



On Scalability Limits of Federated Satellite Network Architectures

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14/10/2014

**2nd International Federated Satellite Systems
Workshop**

Skolkovo Institute of Science and Technology Moscow, Russia

- **Previous work – Motivation**
- **Scalability – some definitions**
 - Scalability on FSS
- **Methodology**
 - Workflow
 - Scheduling algorithm
 - Scenario Definition
- **Results**

Previous work at UPC BarcelonaTech

- On-going research on Distributed Satellite Systems & Fractionated Spacecraft for the last 4 years.
- Dual approach from a theoretical and practical perspective. NanoSat Lab with vacuum chamber, shake table, sun light canyon.
- Work on phone-based smartphones and CubeSats. Recipients of a Google Research Award.

Motivation

- How system where resource sharing and collaboration are essential scale is crucial for its operation and the scientific community has not addressed these issues in the space field yet.
- A general framework to study scalability on different types of fractionated networks has been developed.

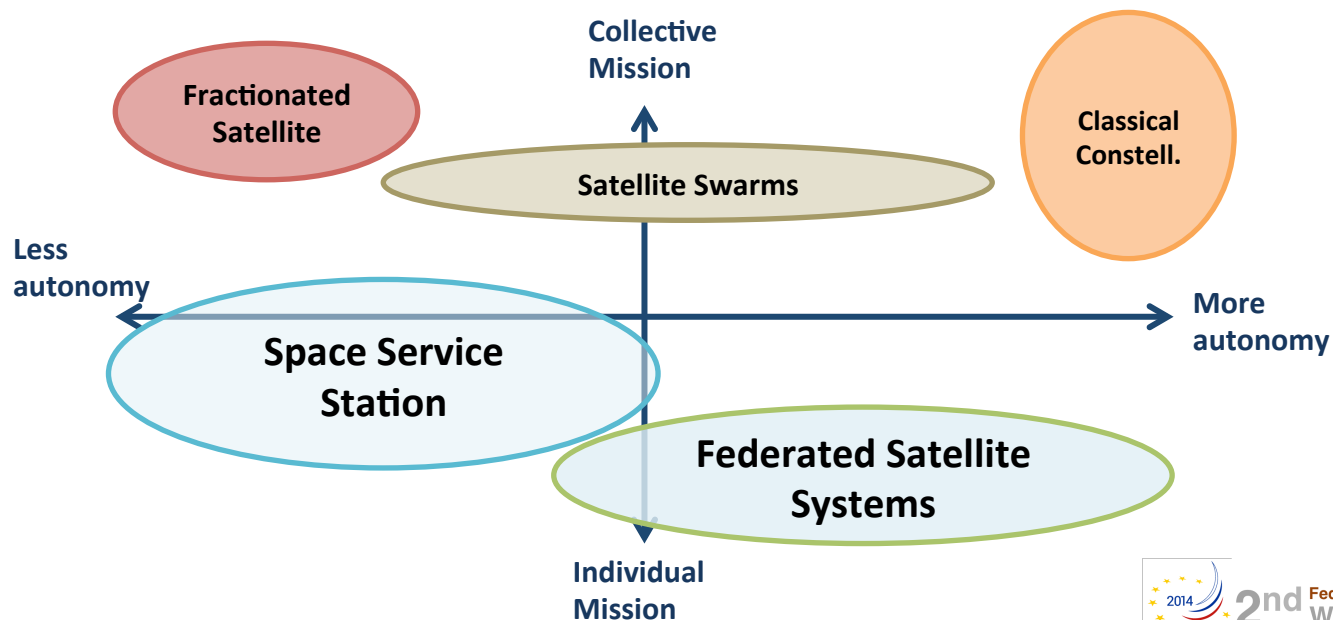


Fig 1.- Different Architecture types based on autonomy and mission purpose

Idea: Even though a lot of configurations of fractionated networks are possible, we believe that scalability of the network (understood in the sense on the evolution of the QoS offered to its users as the number of them increases) highly depends on the nature of the resource exchange process.

- A resource centric model for the system has been developed. Resources are the core of the analysis.
- Architectures (types of networks) are categorized based on the amount of resources given (taken) to (from) other nodes in the network. Defined parameters α and β capture this behavior.
- Exchanges of three main resources are considered: Communications, processing power and energy.
- Interactions among nodes are modelled using graphs.
- Only the resource allocation problem is addressed. No specific allocation algorithm is chosen.

$$\begin{pmatrix} \eta_{1,d(t_1)} P_{1,d(t_1)}^{R,t_1} & \dots & \eta_{N_s,d(t_1)} P_{N_s,d(t_1)}^{R,t_1} \\ \vdots & \ddots & \vdots \\ \eta_{1,d(t_{N_t})} P_{1,d(t_{N_t})}^{R,t_{N_t}} & \dots & \eta_{N_s,d(t_{N_t})} P_{N_s,d(t_{N_t})}^{R,t_{N_t}} \end{pmatrix} \begin{pmatrix} R_1^R \\ \vdots \\ R_{N_s}^R \end{pmatrix} = \begin{pmatrix} R_{obt}^{R,t_1} \\ \vdots \\ R_{obt}^{R,t_{N_t}} \end{pmatrix}$$

$$[MAX] z = \sum U_t p_t = \sum U_t \prod p_t^R = \sum U_t \prod \frac{R_{obt}^R}{R_{need}^R}$$

s.t:

$$R_{need}^R \geq ((T \cdot \eta^R) \circ p^R) R_s^R$$

$$1 \geq (p^R)^T \mathbf{1}$$

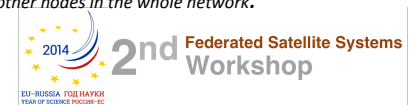
$$p_{ij}^{R,t} \geq 0$$

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	0,2 - 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.



“[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.*”

[Moses J. (2002)]

“*Scalability means not just the ability to operate, but to operate efficiently and with adequate **quality of service**, over the given **range of configurations**.*”

[Jogalekar P. (2000)]

“*An architecture is scalable ... if it has a linear (or sub-linear) increase in **physical resources usage** as **capacity increases**...*”

[Brataas G. (2004)]

“[Scalability is] *a quality of software systems characterized by the causal impact that scaling aspects of the system environment and design have on certain **measured system qualities** as these aspects are **varied** over expected **operational ranges**.*”

[Duboc L. (2007)]

- A FSS is a network of **heterogeneous** space-based systems where **resource sharing** leverages latent capabilities and increases the benefit obtained by each system.
- Initially, **communication**, **data storage** and **processing power** are envisioned as the main shared resources. In the future, **energy** is also envisioned as a shared resource.
- The **dynamics of the network** play a crucial role in the performance of the FSS.

