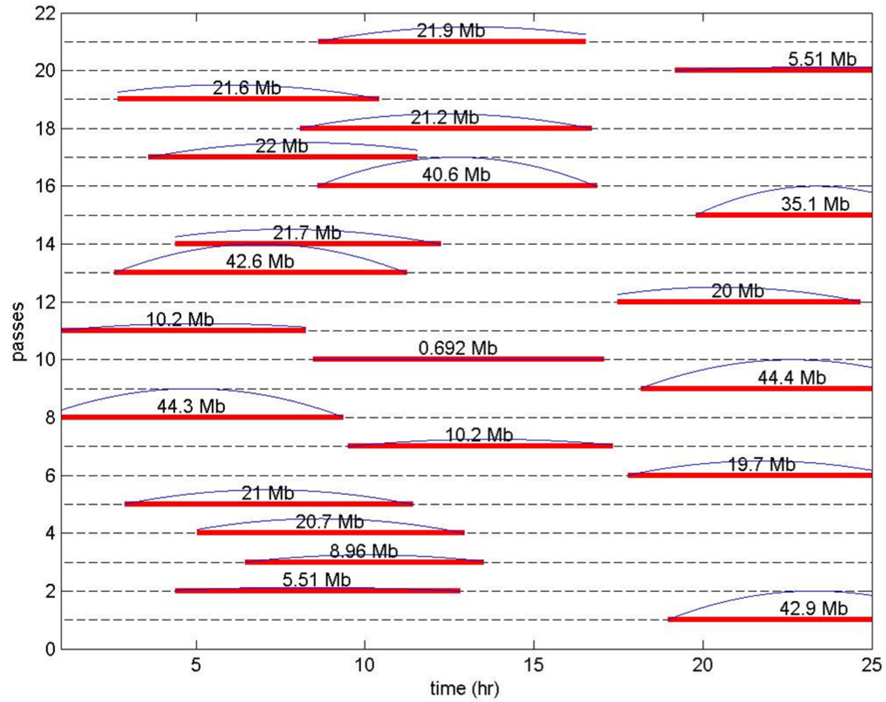


- ➢Not all 27 missions are supported at once
- ➢Missions names are in the vertical axis
- ➢View periods with the missions at Canberra are shown
- ➢Near-Earth missions are shorter (JWST & Chandra)
- ➢Most missions are in view 8-12 hours per day
- ➢Cumulative mission supports at DSN sites are also shown (Max=21)

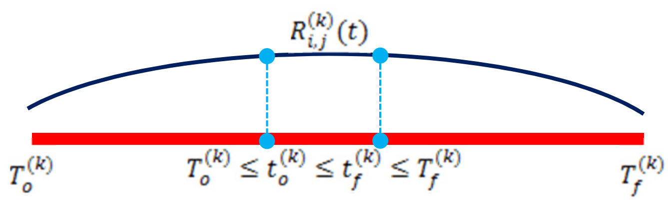
Network Planning Approach

- Consider as Constrained Optimization Problem
- Problem formulations take into account actual spacecraft trajectories, telecom link performances, and missions operation requirements.
- Pair-wise communication link performances between the ground stations of the network and the spacecraft are computed a priori.
- Communications between any 2 nodes within communication network could be momentarily disconnected and at times bursting.
- When connected, the start and end times are optimally scheduled so that
    - Data throughput within the network is maximal
    - Network tracking time is minimal
    - Data latency is minimal
    - Mission operation and requirements are satisfied

