Optimal Download Scheduling for Satellite Missions

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Outline

Goal of the project: Develop a model for quickly and optimally scheduling downloads of a multi-satellite, multi-ground station system.

- Description of the problem
- Optimization model
- Computational experiments and results
- Conclusions and future research
- Introduction of stochastic variations

Small Satellites

Flock 1: 28 Dove Satellites launched on Feb 11th, 2014

Ground station antenna

1 - 50 kg Satellite Launches [1]	
Year:	**Approx. Launches Per Year:**
2006-2012	25
2013	92
2014	140 (estimated)

[1] Elizabeth Buchen and Dominic DePasquale. Nano/Microsatellite Market Assesment. SpaceWorks Enterprises, Inc. 2014

The Multi-Satellite, Multi-Ground Station Scheduling Problem (MMSP)

- **Scheduling data downloads** from a satellite constellation to a network of ground stations
- Objective is to **maximize the total amount of data downloaded**
- **Subject to**:
  - Energy Dynamics
  - Data Dynamics
  - Energy/Data Limitations
  - Unique Ground Stations:
    - Download Rate (bits/sec)
    - Download Cost (joules/bit)
    - Efficiency (percentage of download actually received)

The Multiple Satellite, Multiple Ground Station Scheduling Problem (MMSP)

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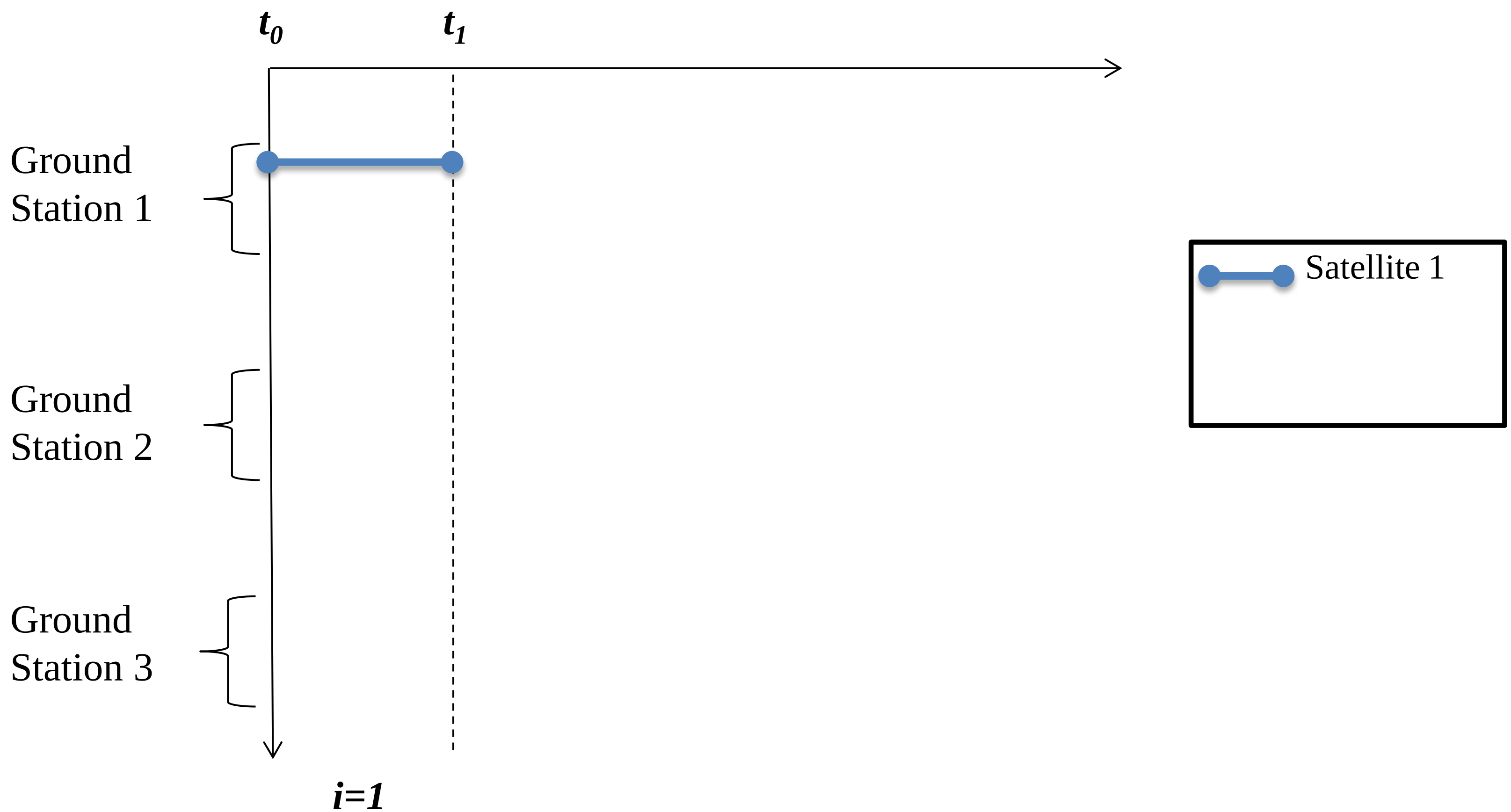

