Optimal Reconfigurations for Increasing Capacity of Communication Satellite Constellations

Afreen Siddiqi*
Massachusetts Institute of Technology, Cambridge, MA, 02139

Jason Mellein†
Airforce Research Laboratory, Hanscom Air Force Base, MA, 01731

Olivier L. de Weck‡
Massachusetts Institute of Technology, Cambridge, MA, 02139

System deployment in stages has been shown to reduce economic risks for large capital intensive systems. In order to follow such a strategy for satellite constellations, some kind of inter-satellite reconfiguration is usually required. This paper explores how the optimal initial stage of a satellite constellation can be determined given the need to reconfigure for an uncertain higher capacity demand at a later time. The set of potential new capacity demands is bounded by a discrete set of future scenarios, each associated with a particular probability of occurence. The specific reconfiguration process considered in this study involves addition of new planes and increase in number of satellites per plane.

Nomenclature

α	voice activity
ϵ_{min}	min elevation angle [deg]
A_{user}	user activity per month
B_{ch}	channel bandwidth
B_g	guard bandwidth
B_T	satellite bandwidth
$\mathbf{C}$	vector of capacities
C_A	Capacity of Constellation in stage A
C_B	Capacity of Constellation in stage B
D_a	satellite antenna diameter
f	cell interfering factor
F	MF-TDMA framing bits
h	altitude [km]
k_B	Boltzmann's constant
K	cluster size
l_m	link margin
L_{tot}	total transmission losses [dB]
LCC	life cycle cost
MA	multi-access scheme
n_{bits}	number of bits per time slot
N_{ch}	channels per satellite
P_{cell}	transmit power per cell(spot beam)
P_t	transmit power [W]
p_A	number of planes in stage A
$\mathbf{P}$	vector of probabilities
$\mathbf{R}$	LCC costs matrix
R_b	carrier data rate [bps]
s_A	number of satellites per plane in stage A
T_f	frame length
T_s	system noise temperature
T	number of carriers
U_s	global system utilization factor
$\mathbf{X}_{iso}$	set of design vectors with same capacity
$\underline{\mathbf{x}a}_i$	stage A constellation design i
$\underline{\mathbf{x}b}_{ij}$	stage B constellation design ij
Z	number of cells (spot beams)

*Graduate Student, Department of Aeronautics & Astronautics, Room 33-409, AIAA Student Member.
†Lieutenant, USAF, Airforce Research Laboratory, Space Vehicles Directorate, Hanscom Air Force Base, MA, 01731 AIAA Member.
‡Assistant Professor of Aeronautics & Astronautics and Engineering Systems, Dept. of Aeronautics & Astronautics, Engineering Systems Division, Room 33-410, 77 Massachusetts Avenue, deweck@mit.edu, AIAA Senior Member.

I. Introduction

Communication satellite constellations are normally designed for a fixed capacity and type of service. Recent economic troubles of Iridium and Globalstar, however, have illustrated the large risks associated with capital-intensive projects affected by uncertainties. Both of these Low Earth Orbit (LEO) satellite communication systems projected a large customer base for a certain type of service (telephony along with fax, messaging, *etc.*) which did not materialize after the constellations were deployed. In service providing systems, one of the greatest uncertainties lie in the subscriber base, and due to increasingly dynamic markets it has become important for systems to be responsive to new or changed needs. De Weck, de Neufville, and Chaize[1] have shown that deploying and subsequently reconfiguring a LEO communication satellite constellation in stages can mitigate economic risks due to the uncertainties in subscriber demand. They show that such a strategy provides an "as-needed, as-afforded" approach which may allow system managers to delay decisions until there is greater certainty of market requirements.

In the traditional design process of systems that are fixed (*i.e.* consist of only one stage) the design that fulfills the requirements and is lowest in cost is generally selected for final implementation. If however, a system is to be designed with the capability of future reconfiguration to meet a new need, then it is unclear what the initial design (or stage) should be. There can be several designs that are low cost and meet the fixed initial objectives of the system, but are not practically reconfigurable since they entail large costs (*i.e.* switching costs) for future adaptation. Similarly, there can be designs that meet the current objectives at somewhat higher cost but are capable of meeting new objectives at a later time at a lower comparative cost. This study focuses on reconfigurable satellite constellations and presents a methodology for determining the optimal design of a constellation that needs to reconfigure at a later time to meet a higher capacity demand.

II. Inter-Satellite Reconfiguration

The reconfiguration of a constellation for capacity expansion through inter-satellite reconfiguration can be achieved in a variety of ways. Two different methods were initially investigated. In the first method (which was assumed in the earlier work[1]) the reconfiguration involved moving existing satellites to new and lower orbits and launching additional satellites. This method allows for reconfiguring from one optimal constellation to another optimal constellation, in which the optimality criteria is minimum number of satellites that provide global coverage and meet the capacity requirement. In such a case, for chemical propulsion the ΔV requirements for moving the satellites to different orbits that require plane changes can be prohibitive. If on the other hand, electric propulsion is used then communication outage costs become significant.

