On Scalability of Fractionated Satellite Network

Iñigo del Portillo, Marc Sanchez-Net, Daniel Selva, Ángel Álvaro, Elisenda Bou, Eduard Alarcón

Universitat Politenica de Catalunya

13 March 2015

IEEE Aeroconf 2015
Big Sky, Montana

Outline

- **Introduction and Motivation**
  - Fractionated Satellite Networks
  - Motivation: Scalability as a critical property of FSN
- **System Model**
- **Implementation**
  - General Framework
  - Resource Allocation
- **Validation of the Resouce Allocation**
- **Case Study**
- **Conclusions**

Fractionated Satellite Networks

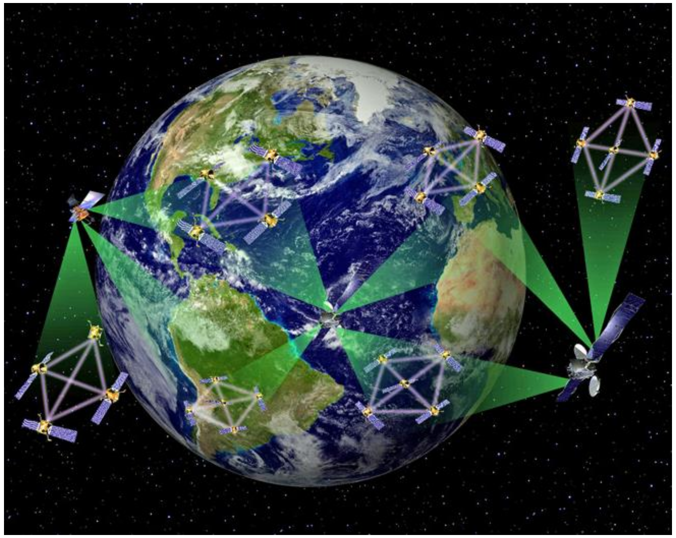
- A generalization of the Fractionated Satellite concept:

  A satellite architecture where the functional capabilities of a conventional monolithic spacecraft are distributed across multiple modules which interact through wireless links.

- Several satellites exchange resources wirelessly to obtain a higher aggregated network capability.

- Various concepts proposed in the last years can be included under this definition:
  - Federated Satellite Systems
  - Space Stations (Space Infrastructure)
  - Satellite Constellations
  - Fractionated Satellites

Fractionated Satellite Concept *(image source: DARPA)*



Fractionated Network Concept *(image source: DARPA)*

Motivation – Scalability as a fundamental property of FSN 4

Fractionated Satellite Networks exhibit multiple advantages as compared to monolithic architectures:

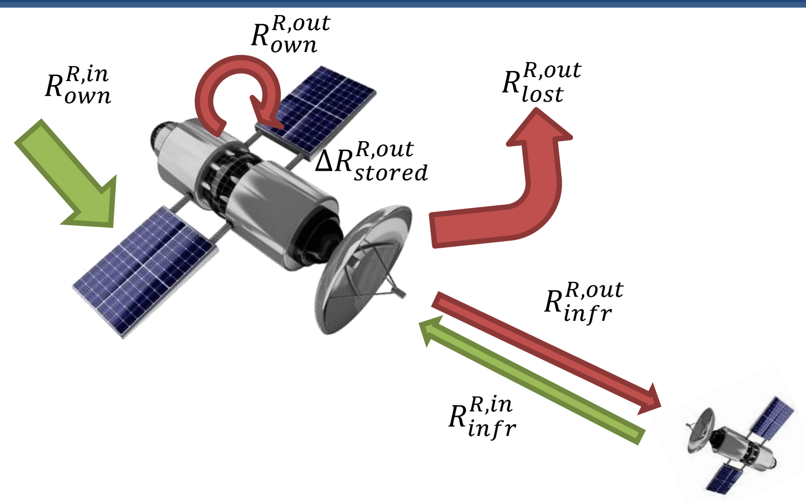
- Higher flexibility, resiliency, maneuverability, robustness
- Scalability has not been extensively studied even though due to the expandable nature of FSN, it is a critical property of these systems.

