Enhancing the Economics of Satellite Constellations via Staged Deployment

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Geneva, July 1, 2004

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Outline

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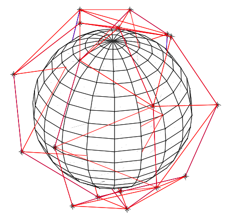
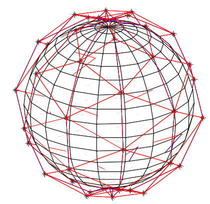
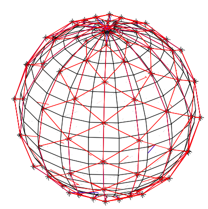
- **Traditional Approach**
- **Conceptual Design (Trade) Space Exploration**
- **Staged Deployment**
- **Path Optimization for Staged Deployment**
- **Conclusions**
- **Discussion (EZ-Sat)**



Stage I
21 satellites
3 planes
h=2000 km



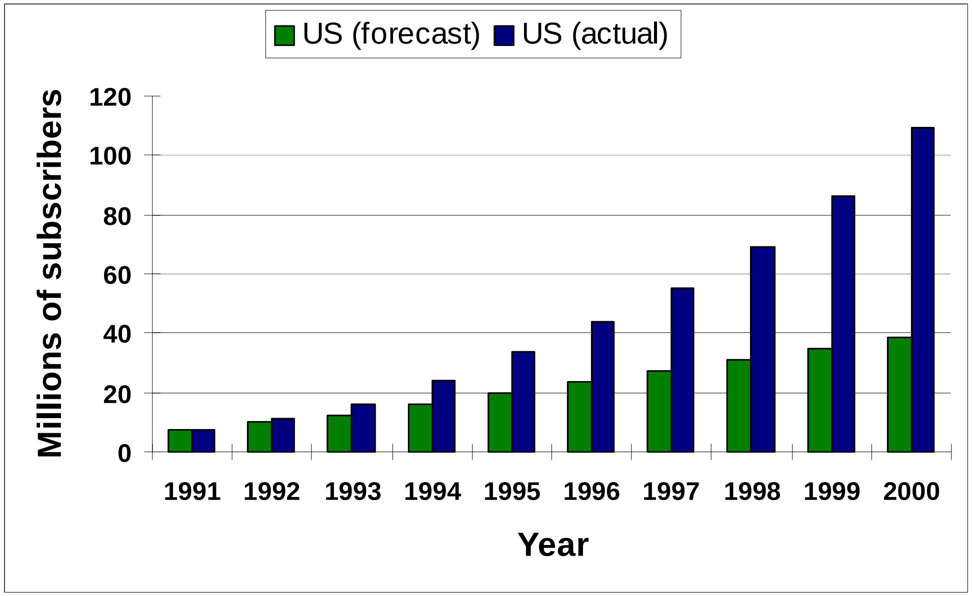
Stage II
50 satellites
5 planes
h=800 km



Stage III
112 satellites
8 planes
h=400 km

Motivation

- Iridium was a technical success but an economic failure:
  - 6 millions customers expected (1991)
  - Iridium had only 50 000 customers after 11 months of service (1998)
- The forecasts were wrong, primarily because they underestimated the market for terrestrial cellular telephones:



- Globalstar was deployed about a year later and also had to file for Chapter 11 protection

Traditional Approach

- Decide what kind of service should be offered
- Conduct a market survey for this type of service
- Derive system requirements
- Define an architecture for the overall system
- Conduct preliminary design
- Obtain FCC/ITU approval for the system
- Conduct detailed design analysis and optimization
- Implement and launch the system
- Operate and replenish the system as required
- Retire once design life has expired

Existing Big LEO Systems

	Iridium	Globalstar
Time of Launch	1997 – 1998	1998 – 1999
Number of Sats.	66	48
Constellation Formation	polar	Walker
Altitude (km)	780	1414
Sat. Mass (kg)	689	450
Transmitter Power (W)	400	380
Multiple Access Scheme	Multi-frequency – Time Division Multiple Access	Multi-frequency – Code Division Multiple Access
Single Satellite Capacity Global Capacity Cs	1,100 duplex channels 72,600 channels	2,500 duplex channels 120,000 channels
Type of Service	voice and data	voice and data
Average Data Rate per Channel	4.8 kbps	2.4/4.8/9.6 kbps
Total System Cost	$ 5.7 billion	$ 3.3 billion
Current Status (2003)	Bankrupt but in operation	Bankrupt but in operation

Individual Iridium Satellite

Individual Globalstar Satellite

Satellite System Economics

Lifecycle cost

$$CPF = \frac{\overbrace{I\left(1+\frac{k}{100}\right)^{T} + \sum_{i=1}^{T} C_{ops,i}}}{\underbrace{\sum_{i=1}^{T} C_s \cdot 365 \cdot 24 \cdot 60 \cdot L_{f,i}}}$$

Number of billable minutes

CPF	Cost per function [$/min]
I	Initial investment cost [$]
k	Yearly interest rate [%]
C_{ops}	Yearly operations cost [$/y]
C_s	Global instant capacity [#ch]
L_f	Average load factor [0…1]
N_u	Number of subscribers
A_u	Average user activity [min/y]
T	Operational system life [y]

Numerical Example:

$I = 3$ [B$]
$k = 5$ [%]
$C_{ops} = 300$ [M$/y]
$T = 15$ [y]

$C_s = 100,000$ [#ch]
$N_u = 3 \cdot 10^6$
$A_u = 1,200$ [min/y]