A second method for reconfiguring the constellation was therefore investigated in which the capacity is increased by adding more planes and more satellites per plane in the constellation. The already deployed satellites that form the original constellation are not moved. In this method the future stage of the constellation can be less optimal on the 'minimum number of satellites' criterion, however it is more optimal from a technical feasibility point of view. The analysis presented here focuses only on this type of reconfiguration.

A. Optimal Initial Stage Determination

If a staged deployment strategy is to be adopted then it is important to determine what the specific stages should be. More importantly the initial stage can determine how optimal or sub-optimal the subsequent stages will be as the system evolves over time.

In this analysis only polar constellations are considered. It is assumed that the constellation is deployed in only two stages, A, and B. The first stage is designed to meet a known capacity demand (which is based on current market demand and can be assumed to be known with reasonable certainty). The second stage is an extension of the first stage in which more planes and satellites per plane are added so that a higher capacity demand is met. The design of the first stage thus needs to be such that it fulfills current requirements but is reconfigurable so that it can fulfill a new but unknown requirement at a later time. The set of potential new requirements is however bounded by a discrete set of future scenarios, each associated with a particular probability of occurence. Figure 1 shows the top view of the Earth's pole and illustrates the reconfiguration process.

The specific problem investigated in this analysis is the determination of the optimal initial stage, A, of the constellation that fulfills an existing capacity requirement C_A, and has minimum reconfiguration cost for meeting an uncertain demand by reconfiguring into stage B that has a higher capacity.

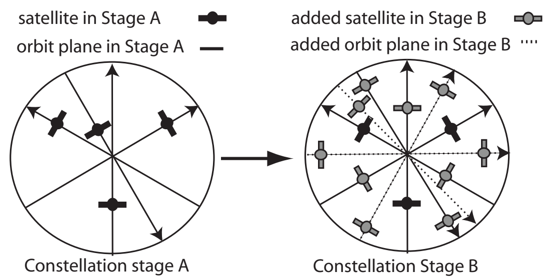


Figure 1. Constellation Reconfiguration from Stage A to Stage B

The initial capacity, C_A , which the first stage, A, has to provide is chosen as a fixed parameter. To make the problem amenable for computation, the future uncertain demand is modeled as a vector of discrete capacities $\mathbf{C}$ with associated probabilities $\mathbf{P}$. It is also assumed that the constellation only undergoes a reconfiguration for a higher capacity demand, *i.e.* $\forall\, C_i \in \mathbf{C},\ C_i > C_A$.

The methodology developed for obtaining a solution for this problem consists of the following steps:

- Specify set of discrete capacities $\mathbf{C}$ with associated probabilities $\mathbf{P}$ that model the uncertain future demand:

$$C = [C_1 \cdots C_i \cdots C_m] \tag{1}$$

$$P = [P_1 \cdots P_i \cdots P_m] \tag{2}$$

- Find the set of iso-performance designs $\mathbf{X}_{iso}$, (in which each design has same capacity C_A within some specified percent, ϵ_{tol}). One of the elements of the set $\mathbf{X}_{iso}$ is the initial constellation that should be deployed to provide the known capacity C_A. However, it needs to be determined which particular element, $\underline{\mathbf{x}a}_i$, of $\mathbf{X}_{iso}$ is the optimal solution given the requirement of reconfiguration for a higher capacity in the future.

- For each constellation $\underline{\mathbf{x}a}_i \in \mathbf{X}_{iso}$, the optimal new constellation, $\underline{\mathbf{x}b}_{ij}$, that meets capacity demand $C_j \in \mathbf{C}$ is found such that reconfiguration cost between $\underline{\mathbf{x}a}_i$ and $\underline{\mathbf{x}b}_{ij}$ is minimized.

- The life cycle cost of each $\underline{\mathbf{x}a}_i$ is computed by determining initial deployment cost of $\underline{\mathbf{x}a}_i$ and cost of subsequent reconfiguration into the corresponding optimal $\underline{\mathbf{x}b}_{ij}$ for each capacity requirement C_j. For n elements in $\mathbf{X}_{iso}$, and m elements in $\mathbf{C}$, a cost matrix R of dimensions $[n\ m]$ is generated in which element r_{ij} is system life cycle cost with $\underline{\mathbf{x}a}_i$ as initial constellation that reconfigures into $\underline{\mathbf{x}b}_{ij}$ to meet new capacity demand C_j. Figure shows a schematic representation of this matrix.

$$\mathbf{R} = \begin{bmatrix} \overbrace{r_{11}}^{C_1} & \overbrace{\cdots}^{C_i} & \overbrace{r_{1m}}^{C_m} \\ \vdots & \vdots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix} \tag{3}$$

- Optimal initial constellation, denoted as $\underline{\mathbf{x}a}^*$, is determined by finding the constellation $\underline{\mathbf{x}a}_i$ that has minimum expected life cycle cost:

$$min(\mathbf{RP}) = E\left[LCC\left(\underline{\mathbf{x}a}^*\right)\right],\quad \mathbf{R} : [n\ m]\,,\ \mathbf{P} : [m\ 1] \tag{4}$$

Figure 2 summarizes the steps graphically.