Several questions arise in relation to how these systems scale:

- How do satellite networks scale when resource sharing is a key function of the system?
- What's the maximum number of satellites that the network can support?
- How many customer satellites can each FSS relay satellite support?
- How should relay satellites be disposed?

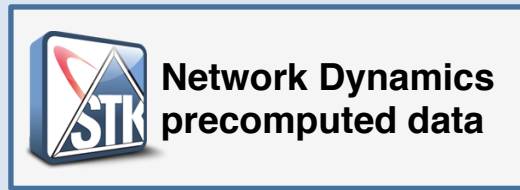
To ...

- determine **how FSS scale** as a function of certain variables
- determine what are the **limiting variables**

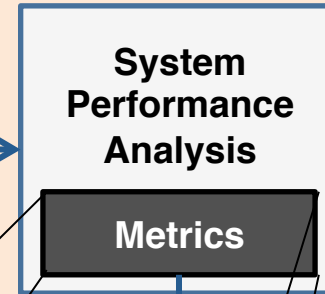
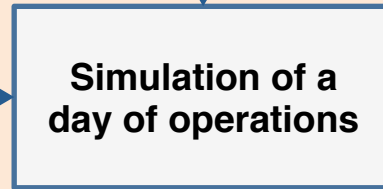
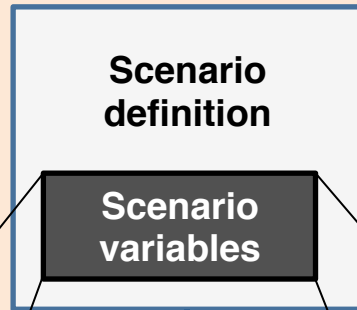
by...

simulating a day of operations and assessing how the **network performance** evolves as some **variables** are **swept**.

1



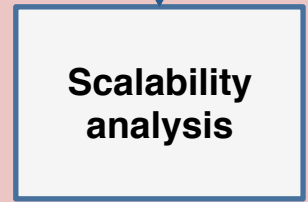
2



- **Scaling variables**
 - Number of customers
 - Number of relay satellites FSS
 - Configuration of relay satellites
 - β (time each relay satellite offers services to customers)
- **Non scaling variables**
 - Number & location of ground stations
 - User operation characteristics
 - Design parameters of the satellites

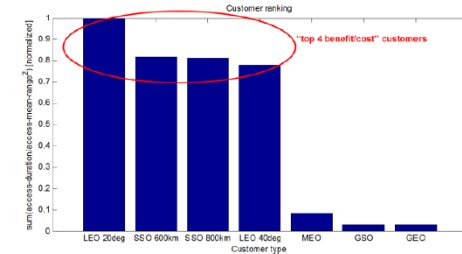
- **Metrics**
 - Δ contact time.
 - Number of intermediate hops
 - Δ data-volume
 - Latency

3



- Customers can belong to one of the following categories [2]:

- LEO inclination of 20 deg
- SSO altitude of 600 km
- SSO altitude of 800 km
- LEO inclination of 40 deg



- Customers are defined by the following parameters:

- Sets with 10, 30, 50, 70, 90 customers are defined
- These are the baseline customer-set for the analysis. All the network types use the same customer baseline

Attribute	Min. Value	Max. Value	Units
Max. Storage Data	100	600	Gb
TX. Data-rate	50	150	Mbps
Data generation	10	80	Mbps
Battery Capacity	10	200	Ah
Solar Array Size	30	130	m ²

- Relay Satellites

- Bus characteristics similar to the ones of Iridium NEXT for the Structured architectures and similar to the previously defined for the Unstructured ones.

[2] Golkar, A., “Federated Satellite Systems: A Case Study on Sustainability Enhancement of Space Exploration System Architectures”, IAC 2013, Beijing.

- Different configurations for the relay-network are considered during the analysis:
 - **Structured:** Similar to the Iridium constellation, as proposed in [1]. (Walker constellations)
 - **Unstructured:** Selecting relay - satellites that belong to one of the categories identified in [2] as promising FSS users.

	# planes	# sats / plane	% sats - Iridium
Iridium-4-7	4	7	42.42
Iridium-5-7	5	7	53.03
Iridium-5-9	5	9	68.18
Iridium-6-9	6	9	81.81
Iridium-6-11	6	11	100.00

	# satellites
Unstructured-28	28
Unstructured-40	40
Unstructured-56	56

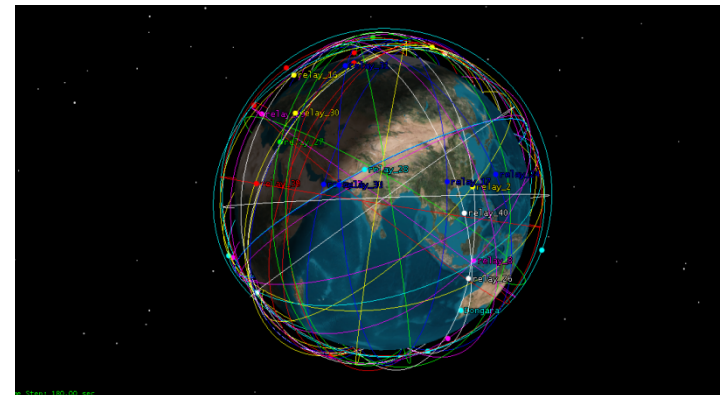
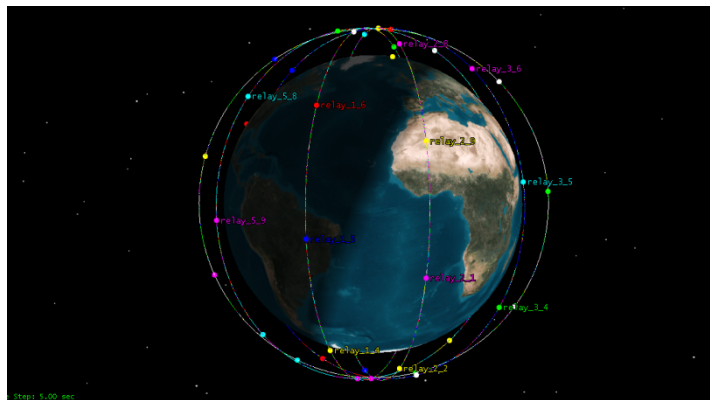


Fig 3.- Iridium-5-9 and Unstructured -40 configurations

[2] Golkar, A., “Federated Satellite Systems: A Case Study on Sustainability Enhancement of Space Exploration System Architectures”, IAC 2013, Beijing.