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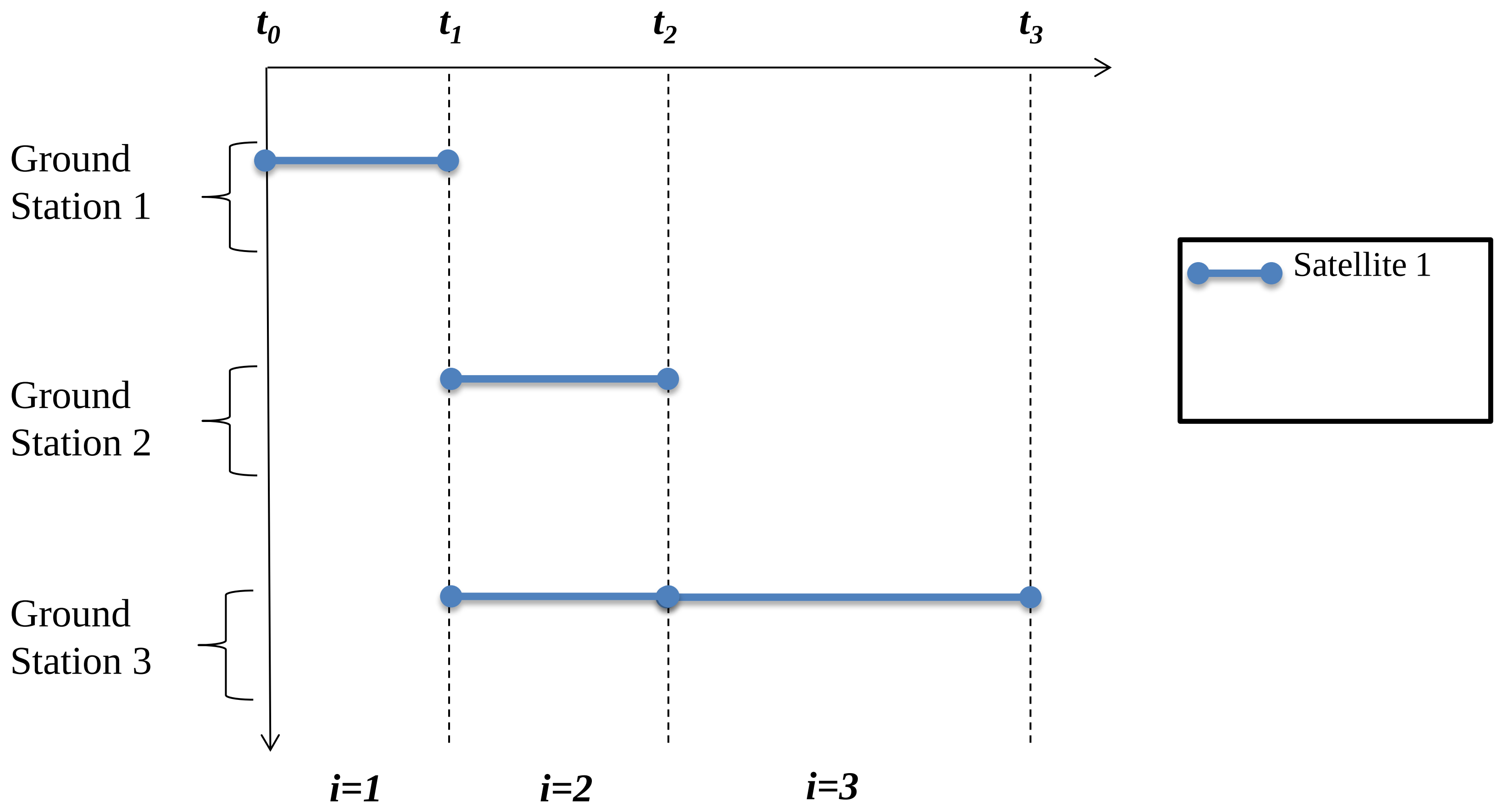