> “[Scalability is] *the ability of a system to maintain its* ***performance*** *and function, and retain all its desired properties when its* ***scale is increased*** *greatly without having a corresponding increase in the system’s complexity.* “
>
> **[de Weck O. (2011)]**

- This paper presents a general framework to analyze scalability in satellite networks:
  - Independent of the degree of fractionation of the network
- The resource allocation process is validated using the closets real system to a FSN: TDRSS
- A hypothetical case example to show the application of the framework to other domains is presented.

Resources and Satellites Models

- Three kind of resources are modeled (Energy, Comms, Processing Power)
- Two parameters characterize how resources are transferred:
  - Transfer efficiency: $\eta_{ij}{}^{R} = \frac{R^{R}_{UTIL}}{R^{R}_{TOTAL}} = \frac{R_{useful}}{R_{useful}+R_{losses}}$
  - Interdependency coefficient: $\kappa^{R_1,R_2} = \frac{R^{R_1}_{TOTAL}}{R^{R_2}_{TOTAL}}$



$$R^{R,in}_{infr} + R^{R,in}_{own} = \Delta R^{R,out}_{stored} + R^{R,out}_{own} + R^{R,out}_{\mathrm{infr}} + R^{R,out}_{lost}$$

- On a satellite, the resource balance equation must hold at any time.
- The expected value of the storage term ($\Delta R^{R,out}_{stored}$) is 0
- To characterize the degree of fractionalization two parameters are defined:

$$\alpha^{R} = \frac{R^{R,in}_{infr}}{R^{R,in}_{infr} + R^{R,in}_{own}} \qquad \beta^{R} = \frac{R^{R,out}_{\mathrm{infr}}}{R^{R,out}_{own} + R^{R,out}_{\mathrm{infr}}}$$

Type Of Node	α	β	Source Of R_{in}	Destination Of R_{out}
Infrastructure Node	0 - 0,1	0,9 - 1	Own Production	Infrastructure
Client Node	0,3 - 1	0 - 0,1	Infrastructure	Own Consumption
Relay Node	1	1	Infrastructure	Infrastructure
Buffer Node	0 - 1	0	Infrastructure or Own Production	Storage
Dedicated Node	0,1 – 0,9	0,1 – 0,9	Infrastructure or Own Production	Own Consumption, Storage or Infrastructure
Autonomous Node	0 - 0,3	0 – 0,1	Own Production	Own Consumption or Storage

Fig 1.- Type of network nodes

α percentage of resources coming from other nodes,

β percentage of resources given to other nodes.

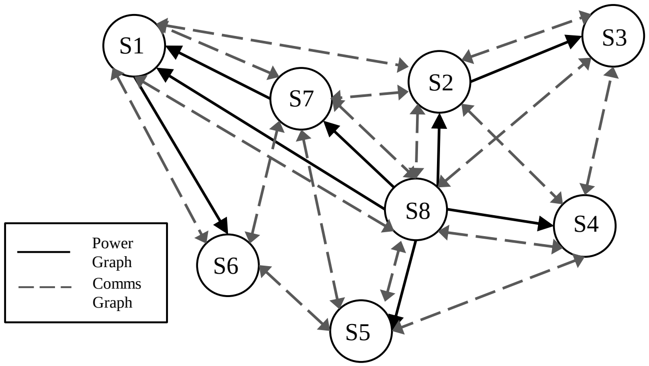
UPC

telecom BCN

Network Model

- The network is modeled using a directed weighted graph
- Weights are the efficiencies of transmission between nodes.
- A modified Dijkstra algorithm is used to compute the highest efficiency path among any pair of nodes.
- Each resource has its own graph.
- Based on the resource exchange on each node (after resource allocation) two parameters are used to classify the degree of fractionalization of the network.

$$\alpha_A = \frac{\sum_{i|n(T^i)>0} \alpha_i R_i^{in}}{\sum_{i|n(T^i)>0} R_i^{in}} \qquad \beta_A = \frac{\sum_i \beta_i R_i^{out}}{\sum_i R_i^{out}}$$



