Chapter

System-of-Systems Enterprise CONOPS Assessment Decision Support Tools

Thomas O. Freeze, Tien M. Nguyen and Charles H. Lee

Abstract

This chapter discusses the implementation of System-of-Systems Enterprise Architecture (SOSEA) CONOPS assessment framework and models in Matlab, and presents preliminary results concerning SOSEA resiliency in the presence of a notional Radio Frequency Interference (RFI) scenario. The chapter provides an overview of the SOSEA CONOPS Assessment Framework, and discusses related SOS Resiliency Models including Resilient Assessment Index Against RFI (RAI-RFI), Spectrum Resiliency Assessment Index (SRAI), and Resilient Capacity (RC).

Keywords: SOS enterprise architecture, CONOPS, resilient capacity, resilience assessment index against radio frequency interference, spectrum resiliency assessment index, satellite communication, satellite operation

1. Background and introduction

In 2011, The Department of Defense (DOD) established a formalized concept of resilience for space systems and Systems-of-Systems (SOS) [1]. They define resilience as the ability of an architecture to support the functions necessary for mission success in spite of hostile action or adverse conditions. Similarly, in Enhancing Space Resilience Through Non-Material Means McLeod, et al. define resilience as "an attribute of a system that generally indicates its ability to maintain critical operations in the face of adverse disruptions" [2]. However, they acknowledge that there is much room for variation to this definition depending on circumstances and priorities. Gregory Edlund splits resilience evaluations into two broad categories of either being analytic or deterministic [3]. For Edlund, analytic models are geared more towards attempting to measure or score a system's resilience. Deterministic models are focused more on characterizing a system's breaking points, which Edlund argues may be more useful in practice. This chapter addresses the modeling of SOS Enterprise Resiliency and its metrics.

The U.S. Military uses communications satellite systems to facilitate beyond line-of sight communications. For decades, the satellite space has been largely uncontested. However, the orbital space around the Earth has become more congested as technology advances. Such advances make the space environment more accessible to various organizations. Third party un-intentional interferences with the military satellite communication system are a growing and serious threat as more and more government, commercial, and civilian entities enter the orbital space environment. This chapter discusses three models to analyze different resiliency aspects of the military's satellite space system against the threats caused by third party RFI with a focus on unintentional interferences. The first model is the Resilience Assessment Index Against RFI (RAI-RFI) that will be used to assess the robustness and reconstitution of a SOS [4, 5, 6, 7]. The Second model is the Spectrum Resilience Assessment Index (SRAI) [4, 6, 7, 8], which is an expansion of the RAI-RFI. By adding spectrum analysis to the RAI-RFI model, the amount of time that a communication link can access its allocated frequency band can be measured in the presence of disruptive events, such as RFI. Various communication technologies can then be compared to identify the best technology for enhanced spectrum resilience. The third model is the Resilient Capacity (RC) model, which assesses a SOS ability against RFI threats [4, 5, 6, 7, 8]. Additionally, the RC score will attempt to be improved when RFI causes disconnections by augmenting the military system with a pre-existing commercial or civilian satellite.

This chapter presents the work done in 2018 by CSUF graduate student team with a focus on the Matlab implementation of RAI-RFI, SRAI and RC models. The chapter organizes as follows: (i) Section 2 provides definition of SOS resiliency and its metrics for evaluation the resiliency; (ii) Section 3 discusses the differences between SOS Enterprise (SOSE) CONOPS and SOSE Architecture (SOSEA) – Section 3 also provides description a notional Satellite Operation (SATOP) SOSE CONOPS and Satellite Communication (SATCOM) SOSE CONOPS; (iii) Section 4 provides an overview of the proposed SOSEA CONOPS assessment approach, including framework and associated models; (iv) Section 5 presents an implementation approach of the framework and models in Matlab commercial-of-the-shelf software; (v) Section 6 discusses SOSE CONOPS Modeling in Matlab; (vi) Section 7 addresses the SOSE RAI-RFI Modeling in Matlab and simulation results; (vii) Section 8 describes SRAI model implementation and simulation results in Matlab; (viii) Section 9 discuss RC Model implementation and simulation results in Matlab; and (viii) Section 10 concludes the chapter with a discussion on the preliminary results and way-forward.

2. Definition of SOS resiliency and its metrics

In this chapter, the metric "Resiliency" is defined in the context of RFI threats, i.e., Resiliency against RFI threats. The RFI threats include both Friendly and Un-friendly RFI threats. The chapter focuses on the following three Resiliency metrics [4]:

- Resilience Assessment Index Against Radio Frequency Interference (RAI-RFI): This is a newly proposed "Robustness-and-Reconstitution" metric that calculates the probability of a ground tracking system or a satellite communication system is being disrupted by RFI events and its ability to reduce RFI by re-routing the desired signal to avoid RFI threats. RAI-RFI provides a measure of SOSE robustness and quality of reconstitution.

- Spectrum Resiliency Assessment Index (SRAI): SRAI is also a newly proposed "Avoidance-Robustness-and-Reconstitution Metric", which derived from the U. K. Ministry of Defense (MOD) that defines the ability of a system that can access the spectrum and be able to response to a disruptive event. SRAI is a metric that is calculated based on the probability that a system can access to its allocated RF frequency band in the presence of un-friendly and/or friendly-RFI threats.

- Resilient Capacity (RC): This metric is derived from the "DOD Definition of Resilience" focusing on Avoidance, Robustness, Reconstitution, and Recovery

> RC is defined as the SOSE's probability that two arbitrary nodes within a SOSE network can communicate with each other amidst RFI adversity. It is a function of Avoidance, Robustness, Recovery and Reconstitution. Nodes can be a ground tracking node on the ground or a satellite node in space

3. SOS enterprise CONOPS vs. SOSEA

The differences between SOSE CONOPS and SOSEA are illustrated in **Figure 1**. The detailed description of this figure can be found in [5].

3.1 Notional satellite operation SOSE CONOPS

Figure 2 illustrates a notional SATOP SOSE CONOPS that will be used for the development of the SOS tools presented in this chapter. The detailed description of this figure can also be found in [5].

3.2 Notional satellite communication SOSE CONOPS

A notional SATCOM SOSE CONOPS can be found in [5]. For the purpose of the SOS tool development, **Figure 3** shows the notional SATCOM SOSE CONOPS used for the demonstration of the SOSE tools discussed in this chapter. Note that the communication satellite RFI Node 4 and exo-atmospheric Jammer Node 1 show a potential un-intentional and intentional RFI sources, respectively, that can disrupt