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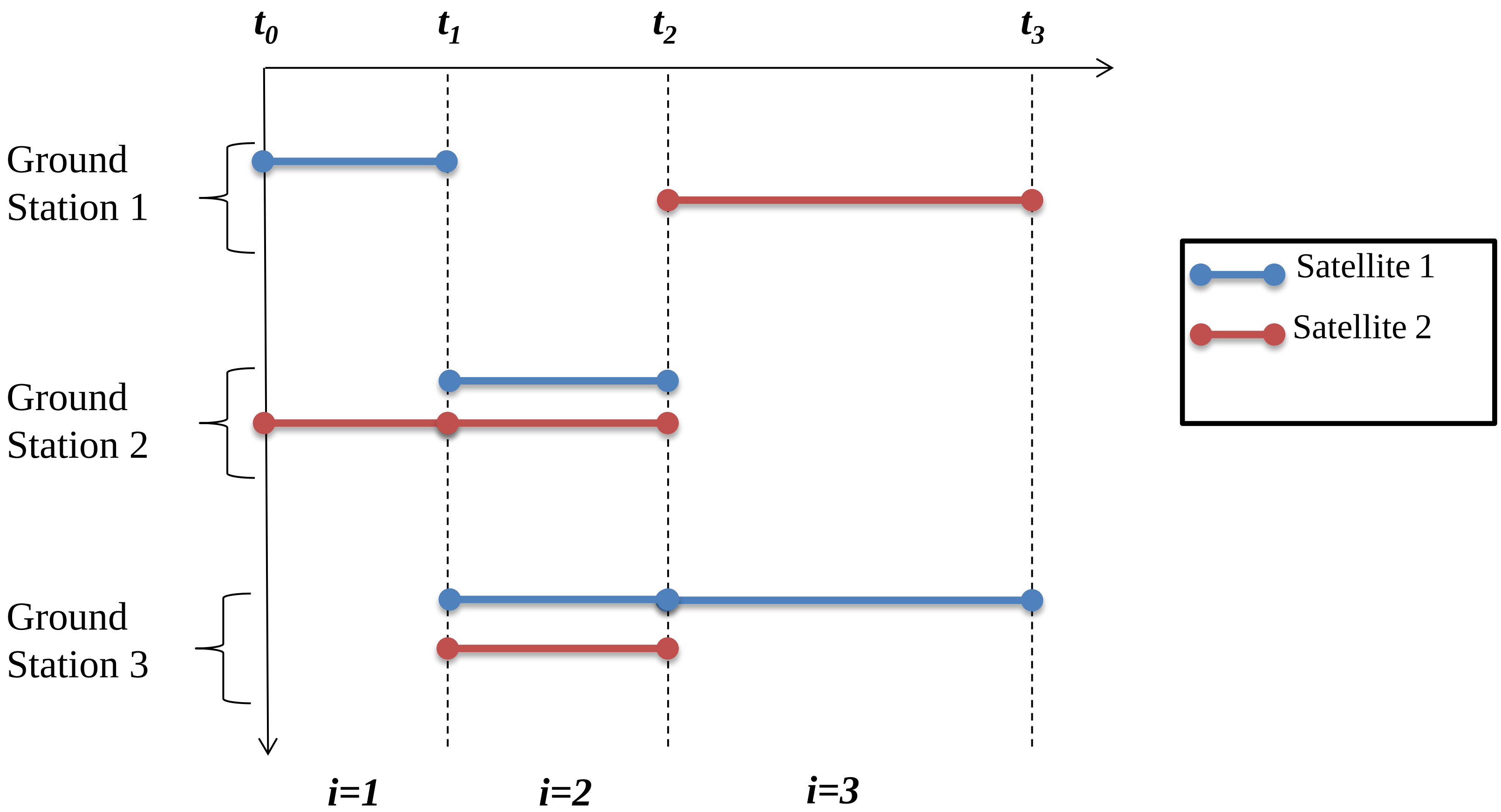