Type of Architecture	α_A	β_A	Observations
Constellation	0 - 0,1	0 - 0,1	Satellites are autonomous, resource exchange is almost not present
Fractionated Network	0,4 - 1	0,2 - 1	Resource sharing is essential for the network to execute its tasks
Federated Satellite System	0,1 - 0,4	0,1 - 1	Some satellites receive some resources from the infrastructure. However, most of the resources come from own sources
Oversized Network	0,4 - 1	0 – 0,2	Resources needed to perform tasks come from the infrastructure, but resources delivered to the infrastructure are very little compared to the amount produced.
Inefficient Network	0 – 0,1	0,9 - 1	Most of the resources are given to the network but they are not used as input resources (losses in the resource exchange are too high)

Fig 2.- Architecture types

α_A percentage of resources coming from other nodes in the whole network,

β_A percentage of resources given to other nodes in the whole network.

Task and QoS$_A$ Model

Mission and Tasks

- The purpose of the network is to execute a set of tasks tat fulfill the requirements of the mission.
- Each satellite carry one or several tasks. A mission can have multiple tasks on different satellites.
- Each task has a resource consumption and a utility value associated to its execution.

Utility Function QoS$_A$

- The performance of the systems is measured using a metric that captures the satisfaction of the stakeholders.
- We define the Aggregated Quality of Service (QoS$_A$)

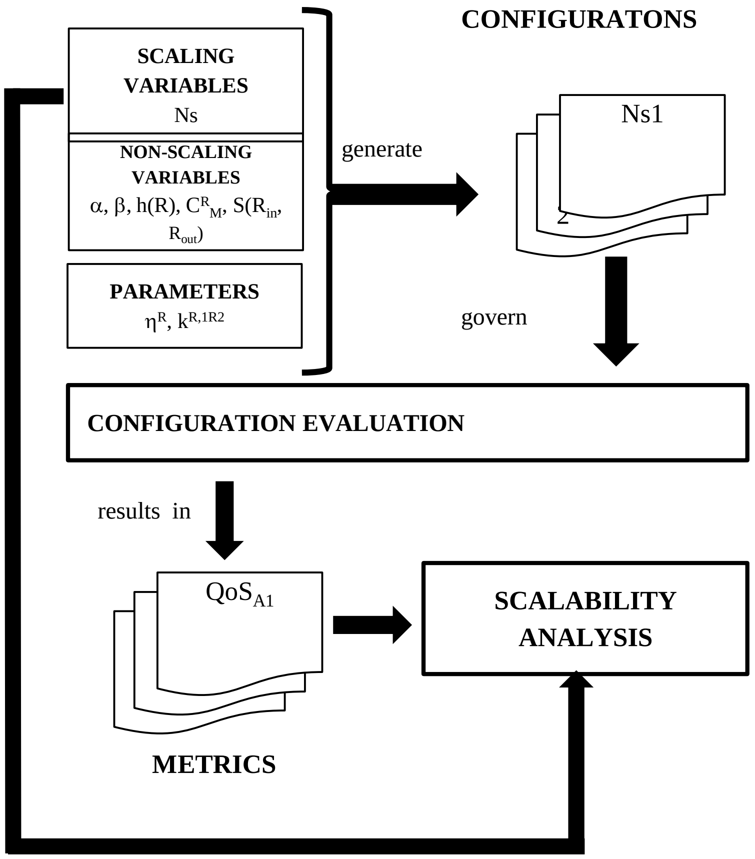
QoS$_A$ provides a common interface among stakeholders to express how well a configuration satisfies their personal preferences related to system qualities (i.e: a stakeholder might prioritize latency over data volume, whereas others might prioritize task completion over partial execution).

$$QoS_A = f(\boldsymbol{N_s}, S_i(R_i^{in}, R_i^{out}, \alpha_i, \beta_i), N(C_M^R, \eta_M^R, \alpha_A, \beta_A), U^t, \boldsymbol{h}(\boldsymbol{R}))$$

$$QoS_A = \frac{\sum U_t p_t}{\sum_t U^t} = \frac{\sum U_t \min(\boldsymbol{f_t^R})}{\sum_t U^t} = \frac{\sum U_t \min\left(\frac{\boldsymbol{R_{t,obt}}}{\boldsymbol{R_{t,need}}}\right)}{\sum_t U^t}$$