- The only shared resource is communications downlink.
- Maximum range to establish a contact is 5000 km.
- Both cases with intermediate hops / without intermediate hops are studied. The network type is assumed to be bent-pipe.
- A set of 4 ground stations is selected (White-Sands, Svalbard, Dongara, Hawaii) These stations are used both as relay SGL ground-stations and DTE ground-stations.

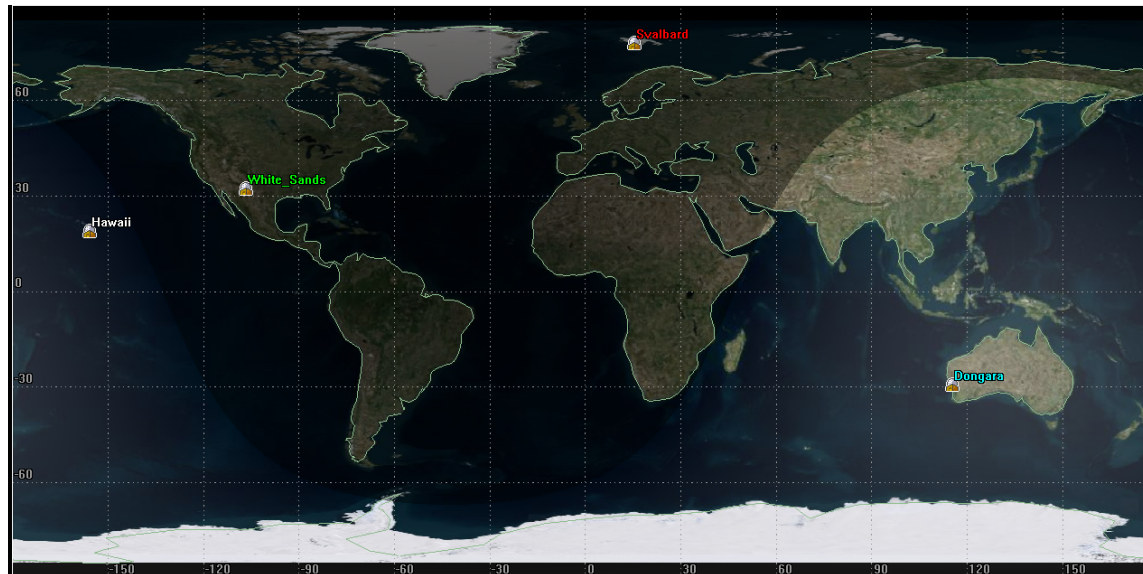


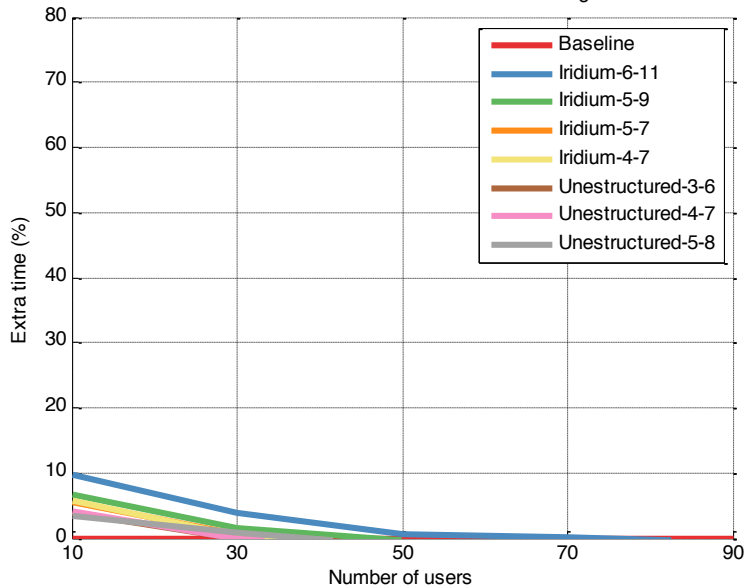
Fig 4.- Location of the ground stations

- Analysis consists on varying the number of users (up to 90). Those are selected form a pool of 100 users.
- Montecarlo analysis over the subsets of user-satellites is performed to average noise.
- A Discrete Event Simulator (DES) is used to perform the analysis:
 - Events include...
 - Eclipses
 - Inter-relay network connections and routing
 - Start / ending of user transmission
 - Not included events:
 - ADC maneuvers
 - Data generation events (measurements acquisition, image capture)
 - Failures or unexpected operations
 - TT&C events
- A graph that contains the viable links information is constructed every 60 s. (DTS, in order to improve execution time)
- FSS satellites can be contacted by other nodes of the network during a percentage (β) of the time.

