Enabling the Next Generation of Small Satellite Missions by Optimization of Communication Networks

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Communication is major constraint for small satellites!

Growing satellite community science missions

- Downloading large amounts of data limited by infrastructure.
- Small satellites are highly constrained by mass, size, power, cost, risk.

Limitations of existing ground station infrastructure

- Systems are complex, non-standardized, and have reliability issues.
- Existing systems are monolithic and designed for single missions.
- Existing ground stations are largely underutilized!

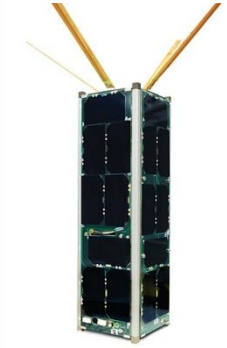
[1] J. Cutler, P. Linder, and A. Fox, "A Federated Ground Station Network," in SpaceOps Conference Proceedings, October 2002.
[2] QB50 von Karman Institute for Fuid Dynamics. www.vki.ac.be/QB50/project2.php, 2009.

Image Credit: Allison Craddock

How can we use federated ground networks to solve this problem?

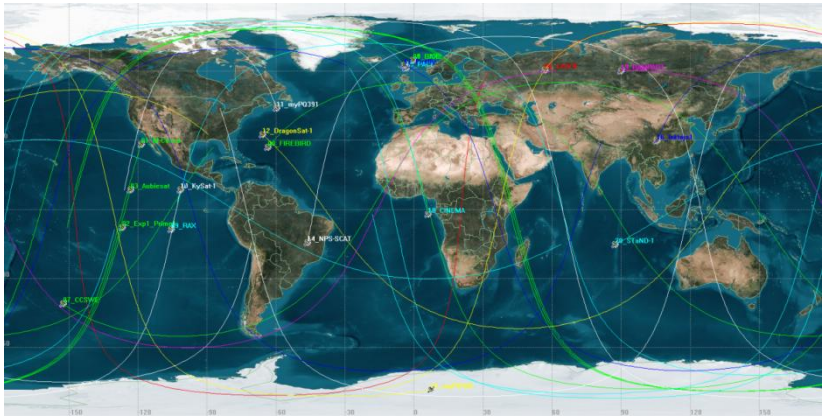
Proposed Solution:

Federated Ground Station Networks



Stages of problem:

1. Micro-scale: spacecraft dynamics
2. Macro-scale: satellites and ground station dynamics



Why is the FGSN scheduling problem hard?

1. Maximizing total/spacecraft network capacity
   Scientist: Get me more data!

2. Sharing of resources for multi-satellite constellations
   Satellite Operators: Share resources according to needs/priorities

3. Complex satellite dynamics
   Limited ability collect/store data/energy

4. Ground Station Networks:
   Limited capacity/capability

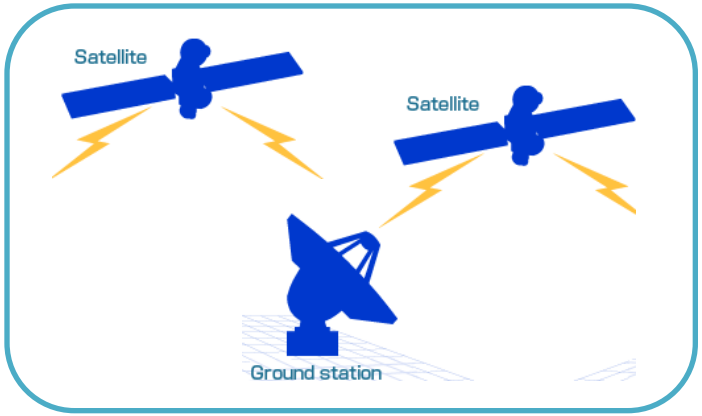


Image Credit: NEC Microwave Tube, Ltd.

So what ingredients are needed take advantage of FGSNs?

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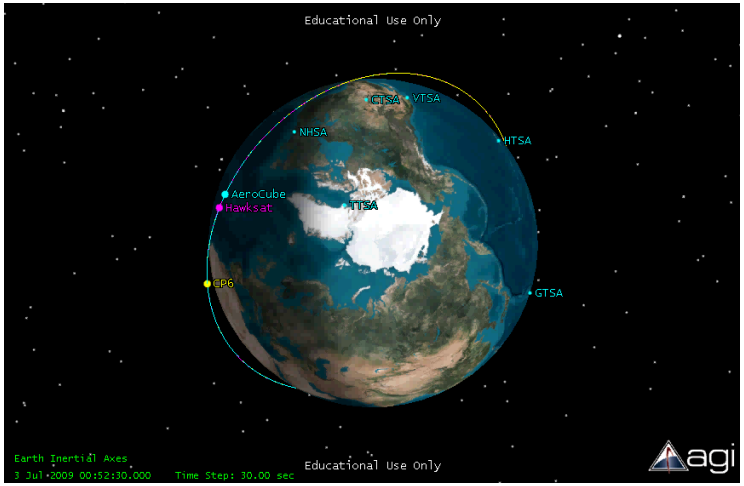
1) Ground Station Model
2) Satellite Model
3) Representative Data
4) Simulation Tools
5) Optimization Tools



1) We need a ground station model which captures diverse networks.

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Capacity: Amount of information exchanged across the network[1]

Effective Data Rate

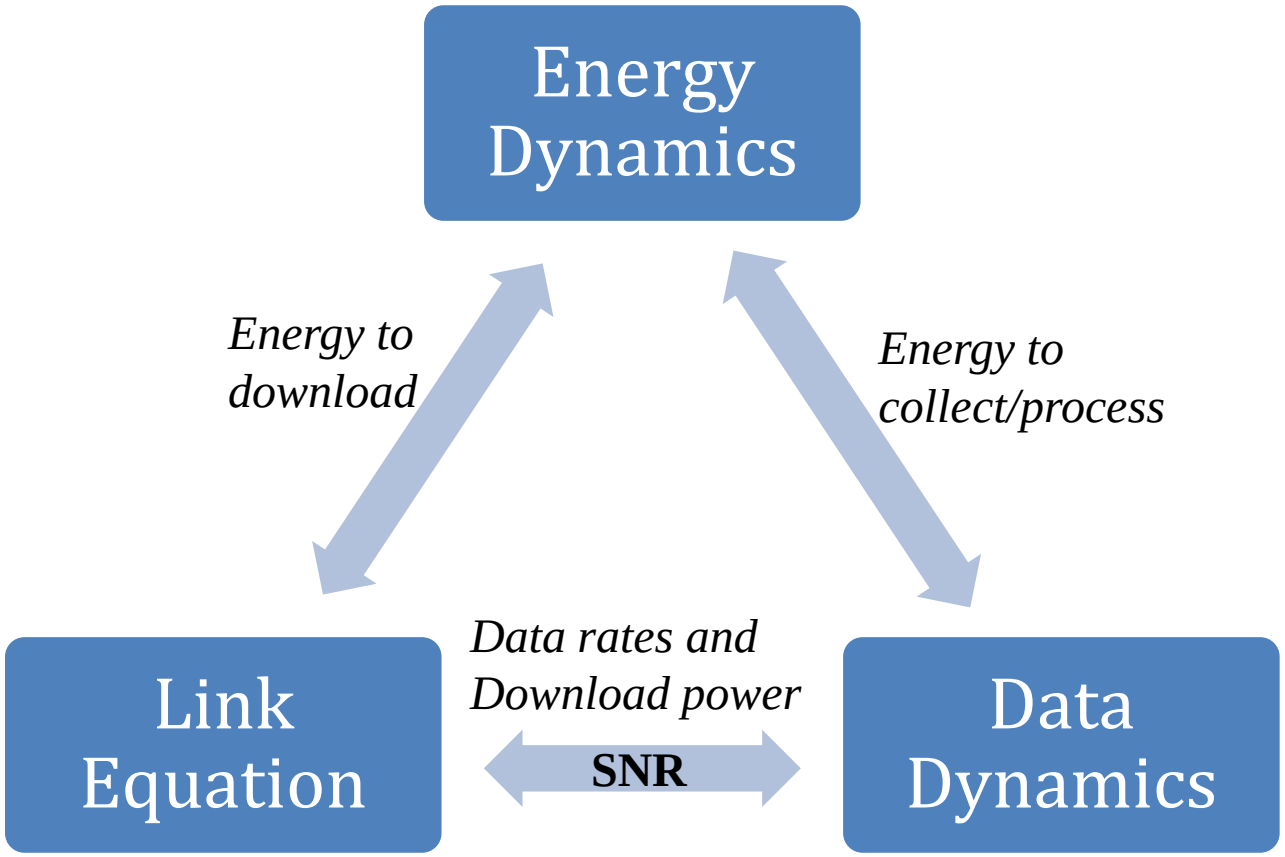
$$C_i = \sum_{j=1}^{m} \int_0^T a_{ij}(t)\ r_{ij}(t) l_{ij}(t) \eta_{ij}(t) dt$$