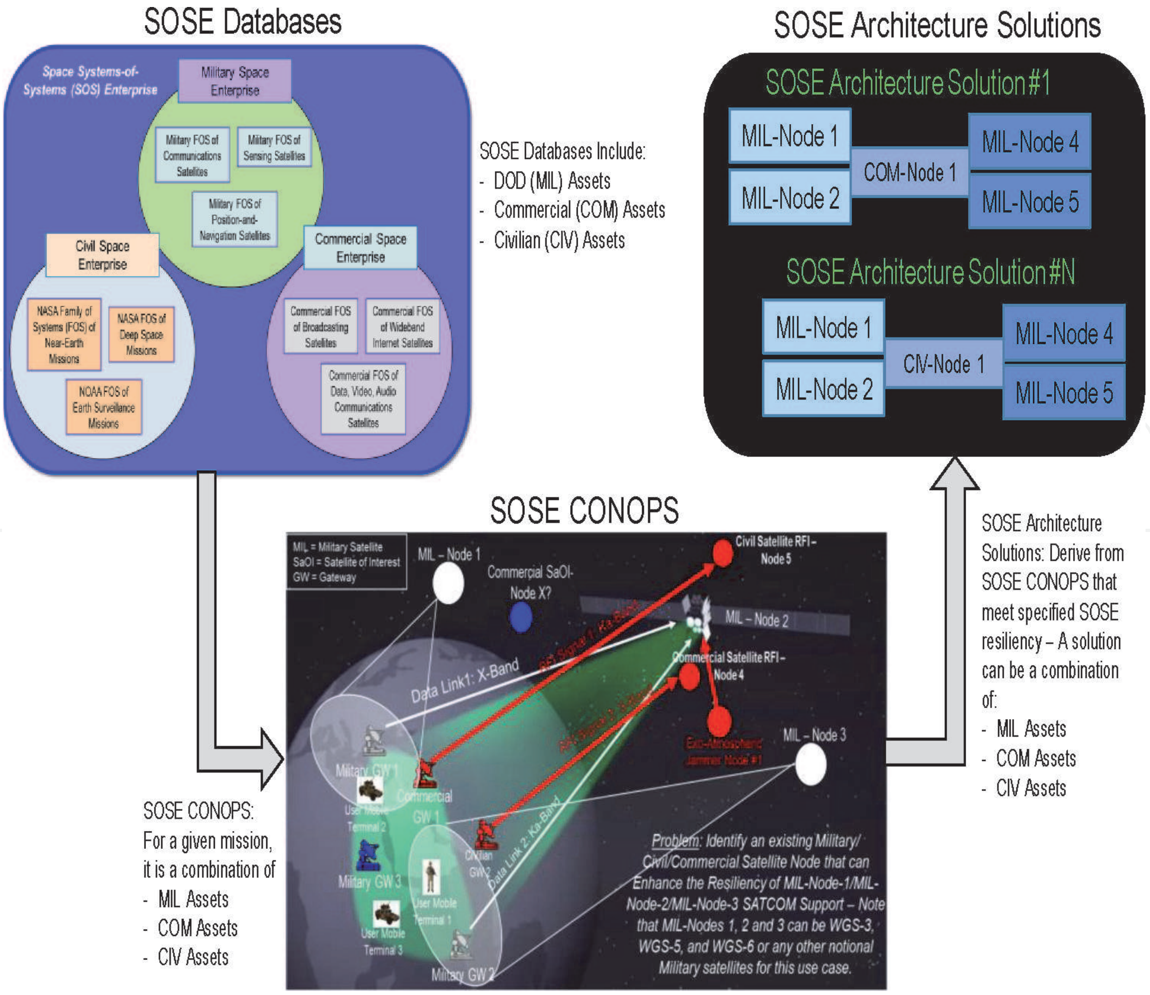
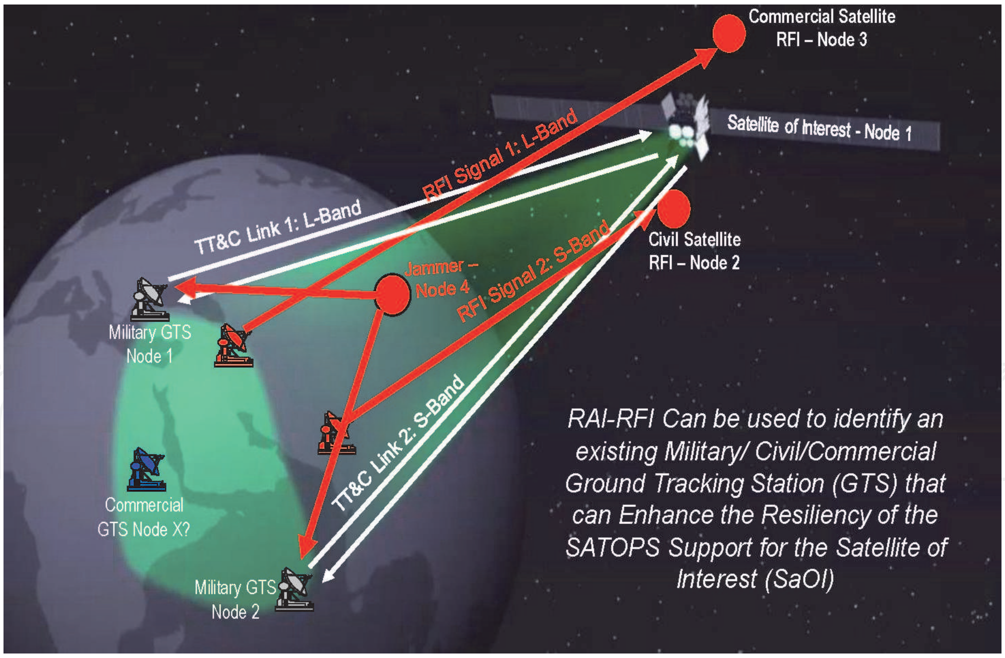


Figure 1.
Overview of SOSE CONOPS and SOSEA solutions [5].



RAI-RFI Can be used to identify an existing Military/ Civil/Commercial Ground Tracking Station (GTS) that can Enhance the Resiliency of the SATOPS Support for the Satellite of Interest (SaOI)

Figure 2.
Notional SATOP SOS Enterprise CONOPS [5].

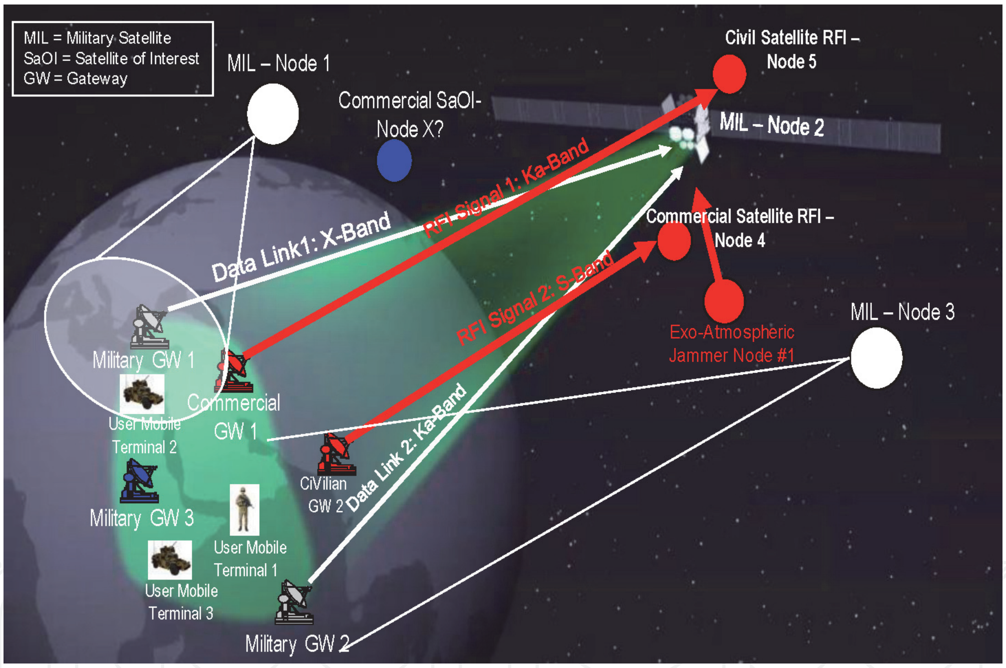


Figure 3.
Notional SATCOM SOS Enterprise CONOPS [5].

the communications links of interest. The simulation results shown in Sections 7, 8 and 9 assumed the intentional RFI Node 1 is off.

4. SOS enterprise architecture CONOPS assessment approach

To address the SOSE Resiliency problem, this section addresses SOSEA CONOPS assessment approach (as shown in **Figure 4**) with the following key SOSE CONOPS framework features:

- SOSEA with three distinct space enterprises consisting of Military Space Enterprise, Commercial Space Enterprise and Civil Space Enterprise.

- Databases include military, commercial and civil satellites and ground systems.

- Four Key SOSE CONOPS Assessment Metrics for measuring the space enterprise performance including Communication Link Margin (focus of this chapter), Communication Link Availability (focus of this chapter), System Availability (not cover in this chapter) and Network Availability (not cover in this chapter)

- Three Key Resiliency Metrics for measuring "Spectrum Resiliency" against RFI threats: RAI, SRAI, and RC.

And, the key SOSE mathematical and simulation models' features are:

- RAI Model: Generates a "Heat-Map" to show areas impacted by RFI threats and associated reconstitution's quality.

- SRAI Model: Generates a "Heat-Map" to show the likelihood that a communication system can access to the allocated frequency-band in the presence of RFI events

- RC Model: Generates SOSE Communication Link Margin and Link Availability for the "areas identified by RAI and SRAI" models.

- System Recovery Time Model: Estimates system recovery time from RFI threats.