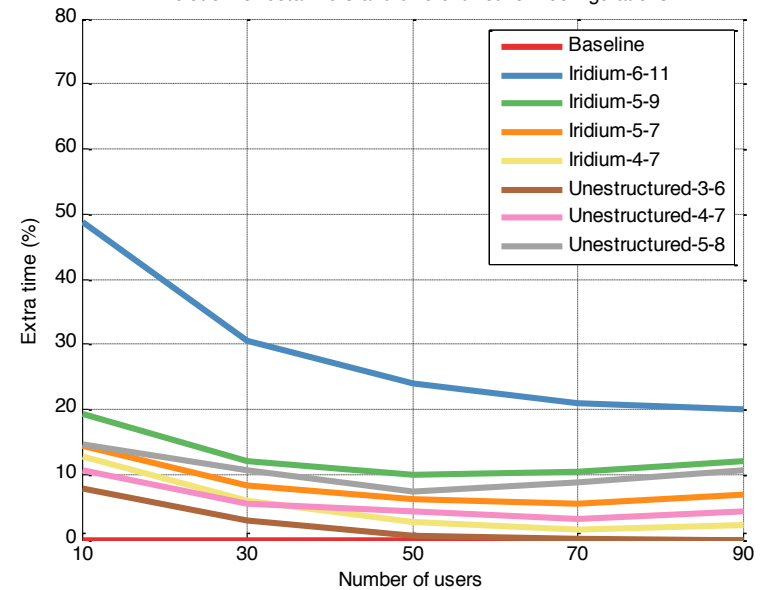
- A day of operations (1st Jan 2014) is simulated.
- A greedy approach to assign downlink time is followed:
 - When a satellite reaches 80% of its maximum storage capacity request a downlink transmission service to the FSS infrastructure / ground stations.
 - Routing policy: shortest path (minimum number of hops) to any ground station is selected.
 - FSS Satellites can either relay an existing communication or be a sink node.
 - A ground station can support 3 accesses from satellites (users and FSS-relays).
 - A bent-pipe network type is used (data-in → data-out)
 - No prioritization is established for accessing to the resources. (No auction algorithms, no pricing strategies). FIFO.

The solution obtained is non-optimal.

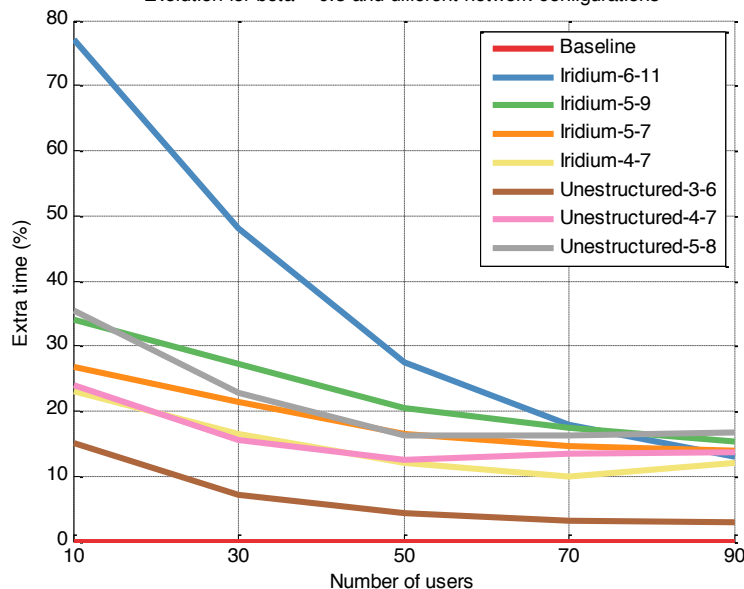
Evolution for beta = 0.1 and different network configurations



Evolution for beta = 0.3 and different network configurations

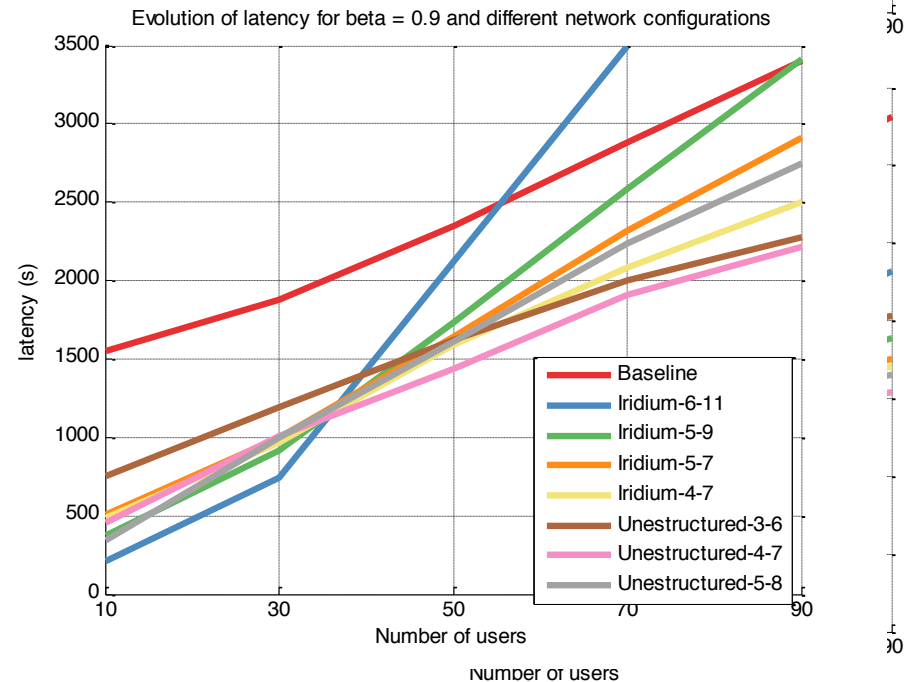
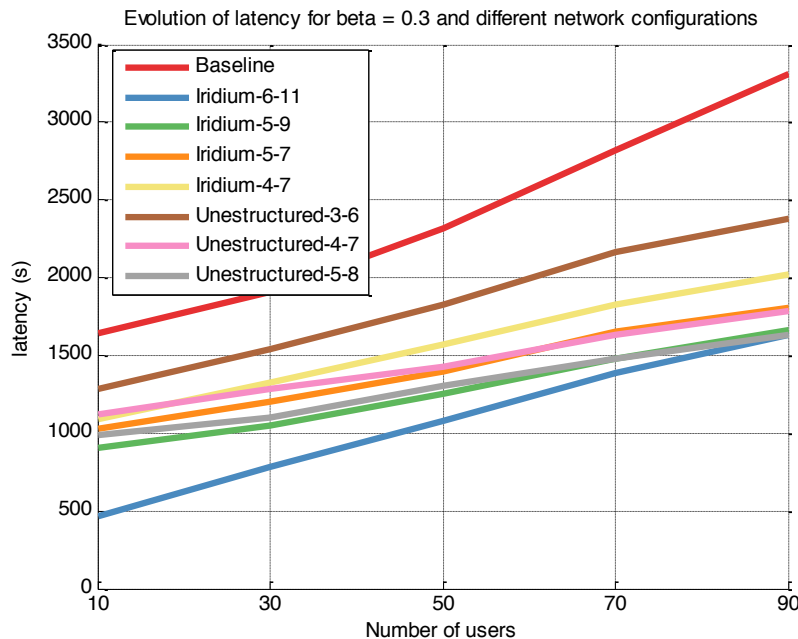
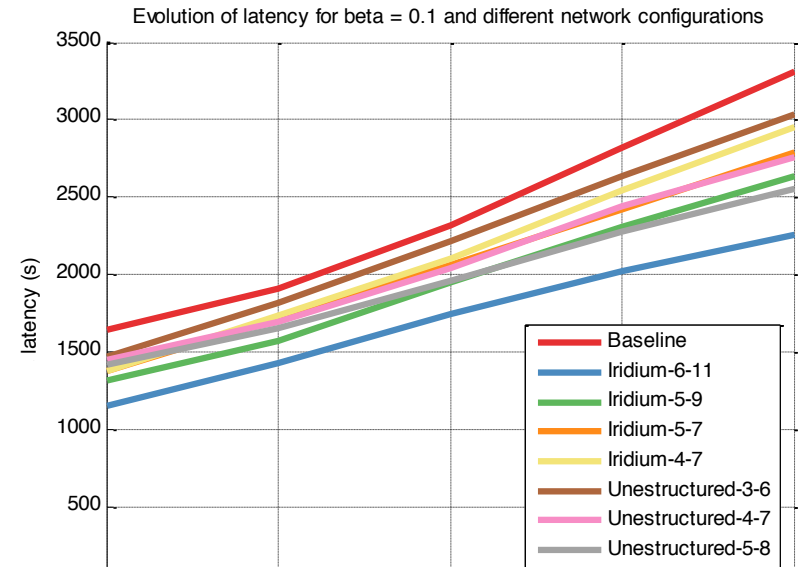