General Framework

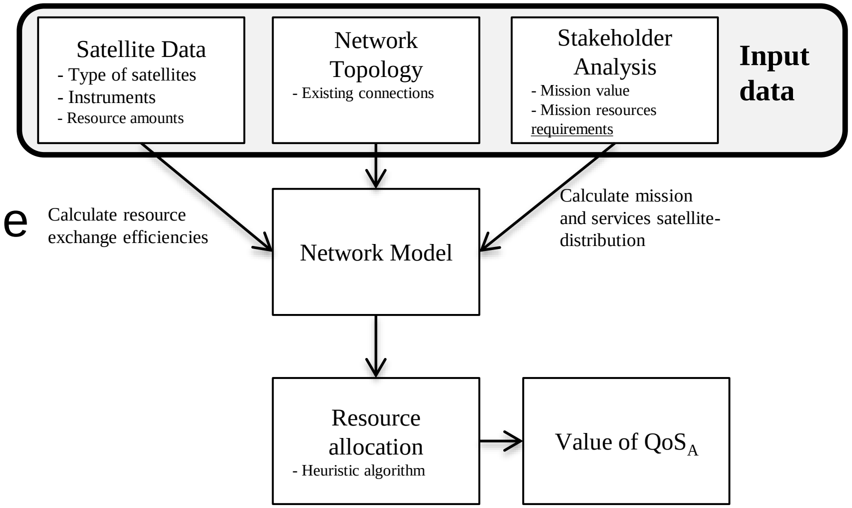
- We build our scalability framework based on the framework created in [1].
- Variables are classified as:
  - **Scaling**: Define the operational range of the system
  - **Non-scaling**: The architect defines them and they define the architecture
  - **Parameters**: Constant values, technological parameters
- Different configurations are generated for each architecture.
- The evaluation of the configurations renders a set of metrics.
- On each analysis different metrics can be defined: Latency, data-volume, percentage of tasks completed.
- The plots of the metrics vs. the variables constitute the scalability analysis.



[1] Duboc, L., Rosenblum, D. S., & Wicks, T. A framework for modelling and analysis of software systems scalability. In *Proceedings of the 28th international conference on Software engineering* (pp. 949-952). ACM.

Configuration Evaluation

- The configurator evaluator has been implemented in MATLAB
- First, inputs are read from and XLS file containing the technological parameters, the satellite data, etc.
- The network model is created. Efficiencies are computed and the resource exchange graphs are generated.
- Resources are allocated among satellites.
- The QoS_A is computed once the resources are assigned.



Resource Allocation in Static Systems

- If the orbital dynamics remain invariant in time, we can get rid of time in the formulation of the problem.
- As all the matrices are constant in time, it is computationally manageable to solve it as an optimization problem.
- Due to the interaction among resources, the formulation is nonlinear.
- MATLAB's *fmincon* optimizer with the SQP algorithm is used to solve the problem

$$[MAX]\; QoS_A = f(\boldsymbol{U_t}, \boldsymbol{R_{obt,t}}, \boldsymbol{R_{need,t}})$$

s.t.

$$\begin{pmatrix} \boldsymbol{R^E_{need}} \\ \boldsymbol{R^C_{need}} \\ \boldsymbol{R^P_{need}} \end{pmatrix} \geq \begin{pmatrix} \boldsymbol{R^E_{obt}} \\ \boldsymbol{R^C_{obt}} \\ \boldsymbol{R^P_{obt}} \end{pmatrix} = \begin{pmatrix} \left(\left(\boldsymbol{T} \cdot \boldsymbol{\eta^E_{CM}}\right) \circ \boldsymbol{x^E}\right) \boldsymbol{R^E_{s,ava}} \\ \left(\left(\boldsymbol{T} \cdot \boldsymbol{\eta^C_{CM}}\right) \circ \boldsymbol{x^C}\right) \boldsymbol{R^C_{s,ava}} \\ \left(\left(\boldsymbol{T} \cdot \boldsymbol{\eta^P_{CM}}\right) \circ \boldsymbol{x^P}\right) \boldsymbol{R^P_{s,ava}} \end{pmatrix}$$

$$\underline{\boldsymbol{1}} = \left(\boldsymbol{x^R}\right)^{\boldsymbol{T}} \underline{\boldsymbol{1}}$$