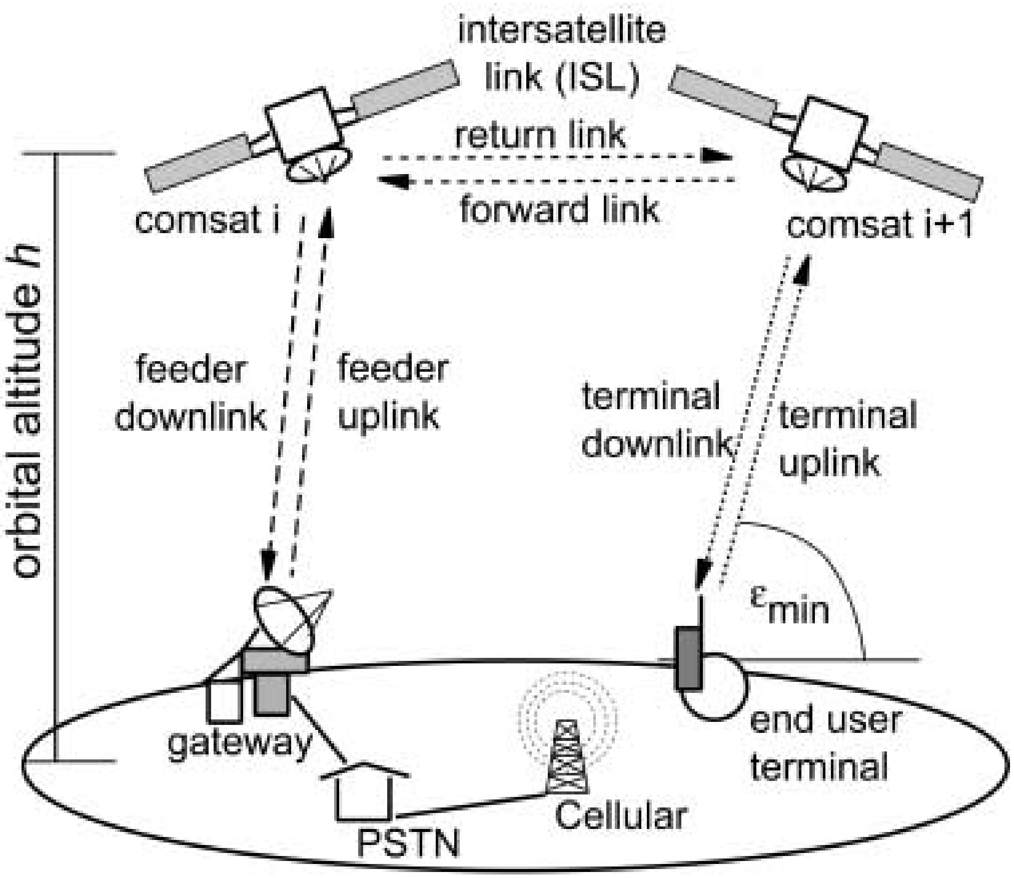
$\rightarrow L_f = 0.068$

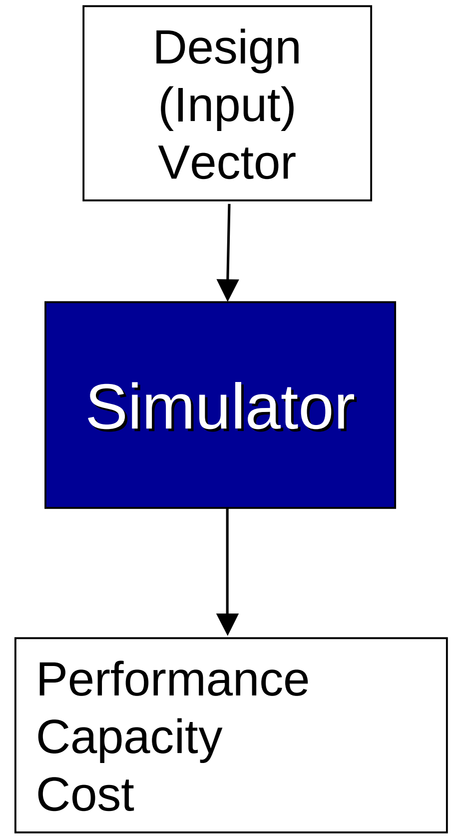
$CPF = 0.20$ [$/min]

$$L_f = \min \begin{cases} \frac{N_u \cdot A_u}{365 \cdot 24 \cdot 60 \cdot C_s} \\ 1.0 \end{cases}$$

But with $N_u = 50,000$
$\rightarrow CPF = 12.02$ [$/min]
Non-competitive

Conceptual Design (Trade) Space





Can we quantify the conceptual system design problem using simulation and optimization?

Design (Input) Vector X

- The design variables are:

Astro-dynamics
  - Constellation Type: C
  - Orbital Altitude: h
  - Minimum Elevation Angle: ε_{min}

Satellite Design
  - Satellite Transmit Power: P_t
  - Antenna Size: D_a
  - Multiple Access Scheme MA:

Network
  - Network Architecture: ISL

Design Space

Polar, Walker	
500,1000,1500,2000	[km]
2.5,7.5,12.5	[deg]
200,400,800,1600,2400	[W]
1.0,2.0,3.0	[m]
MF-TDMA, MF-CDMA	[-]
yes, no	[-]

X_{1440}=

```
   C: 'walker'
   h: 2000
emin: 12.5000
  Pt: 2400
  DA: 3
  MA: 'MFCD'
 ISL: 0
```

This results in a <u>1440</u> full factorial, combinatorial conceptual design space