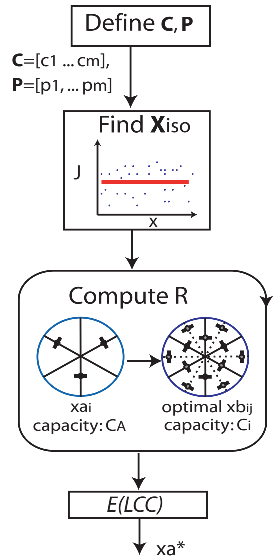


Figure 2. Flowchart for determining optimal initial constellation

B. Case Study

The methodology described above was implemented in a case study of a polar, global coverage, LEO communication satellite constellation providing telephony service. A framework was implemented in MATLAB that utilizes several benchmarked and validated modules originally developed by de Weck and Chang, along with several new modules.

Figure 3 illustrates the solution framework schematically and a detailed description of the main modules is provided below.

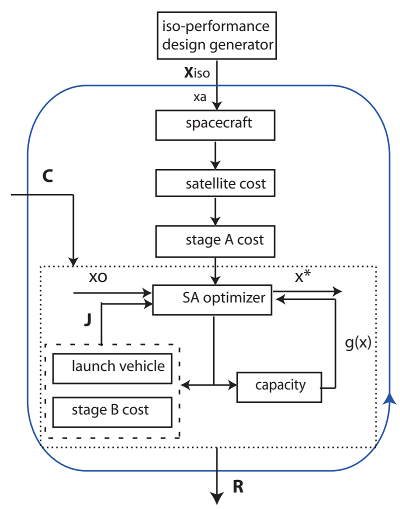


Figure 3. Block diagram of framework modules.

1. Constellation Capacity

INPUTS: constellation altitude, h, minimum elevation angle ϵ_{min}, total number of satellites N_{sat}, satellite antenna diameter D_a, satellite transmit power P_t, and type of multi-access scheme, MA.
OUTPUTS: Total number of channels in constellation, $N_{chConstel}$, and total number of subscribers, C.

The constellation capacity in this analysis is defined as the number of subscribers that the constellation can support. The module uses some fixed parameters which are given in Table 4 in the appendix. The values of the parameters are based on the Iridium satellite constellation which uses an MF-TDMA multi-access scheme and Globalstar constellation which uses MF-CDMA. These values are chosen so that the results from the analysis are close to a realistic scenario. It is assumed that the satellites use multiple spot beams to allow for frequency re-use. It is also assumed that the increased beam interference due to the addition of satellites and planes in the constellation will be compensated with power control and position-dependent frequency assignment.[2]

In the current implementation, the module computes the capacity for only two types of multi-access schemes: MF-TDMA and MF-CDMA. For the MF-TDMA scheme, the number of channels per cell (spot beam) is computed as[3]

$$N_{ch} = \frac{1}{2K}\frac{B_{sat}}{B_T + B_g}\frac{R_b T_f - F}{n_{bits} + R_b T_g} \tag{5}$$

In the MF-CDMA scheme, N_{ch} is calculated as[3]

$$l_d = \frac{k_B T_s R_b l_m}{P_{cell} G_t G_r L_{tot}} \tag{6}$$

$$B_d = \frac{B_{ch} T}{R_b \alpha (1 + f)} \tag{7}$$

$$N_{ch} = \frac{T + B_d \frac{I_{tot}}{E_b}}{1 + B_d l_d} \tag{8}$$

In the present analysis only polar constellations are considered, therefore after accounting for the polar overlap factor the total number of channels per satellite is given as[3]

$$N_{chConstel} = 0.68 Z N_{ch} N_{sat} \tag{9}$$

Note, that since it is reasonable to assume that not all the subscribers will be using the system simultaneously, the actual number of channels in the system will be less than the total subscriber base of the communication satellite constellation. Lutz and Werner[4] have defined how the total number of subscribers can be calculated based on the number of channels, a global utilization factor, U_s and user activity level A_{user}:

$$C = \frac{U_s \frac{365}{12} 24 \cdot 60 N_{chConstel}}{A_{user}} \tag{10}$$

This module has been benchmarked using data from the Iridium and Globalstar satellite constellation. For the Iridium case, the number of channels in the constellation is computed to be 75,000 (Iridium had 84,000). According to Lutz the typical values for U_s are between 10% to 15%. Using a mean value of 0.12 for U_s and 125 min/month[1] for A_{user} the number of subscribers is 2.5 million (Iridium designed the system for a target subscriber base of 3 million). For Globalstar, the number of channels were reported to be 2500. The module computes the number of channels to be 2900. The results are therefore in reasonably good agreement.