$$1 - \alpha_i \geq x_{ii}^{R,t} \geq 0$$

$$\alpha_i \geq \sum_{i \neq j} x_{ij}^{R,t}$$

$$\beta_{d(t_j)} \geq x_{ij}^{R,t} \geq 0, \qquad i \neq j$$

$$R_{s,ava} = R_{own}^{R,in} - R_{interd} =$$

$$= R_{own}^{in} - \begin{pmatrix} \boldsymbol{0} & \boldsymbol{\kappa^{E,C} I_{Ns}} & \boldsymbol{\kappa^{E,P} I_{Ns}} \\ \boldsymbol{\kappa^{C,E} I_{Ns}} & \boldsymbol{0} & \boldsymbol{\kappa^{C,P} I_{Ns}} \\ \boldsymbol{\kappa^{P,E} I_{Ns}} & \boldsymbol{\kappa^{P,C} I_{Ns}} & \boldsymbol{0} \end{pmatrix} \operatorname{diag}\begin{pmatrix} \boldsymbol{R^E_s} \\ \boldsymbol{R^C_s} \\ \boldsymbol{R^P_s} \end{pmatrix} x^T \begin{pmatrix} \boldsymbol{1} \\ \vdots \\ \boldsymbol{1} \end{pmatrix}$$

The interaction among resources is explicitly depicted in this equation.

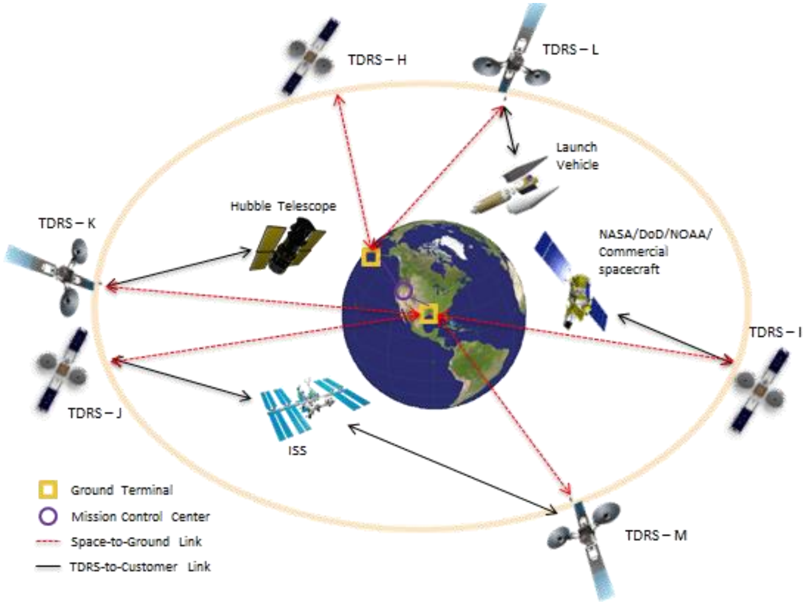
$$QoS_A = \frac{\sum U_t p_t}{\sum_t U^t} = \frac{\sum U_t \min(\boldsymbol{f^R_t})}{\sum_t U^t} = \frac{\sum U_t \min\left(\frac{\boldsymbol{R_{t,obt}}}{\boldsymbol{R_{t,need}}}\right)}{\sum_t U^t}$$

Resource Allocation Validation

- The Tracking and Data Relay Satellite System (TDRSS) was used to validate the resource allocation methodology.
- TDRSS only provides communication resources.
- Real data from 14 days of operations of TDRSS were used

TABLE III
Results of the Validation Test

Metric	Band	| Difference (%) |	
Antenna Utilization	S (SA)	6,48 %	
	Ku (SA)	3,46 %	
	S (MA)	42,74 %	
	Satellite	S-Band | Difference (%) |	Ku-Band | Difference (%) |
Satellite Utilization	TDRS-3	2,28 %	29,75 %
	TDRS-5	10,79 %	31,13 %
	TDRS-7	57,40 %	81,02 %
	TDRS-9	55,06 %	0,24 %
	TDRS-10	31,01 %	102,3 %



- The resource allocation methodology reproduces the behaviour of the network at the system level but is not valid to evaluate particular behaviours at the node level

Cluster of Nanosatellites – System description

- A hypothetical mission similar to EDSN with support of a mother satellite is analyzed:

  A swarm of 8 cubesats into a loose formation approximately 500 km above Earth. EDSN will develop technology to send multiple, advanced, yet affordable nanosatellites into space with cross-link communications to enable a wide array of scientific, commercial, and academic research.