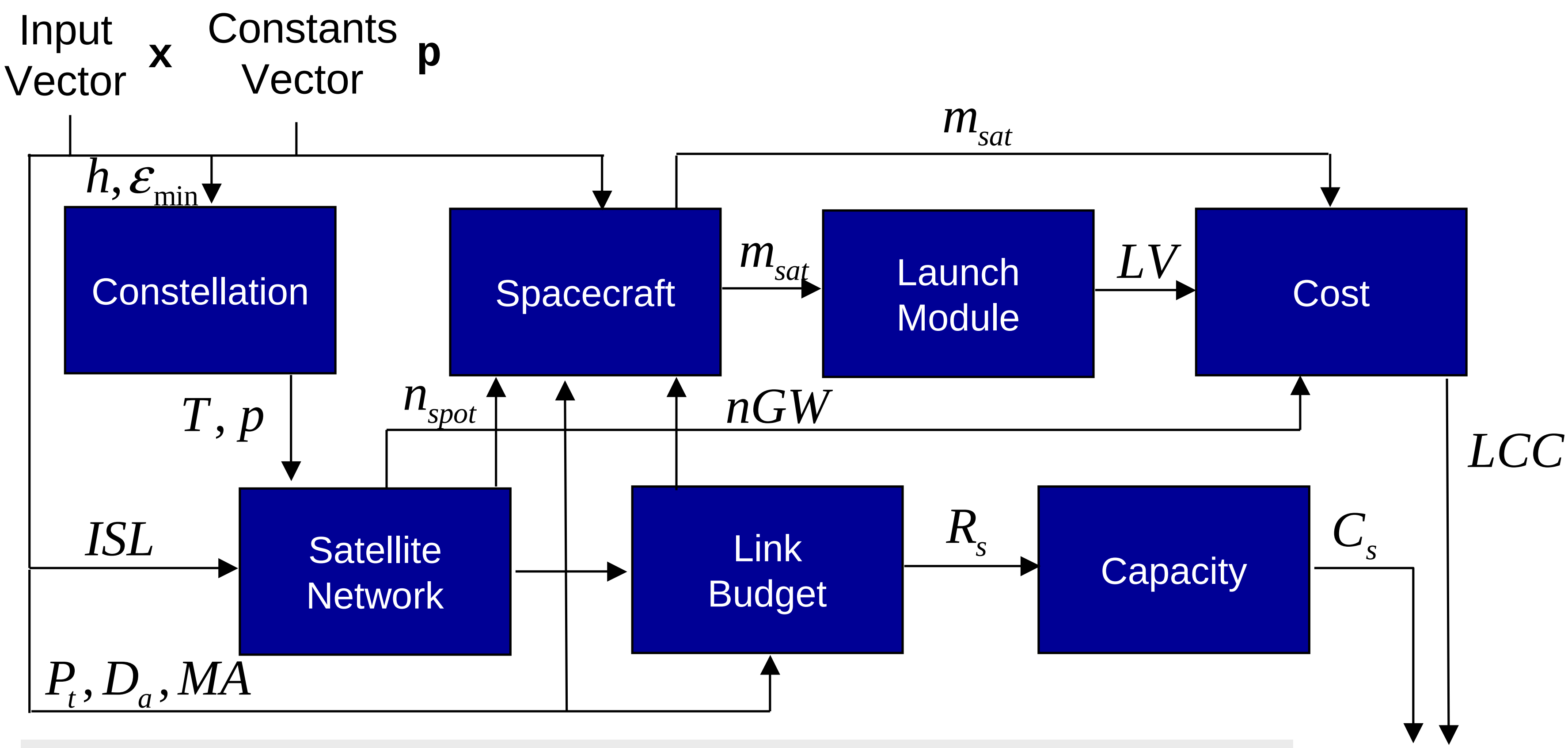
Objective Vector (Output) J

- Performance (fixed)
  - Data Rate per Channel: R=4.8 [kbps]
  - Bit-Error Rate: $p_b=10^{-3}$
  - Link Fading Margin: 16 [dB]
- Capacity
  - C_s: Number of simultaneous duplex channels
  - C_{life}: Total throughput over life time [min]
- Cost
  - Lifecycle cost of the system (LCC [$]), includes:
    - *Research, Development, Test and Evaluation (RDT&E)*
    - *Satellite Construction and Test*
    - *Launch and Orbital Insertion*
    - *Operations and Replenishment*
  - Cost per Function, CPF [$/min]

Consider

$$J_{1440}=\begin{pmatrix} \text{Cs: } 1.4885e+005 \\ \text{Clife: } 1.0170e+011 \\ \text{LCC: } 6.7548e+009 \\ \text{CPF: } 6.6416e-002 \end{pmatrix}$$

Multidisciplinary Simulator Structure



Output Vector **J**

m_{sat}	Satellite Mass	n_{spot}	Number of spot beams
T	Number of Satellites	nGW	Number of gateways
p	Number of orbital planes	LV	Launch vehicle selection

Note: Only partial input-output relationships shown

Governing Equations

a) Physics-Based Models

Energy per bit over noise ratio:

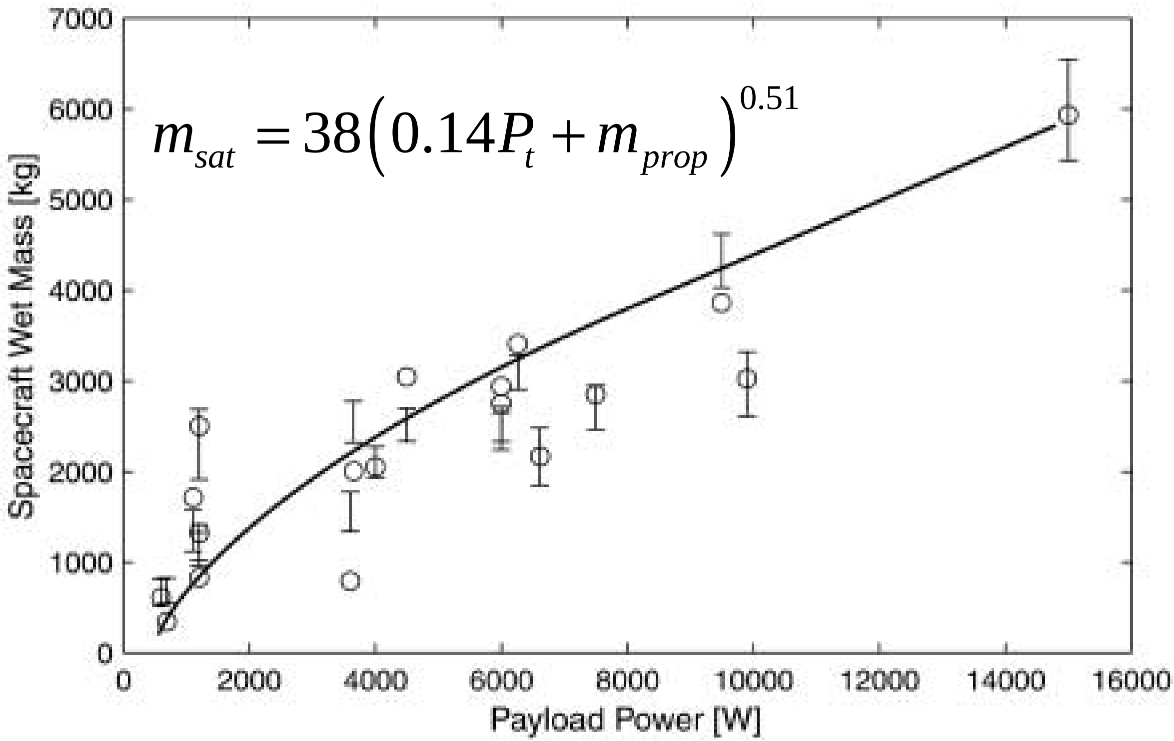
$$\frac{E_b}{N_0} = \frac{PG_rG_t}{kL_{space}L_{add.}T_{sys.}R}$$