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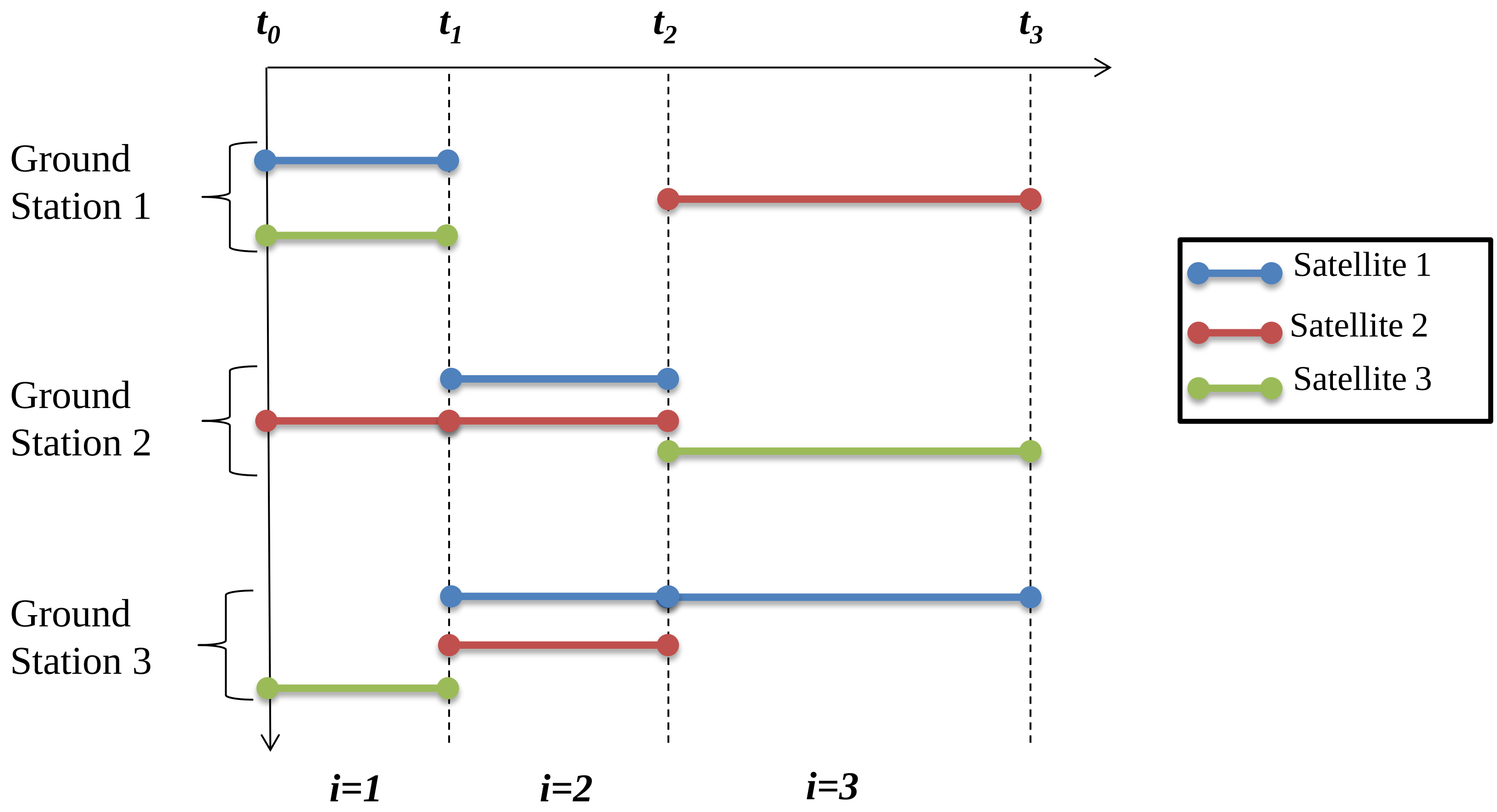

Model Assumptions

- Planning horizon is discretized into intervals corresponding to download opportunities
- Constant energy and data collection rates
- All parameters known in advance with certainty
- Each satellite can only download to one ground station at a time
- Each ground station can only receive information from one satellite at a time

Download Decisions

- x_{sig} – The percentage of interval i that satellite s downloads to ground station g
- q_{sig} – The amount of data downloaded from satellite s during interval i to ground station g

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Example Schedule

	Ground Station 1			
	Interval 1		Interval 2	
	x	**q**	**x**	**q**
Satellite 1	40%	2 Mb	0%	0 Mb

Download Decisions

- x_{sig} – The percentage of interval i that satellite s downloads to ground station g
- q_{sig} – The amount of data downloaded from satellite s during interval i to ground station g

Example Schedule

	Ground Station 1			
	Interval 1		Interval 2	
	x	***q***	***x***	***q***
Satellite 1	40%	2 Mb	0%	0 Mb
Satellite 2	60%	3 Mb	30%	1 Mb

$$\max \sum_{s \in S} \sum_{i \in I} \sum_{g \in G} \eta_{ig} q_{sig}$$

Objective: Maximize total download over the planning horizon

Parameters:

γ_{sig}: Indicator if in view during i
η_{ig}: Download efficiency (% received)
t_i: Duration of interval (sec)
ϕ_{ig}: Download rate (bits/sec)
α_{ig}: Download cost (joules/bit)
δ_{si}^{e}: net amount of energy acquired (joules)
δ_{si}^{d}: net amount of data acquired (bits)

Variables:

x_{sig}: Percent of interval used for download
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e_{si}: Energy available (joules)
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$$x_{sig} \le \gamma_{sig} \qquad \forall s \in S, i \in I, g \in G \qquad (1)$$

Can only download if satellite is in range of ground station

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Ground stations cannot receive data for more than 100% of each interval

Parameters:

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Satellites cannot transmit data for more than 100% of each interval

Parameters:

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η_{ig}: Download efficiency (% received)

t_i: Duration of interval (sec)

ϕ_{ig}: Download rate (bits/sec)

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δ_{si}^{e}: net amount of energy acquired (joules)