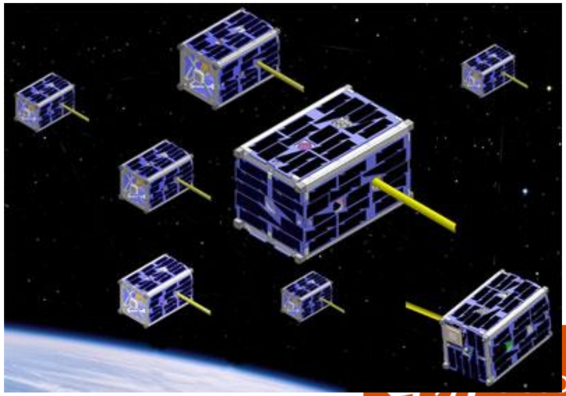
- The network is uniform in terms of the characteristics of the client satellites and their tasks.
- Loose formation is represented by locating the satellites randomly in a sphere of 200 m.
- Satellite and Tasks characteristics are described in the tables on the right side.
- The resources available / taken from the infrastructure (α and β) and the number of client satellites are swept during the analysis.
- Results are grouped depending on values of α_A and β_A

SATELLITES' CHARACTERISTICS

Satellite	Resource	Value	Description
Mother (702HP)	Power Generation	15 kW	2x 33.8m Triple-Junction AsGa
	Comms Data rate	610 Mbps	Ku-band 2 x 300 Mbps S-band 2 x 5 Mbps
Client (A200)	Power Generation	41 W	Body Mounted SmallSat
	Comms Data rate	-	No capabilities for direct downlink to Earth