2. Iso-Performance Design Generator

INPUTS: Tradespace of constellation designs, desired capacity, tolerance, ϵ_{tol}
OUTPUTS: set of iso-capacity designs, $\mathbf{X}_{iso}$

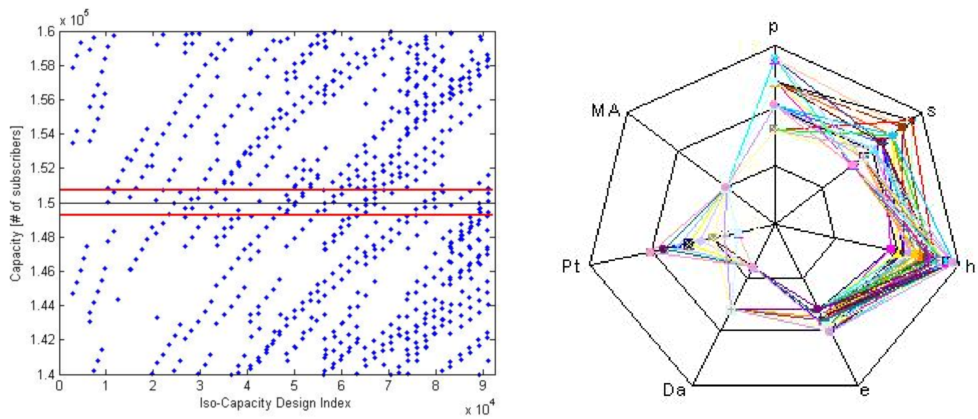
Iso-performance designs are designs that have equal performance. There are certain algorithms that can be used for determining iso-performance contours in a multi-variable design space,[5] however for simplicity, this module performs a full factorial evaluation of a constellation design space and selects all the designs that provide full global coverage and meet a required capacity level with a tolerance of ϵ_{tol}. The variables in the design space are number of planes, p, number of satellites per plane, s, altitude, h, minimum elevation angle, ϵ_{min}, satellite antenna diameter, D_a, satellite transmit power, P_t, and multi-access scheme, MA. The trade space used in the case study for finding the iso-performance designs was

$$\begin{aligned}
&3 \le p \le 7 \\
&8 \le s \le 14 \\
&h = [800 : 50 : 1450] \\
&\epsilon_{min} = [8 : 0.5 : 10] \\
&D_a = [0.4 : 0.4 : 2.0] \\
&P_t = [150 : 50 : 500] \\
&MA = [1, 2]
\end{aligned}$$

A value of 1 in MA was for MF-TDMA, and a value of 2 was for MF-CDMA. It should be noted that p and s are variables in the trade space in addition to h and ϵ_{min}. Usually only h and ϵ_{min} are treated as independent variables, since for polar constellations (which were the only type considered here) the minimum number of planes and satellites per plane can be determined analytically for global coverage based on only these two specifications[6].[7] However, the goal in this problem is not to be limited by constellations that minimize number of satellites (which is the traditional approach). Therefore, p and s are treated independently. This reconfiguration strategy (of addition of planes and satellites) thus essentially turns an initial single-fold coverage constellation into an n-fold coverage constellation (in stage B).

All the designs that are generated by the combination of the variables are tested for single-fold global coverage and those that do not meet full coverage criteria are discarded.

In the specific problem analyzed, designs with a capacity C_A of 150,000 subscribers within a tolerance of $\pm 0.5\%$ were obtained from the isocapacity generator module. This level of capacity was picked to reflect the approximate subscriber base that Iridium and Globalstar actually achieved during the intial years of full operation. The generator produced 70 iso-capacity designs, $\underline{\mathbf{x}a_i}$, shown in Figure 4. The $\mathbf{X}_{iso}$ vector thus had 70 elements in this case study. The radar plot shows that in the designs $\underline{\mathbf{x}a_i}$, there was an even spread in values of p, s, h, ϵ_{min}, and P_t, however the values for D_a were limited to only a few specific ones, while the multi-access scheme was always MF-TDMA.



(a) iso-capacity designs

(b) radar plot

Figure 4. Iso-Capacity designs generated for capacity of 150,000 subscribers.

Figure 5 shows the cost of the iso-capacity designs. This is the cost of developing, manufacturing, and launching the satellites of the 70 iso-capacity constellations. It can be seen that there are clearly a set of designs that are better than another group of designs which are much higher in cost. However it is also evident that there are several designs which have similar low cost levels. The lowest cost design is design index # 39 with cost of approximately $660 million.

In the traditional approach, if the aim was to deploy a constellation that provides service to 150,000 subscribers, and would later not be reconfigured, the lower cost designs would be picked. However, the problem here is to determine which one should be used as the first stage, A, so that future reconfiguration is cheaper.

3. Spacecraft

INPUTS: altitude, h, transmit power, P_t, antenna diameter, D_a number of inter-satellite links (ISLs) on a satellite, and satellite design life, T_{sat}
OUTPUTS: satellite total power, P_{tot}, wet mass, M_{sat-w}, dry mass, M_{sat-d}, and volume, V_{sat}

The spacecraft module is based on a parametric non-geostationary satellite model originally developed by Richharia,[8] and improved by Springmann.[9] This module is used for estimating the mass and volume of a LEO satellite based on basic input design parameters. The outputs provided by this module are subsequently used for selecting launch vehicles and estimating satellite costs.

4. Launch

INPUTS: M_{sat-w}, V_{sat}, altitude h, inclination of the orbit i, number of planes in stages A and B, p_A and p_B, and number of satellites per planes in stages A and B, s_A and s_B respectively.
OUTPUTS: launch vehicle type, number of launches required, number of satellites per launch vehicle, launch costs.