Evolution for beta = 0.5 and different network configurations

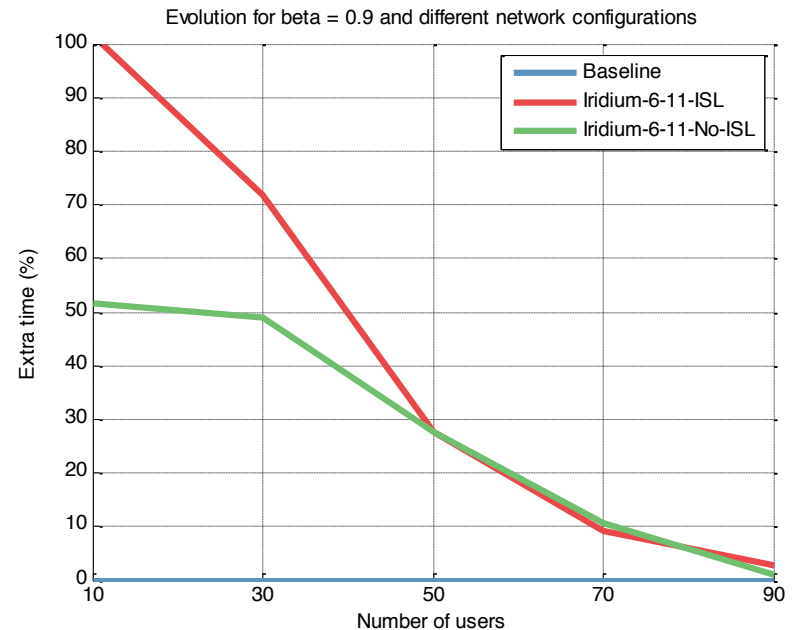
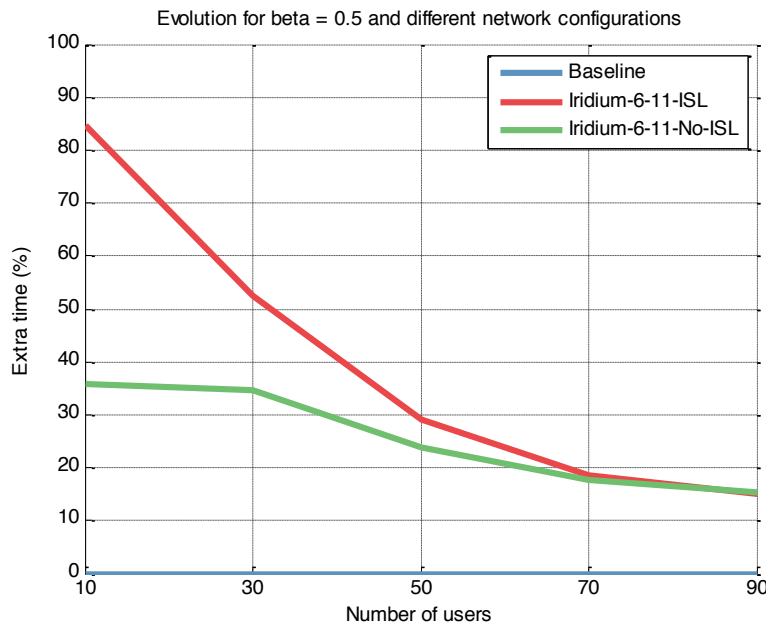
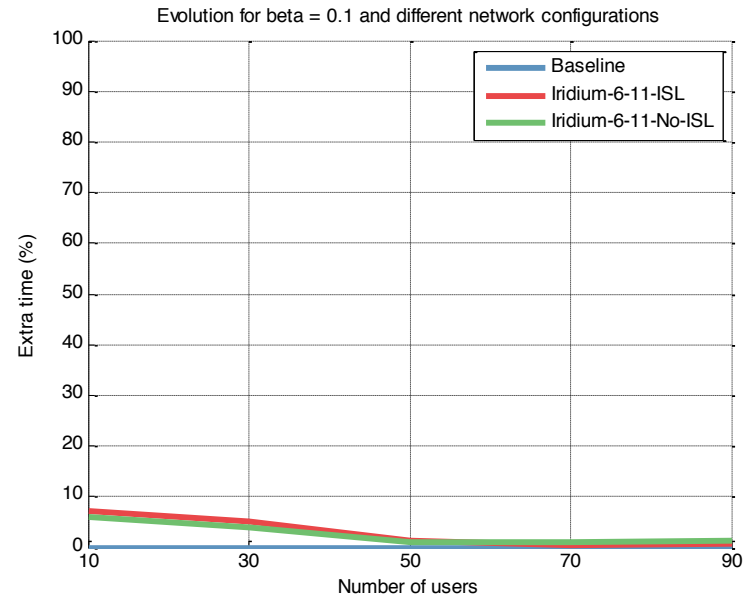