(Link Budget)

b) Empirical Models

(Spacecraft)

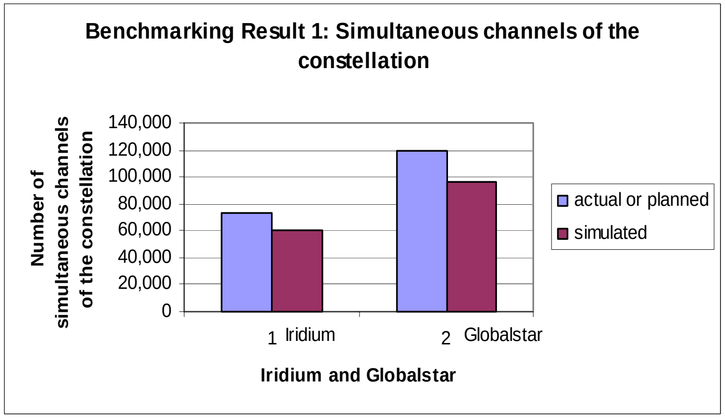
Scaling models derived from FCC database

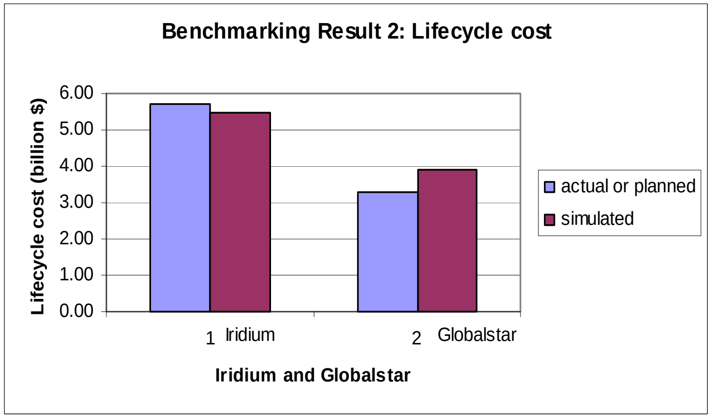


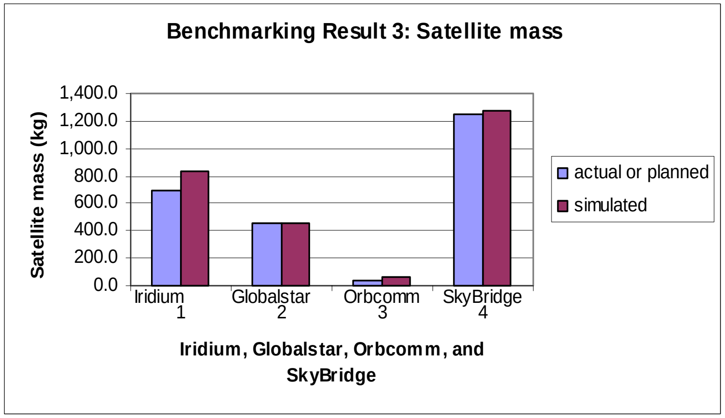
Springmann P.N., and de Weck, O.L. "A Parametric Scaling Model for Non-Geosynchronous Communications Satellites", *Journal of Spacecraft and Rockets*, May-June 2004

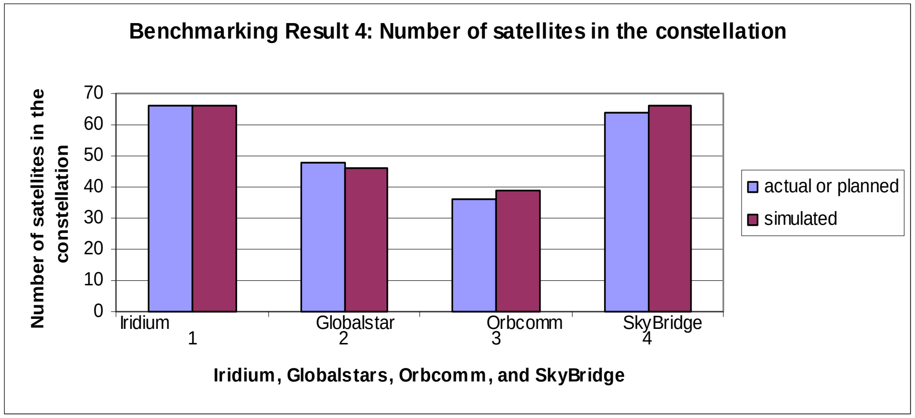
Benchmarking

Benchmarking is the process of validating a simulation by comparing the predicted response against reality.