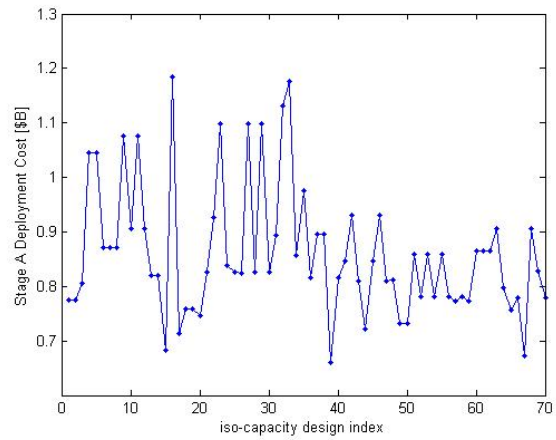


Figure 5. Stage A costs of iso-capacity designs

This module uses a Matlab database to select a suitable launch vehicle that gives minimum total launch cost. The database is populated with information from Isakowitz's launch reference guide[10] and contains information of US, European, Chinese, and Japanese launchers. It is assumed that international launches are permissible (which may not always be the case in reality due to policy issues).

The module, based on the satellite data, selects all launch vehicles that are capable of delivering that payload to the specified orbit, computes the number of required launches, and based on the costs selects the vehicle that has the minimum total launch total. For launch vehicles capable of carrying multiple satellites, it is assumed that they are filled to full payload capacity (so several satellites get assigned as payload for a single launch). In reality, due to risk considerations the number of satellites per launch vehicle will be lower. Risk issues are not factored presently in this analysis, therefore a limit to the maximum number of satellites that a single launch is allowed to carry was not imposed. Any such limit can greatly influence the results. Since a rigorous analysis of risk issues was not included, any arbitrary limit was not set to allow for consistency in results. It is also assumed that a particular launch delivers payload to a single plane and does not make plane changes within the same launch mission.

5. Cost

The constellation stage A costs (shown in Figure 5) account for only satellite development, manufacturing, and launch. Reconfiguration costs include manufacturing costs of additional satellites and launch of additional satellites only. Other programmatic cost segments such as operation costs *etc.* are not factored in.

The satellite costs are determined from a simple cost model, SVLCM,[11] that provides a rough-order-of-magnitude cost estimate based on the dry mass of the spacecraft. The model gives estimates of the development and production cost of un-manned earth orbiting spacecraft. The SVLCM is a top-level model derived from the NASA/Air Force Cost Model (NAFCOM) database.

Radiation hardening costs are also included in the satellite costs. The radiation hardening cost estimator takes the altitude of a circular polar orbit, the lifetime of the satellite, and the thickness of its aluminum shielding in centimeters and approximates the hardness required of the vehicle and the percent total cost of the vehicle to include that hardness. The cost relationship was obtained from.[12] The total dose equation was developed by running the CRRESRAD model in the Air Force Geospace modeling environment for polar orbits from 350 km to 2050 km in 50 km increments for 1 year. The data was then surface fitted to obtain a parametric relationship.

6. Optimal Second Stage Constellation

The second stage of the constellation that meets a given capacity demand occurring in the future with some probability is determined through optimization. For each iso-performance design, $\underline{\mathbf{x}a}_i$, the optimal constellation it should reconfigure into (based on minimization of the reconfiguration cost) is determined for each capacity $C_j \in \mathbf{C}$. Each C_j is assumed to have a probability P_j of occurring.

Since we assumed a set of discrete capacities, $\mathbf{C}$, with associated probabilities, $\mathbf{P}$, that define the uncertain future demand we, described the demand possibilities with the two vectors:

$$C = \left[8.3 \cdot 10^5, 1.7 \cdot 10^6, 2.2 \cdot 10^6\right] \tag{11}$$

$$P = [0.15, 0.35, 0.5] \tag{12}$$

The optimal stage B for each possible starting stage design $\underline{\mathbf{x}a}_i$ for each C_j is found by solving the following optimization problem:

$$\begin{aligned}
&\min J = ReconfigCost(\underline{\mathbf{x}})_{A \to B} \\
&\text{s.t.} \\
&\text{p}_A \leq p_B \leq 5p_A \\
&\text{p}_B = kp_A,\ k = 1, 2, 3 \ldots \\
&\text{s}_A \leq s_B \leq 35 \\
&\text{C}_B \geq C_j \; (C_j \in C)
\end{aligned}$$

The design vector $\underline{\mathbf{x}}$ used in this optimization problem consists of only two variables $\underline{\mathbf{x}} = [p, s]^T$. It is important to note that although in the iso-capacity design generator the design vector was $\underline{\mathbf{x}} = [p, s, h, \epsilon_{min}, P_t, D_a, MA]^T$, in this case the design vector is only a subset of that and is $\underline{\mathbf{x}} = [p, s]^T$. This is because once the constellation stage A has been fielded, satellite design parameters such as antenna diameter and transmit power are fixed. Since the reconfiguration process in this analysis was only considering addition of planes and satellites per plane, the design vector used for determining the reconfiguration cost to stage B only involves these variables. This is in contrast to earlier work[1] where the reconfiguration was assumed to consist of change in orbital altitude and minimum elevation angle. As mentioned earlier, due to large ΔV requirement issues in this new study the reconfiguration involves only addition of orbital planes and satellites.