δ_{si}^{d}: net amount of data acquired (bits)

Variables:

x_{sig}: Percent of interval used for download

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Download amount is limited by length of interval and download rate

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Set the initial amount of energy available

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Satellites have energy storage limits that are enforced every interval

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$$e_{s,i+1} = e_{si} + \delta_{si}^{e} - \sum_{g \in G} \alpha_{ig} q_{sig} - h_{si}^{e} \quad \forall s \in S, i \in I \quad (7)$$

Energy available is based on previous energy + energy gained - energy used - any excess energy that must be spilled

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$$0 \le d_{si} \le d_{max} \quad \forall s \in S, i \in I \quad (9)$$

Each satellite has a maximum amount of energy it can store

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Variable limits for percent download

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$$0 \le x_{sig} \le 1 \quad \forall s \in S, i \in I, g \in G \quad (11)$$

$$q_{sig}, e_{si}, d_{si}, h^e_{si}, h^d_{si} \in \mathbb{R}^+ \quad \forall s \in S, i \in I, g \in G \quad (12)$$

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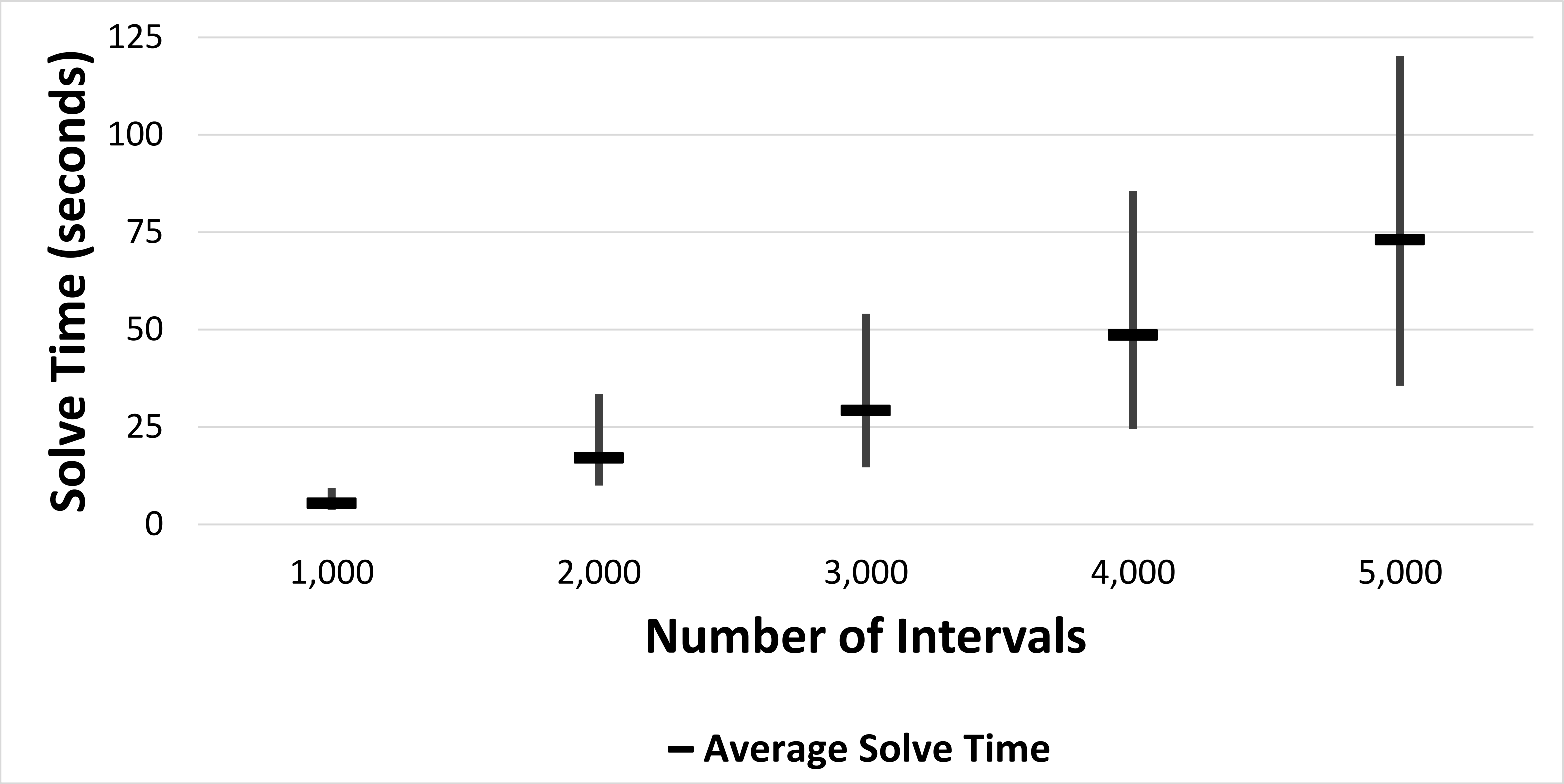
Generating Data for Testing