Note that the SOSE System Availability and Network Availability metrics are not covered in this chapter. **Figure 4** presents the proposed SOSE framework and

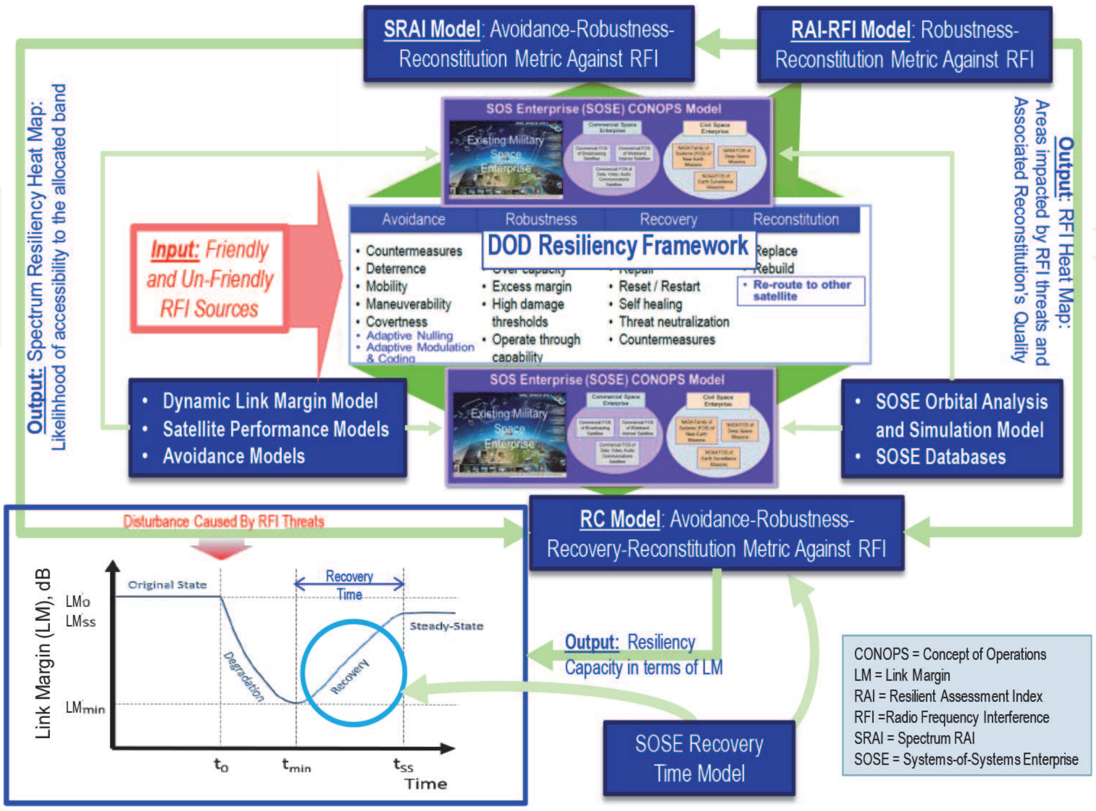


Figure 4.
Integrated SOS enterprise framework and models.

models to be implemented in Matlab for the evaluation of SOS metrics, including RAI, SRAI and RC.

4.1 RAI-RFI model description

RAI-RFI model can be used to select an optimum placement of a new ground station within existing SOSEA to reconstitute ground-station-to-satellite links when adverse RFI events occur. The model can also be used to select the best space and ground network nodes within existing SOSEA when adverse RFI events occur.

Let N_{GS} be the number of Ground Stations (GS) in our SOSE and N_{Sat} be the number of satellites in our SOSE. Then we define p_{ij} at time t under ideal conditions (no RFI) as follows [4, 6]:

$$p_{ij}(t) = \begin{cases} 0, \textit{if GS has no link with Satellite j at time t in ideal case} \\ 1, \textit{if GS has a link with Satellite j at time t in ideal case} \end{cases} \tag{1}$$

for $i = 1, \dots, N_{GS}$ and $j = 1, \dots, N_{Sat}$.

Let P(t) be:

$$P(t) = \sum_{i=1}^{N_{GS}} \sum_{j=1}^{N_{Sat}} p_{ij}(t) \tag{2}$$

We define $\tilde{P}$ at a given time t as follows:

$$\tilde{P}^{X}(t) = \sum_{i=1}^{N_{GS}} \sum_{j=1}^{N_{Sat}} \tilde{p}_{ij}^{X}(t) \tag{3}$$

Where

$$\tilde{p}_{ij}(t) = \begin{cases} 0, \textit{if the set of node X does not reconstitute the link} \\ 1, \textit{if node x reconstitutes the link} \end{cases} \tag{4}$$

Note that $\tilde{p}_{ij}(t)$ is only eligible to be 1 if both $p_{ij}(t) = 1$ (a link exists in ideal conditions) and $\hat{p}_{ij}(t) = 1$ (the link is down to due RFI). The RAI-RFI robustness metric is given as [4, 6]:

$$\mathbf{R_{RAI}(t)} = \frac{\mathbf{P(t) - \hat{P}(t)}}{\mathbf{P(t)}} \tag{5}$$

The augmented RAI-RFI metric which incorporates reconstitution via hypothetical ground stations is given as [6]:

$$\tilde{R}_{RAI}(t) = \frac{(P(t) - \hat{P}(t)) + \tilde{P}(t)}{P(t)} \tag{6}$$

4.2 SRAI model description

As mentioned above, the Spectrum Resiliency is the ability of systems that access the spectrum to respond to a disruptive event such as RFI [4]. On the other hand, Section 4.1 shows that RAI is a metric describing if the systems can contact each other. The SRAI metric weights in the band sharing when a contact is made, and it is defined as follow:

$$\mathbf{SRAI} = \mathbf{SRAI_0} + \mathbf{R_{RAI}} \tag{7}$$

where $\mathbf{R_{RAI}}$ is given by Eq. (5), and $\mathbf{SRAI_0}$ can be calculated using a simplified mathematical model presented in **Figure 4**.2 [4, 8]. This simplified model is derived for two popular multiple access techniques, namely, Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA). **Figure 5(a)** describes the simplified model for calculating$\mathbf{SRAI_0}$, where the SAS Index (SASI) can be calculated using a mathematical model shown in **Figure 5(b)**. Sample calculations of notional SRAI metric for FDMA, TDMA and Code Division Multiple Access (CDMA) can be found in [8].

4.3 RC model description

This subsection describes the RC model derived from the U.S. DOD definition for resiliency [1, 4]. In SOSE context, RC is defined as the SOSE's probability that two arbitrary ground nodes can communicate with each other amidst adversity. It is a function of the following four metrics [1, 4]:

- Avoidance (R_{AV}) is the probability a threat can be avoided or prevented altogether

- Robustness (R_{RO}) is the probability two arbitrary nodes can communicate amidst degradation (i.e. radio frequency links lost due to increased RFI)

- Recovery (R_{RV}) is the probability two arbitrary nodes can communicate when links survive via band flipping (in presence of RFI)

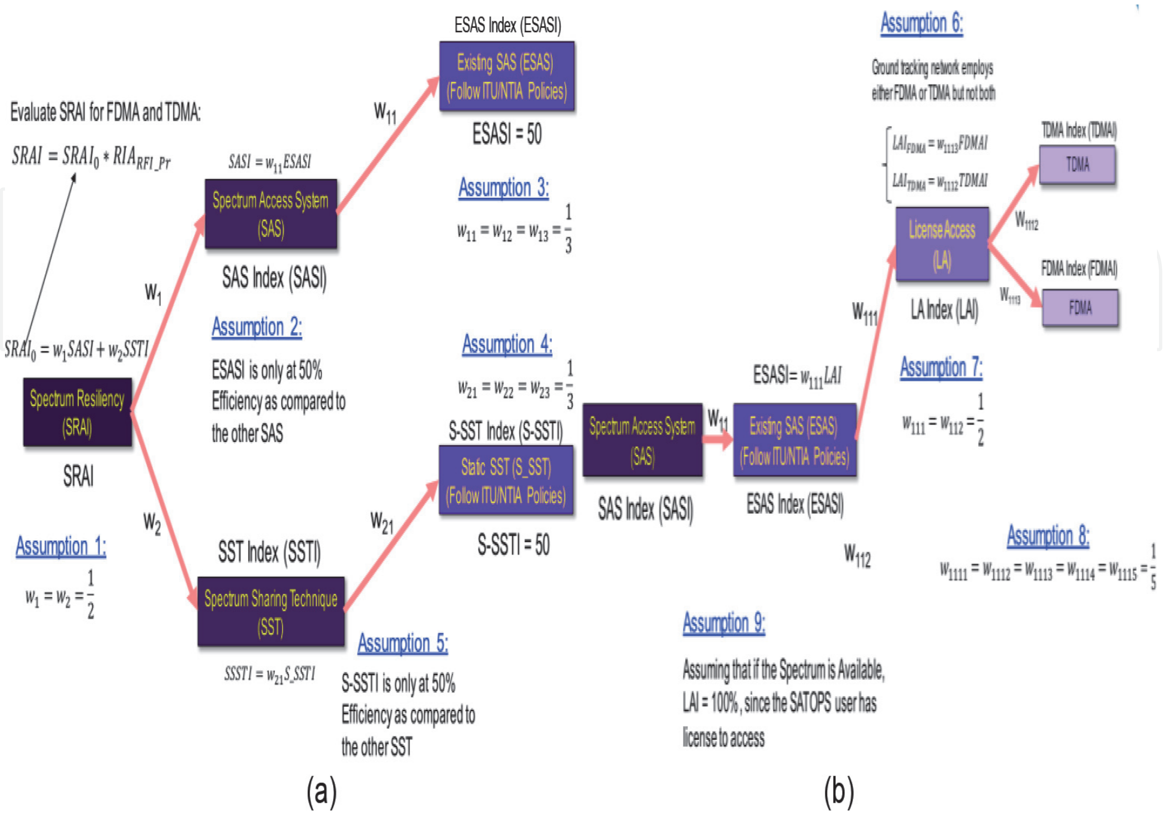


Figure 5.
Simplified SRAI model for FDMA and TDMA. (a) Calculation of SRAIo. (b) Calculation of SAS Index (SASI).