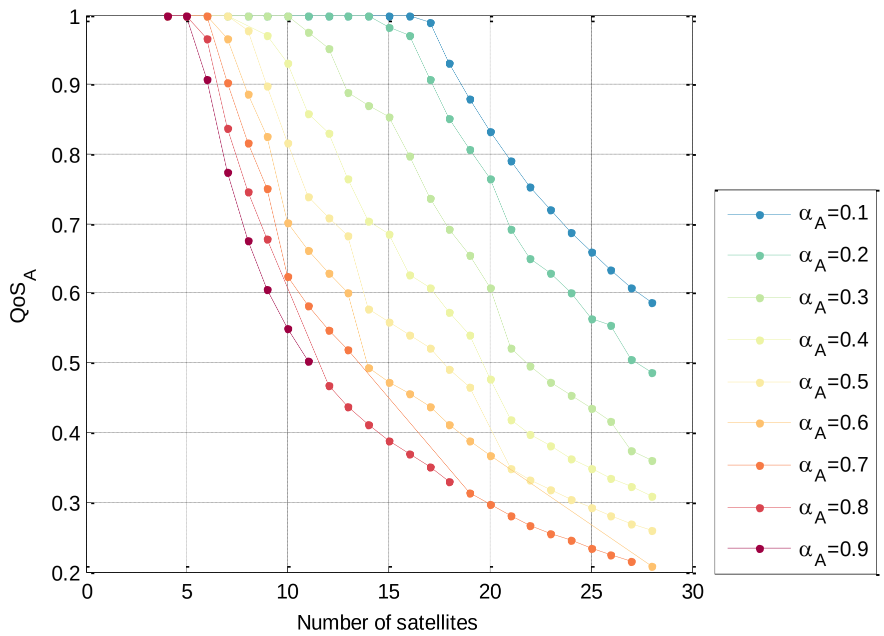
TASKS' CHARACTERISTICS

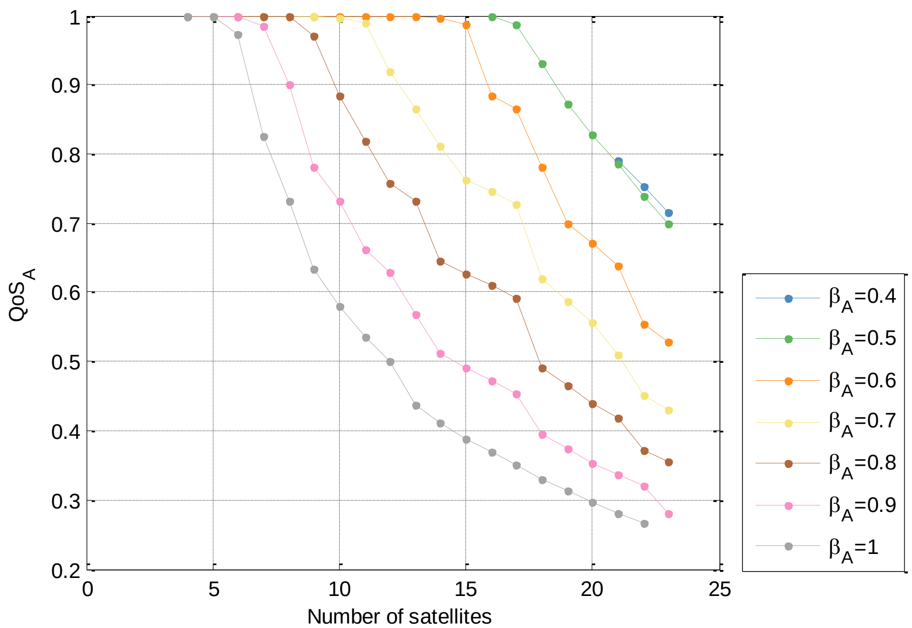
Task Name	Satellite	Utility	Resource	Consumption
Housekeeping Operations	*Mother*	100	Power	3 kW
			Data Volume	5Mbps
			Duty-cycle	100%
Housekeeping Operations	*Daughter*	100	Power	35 W
			Data Volume	1 Mbps
			Duty-Cycle	100%
Mission Data Download	*Daughter*	50	Power	40 W
			Data Volume	150 Mbps
			Duty-Cycle	40%