- 20 Satellites, 15 Ground Stations, 100 Intervals
- 25% chance of 0, 1, 2, or 3 ground stations in view of each satellite for each interval
  - Randomly select the specific ground stations in view
- Energy Gained, Data Gained, Efficiency of G.S., Data Rate, and Energy Cost from Normal Distribution
- For each test scenario, 50 random instances solved

Comparison Methods

- Greedy Heuristic
  - Divide each interval into many (200) pieces
  - For each piece (starting with the first):
    - Identify maximum possible download for each satellite
    - Schedule the maximum download
    - Repeat until no more feasible downloads
  - Repeat process for each interval
- Unrestricted Ground Stations
  - Use MMSP formulation, but allow ground stations to receive data from numerous satellites simultaneously
  - Example: Deep-Space Network (DSN)

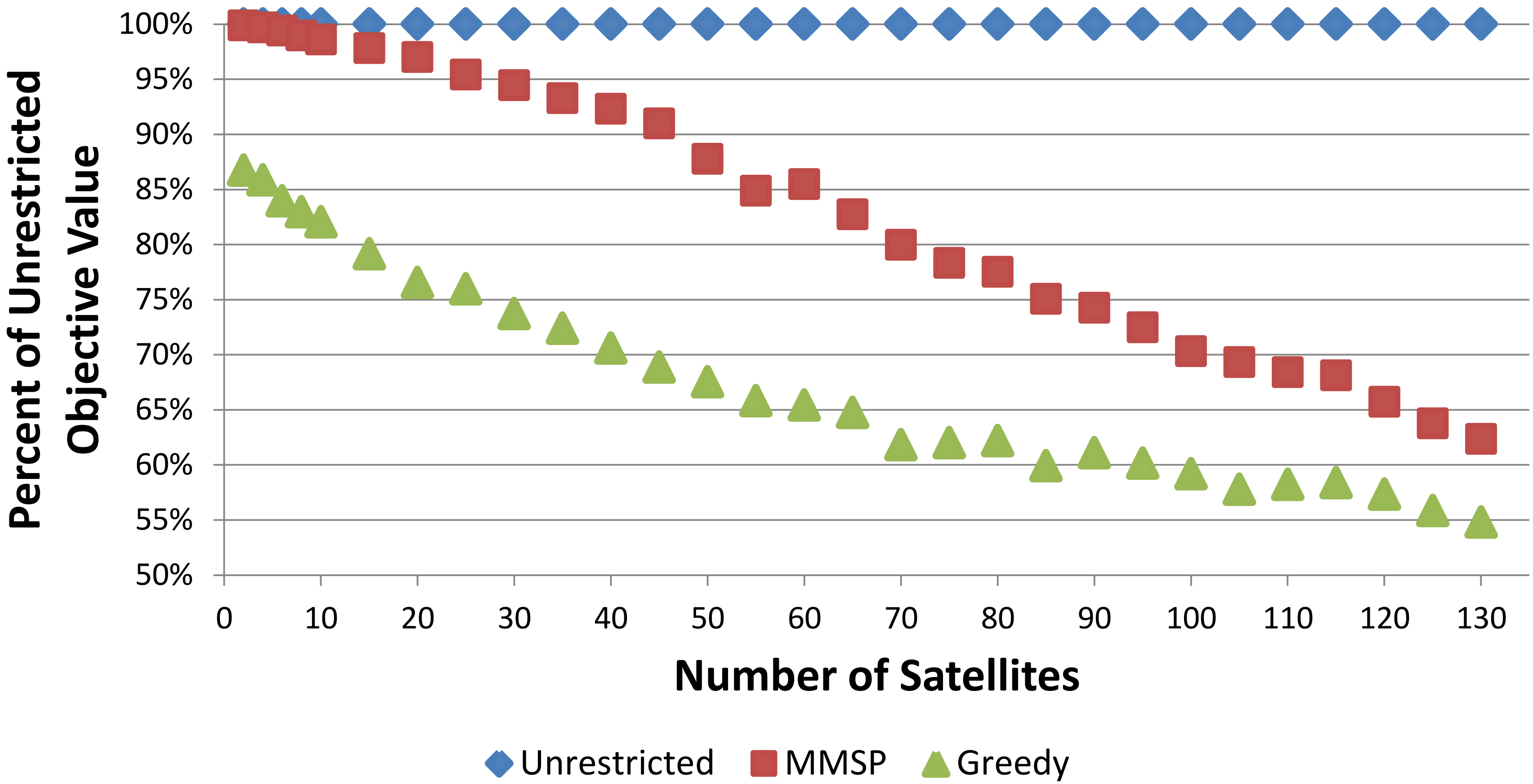
Min, Max, and Average Solve Times



- Programmed in C++ and solved with CPLEX 12.6
- CPU: Intel Xeon E3-1230 quad-core running at 3.20 GHz with hyper-threading and 32 GB of RAM.
- Unrestricted computational times are similar
- Greedy averages 10 sec with 5000 intervals and is less variable