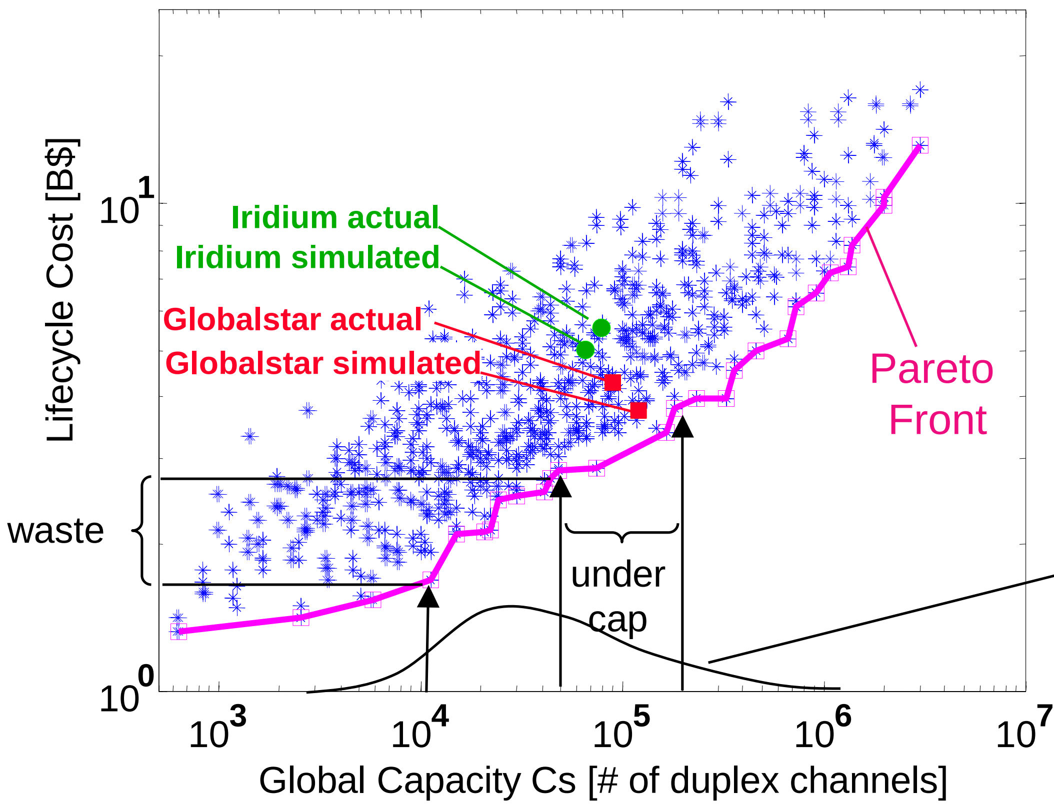






Traditional Approach

- The traditional approach for designing a system considers architectures to be fixed over time.
- Designers look for a Pareto Optimal solution in the Trade Space given a targeted capacity.



If actual demand is below capacity, there is a <u>waste</u>

If demand is over the capacity, <u>market opportunity</u> may be missed

Demand distribution
Probability density function

$$P\{a < C_s \le b\} = \int_a^b f_{C_s}(C_s)\mathrm{d}C_s$$

$$0 \le f_x(C_s) \text{ for all } C_s$$

$$\int_{-\infty}^{\infty} f_{C_s}(C_s)\mathrm{d}C_s = 1$$

Staged Deployment

- The traditional approach doesn't reduce risks because it cannot adapt to uncertainty
- A flexible approach can be used: the system should have the ability to adapt to the uncertain demand
- This can be achieved with a staged deployment strategy:
  - A smaller, more affordable system is initially built
  - This system has the flexibility to increase its capacity if demand is sufficient and if the decision makers can afford additional capacity

Does staged deployment reduce the economic risks?

Economic Advantages

- The staged deployment strategy reduces the economic risks via two mechanisms
- The costs of the system are spread through time:
  - Money has a time value: to spend a dollar tomorrow is better than spending one now (Present Value)
  - Delaying expenditures always appears as an advantage
- The decision to deploy is done observing the market conditions:
  - Demand may never grow and we may want to keep the system as it is without deploying further.
  - If demand is important enough, we may have made sufficient profits to invest in the next stage.

How to apply staged deployment to LEO constellations?

Proposed New Process

- Decide what kind of service should be offered
- Conduct a market survey for this type of service
- Conduct a baseline architecture trade study
- Identify Interesting paths for Staged Deployment
- Select an Initial Stage Architecture (based on Real Options Analysis)
- Obtain FCC/ITU approval for the system
- Implement and Launch the system
- Operate and observe actual demand
- Make periodic reconfiguration decisions
- Retire once Design Life has expired

Δt

Focus shifts from picking a "best guess" optimal architecture to choosing a valuable, flexible path

Step 1: Partition the Design Vector

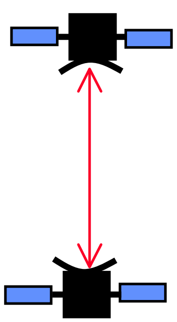
$x_{flexible}$ — Astro-dynamics
- Constellation Type: C
- Orbital Altitude: h
- Minimum Elevation Angle: ε_{min}

x_{base} — Satellite Design
- Satellite Transmit Power: P_t
- Antenna Size: D_a
- Multiple Access Scheme MA:

x_{base} — Network
- Network Architecture: ISL

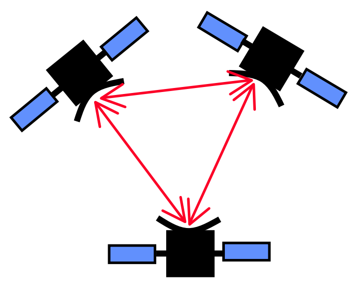
<u>Rationale:</u>
Keep satellites the same and change only arrangement in space

Stage I



```
   C: 'walker'
   h: 2000
emin: 12.5000
  Pt: 2400
  DA: 3
  MA: 'MFCD'
 ISL: 0
```

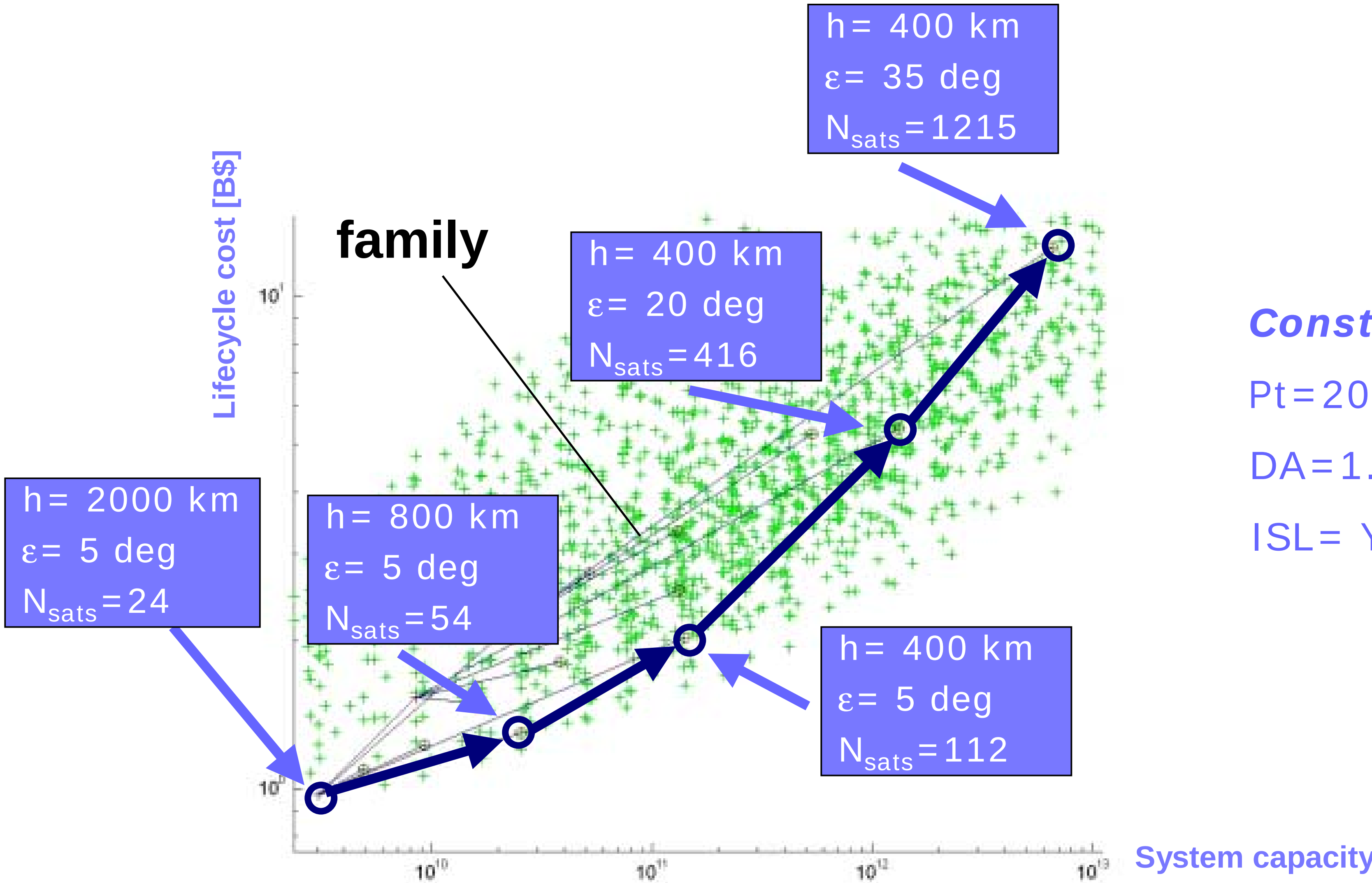
Stage II



```
   C: 'polar'
   h: 1000
emin: 7.5000
  Pt: 2400
  DA: 3
  MA: 'MFCD'
 ISL: 0
```