For n iso-capacity designs, and m capacities (in $\mathbf{C}$), the optimization is performed nm times. In a particular optimization run, the p_A and s_A are the number of planes and satellites per plane in a particular $\underline{\mathbf{x}a}_i$.

The capacity constraint was set to an inequality ($i.e$ $C_B \geq C_j$) to allow for easier convergence. Since the designs that would have higher capacity than the required level will also be more expensive, they would get filtered out from the optimization process. The number of planes in stage B is restricted to be a multiple of the number of planes in A so that the inter-orbit spacing remains uniform in order to ensure uniform level of capacity over the globe. A maximum limit of 35 satellites per plane is added to allow for uniform distribution of satellites over the latitudes.

Simulated Annealing was used to perform the optimizations. Since this is a probabilistic method, each optimization run was executed three times to improve the chances of finding the optimal solution. Figure 6 shows the convergence history of a sample optimization run.

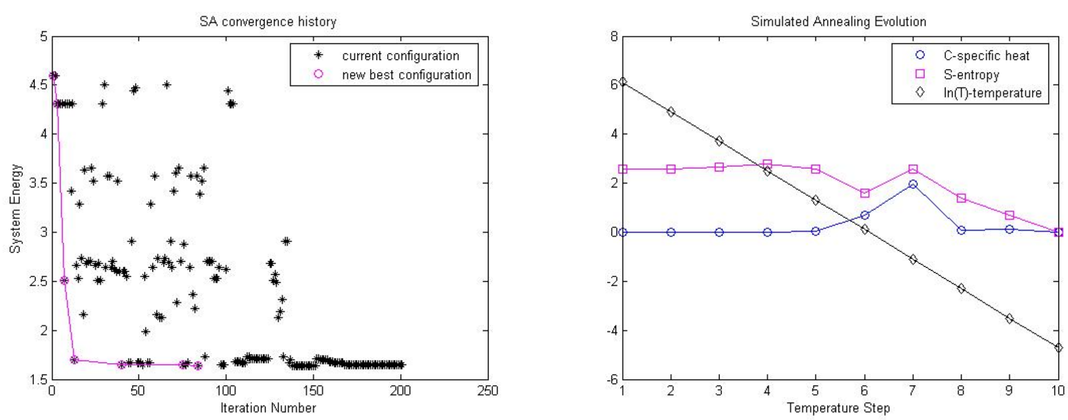
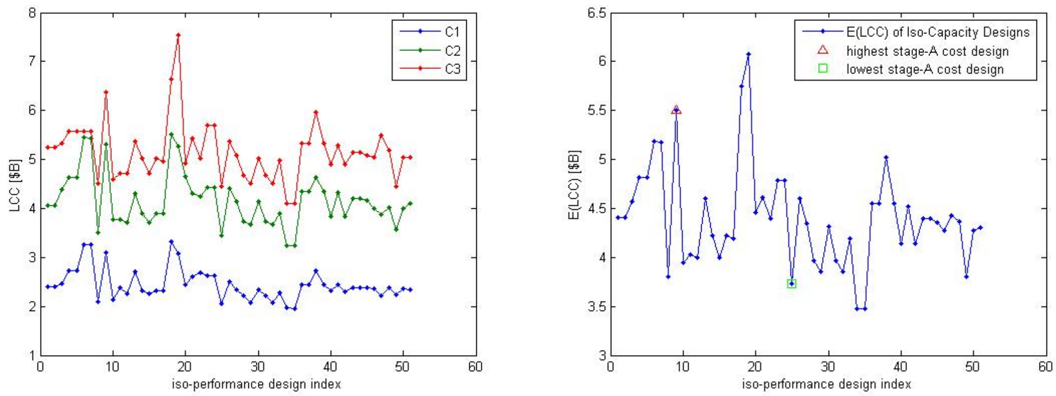


Figure 6. Simulated Annealing Convergence History for Finding Optimal Solution

C. Optimal Initial Constellation Results

From the original set of 70 iso-capacity designs, 19 designs were not able to converge to feasible solutions for some of the given capacity requirements. Those designs were excluded from subsequent analysis. Table 5 in the Appendix provides a mapping of the design indices in the original set of 70 and the remaining 51 designs that were actually used for evaluating the optimal life cycle cost.



(a) LCC

(b) E(LCC)

Figure 7. Life Cycle Costs of iso-capacity designs

Figure 7 (a) shows a plot of the life cycle cost of each of the 51 feasible iso-capacity designs as they are reconfigured into a second stage to meet the three different given capacities (in Equation 11). It is evident that the mean life cycle cost is higher for increasing capacity levels of 830,000, 1.7 million and 2.2 million subscribers respectively. This data is then used to find the expected life cycle cost of each iso-capacity design using **P**. Using the specified probabilities (in Equation 12) for the different possible capacities the expected life cycle cost for the iso-performance designs, $E[LCC(\underline{\mathbf{x}a}_i)]$, is obtained as shown in Figure 7 (b). The figure also shows how the iso-capacity designs that were best or worst in terms of stage A costs compare on the expected life cycle cost metric when reconfiguration costs to stage B are included in. It is clear that designs that may be more expensive initially are less expensive when subsequent reconfiguration issues are considered. Similarly designs that are originally of lowest cost (for only stage A) are no longer the best designs when reconfiguration costs are factored in.

