On Scalability of Fractionated Satellite Network

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• Introduction and Motivation
  – Fractionated Satellite Networks
  – Motivation: Scalability as a critical property of FSN
• System Model
• Implementation
  – General Framework
  – Resource Allocation
• Validation of the Resource 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 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 closest real system to a FSN: TDRSS
- A hypothetical case example to show the application of the framework to other domains is presented.
Three kind of resources are modeled (Energy, Comms, Processing Power).

Two parameters characterize how resources are transferred:
- Transfer efficiency: \( \eta_{ij}^R = \frac{R_{R_{\text{UTIL}}}}{R_{R_{\text{TOTAL}}}} = \frac{R_{\text{useful}}}{R_{\text{useful}} + R_{\text{losses}}} \)
- Interdependency coefficient: \( \kappa_{R_1,R_2}^R = \frac{R_{R_1 + R_{R_{\text{TOTAL}}}}}{R_{R_2}} \)

On a satellite, the resource balance equation must hold at any time.
The expected value of the storage term \( (\Delta R_{R_{\text{stored}}}) \) is 0.

To characterize the degree of fractionalization two parameters are defined:

\[
\alpha^R = \frac{R_{R_{\text{in}}}}{R_{R_{\text{in}}} + R_{R_{\text{in}}}}
\]
\[
\beta^R = \frac{R_{R_{\text{out}}}}{R_{R_{\text{out}}} + R_{R_{\text{out}}}}
\]

<table>
<thead>
<tr>
<th>Type Of Node</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>Source Of ( R_{\text{in}} )</th>
<th>Destination Of ( R_{\text{out}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure Node</td>
<td>0 - 0,1</td>
<td>0,9 - 1</td>
<td>Own Production</td>
<td>Infrastructure</td>
</tr>
<tr>
<td>Client Node</td>
<td>0,3 - 1</td>
<td>0 - 0,1</td>
<td>Infrastructure</td>
<td>Own Consumption</td>
</tr>
<tr>
<td>Relay Node</td>
<td>1</td>
<td>1</td>
<td>Infrastructure</td>
<td>Infrastructure</td>
</tr>
<tr>
<td>Buffer Node</td>
<td>0 - 1</td>
<td>0</td>
<td>Infrastructure or Own Production</td>
<td>Storage</td>
</tr>
<tr>
<td>Dedicated Node</td>
<td>0,1 - 0,9</td>
<td>0,1 - 0,9</td>
<td>Infrastructure or Own Production</td>
<td>Own Consumption, Storage or Infrastructure</td>
</tr>
<tr>
<td>Autonomous Node</td>
<td>0 - 0,3</td>
<td>0 - 0,1</td>
<td>Own Production</td>
<td>Own Consumption or Storage</td>
</tr>
</tbody>
</table>

\( Fig 1. - Type \ of \ network \ nodes \)
\( \alpha \) percentage of resources coming from other nodes,
\( \beta \) percentage of resources given to other nodes.
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.

\[
\alpha_A = \frac{\sum_{i|n(T^i) > 0} \alpha_i R^i_{in}}{\sum_{i|n(T^i) > 0} R^i_{in}} \\
\beta_A = \frac{\sum_i \beta_i R^i_{out}}{\sum_i R^i_{out}}
\]

<table>
<thead>
<tr>
<th>Type of Architecture</th>
<th>$\alpha_A$</th>
<th>$\beta_A$</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constellation</td>
<td>0 - 0,1</td>
<td>0 - 0,1</td>
<td>Satellites are autonomous, resource exchange is almost not present</td>
</tr>
<tr>
<td>Fractionated Network</td>
<td>0,4 - 1</td>
<td>0,2 - 1</td>
<td>Resource sharing is essential for the network to execute its tasks</td>
</tr>
<tr>
<td>Federated Satellite System</td>
<td>0,1 - 0,4</td>
<td>0,1 - 1</td>
<td>Some satellites receive some resources from the infrastructure. However, most of the resources come from own sources</td>
</tr>
<tr>
<td>Oversized Network</td>
<td>0,4 - 1</td>
<td>0 - 0,2</td>
<td>Resources needed to perform tasks come from the infrastructure, but resources delivered to the infrastructure are very little compared to the amount produced.</td>
</tr>
<tr>
<td>Inefficient Network</td>
<td>0 - 0,1</td>
<td>0,9 - 1</td>
<td>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)</td>
</tr>
</tbody>
</table>

*Fig 2.* Architecture types

$\alpha_i$, percentage of resources coming from other nodes in the whole network, $\beta_i$, percentage of resources given to other nodes in the whole network.
Mission and Tasks

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

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

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

• 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.