$x^{I}_{base} = x^{II}_{base}$

Step 2: Search Paths in the Trade Space



Constant:

Pt=200 W

DA=1.5 m

ISL= Yes

Choosing a path: Valuation

- We want to see the adaptation of a path to market conditions:
  - How to mathematically represent the fact that demand is uncertain?
  - Usual valuation methods try to minimize costs and will recommend not to deploy after the initial stage
- We don't know how much it costs to achieve reconfiguration:
  - The technical method that will be used is not well known
    - onboard propellant, space tug, refueling/servicer
  - Even if a method was identified, the pricing process may be long
  - Focus on the value of flexibility ("economic opportunity")
- Many paths can be followed from an initial architecture:
  - Optimization over initial architectures seems difficult
  - Many cases will have to be considered

Assumptions

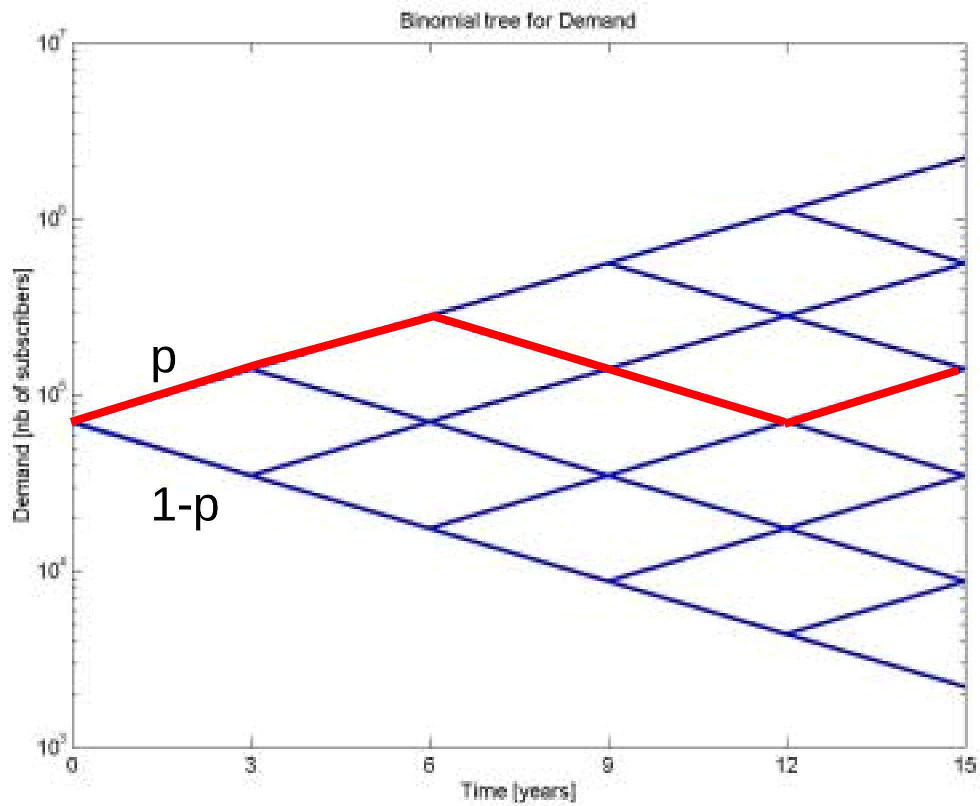
- Optimization is done over paths instead of initial architectures:
- The capability to reconfigure the constellation is seen as a ``real option'' we want to price:
  - We have the right but not the obligation to use this flexibility
  - We don't know the price for it but want to see if it gives an economic opportunity
  - The difference of costs with a traditional design will give us the maximum price we should be willing to pay for this option
- Demand follows a geometric Brownian motion:
  - Demand can go up or down between two decision points
  - Several scenarios for demand are generated based on this model
- The constellation adapts to demand:
  - If demand goes over capacity, we deploy to the next stage
  - This corresponds to a worst-case for staged deployment
  - In reality, adaptation to demand may not maximize revenues but if an opportunity is revealed with the worst-case, a further optimization can be done