Table 1 shows the details of the top five optimal initial designs that have lowest expected LCC. These are picked from the 51 feasible initial designs whose LCC is shown in Figure 7 (b). There are certain trends in those solutions, such as high altitude which leads to lower number of satellites for global coverage, and smaller satellites. The Iridium constellation consisted of 66 satellites at an altitude of 780 km. The satellites had 1.5 m antennas and 400 W transmit power. In the optimal solutions, the number of satellites range between 40 and 50, and the antennas are almost half the size and also half in power as compared to Iridium's satellites. The optimal stage A is thus a constellation at high altitude, with comparatively small satellites.

The design ranked 3 (with $E(LCC)$ of \$3.73 billion) is also the lowest stage A cost design (highlighted in Figure 7 (b) with a square marker). This design can thus be of interest since it has lowest cost for stage A deployment, and also ranks in the top 5 designs when subsequent reconfiguration costs are factored in.

1. Best and Worst Designs

The corresponding optimal constellations into which the initial constellations (shown in Table 1) need to reconfigure into for the three capacity demand possibilities are shown in Table 2. The first element of each vector denotes the number of planes and the second element denotes the number of satellites per plane. For instance, the constellation ranked 1 (in Table 1), which is $\underline{\mathbf{x}a}^*$, with originally 5 planes and 8 satellites per plane needs to reconfigure into a constellation of 20 planes and 11 satellites per plane in order to meet capacity C_1 (which was 830,000 subscribers). Figure 8 illustrates the constellations in stage A and B for the top ranked design.

Table 1. **Top five optimal initial reconfigurable constellations**

Rank	1	2	3	4	5
p	5	5	5	5	5
s	8	8	10	10	9
h [km]	1350	1350	1300	1100	1450
ϵ [deg]	9.5	9	9.5	10	9.5
$Constel_{cost}$ [$B]	0.73	0.73	0.66	0.68	0.78
Sat_{cost} [$M]	11.1	11.1	7.5	7.8	10.9
M_{sat} [kg]	340	340	320	342	340
V_{sat} [m^3]	2.8	2.8	2.6	2.8	2.8
D_a [m]	0.8	0.8	0.8	0.4	0.8
P_t [W]	200	200	150	250	200
$E(LCC)$ [$B]	3.47	3.48	3.73	3.80	3.80

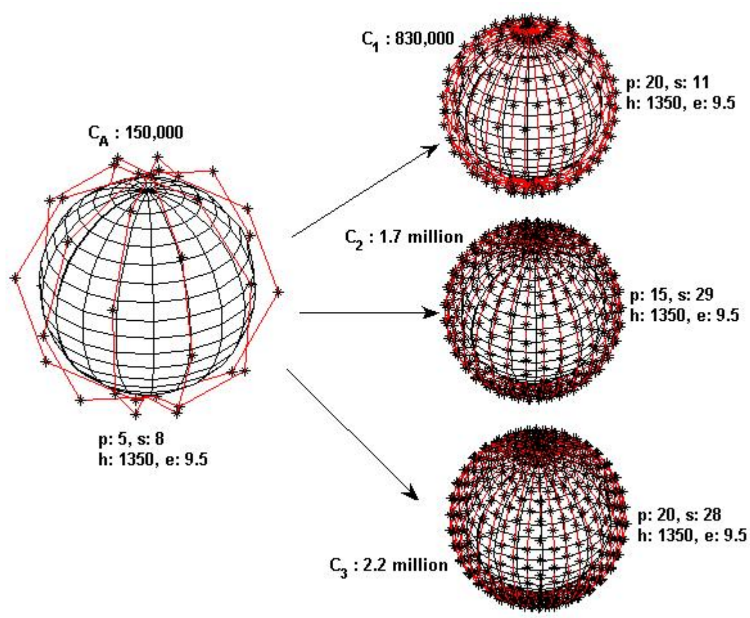


Figure 8. Optimal stage A and stage B constellations

It is important to note that the results will be greatly affected if the number of satellites that can be launched on one vehicle is restricted. In the present analysis the launch vehicles were allowed to carry as many satellites as possible depending on the total payload capacity (and capability of the vehicle to deploy multiple payloads).