Availability Data rate Link feasibility Efficiency

i: satellite
j: ground station

[1]S. Spangelo, D. Boone, and J. Cutler. Assessing the Capacity of a Federated Ground Station Network. In IEEE Aerospace Conference Proceedings, March 2009

2) The satellite model needs to capture on-board dynamics.



3) Ground Station Survey has provided info on over 100 stations!

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Introduction
Modeling
Simulation
Optimization
Results
Conclusion

CubeSat Ground Station Community

Fill out the survey here: http://gs.engin.umich.edu/gs_survey/

3) Satellite Survey has provided info on over 15 satellites.

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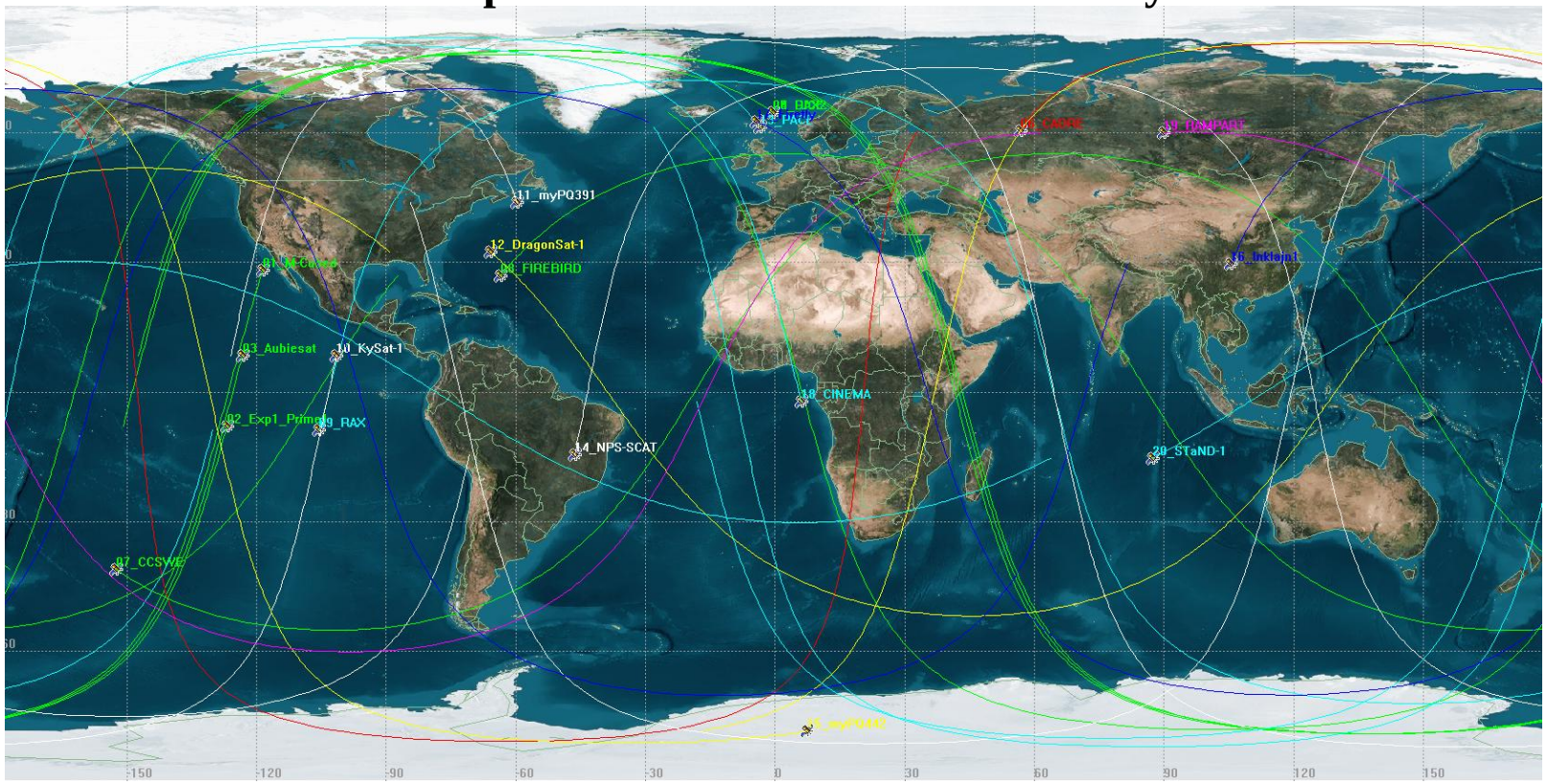
Representative Satellites from Survey



Estimated orbits based on survey results

Satellites from Survey: F-1, XSAS, Explorer-1 [Prime], FIREBIRD, KySat-1, DICE, myPocketQub,391, NPS-SCAT, Aalto-1, PACE, Trailblazer, RAMPART, STRaND-1, Draco/GragonSat-1, Inklajn1, CCSWE

Fill out the survey here: http://gs.engin.umich.edu/sat_survey/

3) Here are some interesting statistics on the satellite survey.