Network Optimization Problem Setup

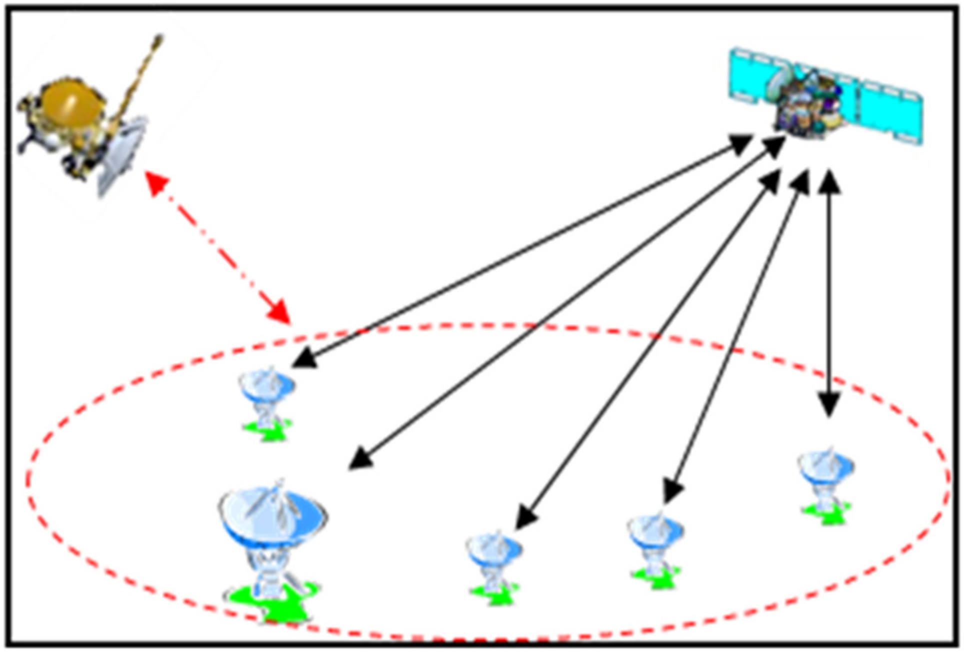


Spacecrafts	Ground Stations	Passes
$1 \leq i \leq N_{sc}$	$1 \leq j \leq N_{gs}$	$1 \leq k \leq N_p$



What are the start and end times?

Mixed Integer Programming



Example: One spacecraft is in view with a DSN site with Ngs stations. The search space for that spacecraft and that pass is 2Ngs. If antenna arraying is considered, then the search space $2(2^{Ngs}-1)$. If Mixed Integer Programming is considered, the search space becomes just 3 (ground station, start time, end time).

Constrained MIP Problem

Search space variables

$$\vec{x} = [\vec{x}^{(k)}]_{k=1}^{N_p}$$

$$\vec{x}^{(k)} = \left[\; gs^{(k)}, \quad t_o^{(k)}, \quad t_f^{(k)} \;\right]^T$$

$$gs^{(k)} \in \{1, 2, \dots, N_{gs}\}$$

Ground Stations

$$T_o^{(k)} \le t_o^{(k)} \le t_f^{(k)} \le T_f^{(k)}$$

$$1 \le k \le N_p$$

Passes

So that it maximizes

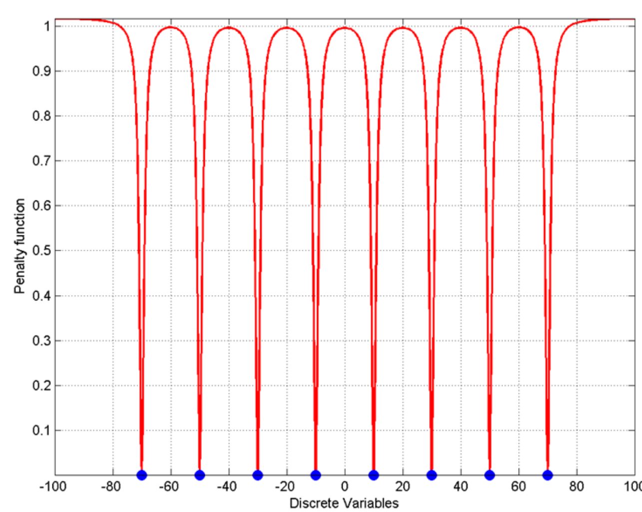
$$J(\vec{x}) = \sum_{k=1}^{N_p} DV(\vec{x}^{(k)})$$