\[
\begin{align*}
\text{MAX} & \quad QoS_A = f(U_t, R_{\text{obt}}, R_{\text{need}}) \\
\text{s.t.} & \quad \begin{pmatrix}
R_{\text{need}}^E \\
R_{\text{need}}^C \\
R_{\text{need}}^P
\end{pmatrix} \geq \begin{pmatrix}
R_{\text{obt}}^E \\
R_{\text{obt}}^C \\
R_{\text{obt}}^P
\end{pmatrix} = \begin{pmatrix}
\left( (T \cdot \eta_{CM}^E) \circ x^E \right) & R_{\text{s,ava}}^E \\
\left( (T \cdot \eta_{CM}^C) \circ x^C \right) & R_{\text{s,ava}}^C \\
\left( (T \cdot \eta_{CM}^P) \circ x^P \right) & R_{\text{s,ava}}^P
\end{pmatrix} \\
1 &= (x^R)^T 1 \\
1 - \alpha_i &\geq x_{ii}^{R,t} \geq 0 \\
\alpha_i &\geq \sum_{i \neq j} x_{ij}^{R,t} \\
\beta_{a(t_j)} &\geq x_{ij}^{R,t} \geq 0, \quad i \neq j
\end{align*}
\]

The interaction among resources is explicitly depicted in this equation.

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

<table>
<thead>
<tr>
<th>Metric</th>
<th>Band</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna Utilization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S (SA)</td>
<td></td>
<td>6.48 %</td>
</tr>
<tr>
<td>Ku (SA)</td>
<td></td>
<td>3.46 %</td>
</tr>
<tr>
<td>S (MA)</td>
<td></td>
<td>42.74 %</td>
</tr>
<tr>
<td><strong>Satellite Utilization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite</td>
<td>S-Band</td>
<td>Ku-Band</td>
</tr>
<tr>
<td></td>
<td>Difference (%)</td>
<td>Difference (%)</td>
</tr>
<tr>
<td>TDRS-3</td>
<td>2.28 %</td>
<td>29.75 %</td>
</tr>
<tr>
<td>TDRS-5</td>
<td>10.79 %</td>
<td>31.13 %</td>
</tr>
<tr>
<td>TDRS-7</td>
<td>57.40 %</td>
<td>81.02 %</td>
</tr>
<tr>
<td>TDRS-9</td>
<td>55.06 %</td>
<td>0.24 %</td>
</tr>
<tr>
<td>TDRS-10</td>
<td>31.01 %</td>
<td>102.3 %</td>
</tr>
</tbody>
</table>

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.
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 ($\alpha$ and $\beta$) and the number of client satellites are swept during the analysis.

Results are grouped depending on values of $\alpha_A$ and $\beta_A$
The QoS_A degrades exponentially for a fixed value of $\alpha_A$ or $\beta_A$.

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 $\beta_A = 0.5$. 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 \( \alpha \) and \( \beta \) and QoS\(_A\) as a function of type of network

- While the degradation on the number of satellites supported by the system with \( \alpha_A \) follows an exponential trend, the degradation with \( \beta_A \) 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.
• A holistic resource-based system model has been presented. Parameters $\alpha$ and $\beta$ 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 at 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
Three methods of energy exchange are considered:

- **RIC**:
  \[ \eta^E_{RIC} = 0.81 \left( 1 - \frac{\tan^{-1}\left( \frac{0.9(d-2)}{3.5} \right)}{2} \right) \]

- **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

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Data-rate</th>
<th>AMPLIFIER TECHNOLOGY</th>
<th>RF POWER</th>
<th>EFFICIENCY</th>
<th>K_{E,C}</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band</td>
<td>1 Mbps</td>
<td>SSPA</td>
<td>15 W</td>
<td>40 %</td>
<td>37.5 J/Mb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWTA</td>
<td>30 W</td>
<td>60 %</td>
<td>50 J/Mb</td>
</tr>
<tr>
<td>X-band</td>
<td>100 Mbps</td>
<td>SSPA</td>
<td>15 W</td>
<td>28 %</td>
<td>0.54 J/Mb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWTA</td>
<td>25 W</td>
<td>60 %</td>
<td>0.42 J/Mb</td>
</tr>
<tr>
<td>Ka-band</td>
<td>300 Mbps</td>
<td>SSPA</td>
<td>9 W</td>
<td>17 %</td>
<td>0.18 J/Mb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWTA</td>
<td>50 W</td>
<td>50 %</td>
<td>0.33 J/Mb</td>
</tr>
</tbody>
</table>

### TABLE VII

<table>
<thead>
<tr>
<th>Microprocessor</th>
<th>Performance</th>
<th>Consumption</th>
<th>K_{E,P}</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAD750</td>
<td>400 MIPS</td>
<td>5 W</td>
<td>0.0125 J/MI</td>
</tr>
<tr>
<td>ATMEL AT697F</td>
<td>86 MIPS</td>
<td>1 W</td>
<td>0.0116 J/MI</td>
</tr>
<tr>
<td>TSC695FL</td>
<td>12 MIPS</td>
<td>0.3 W</td>
<td>0.025 J/MI</td>
</tr>
</tbody>
</table>