Number of Satellites

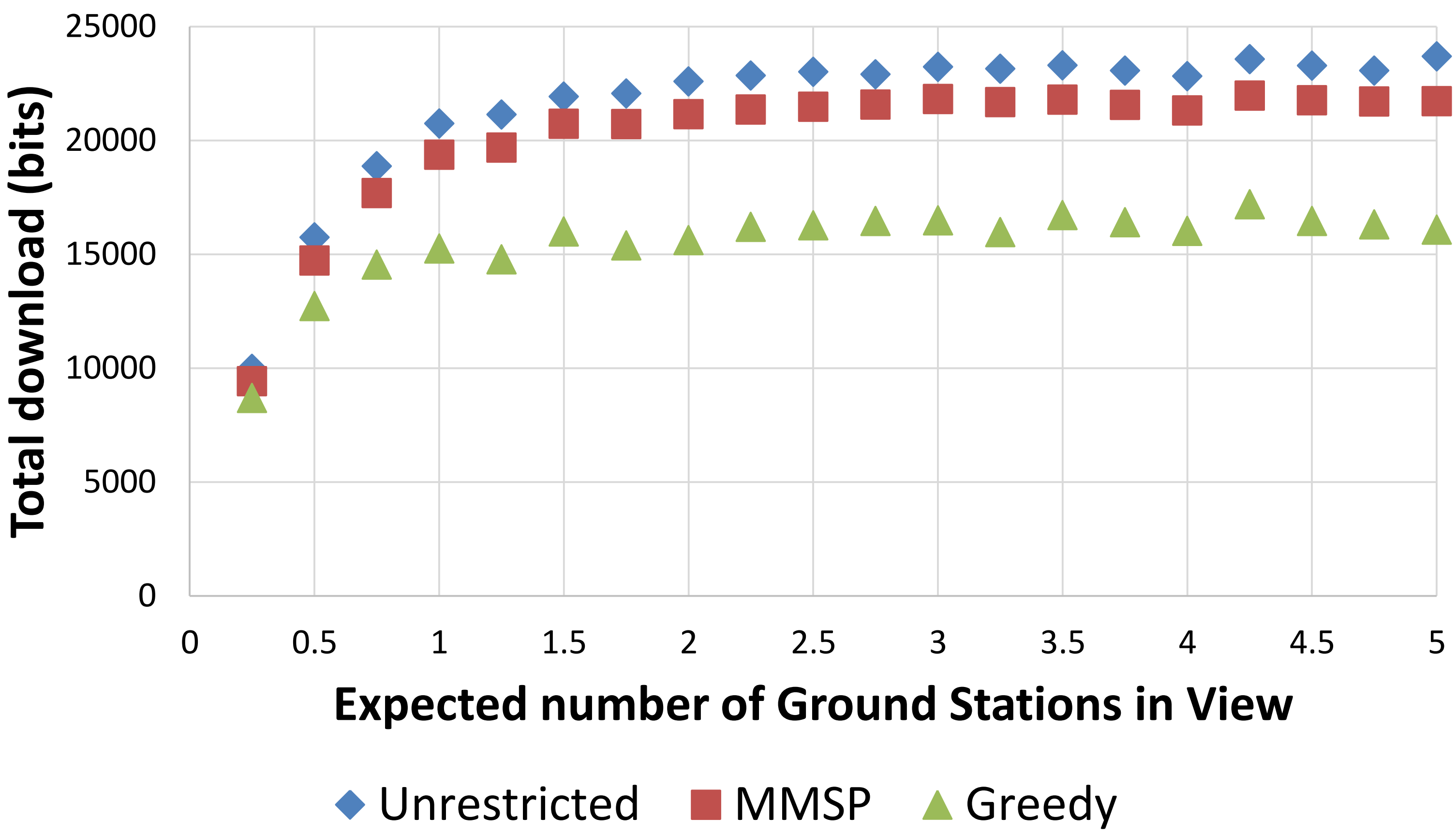
(with 20 ground stations)



1) **MMSP is less beneficial over Greedy in scenarios with very high congestion**
2) **Congested systems could benefit from more ground station capacity**