$$\frac{\Delta S}{S} = \mu \Delta t + \sigma \varepsilon \sqrt{\Delta t}$$

***S* -stock price**
***Δt* – time period**
***ε*- SND random variable**
***μ, σ* - constants**

Step 3: Model Uncertain Demand

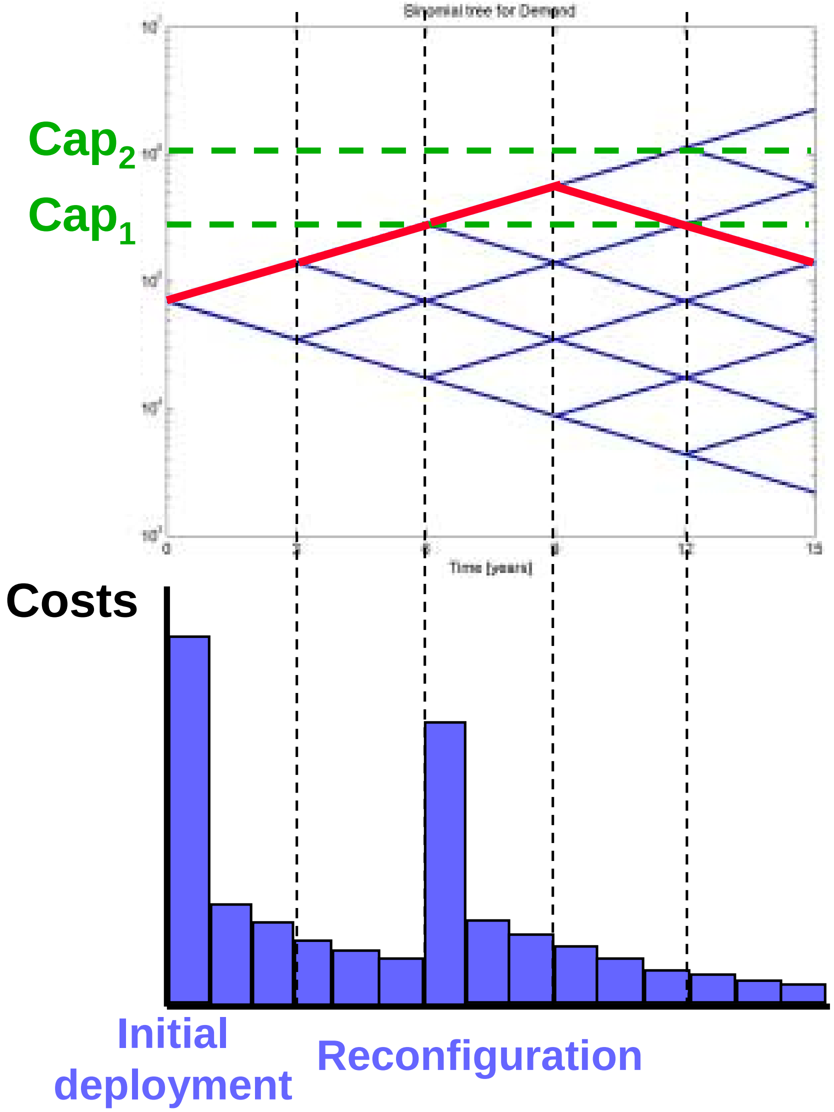
- The geometric Brownian motion can be simplified with the use of the Binomial model (see Lattice method):



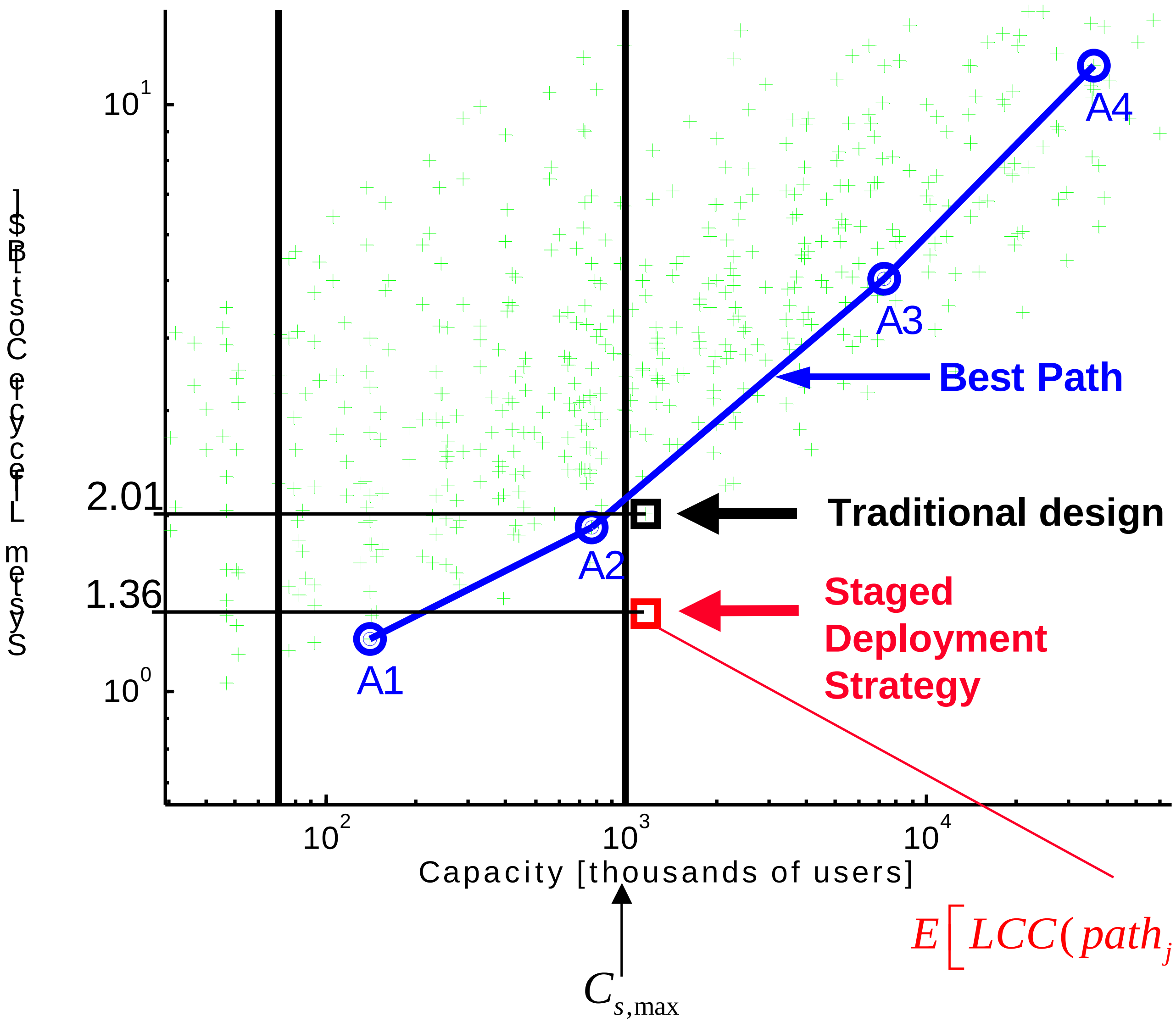
- A scenario corresponds to a series of up and down movements such as the one represented in red