- Reconstitution (R_{RC}) is how likely the system can be re-established to full operational capacity while using 3rd party satellite support.

Figure 6 describes a simplified RC behavior modeling in a SOSE environment. A simple mathematical model can be developed to characterize the RC behavior, and it is given below [1, 4]:

$$\begin{aligned} R = R_{AV} + (1 - R_{AV})R_{RO} + (1 - R_{AV})(1 - R_{RO})R_{RV} \\ + (1 - R_{AV})(1 - R_{RO})(1 - R_{RV})R_{RC} \end{aligned} \tag{8}$$

Note that the RAI model encompasses the "Avoidance" and "Reconstitution" resiliency features, since it is used to select (i) an optimum placement of a new ground station within existing SOSE architecture to "Reconstitute" ground-station-to-satellite links when adverse RFI events occur, and (ii) the best space and ground network nodes within existing SOSE architecture when adverse RFI events occur (i.e., RFI avoidance).

5. Implementation approach: decision support tool

The Graduate student team's approach is to build mathematical models and develop numerical algorithms from scratch. The team implements models using MATLAB without any other Commercial of the Shelf (COTS) software, freeware (e.g., STK, SOAP, NAIF, etc.) to avoid licensing and interfaces. The team collected and maintained a database of ground and space systems including:

- Module-base extension
    - Trajectory propagator (fundamental, core, no black-box software, flexibility, scenario-driven)
    - Resilience calculation (modeling, assessing, etc.)
    - Signal processing (near future, testing advanced techniques)
    - Add-on/Future projects
- Document technical reports, codes, and user manuals (easy to pass on to future students).

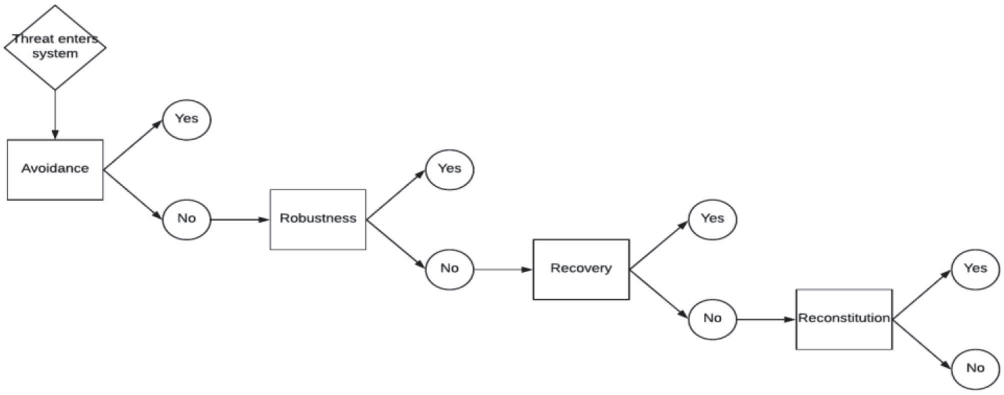


Figure 6.
RC behavior modeling in a SOSE environment.

6. SOSE CONOPS modeling in Matlab

SOSE CONOPS modeling in Matlab includes two key activities, namely, Data collection and input into model simulation (Section 6.1) and orbital dynamic modeling (Section 6.2).

6.1 Data collection and input into simulation

In our proof of concept simulations, we use publicly available data on satellites and ground stations from [6]:

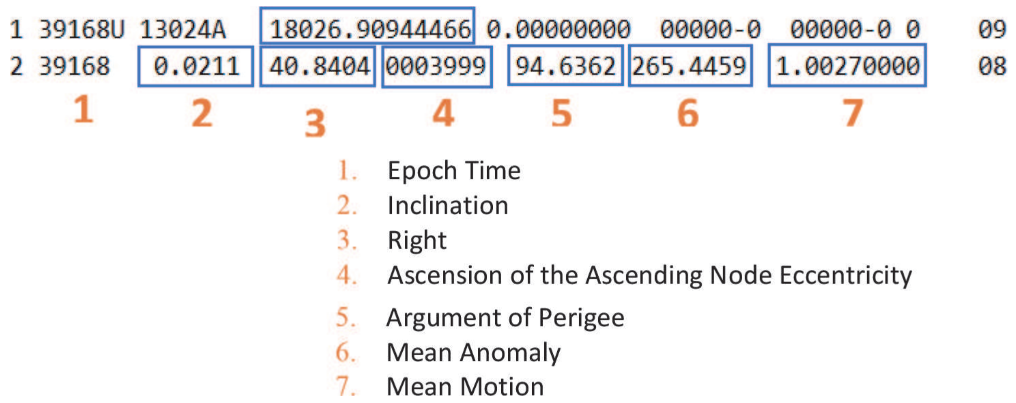
- CelesTrak
- CCSDS
- World Meteorological Organization
- NASA Near Earth Network, Deep Space Network, and TDRSS Network
- Air Force Satellite Control Network (AFSCN)
- NOAA, etc.

The data are then parsed the two-line elements for satellites as seen in **Figure 7** and placed them into our orbital model. Ground Systems were added to the simulation by latitude, Longitude and Height and converted into (x,y,z) tuples used in the Earth Centered Inertial (ECI) model. Once the satellites and ground systems were added to the system their positions are updated using a Kepler propagator [6].

6.2 Orbital dynamic modeling and simulation results

In our simulations we use a simplified "Dynamic Link Margin" (DLM) model [4]. The simplified DLM model assumes the following [4, 6, 7, 8]:

- An Approximation of the link budget model with simplified RFI and signal strength degradation model
- A fixed cross-polarization isolation loss
- Zero recovery time



```
1 39168U 13024A   18026.90944466 0.00000000  00000-0  00000-0 0    09
2 39168   0.0211  40.8404 0003999  94.6362 265.4459  1.00270000    08
```

1. Epoch Time
2. Inclination
3. Right
4. Ascension of the Ascending Node Eccentricity
5. Argument of Perigee
6. Mean Anomaly
7. Mean Motion

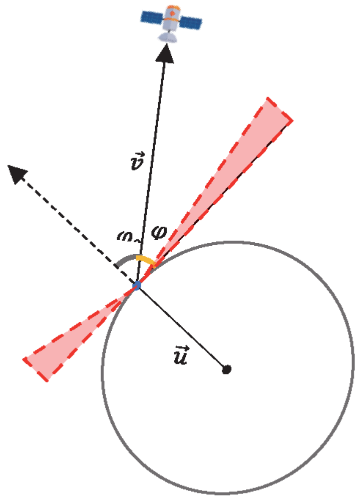
Figure 7.
Two-line elements for satellites [6].

Our first step is to make sure the two systems are in view of each other. **Figure 8** Shows the calculation for ground to satellite and associated diagram of the geometry. **Figure 9** shows the calculated area of coverage for a beam cone along with its resulting coverage.

Once, we calculate that the satellite and ground station have each other in Field-of-View (FoV), We calculate our link margin using our link margin model which factors in antenna geometry and each satellites/ground stations unique parameters.