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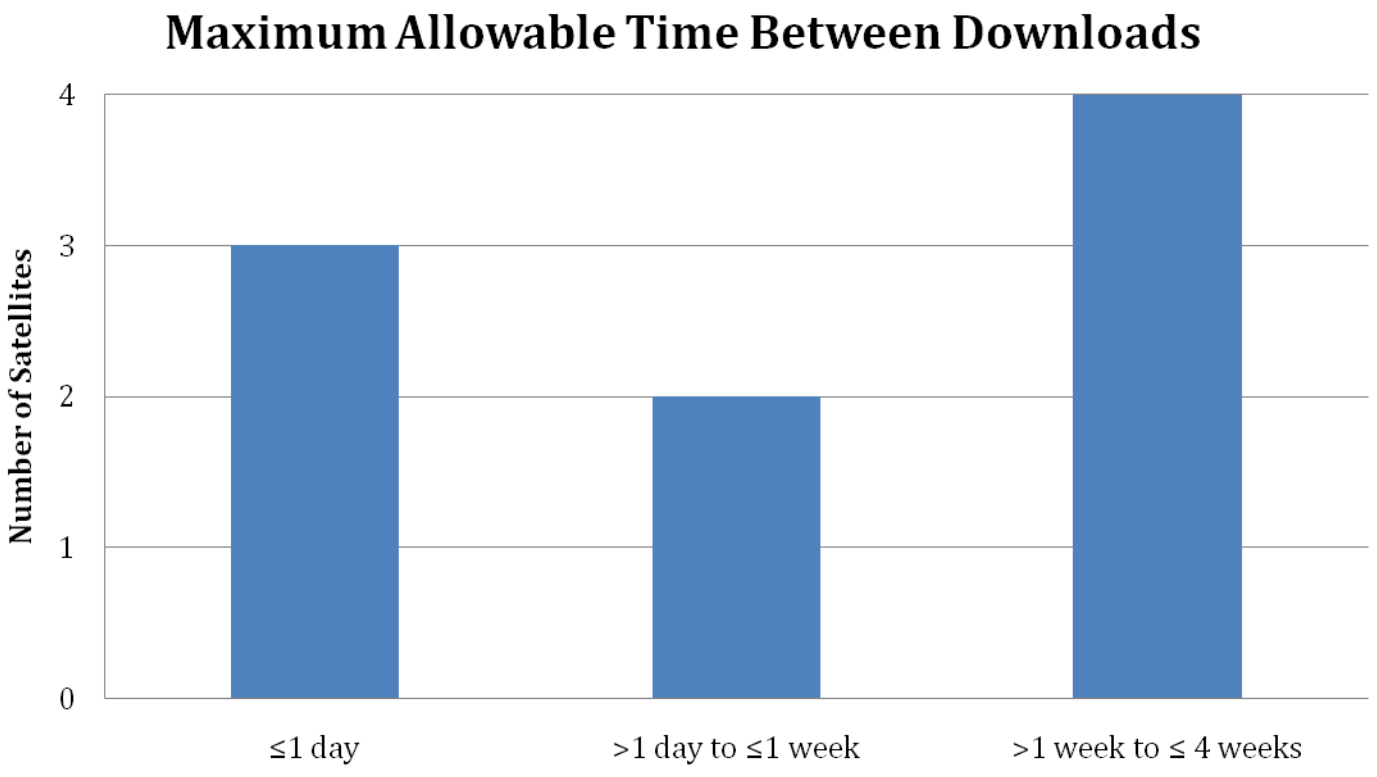
Introduction
Modeling
Simulation
Optimization
Results
Conclusion



Preliminary survey results

3) Here are some interesting statistics on the satellite survey.

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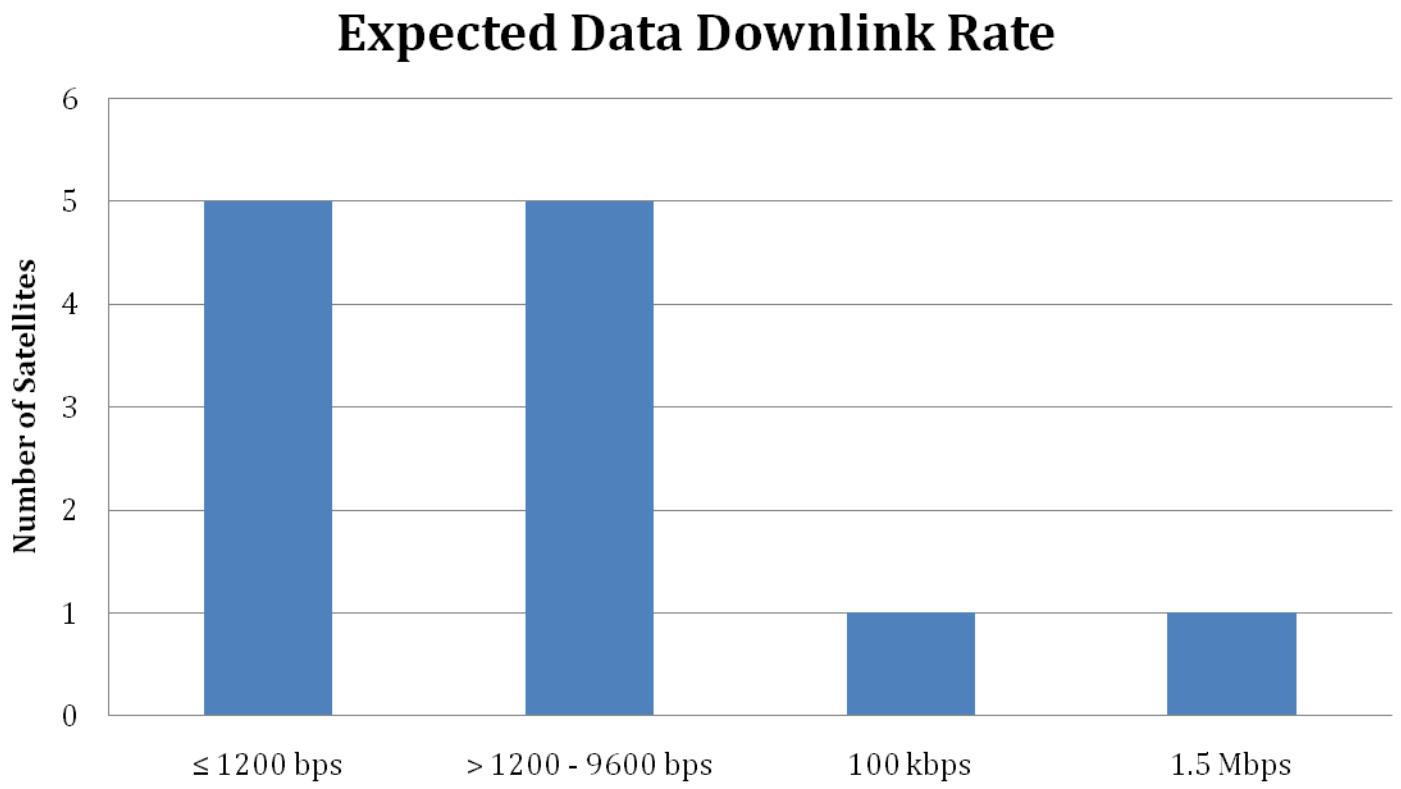
Introduction
Modeling
Simulation
Optimization
Results
Conclusion



Preliminary survey results

4) The simulator first identifies the inputs to the satellite scheduler.