Penalty Function

$$P(gs^{(k)}) = \prod_{j=1}^{N_{gs}} \frac{\left(gs^{(k)} - j\right)^2}{\left(gs^{(k)} - j\right)^2 + 1}$$

$$1 \le gs^{(k)} \le N_{gs}$$

$$J_\sigma(\vec{x}) = J(\vec{x}) + \sigma \sum_{k=1}^{N_{gs}} P(gs^{(k)})$$



Constraints

Communication in a view-period must happen within the view-period itself

$$T_0^{(k)} \le t_0^{(k)} \le t_f^{(k)} \le T_f^{(k)}$$

The ground station number is bounded by

$$1 \le gs^{(k)} \le N_{gs}$$

Each pass must be longer than a minimum pass length

$$t_f^{(k)} - t_0^{(k)} \ge T_{\min}$$

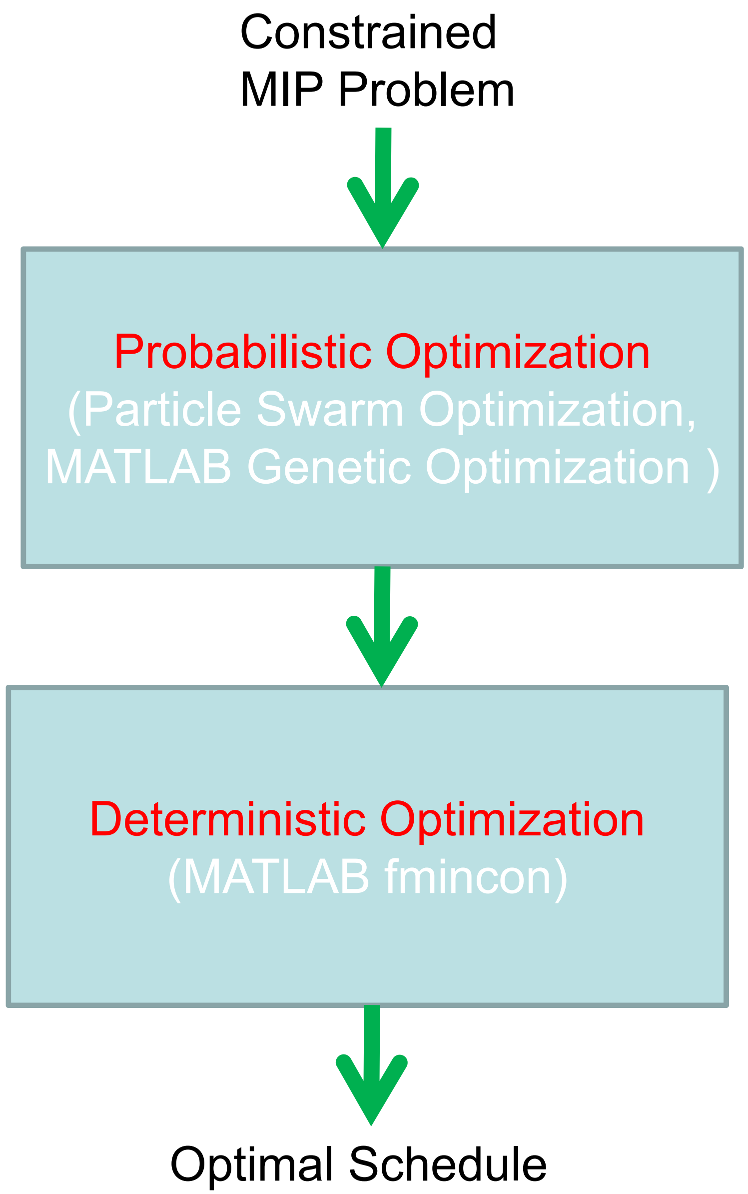
Transmission time cannot overlap

$$[t_0^{(k_1)}\ t_f^{(k_1)}] \cap [t_0^{(k_2)}\ t_f^{(k_2)}] = \varphi$$

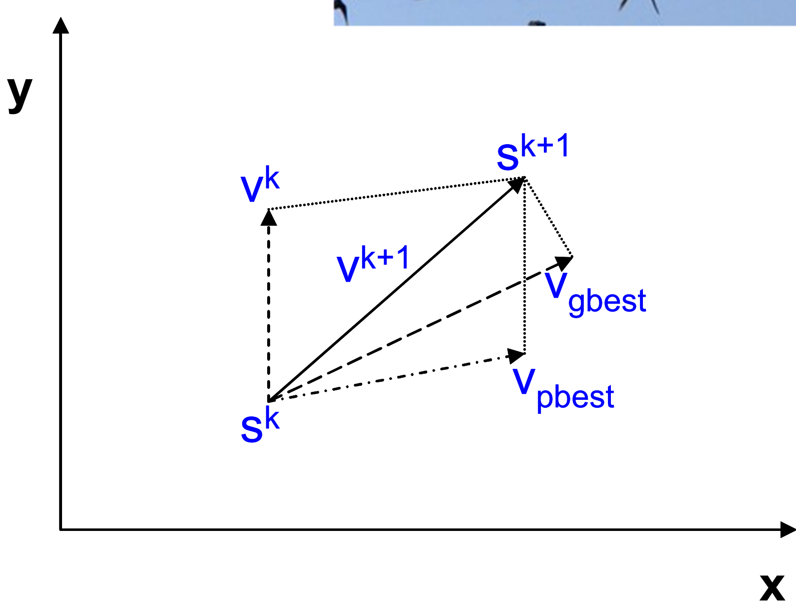
Minimum Required Data Throughput

$$\sum_{\substack{k=1 \\ sc^{(k)}=i}}^{N_p} DV(\vec{x}^{(k)}) \ge DV_{req}^{(i)}$$