The In-View and Footprint model implemented in Matlab are shown in **Figure 10** [6]. The model assumed that:

- Minimum elevation angle of ground station is known and is constant
- Satellite beams are circular or elliptical
- Half-power beam width of satellite is known and is constant



Construction of In-view Line:

- $\vec{u} = \frac{GS\ Position}{\|GS\ Position\|}$, $\vec{v} = \frac{Sat\ Position - GS\ Position}{\|Sat\ Position - GS\ Position\|}$
- We get the co-elevation angle,

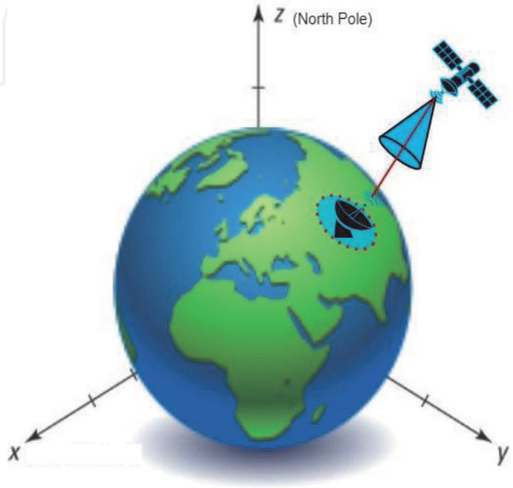
$$\varphi_0 = \cos^{-1}(\vec{u} \cdot \vec{v}) \tag{9}$$

- Satellite elevation angle,

$$\varphi = 90^{\circ} - \varphi_0 \tag{10}$$

- If $\varphi \geq$ minimum elevation angle , draw line from satellite to ground station

Figure 8.
Calculation for ground to satellite.



Construction of Beam Cone and Area of Coverage:

- Let θ_{NS} and θ_{EW} be the beam angles in the North-South and East-West directions respectively. The beam angle is denoted by the "Blue" beam cone comes from the satellite
- Construct N many points on an ellipse on the yz-plane that satisfy:

$$\frac{y^2}{\tan^2(\theta_{EW})} + \frac{z^2}{\tan^2(\theta_{NS})} = 1$$

- Project every point in the x-direction a distance of 1 unit
- Create vectors from origin to each point.

Figure 9.
Calculation for area of coverage for a beam cone [6].

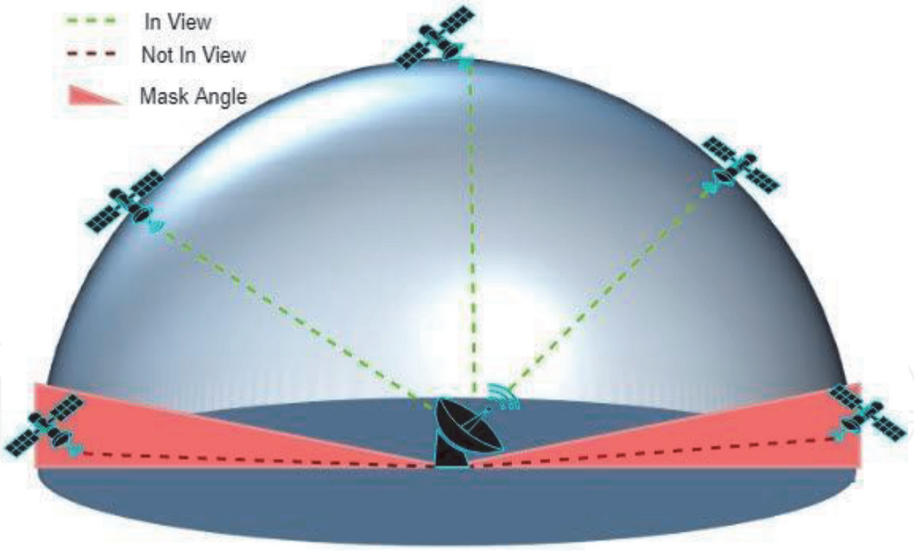
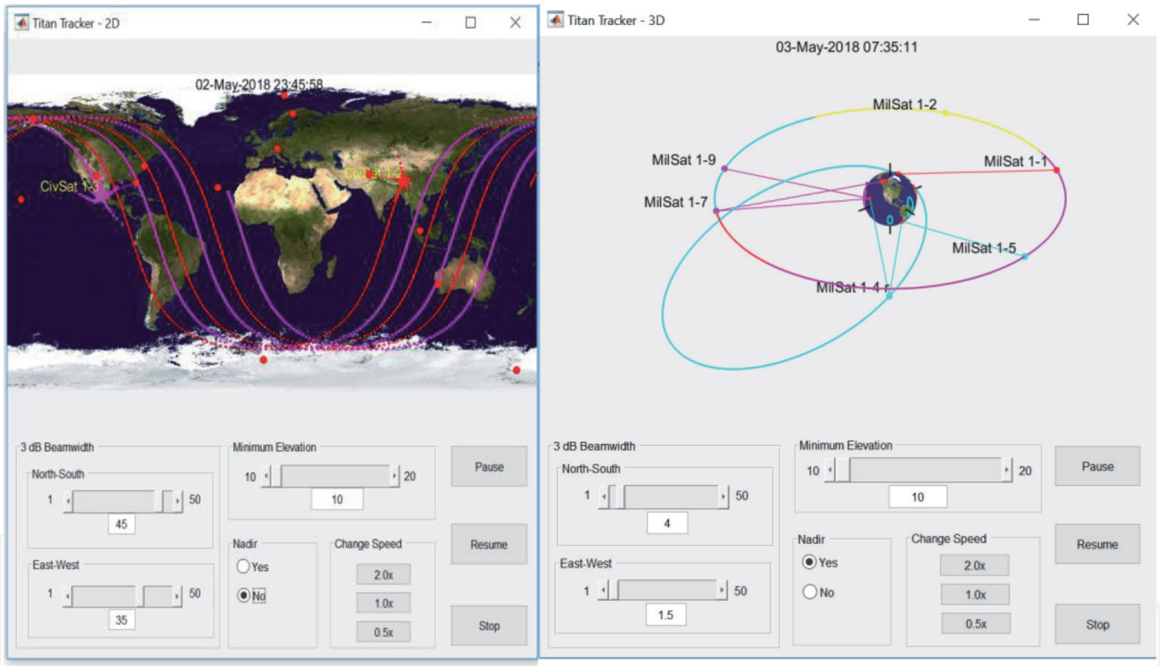


Figure 10.
In-view and footprint model implemented in Matlab [6].



3 dB Beamwidth
North-South 1 – 50: 45
East-West 1 – 50: 35
Minimum Elevation 10 – 20: 10
Nadir ○ Yes ● No

(a)

3 dB Beamwidth
North-South 1 – 50: 4
East-West 1 – 50: 1.5
Minimum Elevation 10 – 20: 10
Nadir ● Yes ○ No

(b)

Figure 11.
Matlab simulation results of a notional SOSE scenario [6].

- "Aim point" is Nadir if satellite antenna is not steerable, and towards ground station if satellite antenna is steerable

- A satellite is In-view if its elevation is greater than its minimum elevation angle.

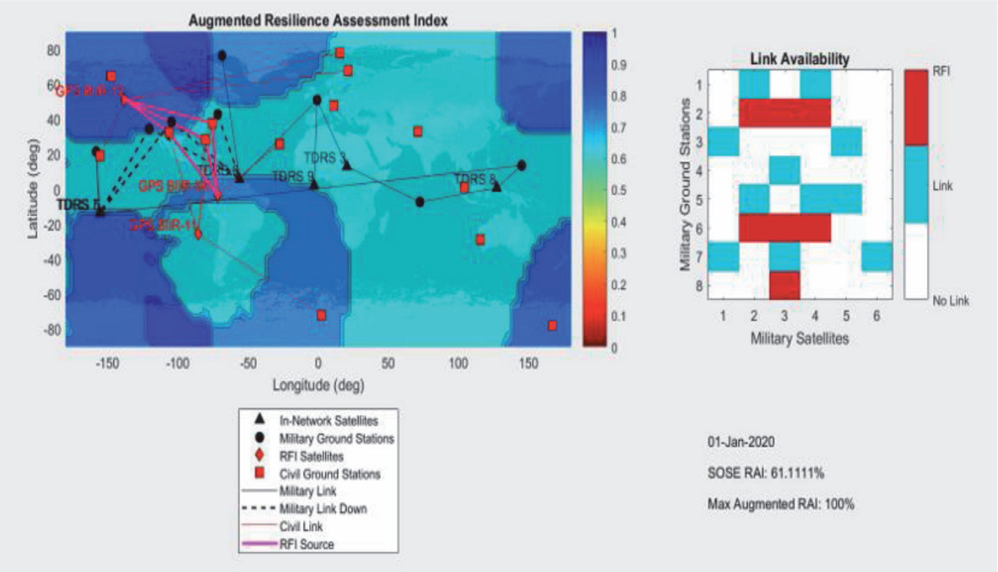
Figure 11 demonstrates the Matlab Simulation Results of a Notional SOSE Model [6]. **Figure 11(a)** shows the 2-D view of the simulation results. **Figure 11(b)** shows the 3-D view.