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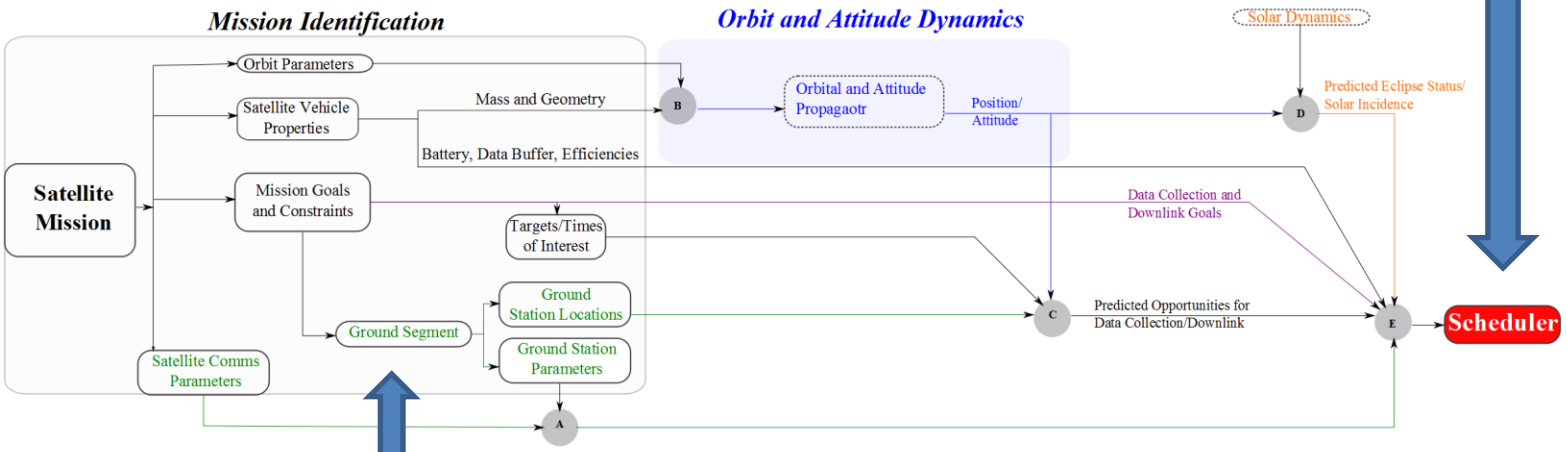
Satellite Survey

STK

Optimizers



Ground Station Survey

4) Next we model/simulate the on-board energy and data dynamics.

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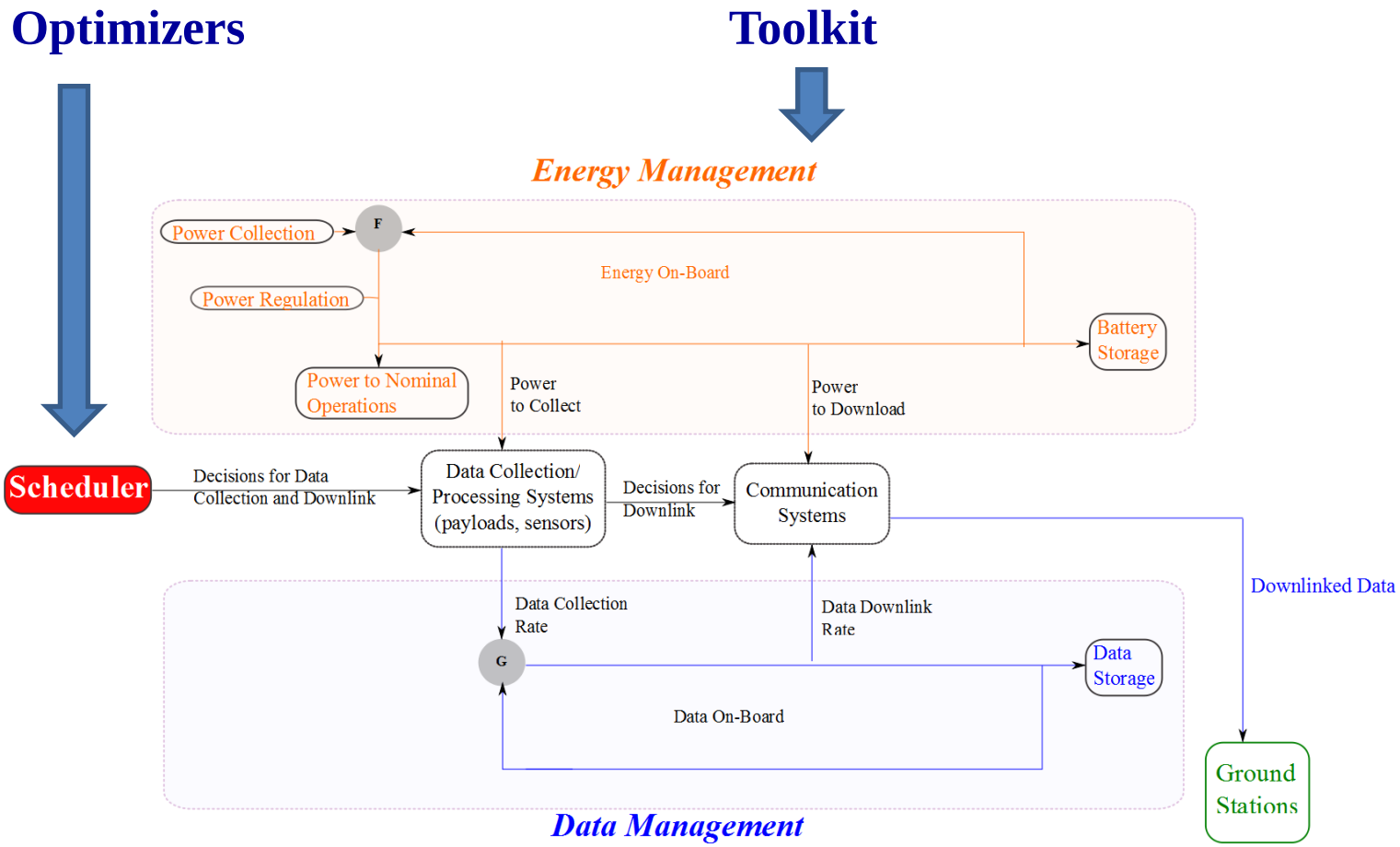

5) So what exactly are we optimizing?

Two goals in optimizing communication capacity:

1. Maximizing total network capacity
2. Sharing of resources for satellites

Decisions (for each satellite):

1. When/what ground stations?
2. What rate/amount to downlink

Constraints:

1. Satisfying minimum downlink requirements
2. Limited availability for communication
3. On-board satellite dynamics (data, energy)

Image Source: NSF Website

5) Don't forget about all those constraints…

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$$1 \geq \sum_{s \in s_i} x_{ij} \qquad \forall j \in J, i \in I_j,$$

$$1 \geq \sum_{j \in J_i} x_{ij} \qquad \forall s \in S, i \in I_s.$$

Only a single communication link

MACRO

$$q_{ij} \leq t_i \cdot r \cdot x_{ij} \qquad \forall s \in S, i \in I_s, j \in J_i$$

Data restricted by time/rate

$$e_{i+1} = e_i + \delta_i^e - \sum_{j \in J_i} \sum_{k \in K_j} \alpha_{jk} q_{ijk} - h_i,$$

Energy balance within bounds

$$b_{min} \leq e_i \leq b_{max},$$

$$d_{i+1} = d_i + \delta_i^d - \sum_{j \in J_i} \sum_{k \in K_j} q_{ijk} - f_i,$$

Data balance within bounds

$$0 \leq d_i \leq d_{max}.$$

$$e_{start} = e_{end}$$

Initial/final conditions

$$\delta_i^e = (p_{sol} - p_m - p_{pr}) t_i$$

Power difference

MICRO

So how big of a network do I need to support my mission?