- The network's D contact time shows a quick initial exponential degradation followed by a linear degradation.
- For $\beta = 0.1$ and most types of networks the extra duration of contacts is between 3 and 6 % of what was obtained on the Baseline scenario (Only GS)
- No big differences are observed between Structured (Iridium) and non structured constellations.
- For $\beta = 0.5$ implies having $\sim 8x$ more extra contact time than with $\beta = 0.1$

- Unstructured networks offer a better latency reduction than the structured ones.
- At first glance, seems that the more satellites that act as a relay, the lower the latency is. (Customers get higher reduction in latency compared to the baseline)
- If the network is close to full meshed, this tendency changes, and users actually get a worse performance due to “network flooders”



- For very low β , having multiple hops doesn't bring any extra benefit as compared to not having them.
- For low number of customers and medium-high β , multiple hops allow to double the extra time as
- For high number of users, again, the performance of the ISL network is indistinguishable from the no-ISL network.



Conclusions

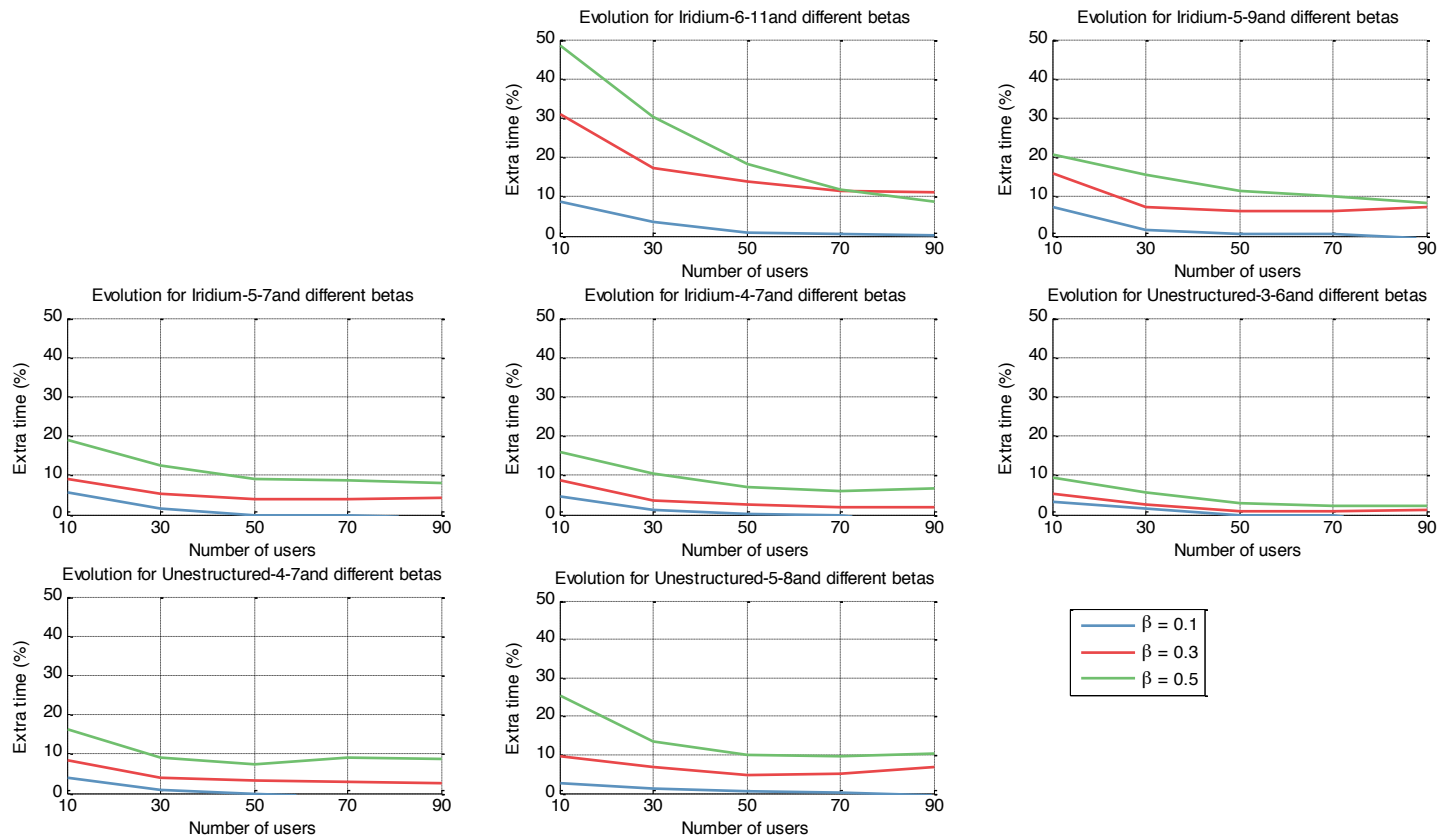
- β is the driving variable for the extra time of contact.
- Constellations with low numbers of users obtain the highest Δ of contact time. Then, the performance degrades exponentially until it is similar to the obtained without the presence of FSS.
- Unstructured vs. Structured networks don't show great differences in terms of the extra time guaranteed. However, Unstructured networks offer improvements in terms of latency as compared to structured networks..
- Very high values of β can led to network flooding by some users if measures to alleviate this effect are not taken. This results in higher latencies and lower Δ contact time for the rest of the users.
- Multiple hops bring value for medium-high values of β . Multiple hops allow to double the Δ contact time for low-number-customers scenarios but brings no value for high number customers scenarios.