Results(I) – Cluster of Nanosatellites

QoS_A as a function of α and β

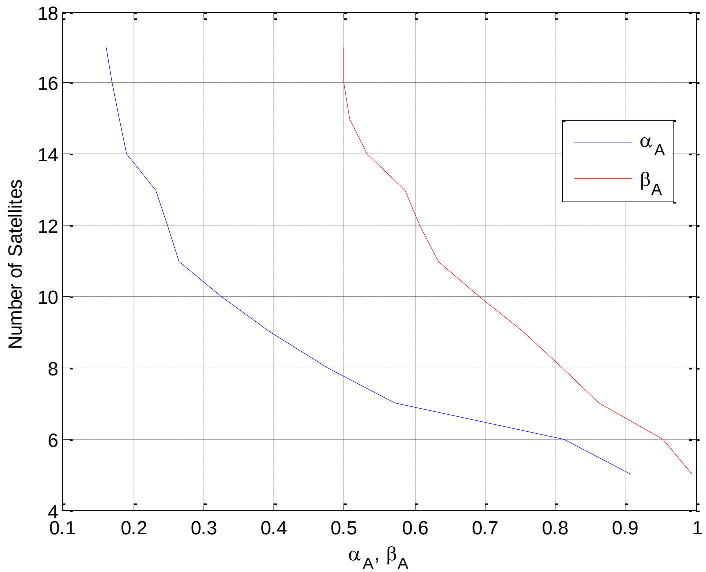


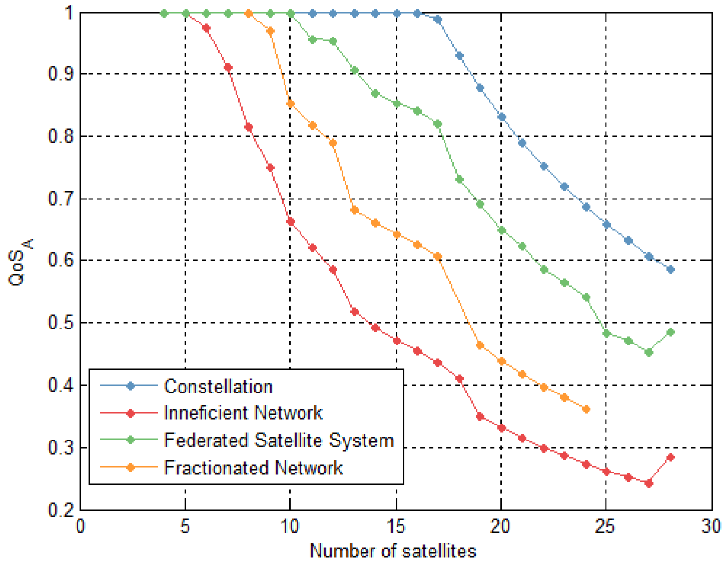


- The QoS_A degrades exponentially for a fixed value of α_A or β_A.
- Two regions are clearly differentiated. After certain point the network is saturated and it's impossible to get a higher value of QoS_A.
- The change to the second region occurs for values of β_A = 0.5. Even though only the mother satellite is giving all the communication resources to the system, there are so many satellites that the system isn't capable of downlinking enough information to achieve full stakeholder satisfaction .

Results(II) – Cluster of Nanosatellites

Maximum number of satellite by α and β and QoS_A as a function of type of network





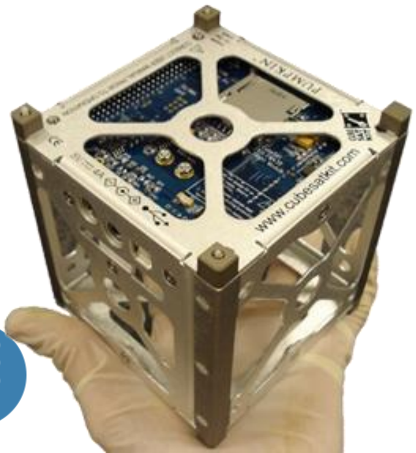
- While the degradation on the number of satellites supported by the system with α_A follows an exponential trend, the degradation with β_A follows a lineal trend.
- On the other hand, Federated Satellite Networks show a much better performance in terms of scalability than Fractionated Networks. This is due to the high losses that occur when extensive resource exchange happens.

Conclusions and Future work

- A holistic resource-based system model has been presented. Parameters α and β have been defined to classify satellites and architectures using a taxonomy.
- The scalability problem has been studied for static systems. The resource allocation process has been formulated as an optimization problem using integer programming.
- The resource allocation process was validated using real data from TDRSS as the input of the model. The results at the system level were coherent (errors < 10%), but not a satellite level.
- A case study using data from NASA's EDSN mission was presented to illustrate the utility and usefulness of the framework

Thanks for your attention ☺

Q&A



BACK UP SLIDES

Technological Parameters

- Three methods of energy exchange are considered:

- RIC:

$$\eta^{E}_{RIC} = 0.81 \frac{\left(1 - \operatorname{atan}\left(\frac{0.9(d-2)}{3.5}\right)\right)}{2}$$

- LASER

$$\eta^{E}_{LASER} = 0.37$$

- RF

$$\eta^{E}_{\mu W} = \eta_E G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$

TABLE VI
INTERDEPENDANCY COEFFICIENT BETWEEN ENERGY AND COMMS

Frequency Band	Data-rate	Amplifier Technology	RF Power	Efficiency	$K^{E,C}$
S-band	*1 Mbps*	SSPA	15 W	40 %	37.5 J/Mb
		TWTA	30 W	60 %	50 J/Mb
X-Band	*100 Mbps*	SSPA	15 W	28 %	0.54 J/Mb
		TWTA	25 W	60 %	0.42 J/Mb
Ka-band	*300 Mbps*	SSPA	9 W	17 %	0.18 J/Mb
		TWTA	50 W	50 %	0.33 J/Mb

TABLE VII
INTERDEPENDANCY COEFFICIENT BETWEEN ENERGY AND COMPUTING POWER

Micro-processor	Performance	Consumption	$K^{E,P}$
RAD750	*400 MIPS*	*5 W*	*0.0125 J/MI*
ATMEL AT697F	*86 MIPS*	*1 W*	*0.0116 J/MI*
TSC695FL	*12 MIPS*	*0.3 W*	*0.025 J/MI*