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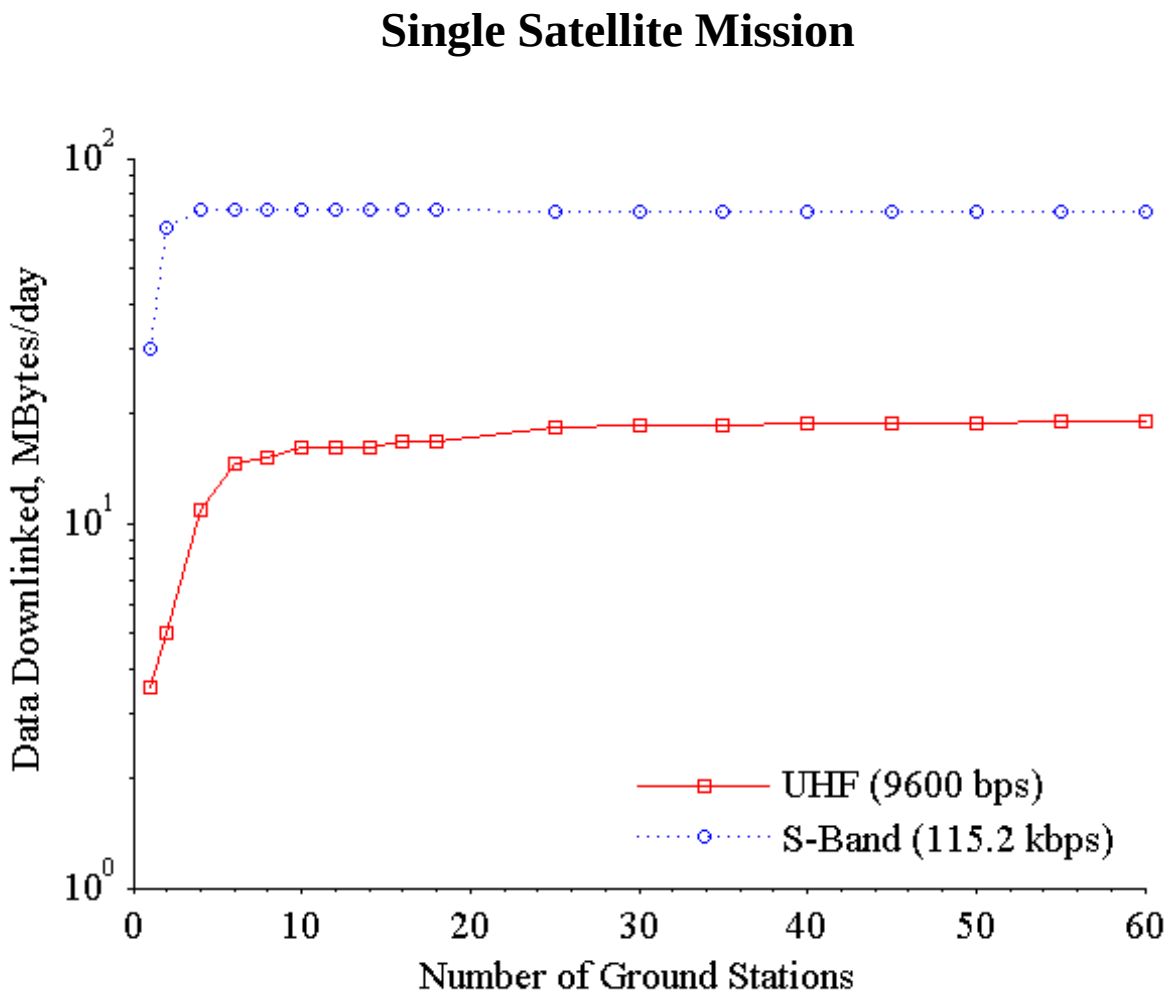

So how much power do I need to support my mission?

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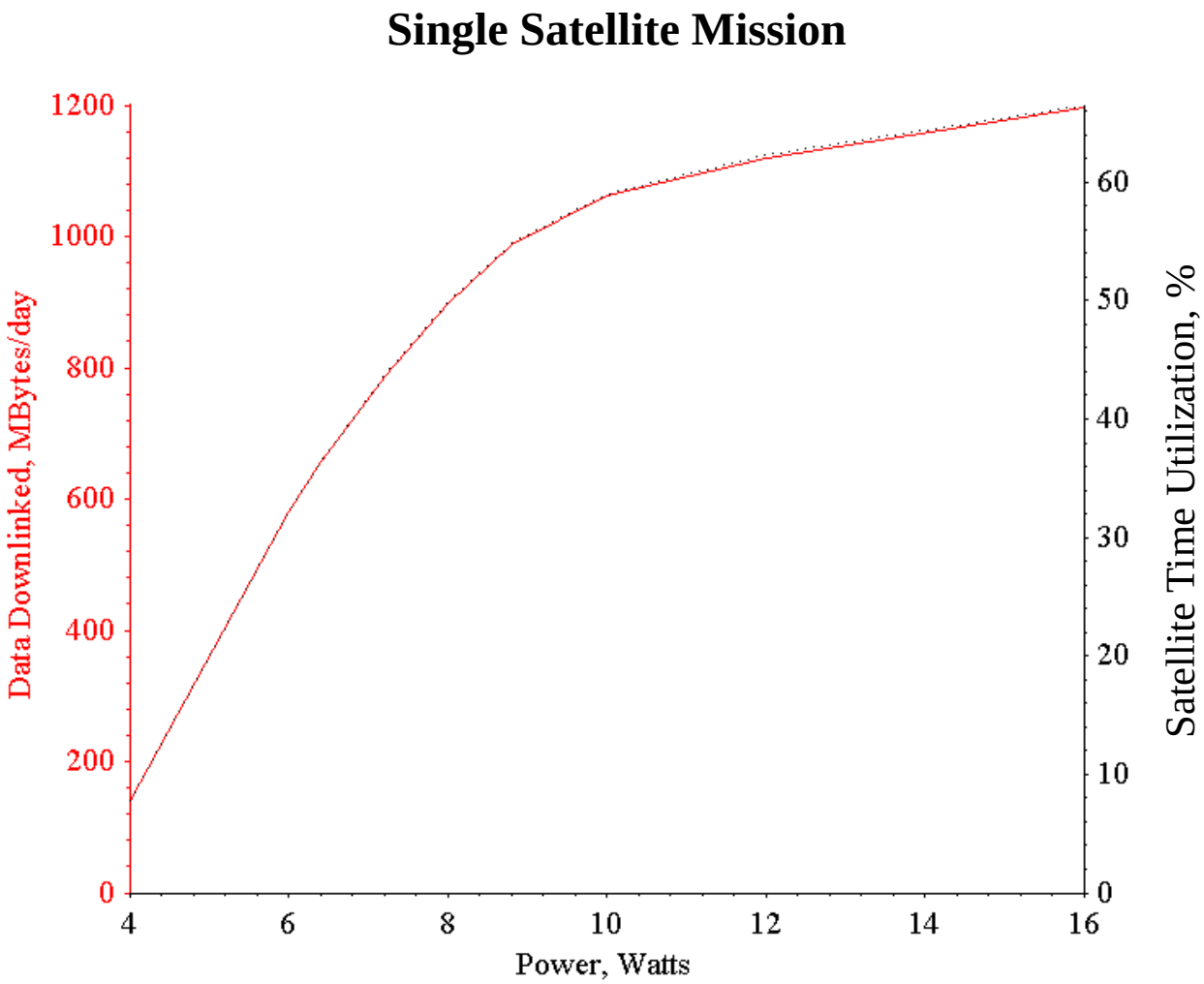
Introduction
Modeling
Simulation
Optimization
Results
Conclusion