7. RAI-RFI implementation in Matlab and simulation results

The RAI-RFI model described in Section 4.1 is implemented in Matlab. The following notional SOSE scenario was implemented in the model for demonstration purpose [7].

- Simulation duration: January 1, 2020
    - 5-minute intervals for 12 hours
- Notional Military System
    - 8 military ground stations
    - 6 geostationary satellites
- Notional Civil System
    - 15 civil ground stations
    - 3 civil satellites
- RAI-RFI computed for SOS described above and
- Augmented RAI-RFI computed for SOS with a single hypothetical additional node to create a heat map
- Computed heat map for every 5 degrees of latitude and longitude

The plots of RAI-RFI heat map are shown in **Figure 12** [7]. Where we can analyze coverage and spot ideal locations for adding in new ground stations as shown in the "Dark Blue" areas. Link availability is shown on the right side of the figure. The rows are for each ground station and the columns for each military satellite. Blue boxes indicate connections above the link margin threshold. Red boxes indicate connections that have been lost due to RFI. White boxes indicate that



01-Jan-2020

SOSE RAI: 61.1111%

Max Augmented RAI: 100%

Figure 12.
RAI-RFI plot: time-averaged heat map [7].

no connection is possible between the ground station and satellite which is usually due to geometry. At each time interval the link availability chart is recalculated.

8. SRAI implementation in Matlab and simulation results

As discussed in Section 4.2, the Spectrum Resiliency Assessment Index (SRAI) is an add on to RAI that considers issues of spectrum access and usage [8]. This metric augments our tools by allowing us to consider spectrum access policy and spectrum access interference use cases. Existing SATOPS are conducted using FDMA and TDMA. We want to demonstrate that using CDMA we could increase SRAI, and hence increase spectrum resiliency. **Table 1** summarizes our reasoning for the calculation of SRAI index for FDMA, TDMA and CDMA [4].

The intent is of this section is to demonstrate the tool capabilities, hence the details of the simulation scenario is not provided here. But it should be noted that the RFI sources considered in this section are the interferences from friendly satellites and ground stations shown in **Figure 3** [5], and the amount of interference power is calculated assuming that the interferer satellites used omni antenna and transmitted power was extracted from our database. For the SATOPS scenarios shown in **Table 1**, the results show that FDMA is only 5% efficiency as compared to CDMA and TDMA is 20% efficiency as compared to CDMA. For the same notional SOS scenario presented in Section 6, using the results presented in **Table 1** along with Eq. (7) and **Figure 5**, the following 3 figures illustrate how different access protocols can affect the SRAI results:

- **Figure 13**: SRAI for FDMA model described in Section 4.2. For the notional SOS scenario described in Section 7, the simulation results show that the FDMA allowed very limited spectrum access to share a frequency at once. The SRAI index is less than 0.1.

SATOPS	FDMA	TDMA	CDMA
Allocated Bandwidth	25 MHz	25 MHz	25 MHz
Frequency reuse	2	2	1
Required channel BW	4 MHz	4 MHz	4 MHz
No. of RF channels	25/4 = 6	25/4 = 6	6
Channels/Coverage Area	6/2 = 3	6/2 = 3	6/2 = 3
Control channels/Coverage Area	1	1	1
Usable channels/Coverage Area	3–1 = 2	3–1 = 2	3–1 = 2
SATOP Service per RF channel	1	4*	20**
SATOP channels/Coverage Area	2 × 1 = 2	4 × 2 = 8	20 × 2 = 40
Capacity vs. FDMA	2/2 = 1	8/2 = 4	40/2 = 20
SRAI Index for FDMA	1/20 = 5%		
SRAI Index for TDMA		4/20 = 20%	
SRAI Index for CDMA			100%

**Depends on the number of TDMA slots.*
***Depends on the number of codes.*

Table 1.
Sample calculation of SRAI index for FDMA, TDMA and CDMA [4].

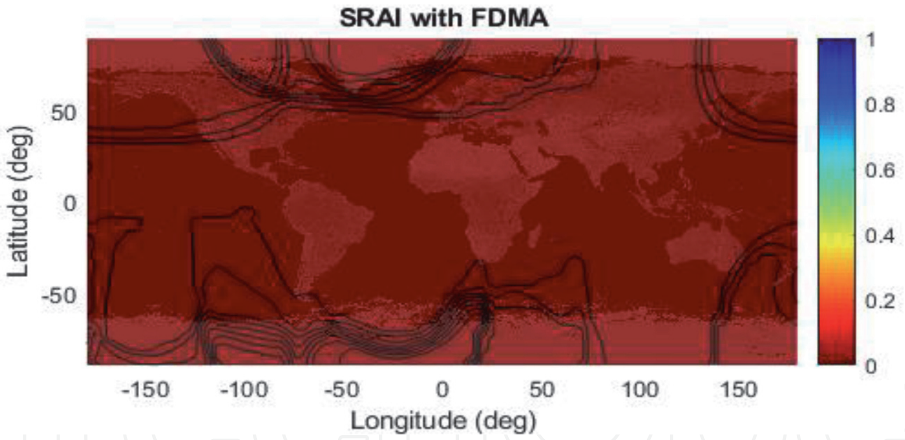


Figure 13.
SRAI simulation results for FDMA.

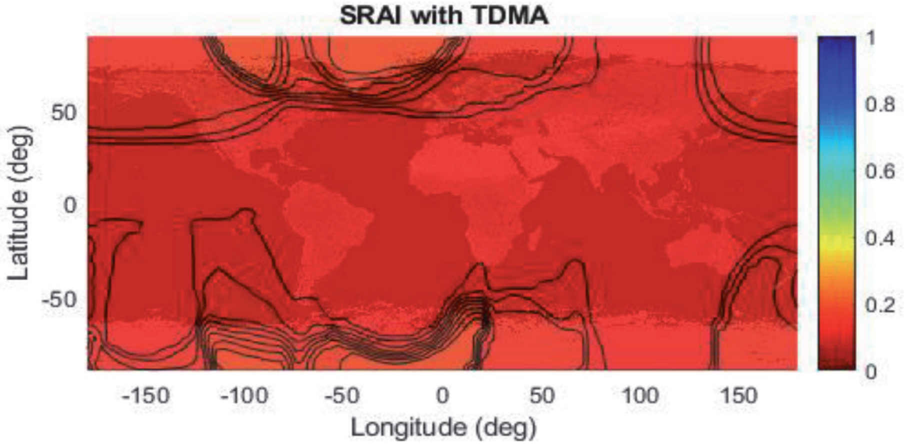


Figure 14.
SRAI simulation results for TDMA.

- **Figure 14**: SRAI for TDMA model described in Section 4.2. For the same notional SOS scenario described in Section 7, the simulation results show that the TDMA allowed more spectrum access than FDMA. The SRAI index is ranging from 0.15 to 0.3.

- **Figure 15**: SRAI model shown in Section 4.2 is modified for CDMA model. Using the same notional SOS scenario described in Section 7, the simulation

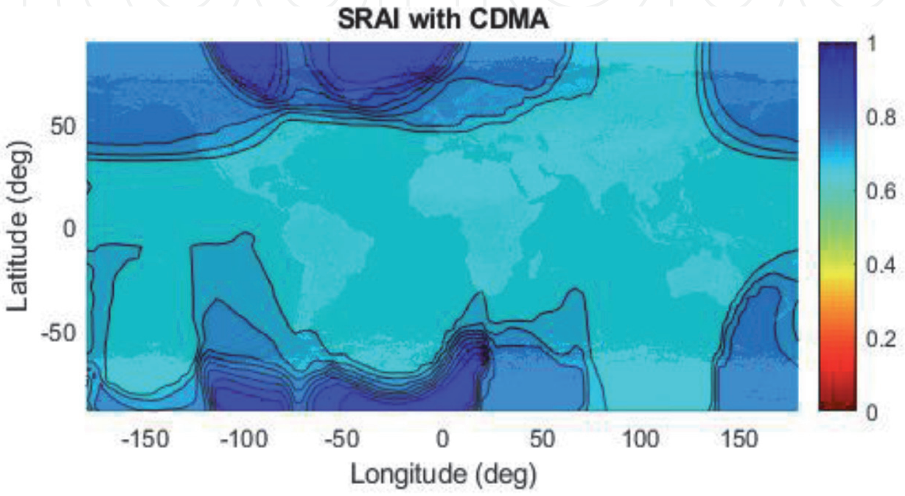


Figure 15.
SRAI simulation results for CDMA.

results show that the CDMA allowed the highest level of spectrum access by allowing more user to share a frequency at once. The SRAI index is ranging from 0.65 to 1.