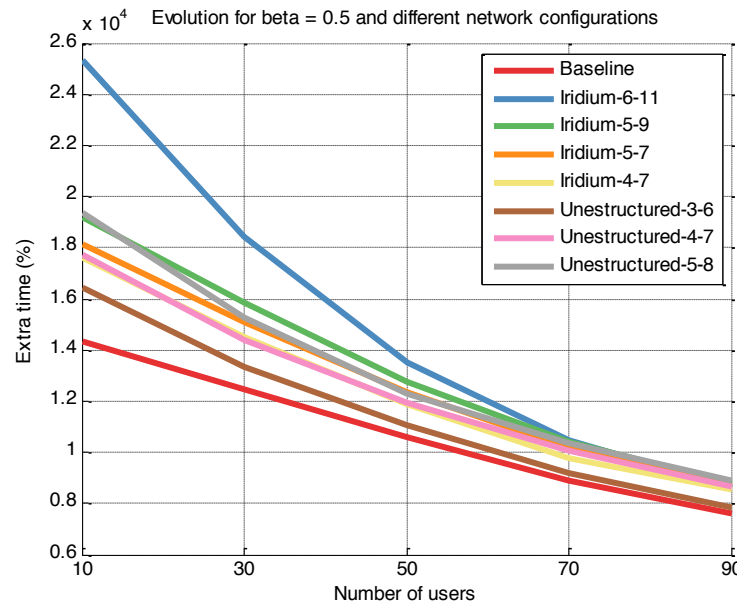
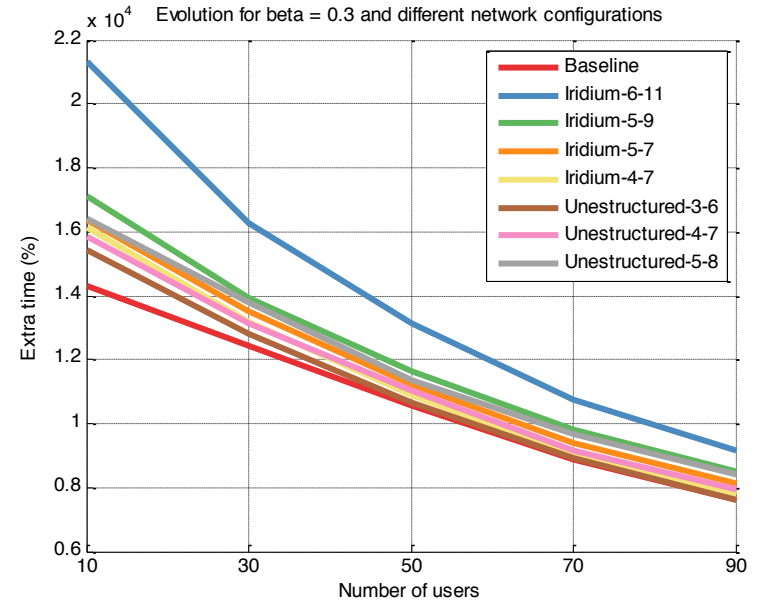
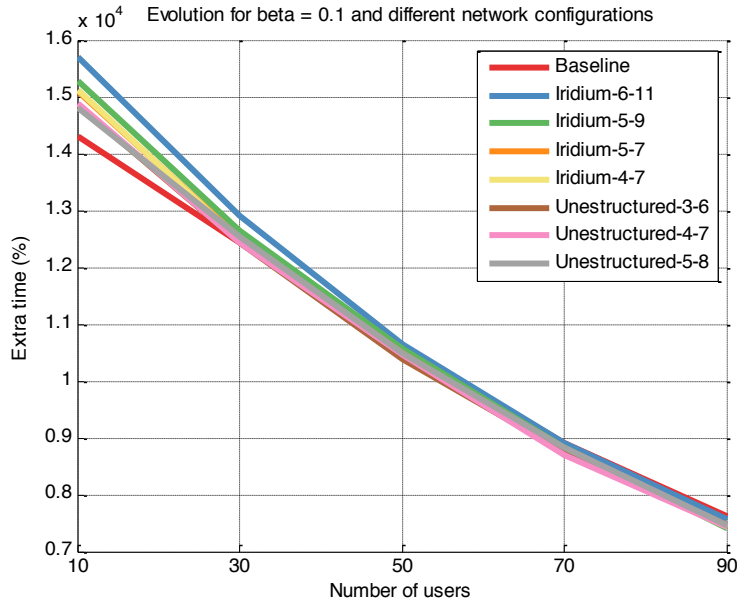
THANK YOU