10 Ground Station Network

Comparison of Requirements and Optimal Solutions

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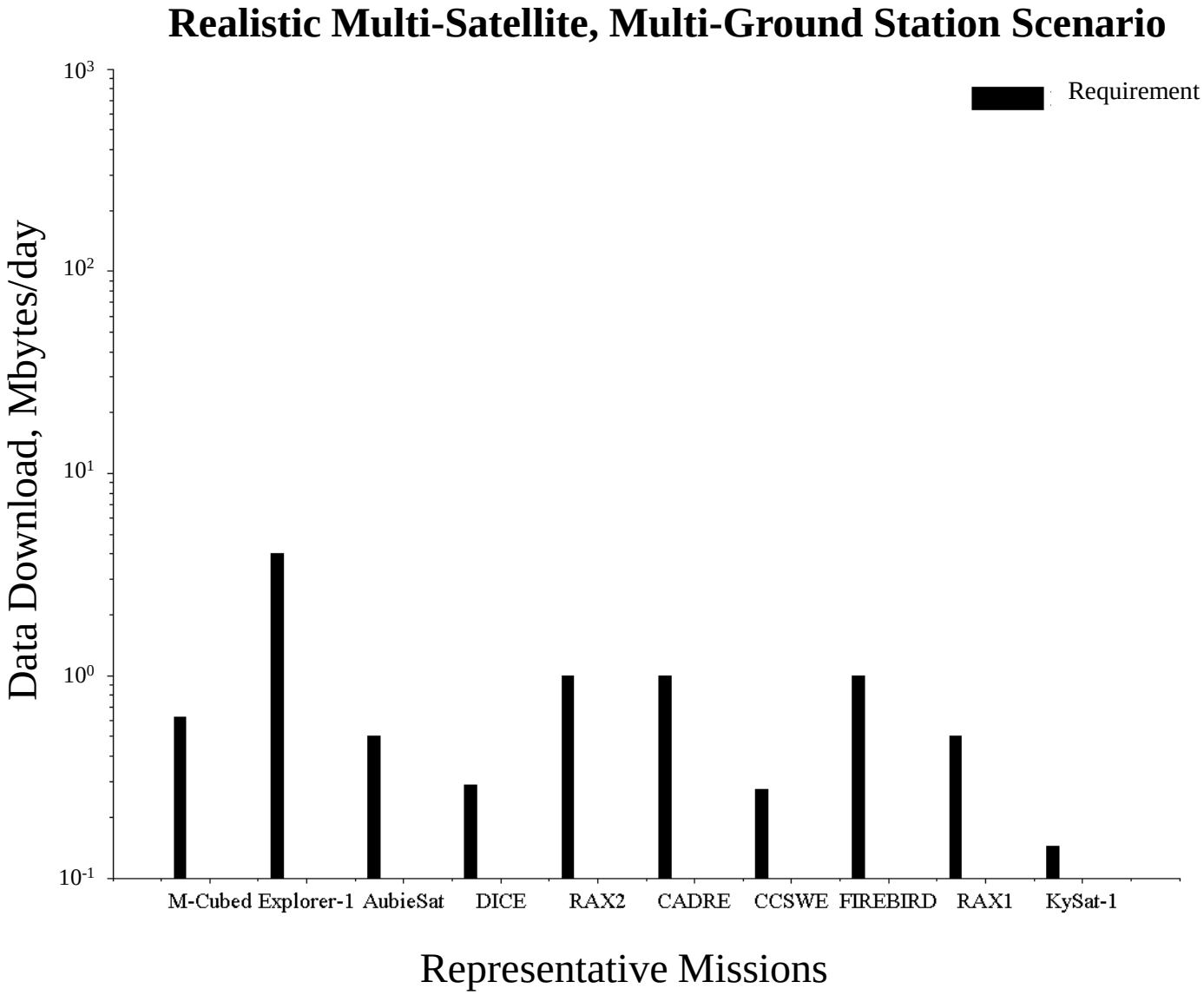
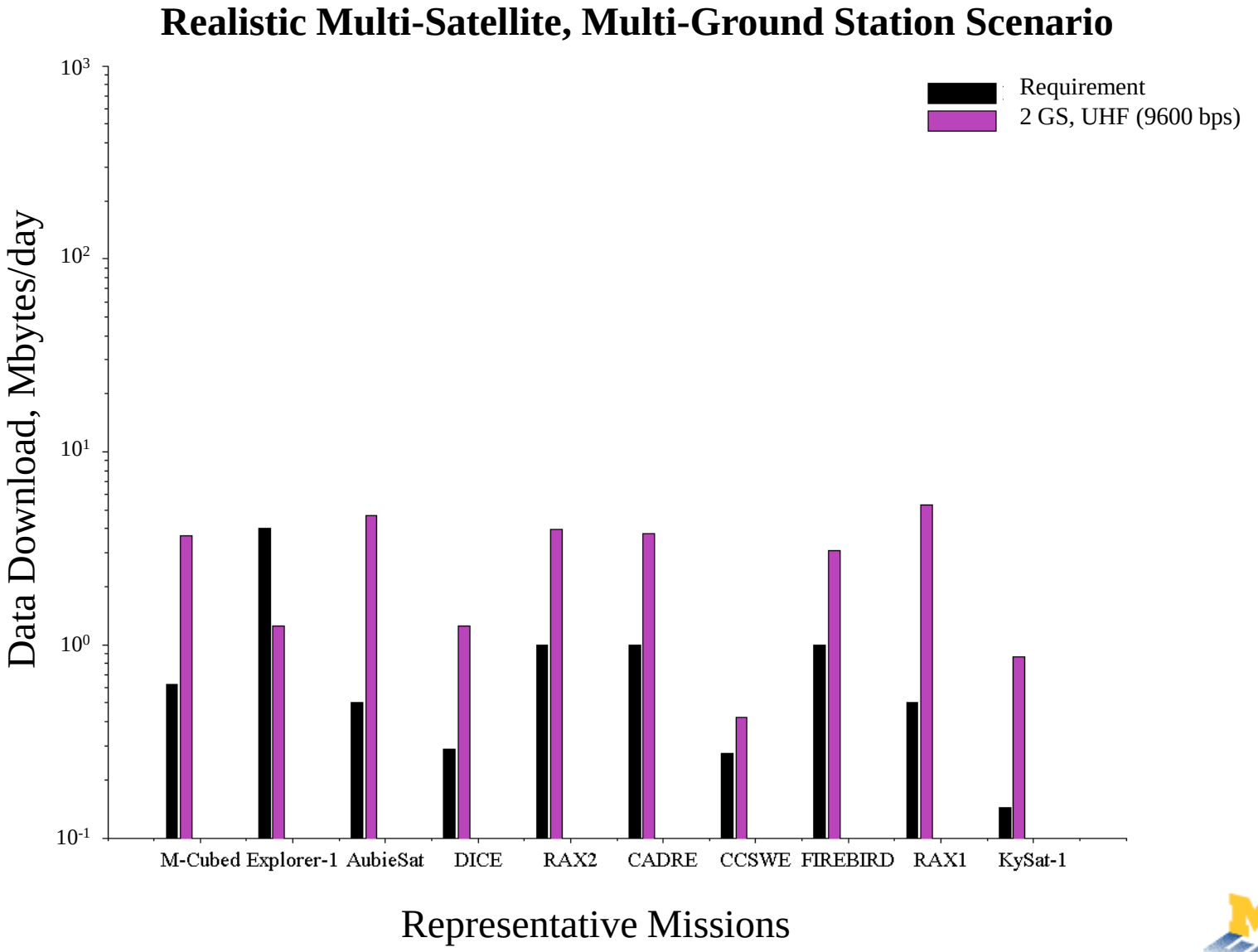
Introduction
Modeling
Simulation
Optimization
Results
Conclusion