9. RC implementation in Matlab and simulation results

The RC model presented in Section4.3 was implemented in Matlab, which takes a traditional approach defined by U.D. DOD for modeling avoidance, robustness, recovery, and reconstitution. This model can be broken down into many of the links in a network and they are in any of the given states shown in **Figure 16**. The six possible states shown in **Figure 16** are:

- Radio Frequency (RF) Link achieves maximum capacity as planned
- RF Link avoids the RFI threats with acceptable signal degradation
- RF Link is lost due to increased RFI power
- RF Link has recovered from un-acceptable signal degradation caused by RFI
- RF link has re-established to full-operational capacity while using the 3rd party satellite support
- RF link is disconnected by the users.

The notional SOSE scenario presented in Section 6 was modified for demonstration of the RC model with the following assumptions [8]:

- Simulation time duration: Jan 1, 2020 00:00:00 – Jan 3, 2020 00:00:00
    - 10 second intervals
- $\mathrm{SNR}(dist) = -8\tan^{-1}((dist - 35{,}000)/35{,}000$ “) + 14”
- RFI Power = $\mathrm{SNR}(dist) \times (1–2\varphi/100$ “)”

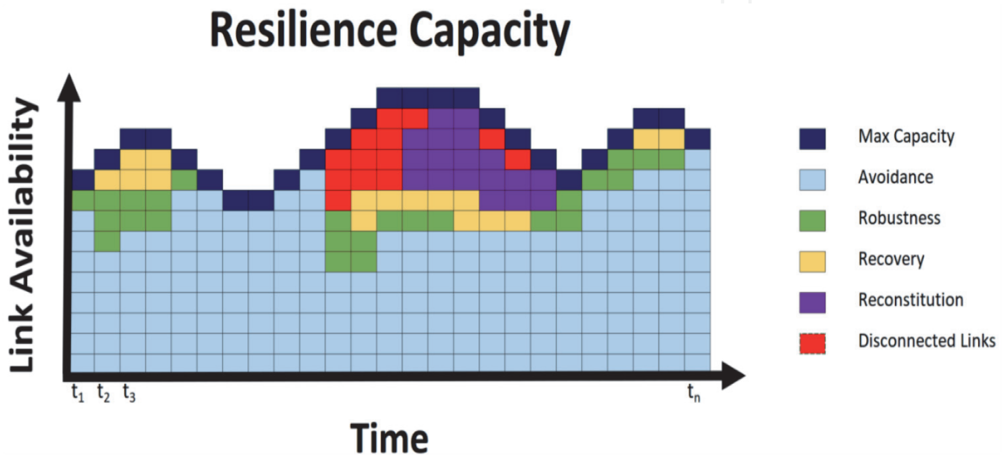


Figure 16.
Potential RC states at any given time.

- For commercial/civilian groups, RFI was not considered as a factor in their internal communication
    - Only the SNR function with Link Margin (LM) > 3
- Only considered RFI on satellites, not ground stations
- If a satellite is only connected to one ground station, then it is not connected
- Ground stations can receive/transmit in different bands, but satellites receive/transmit in same band.

Simulation results show that avoidance was at 74%, robustness at 50% and recovery at 17%. In our simulation, we were able to have full reconstitution of 100%. **Figure 17** shows Network Score[1] for each time step, where each unit of the x-axis represents a 10 second interval from our start time of the 1 sr of January 2020 at time 00:00. The y-axis represents Network Score at each time interval. Whenever a point on the y-axis drops below 1, it means that some portion of ground stations have been cut off from the other ground stations. We observed seven of these downtime windows during our two-day simulation, where RFI from civilian and commercial sources caused a disruption in communication between ground stations via satellite [8].

Figure 18 illustrates seven downtime windows. They are represented on the x-axis. The color bar represents "mean" Network Score over a downtime window.

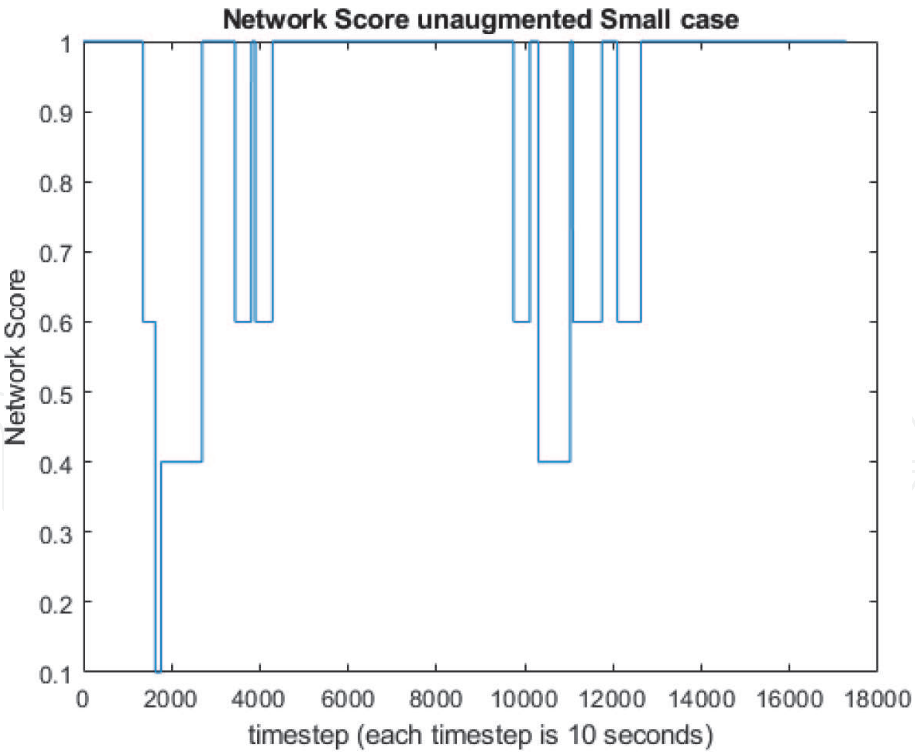
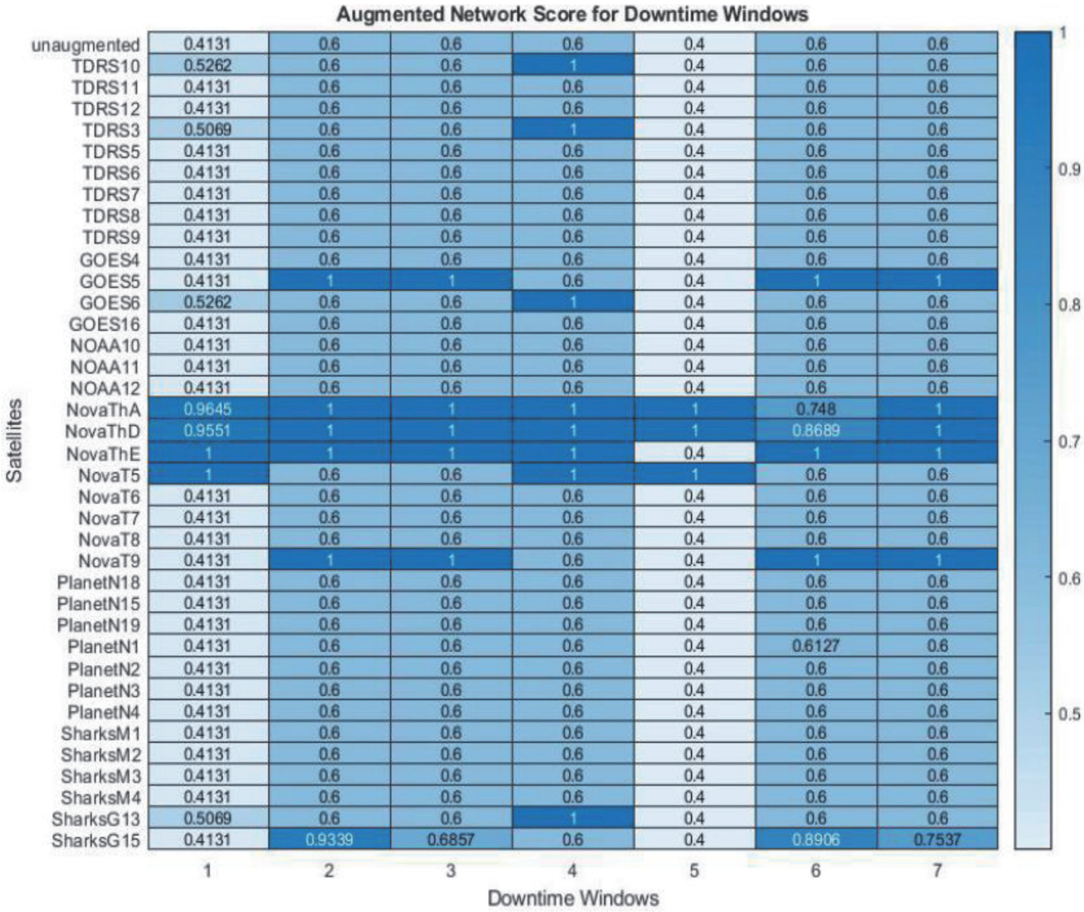


Figure 17.
RC simulation results: all downtime windows.