Step 4: Calculations of costs

- We compute the costs of a path with respect to each demand scenario
- We then look at the weighted average for cost over all scenarios
- We adapt to demand to study the ``worst-case'' scenario
- The costs are discounted: the present value is considered



Step 5: Identify optimal path



- For a given targeted capacity, we compare our solution to the traditional approach
- Our approach allows important savings (30% on average)
- An economic opportunity for reconfigurations is revealed but the technical way to do it has to be studied

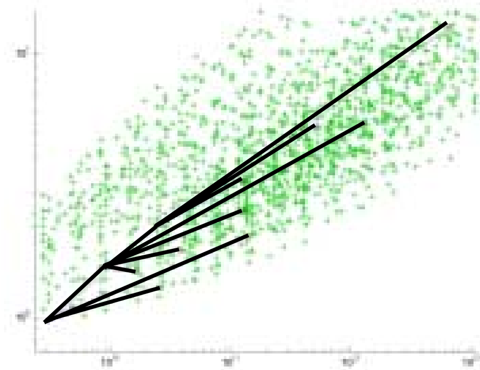
$$E\left[LCC(path_j)\right] = \sum_{i=1}^{n} p_i LCC\left(scenario^i_{path_j}\right)$$

Framework: Summary

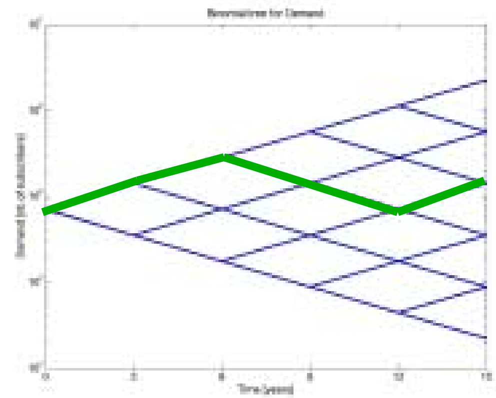
Identify Flexibility

$$x = \begin{bmatrix} x_{flex} \\ x_{base} \end{bmatrix}$$

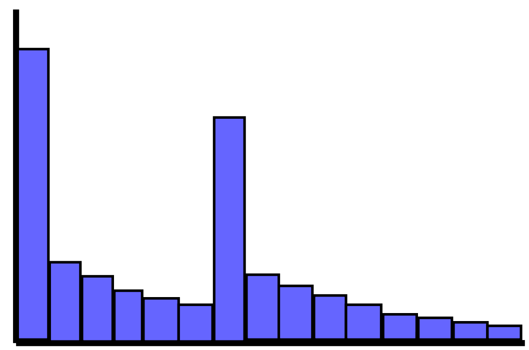
Generate “Paths”



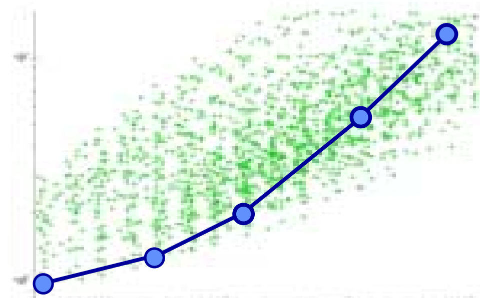
Model Demand



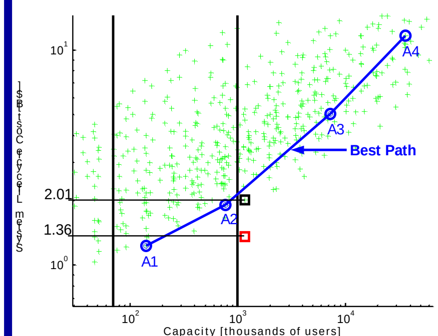
Estimate Costs



Optimize over Paths



Reveal opportunity



Conclusions

- The goal is not to rewrite the history of LEO constellations but to identify future opportunities
- We designed a framework to reveal economic opportunities for staged deployment strategies
  - Inspired by Real Options approach
- The method is general enough to be applied to similar design problems
- Reconfiguration needs to be studied in detail and many issues have to be solved:
  - Estimate ΔV and transfer time for different propulsion systems
  - Study the possibility of using a Tug to achieve reconfiguration
  - Response time
  - Service Outage

Reference

de Weck, O.L., de Neufville R. and Chaize M., “Staged Deployment of Communications Satellite Constellations in Low Earth Orbit”, *Journal of Aerospace Computing, Information, and Communication*, 1, 119-136 , March 2004

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Discussion – Comsats for Dev. World

- Japanese EZ-Sat System (proposed 1994)
  - Ref: AIAA-94-0973
- 55.6% (94/169) of countries and 38.8% (1.98/5.11 B) of world population are within +/- 20 deg latitude
- Almost all of these countries are developing nations
- Proposed constellation
  - h=1264 km orbit, ε_{min}=8 deg, 1 orbital plane, i=0 deg, 9 satellites
- Service
  - 20 channels per sat., 2.4 kbps voice and data
  - Handheld terminals, 0.5 W xmit power
- Link budget
  - Up: 1.6 GHz (L), 4 spot beams, 11 dB fading margin
- Satellites
  - 12 (9 + 3 spares), 155 kg (wet mass), 190 W total power
- System Cost estimate: $280 million (1994)

Research Questions

- User view
  - What types of service are most beneficial?
  - Current “holes” in coverage by terrestrial systems
  - Affordability (linked to GDP/capita) for end terminals, $/min charges
  - Billing, system administration ?
  - Literacy ?
- Regulatory view
  - Frequency allocation, Interference with GEO systems
  - Multi-national agreements
  - Systems financing, ownership structure
- Technical view:
  - DfA: “Design for Affordability”
  - Duplex vs. Store & Forward (messaging) is crucial
  - Launch and progressive deployment strategy
  - End terminal design: ruggedness, keyboards, power recharging