Comparison of Requirements and Optimal Solutions

Spangelo *et al.*

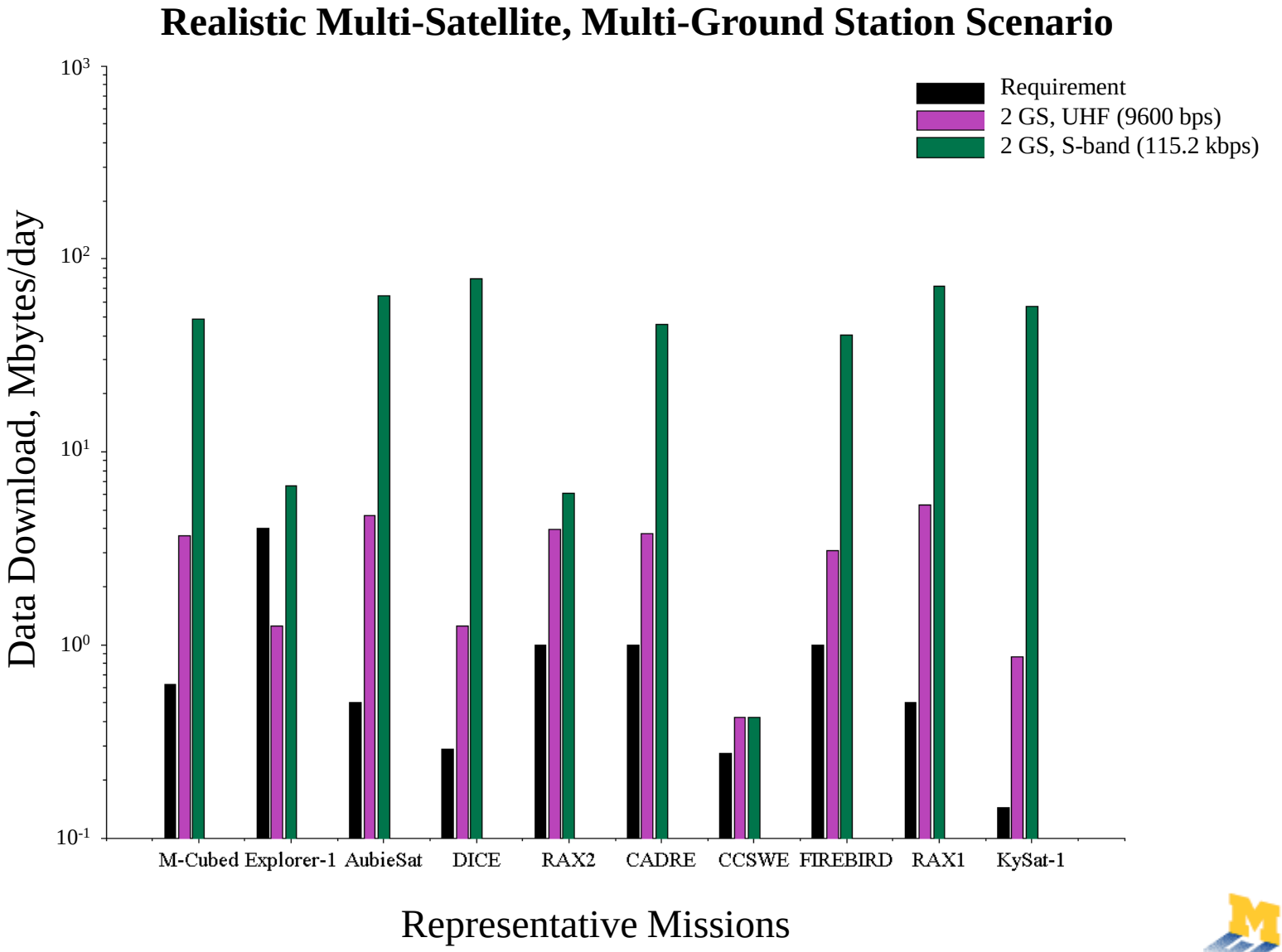
Introduction
Modeling
Simulation
Optimization
Results
Conclusion