---

[1] The network score is defined as the ratio between the number of actual connected network nodes to the ideal number of possible network nodes can be connected. Network score is ranging from 0 to 1, where 1 represents 100% connections in a network.



Satellites	1	2	3	4	5	6	7
unaugmented	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
TDRS10	0.5262	0.6	0.6	1	0.4	0.6	0.6
TDRS11	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
TDRS12	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
TDRS3	0.5069	0.6	0.6	1	0.4	0.6	0.6
TDRS5	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
TDRS6	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
TDRS7	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
TDRS8	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
TDRS9	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
GOES4	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
GOES5	0.4131	1	1	0.6	0.4	1	1
GOES6	0.5262	0.6	0.6	1	0.4	0.6	0.6
GOES16	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
NOAA10	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
NOAA11	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
NOAA12	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
NovaThA	0.9645	1	1	1	1	0.748	1
NovaThD	0.9551	1	1	1	1	0.8689	1
NovaThE	1	1	1	1	0.4	1	1
NovaT5	1	0.6	0.6	1	1	0.6	0.6
NovaT6	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
NovaT7	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
NovaT8	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
NovaT9	0.4131	1	1	0.6	0.4	1	1
PlanetN18	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
PlanetN15	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
PlanetN19	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
PlanetN1	0.4131	0.6	0.6	0.6	0.4	0.6127	0.6
PlanetN2	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
PlanetN3	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
PlanetN4	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
SharksM1	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
SharksM2	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
SharksM3	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
SharksM4	0.4131	0.6	0.6	0.6	0.4	0.6	0.6
SharksG13	0.5069	0.6	0.6	1	0.4	0.6	0.6
SharksG15	0.4131	0.9339	0.6857	0.6	0.4	0.8906	0.7537

Figure 18.
RC simulation results: seven downtime windows.

The y-axis represents augmentation of the notional military SATCOM network with the labeled satellite during a specific downtime window. The top-most row, labeled "Un-augmented" shows the network status with no additional satellites. The RC model generates these values via the simulation and then searches each column to find the entry with the highest value. It then records this value and which satellite was most supportive to the network during the window. For instance, we find the "mean" network scale for downtime 1 in the first column on the left. The top entry, 0.4131, is the mean network score with no recruited civilian or commercial assisting satellites. We then search down the column noting the maximum of 1 which occurs when the military network is augmented with our theoretical commercial satellite NovaThE. A score of 1 represents full reconstitution of SATCOM network during the window.

10. Conclusion

The RAI-RFI, SRAI and RC models discussed are useful tools in analyzing a space-based SOSE against RFI threats. The models separately address different facets of a space based SOSE. The RAI-RFI model provides a statistical approach for evaluating the best operating network node in the presence of RFI events. The SRAI expands on the RAI-RFI model to account for different spectrum accessing technologies, e.g., FDMA, TDMA or CDMA.

The RC model provides probabilistic analysis of a space based SOSE's ability to successfully maintain communication amidst RFI threats. A network scoring metric has been proposed to assess the state of the network when disconnects occur. The network score is then utilized to identify optimal pre-existing support satellites from third party sources that be leveraged by the military during times of disconnect. Aspects of our model can be refined by expanding on various details that have been oversimplified.

Future work should incorporate an actual dynamic link budget model instead of an approximation. Additionally, more thorough calculations should be considered for RFI noise and the actual signal strength degradation that occurs when moving from the center of the beam to the edge of the beam. Similarly, future considerations should address the cross-polarization isolation that occurs between the signal of interest and the friendly RFI signal. Other important aspects to incorporate might be a recovery time model when RFI becomes present or financial cost as part of the optimization assessment when looking for solutions to the degradation or disruptions caused by RFI. Additional work should also include details regarding existing and future Spectrum Access Systems and Spectrum Sharing Systems. For example, we could implement actual Spectrum Access Systems using FDMA and TDMA. For Spectrum Sharing Systems considerations can be made regarding licensed and unlicensed underlay sharing techniques where secondary users can simultaneously transmit with primary users, and the interference caused by the secondary users over primary users must comply with a threshold level per National Telecommunications and Information Administration (NTIA)/ International Telecommunication Union (ITU) interference protection criterion. Furthermore, additional work should consider actual communication capacities and capabilities per communication link by weighting each link. This can be used to further evaluate Spectrum Access Systems and Spectrum Sharing Systems based on allocated bandwidths. New parameters associated with cognitive radio could also be introduced.

Notes/Thanks/Other declarations

The authors would like to thank the following CSUF graduate students:

- Lauren Benson, Jordan Golemo, and Maria Heinze for their contributions to Section 6 and Reference 6;

- Nicole Hemming-Schroeder and Catherine Osbornefor their contributions to Section 4, Section 7 and Reference 7;

- Scott Digiam battistafor his contribution to Section 9 and Reference 8.

Conflict of interest

The preparation of this chapter was not funded by The Aerospace Corporation, and it was done by the author using his own time and resources, thus it does not represent The Aerospace Corporation's view on the results presented in this chapter.

Author details

Thomas O. Freeze[1]*, Tien M. Nguyen[2] and Charles H. Lee[3]

1 The first author performed the work presented in this chapter when he was a Graduate Student at California State University in Fullerton (CSUF). Currently he is with The Aerospace Corporation, El Segundo, California

2 The second author serves as Adjunct Research Professor and CSUF and he is also with The Aerospace Corporation

3 The third author serves as Professor at Program Director of industrial Collaboration Program in Applied Mathematics at CSUF

*Address all correspondence to: tom.freeze@aero.org

References

[1] Fact Sheet: Resilience of Space Capabilities. Department of Defense. https://www.defense.gov/Portals/1/features/2011/0111_nsss/docs/DoD%20Fact%20Sheet%20-%20Resilience.pdf., Jan 11, 2011.

[2] McLeod, Gary. Nacouzi, George. Dreyer, Paul. Eisman, Mel. Hura, Myron. Langeland, Krista S. Manheim, David. Torrington, Geoffrey. Enhancing Space Resilience Through Non-Material Means. Santa Monica, CA, RAND Corporation, 2016.

[3] Edlund, Gregory Military Space Resiliency: Definition, Measurement and Application. Northrop Grumman Aerospace Systems Case 13–1828, Sept. 16, 2013.

[4] Tien M. Nguyen, “Systems-of-Systems Enterprise CONOPS Assessment and Spectrum Resiliency Modeling,” Lecture Notes, 2017–2018.

[5] Tien M. Nguyen, Book Chapter titled “SOS Enterprise, SOSE CONOPS, SOSE Architecture Design Approach: A Perspective on Space and Airborne Systems,“ to be published in the Book titled “Systems-of-Systems Engineering, Modeling, Simulation and Analysis,” Intech|Open Publisher, September 2020.

[6] Lauren Benson, Jordan Golemo, and Maria Heinze, “System-of-Systems Enterprise (SOSE) Modeling - SOSE Databases, Data Management and Orbital Dynamics Modeling,” Math-597 Final Report, 18 May 2018, California State University in Fullerton.

[7] Nicole Hemming-Schroeder and Catherine Osborne, “System-of-Systems Enterprise (SOSE) Resilience Assessment Index (RAI) Modeling - Modeling of RAI Against Radio Frequency Interference (RAI-RFI) for Ground-Based SOSE Applications with Dynamic Communication Link Margin and Availability,” Math-597 Final Report, 18 May 2018, California State University in Fullerton.

[8] Thomas Freeze and Scott Digiambattista, “SOSE Spectrum Resiliency Assessment Index (SRAI) and Resilient Capacity (RC) Modeling: Modeling of SRAI and RC Against RFI Threats for Space-Based SOSE Applications with Dynamic Communication Link Margin and Availability,” Math-597 Final Report, 18 May 2018, California State University in Fullerton.