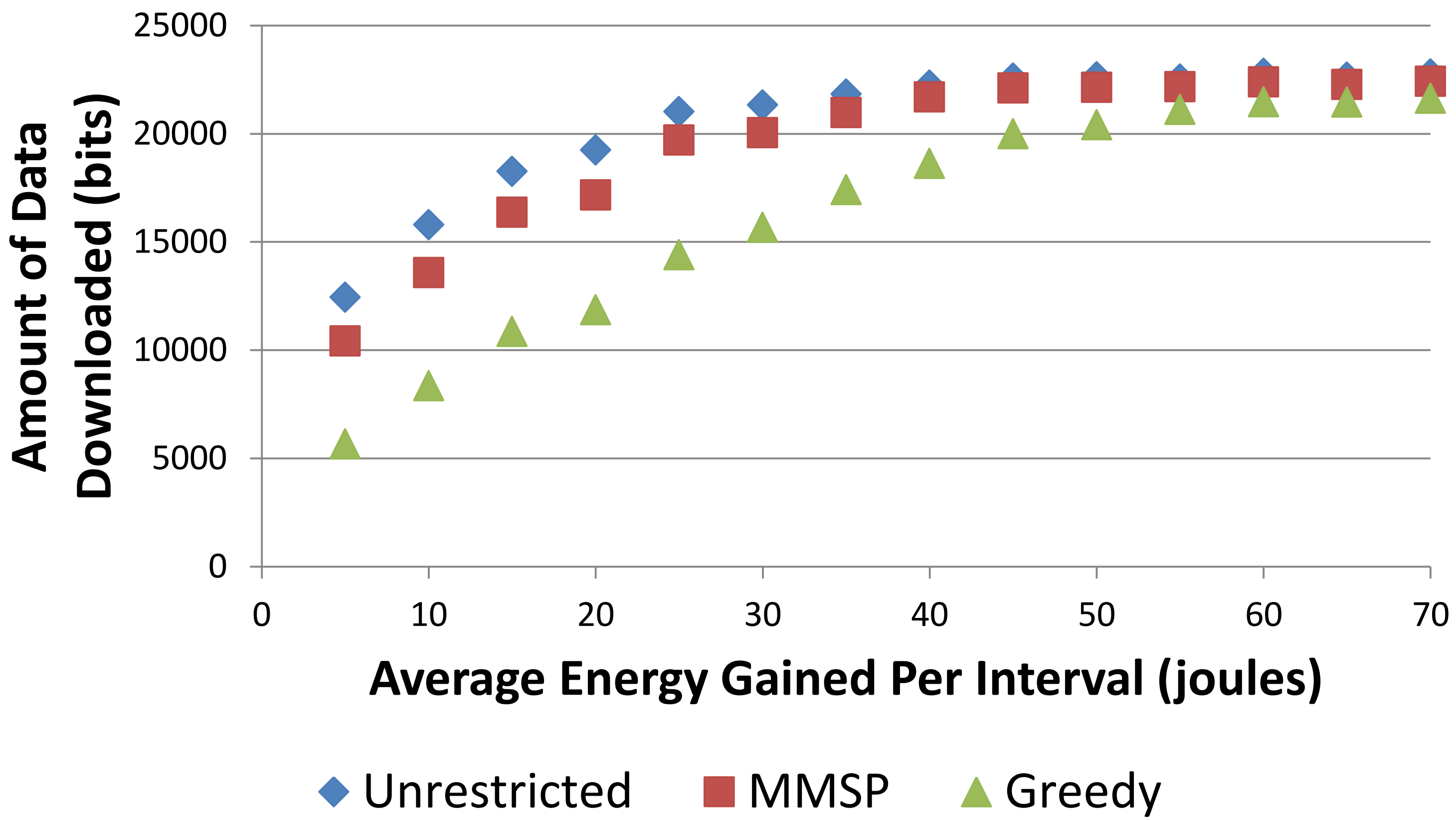
Ground Stations in View

(with 20 Satellites)



MMSP adds value when there are more conflicts

Energy Gained Per Interval



MMSP is most beneficial when energy is a limiting resource

MMSP Conclusions and Future Work

- Capable of quickly solving real problems with clear benefits over more traditional methods
  - Plan to use a real data set in the future
  - Can use as tool for sensitivity analysis for evaluating system capabilities and bottlenecks
- MMSP adds the most value in scenarios where it’s worth waiting for better download opportunities
- Future Work: Stochastic instances, prioritized downloads, fairness of downloads, web-based scheduler for public use

Stochastic Variations

- Sources of uncertainty:
  - Data and energy collection rates
  - Efficiency of the ground stations
  - Availability of ground stations
    - Bernoulli random variable:

$$x_{gi} = \begin{cases} 1 \text{ with probability } p_{gi} \\ 0 \text{ with probability } 1 - p_{gi} \end{cases}$$

- Rules of the game:
  - Allow Recourse? (adapt our decision during planning horizon?) *This requires communication with the satellite
  - Lose energy if ground station is not available?
  - Do we have a chance constraint? (e.g. The total amount downloaded must be greater than 50 Mb 90% of the time)

Thank You!

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