Heuristic Scheduling



Particle Swarm Optimization(PSO) Concept



s^k : current searching point

s^{k+1}: next searching point

v^k: current velocity

v^{k+1}: modified velocity

v_{pbest} : velocity based on personal best

v_{gbest} : velocity based on global best

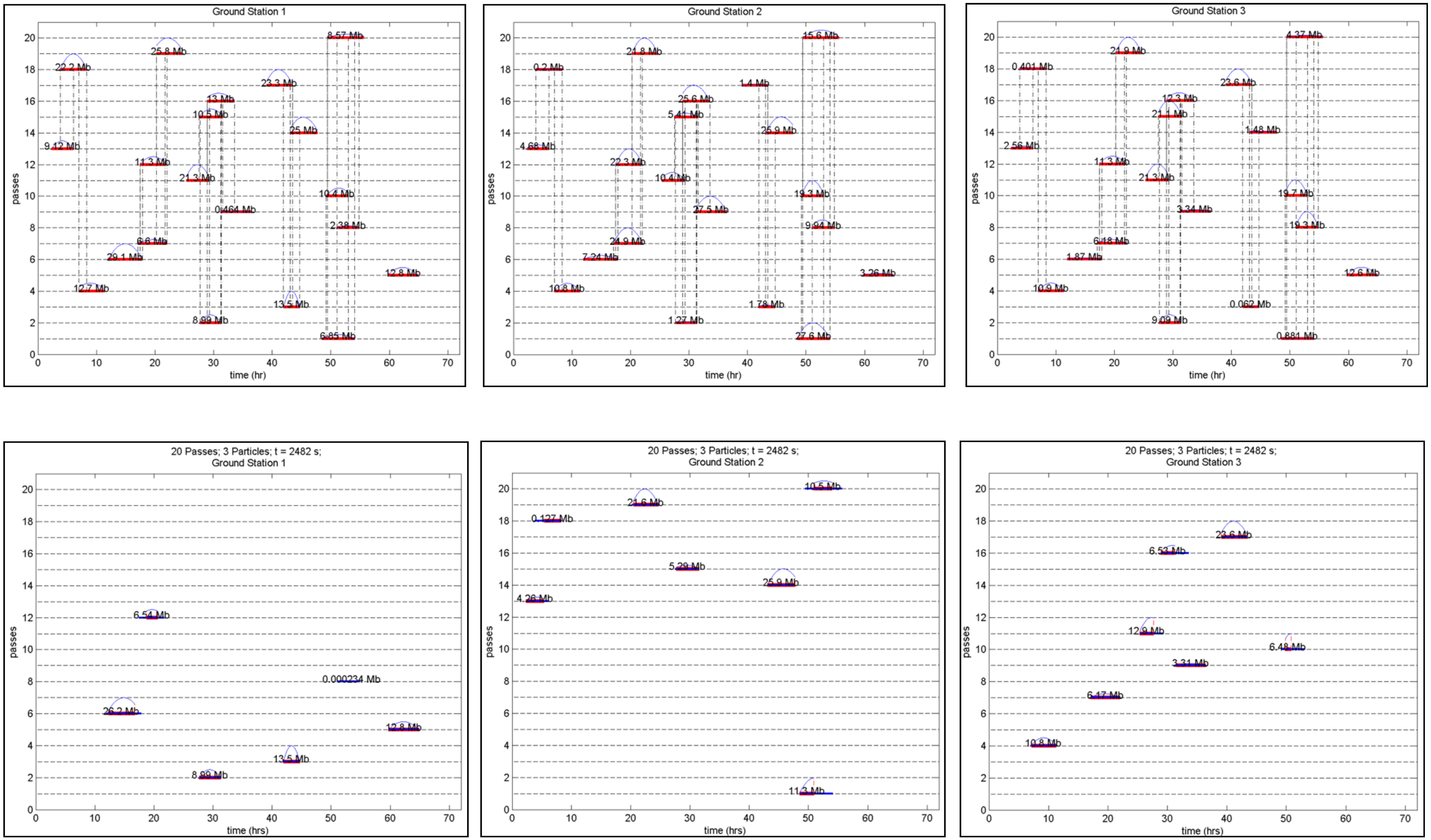
Optimal Communication Scenarios Proof-of-Concept

❖A network of 20 spacecraft with one DSN site (containing 3 ground stations)
❖Max data throughputs
❖Constraints considered are:

(i) the achieved network data throughput is maximized,
(ii) the individual mission data volume requirements are met,
(iii) each ground station supports one spacecraft at any one time (non-overlapping pass),
(iv) each pass must be sufficiently long to ensure efficient usage of a ground station, and
(v) each pass must start and end within its bounds.

❖The dimension for the search space is 60 in this scenario.
❖There are 20 linear bounds, 60 upper bounds, 60 low bounds, and 23 nonlinear constraints (3 non-overlapping and 20 mission data volume).
❖200 randomly generated particle elements.
❖The process for both PSO and FMINCON with 200 iterations takes about 2482 seconds.

Network Communication Optimization



Summary

✓We developed framework and the mathematical formulation for optimizing communication network using mixed integer programming. The design yields a system that is much smaller, in search space size, when compared to the earlier approach.

✓Our constrained network optimization takes into account the dynamics of link performance within the network along with mission and operation requirements.

✓A unique penalty function is introduced to transform the mixed integer programming into the more manageable problem of searching in a continuous space.

✓The constrained optimization problem was proposed to solve in two stages: first using the heuristic Particle Swarming Optimization algorithm to get a good initial starting point, and then feeding the result into the Sequential Quadratic Programming algorithm to achieve the final optimal schedule.

✓We demonstrate the above planning and scheduling methodology with a scenario of 20 spacecraft and 3 ground stations of a Deep Space Network site.

✓Our approach and framework have been simple and flexible so that problems with larger number of constraints and network can be easily adapted and solved.