Q&A

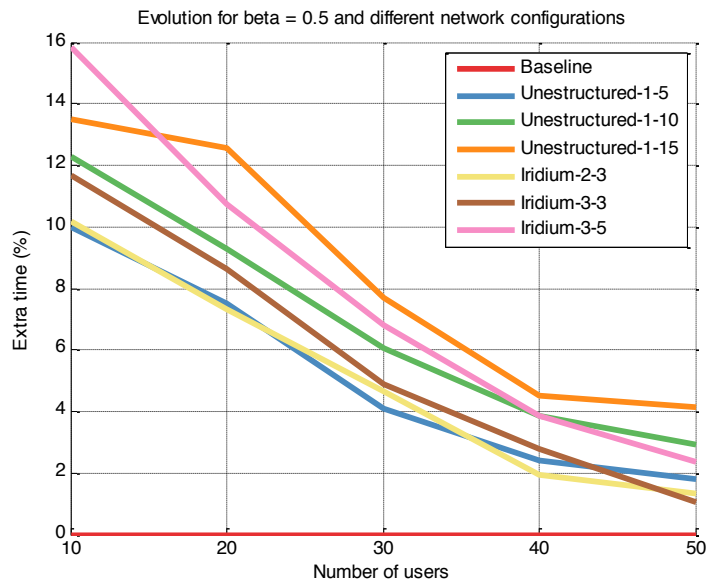
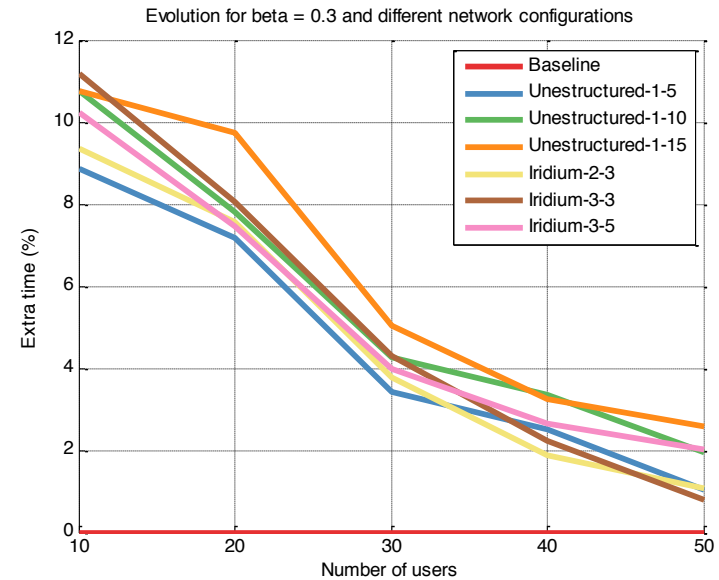
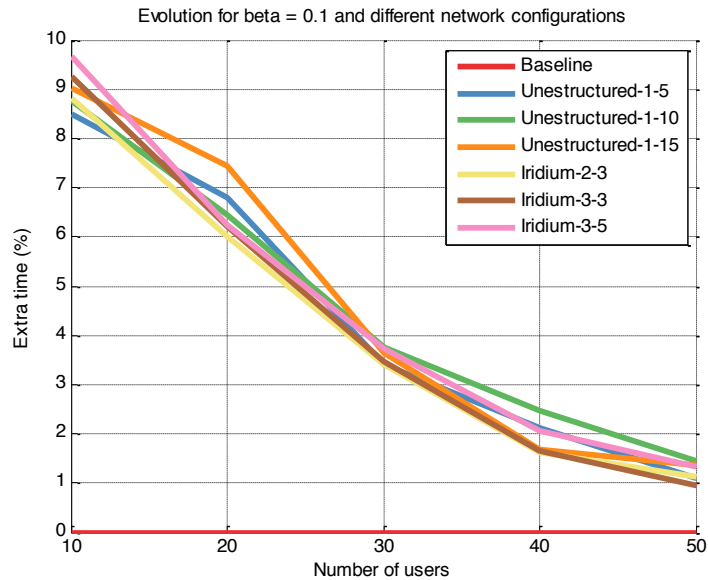


- β is the driving variable for the extra time (amount of data) that can be obtained (downloaded).
- For low values of β the network rapidly degrades as the number of users increases. Even for massive configurations such as Iridium-6-11.

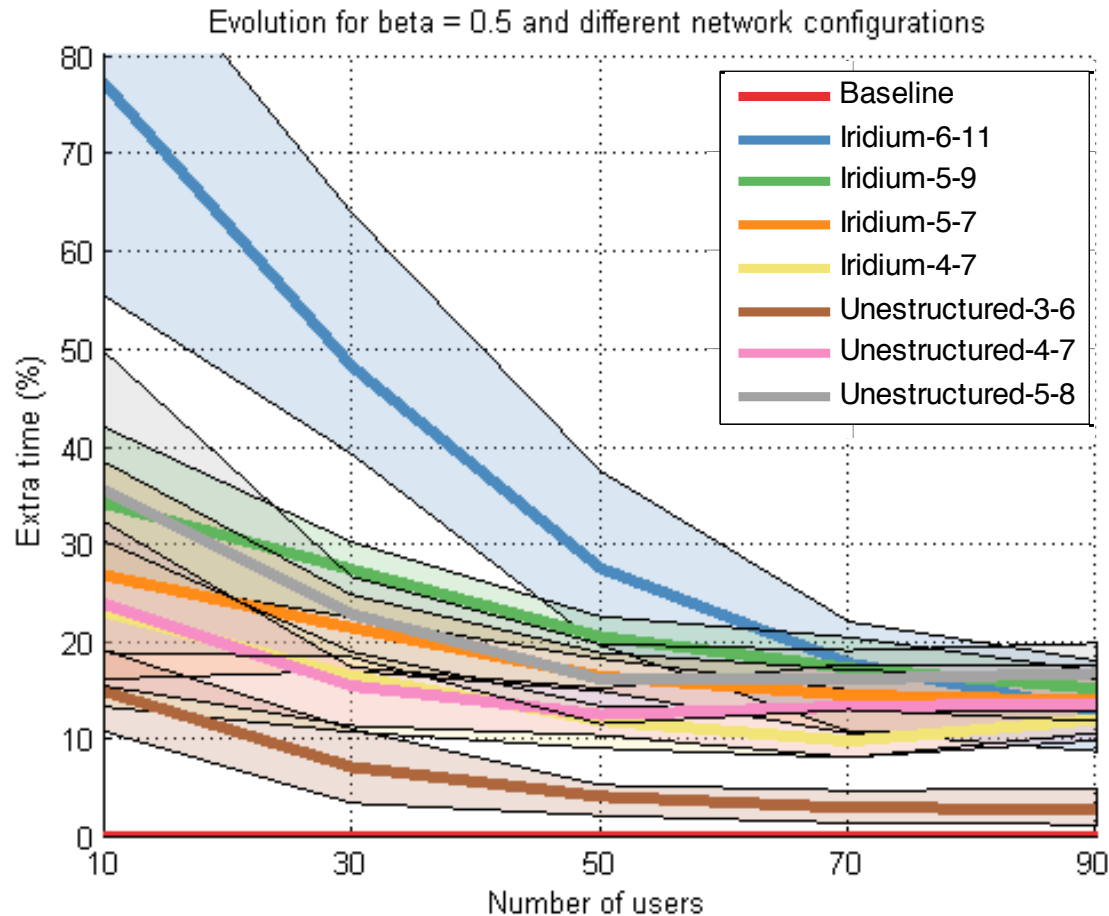




NOTE: Y-Axis range is not always the same



- For $\beta = 0.1$ and small amounts of relay-satellites (5-15), all types of the networks behave in a similar way.
- Again, no big differences are observed between Structured (Iridium) and non structured constellations.
- For $\beta = 0.5$ the $\sim 8x$ extra time respect to the $\beta = 0.1$ is not valid anymore.



- Shape shows the range of values found for a 16 user-set Montecarlo simulation.
- For low number of users uncertainty is high, due to the heterogeneity of the network. In contrast, the more users, the more averaged are all the values.