Comparison of Requirements and Optimal Solutions

Spangelo *et al.*

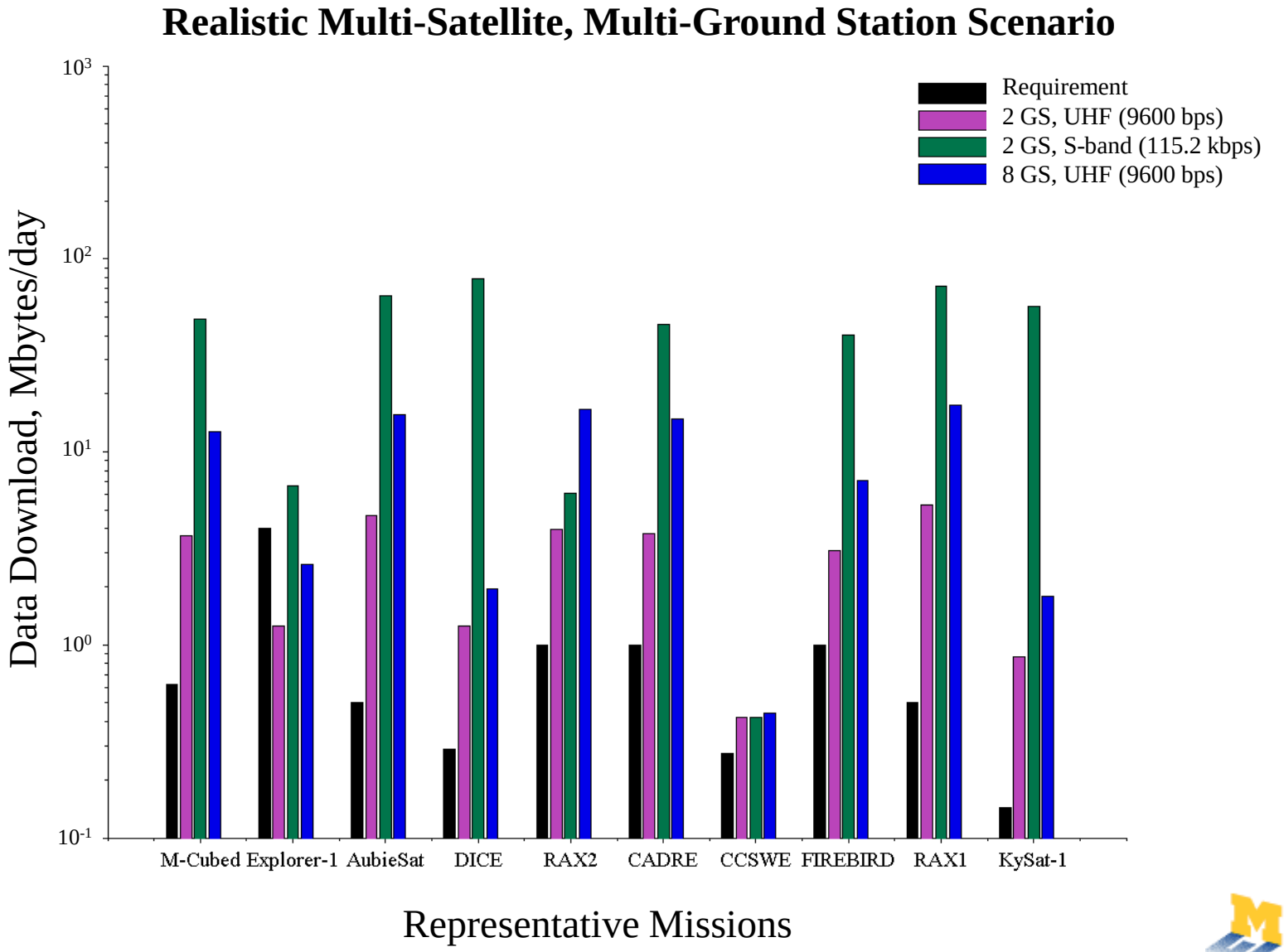
Introduction
Modeling
Simulation
Optimization
Results
Conclusion



Comparison of Requirements and Optimal Solutions

Spangelo *et al.*

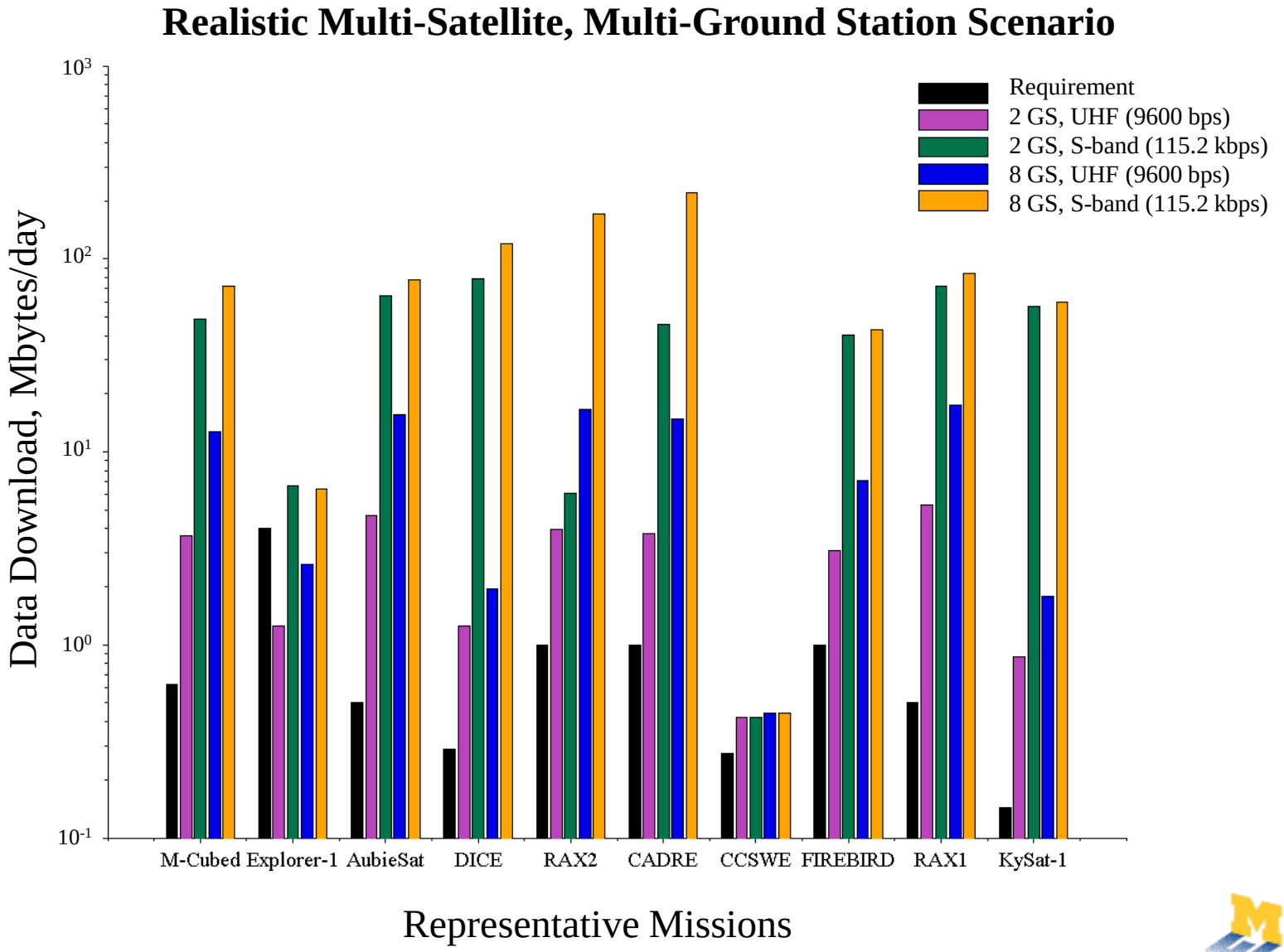
Introduction
Modeling
Simulation
Optimization
Results
Conclusion



Comparison of Requirements and Optimal Solutions

Spangelo *et al.*

Introduction
Modeling
Simulation
Optimization
Results
Conclusion



Applications of our work on *optimal* mission and vehicle design.

Model, simulation and optimization enable:

- Enhanced satellite operational schedules
- Improved satellite vehicle designs

Future Work

- More complex networks
- Different approaches to optimization:
  - Strategic objective functions/problems
  - Different decision variables

Acknowledgments

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Questions?

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Photo Credit: Allison Craddock