Table 2. Optimal second stage constellations

Rank	C_1	C_2	C_3
1	[20,11]	[15,29]	[20,28]
2	[20,11]	[15,29]	[20,28]
3	[15,18]	[25,22]	[25,28]
4	[10,27]	[25,22]	[25,28]
5	[10,24]	[15,33]	[20,32]

In addition to the optimal designs, it is evident from Figure 7 that there are some particularly bad designs *i.e.* those with much higher expected LCC as compared to others. Table 3 shows their details. It is easy

Table 3. Worst initial reconfigurable constellations

Rank	1	2	3
p	7	6	7
s	12	14	13
h [km]	1300	1300	1150
ϵ [deg]	8	8	8
$Constel_{cost}$ [\$B]	1.17	1.17	1.13
Sat_{cost} [\$M]	6.7	6.7	6.3
M_{sat} [kg]	326	326	307
V_{sat} [m^3]	2.7	2.7	2.5
D_a [m]	0.4	0.4	0.4
P_t [W]	200	200	150
$E(LCC)$ [\$B]	6.08	5.75	5.5

to observe that these are the designs with higher number of planes and number of satellites per plane as compared to most of the other iso-capacity designs. Subsequent reconfigurations of these constellations will therefore be more expensive.

2. *Sensitivity Analysis*

In order to determine the sensitivity of the optimal solutions, the values of the probabilities in **P** were randomly varied. Figure 9 shows that although the optimal expected LCC varied, the same top designs were always picked in their respective ranks. For a more rigorous analysis the values in **C** should also be altered, however this issue will be addressed in future work.

3. *Benefits and Limitations*

The benefit for a staged deployment strategy is that it allows for lesser economic risks as illustrated in the earlier work.[1] Futhermore, as presented in this case, this type of analysis may reveal certain designs that have lowest stage A costs, and are also among the top optimal reconfigurable design choices. Such designs can then be investigated in more detail for implementation considerations, since they have low upfront costs and also competitive reconfiguration costs (which will be discounted for the future and hence will make the financial outlook even more favorable).

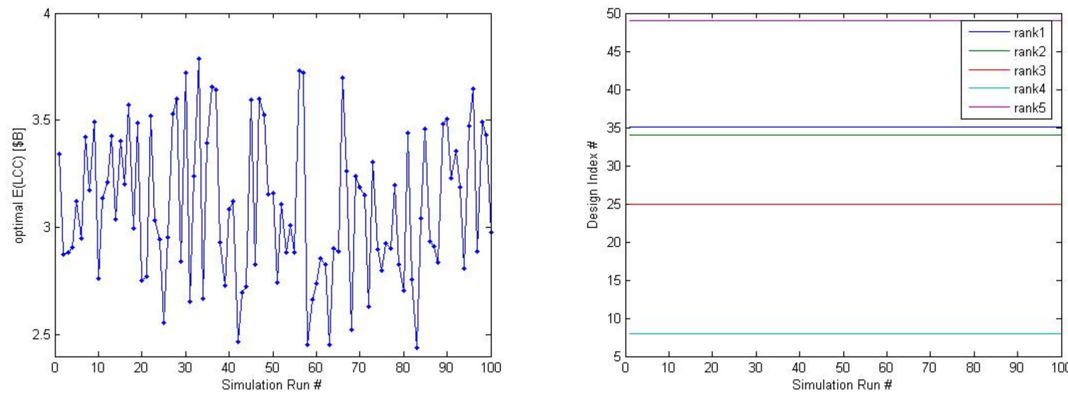


Figure 9. Sensitivity Analysis of Optimal Designs to variations in P

The limitations of this study are in the modeling aspects of the uncertainty. The uncertainty is essentially described by a specific bounded set of possible scenarios. If the actual demand turns out very differently from the modeled scenarios, then the advantages may not be fully realized.

III. Conclusions

A methodology for determining the optimal initial stage of a satellite constellation for a two-stage (A and B) deployment strategy has been presented. A five step computation process is outlined and is described in detail with a case study of a polar LEO constellation. The results show that iso-capacity designs which have lowest stage A costs, are not necessarily the lowest cost designs when life cycle cost which includes reconfiguration costs to stage B are factored in. The optimal initial stage for a reconfigurable constellation is not the same design as the optimal fixed constellation. It is thus important to account for future reconfiguration issues upfront in the constellation design process so that an appropriate first stage design is deployed. There may, however, be designs that are optimal for stage A, and among the top choices for optimal reconfigurable designs, and thus merit detailed investigation.

In the specific case study analyzed in this work, the optimal solutions for stage A constellations consist of small satellites and lower number of total satellites as compared to the Iridium and Globalstar constellations.

Future Work

In future work, several improvements will be made in the proposed methodology to make it more accurate and robust. Currently, the iso-performance designs were found through a full-factorial evaluation and then the reconfiguration cost for each was computed one by one. A better approach will be to find the iso-capacity designs through optimization. Additionally, the uncertainty of capacity demand was modeled very simply. This can be improved by performing stochastic optimization in which the uncertain parameter is part of the objective function of the optimizer.

Intra-satellite reconfiguration will also be explored as a means for increasing capacity.

References

[1] O. L. de Weck, R. D. Neufville, M. C., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit," *Journal of Aerospace Computing, Information, and Communication*, Vol. 1, No. 3, 2004, pp. 119–136.

[2] Loreti, P. and Luglio, M., "Interference evaluations and simulations for multisatellite multibeam systems," *International Journal of Satellite Communications*, , No. 20, 2002, pp. 261–281.

[3] Chang, D. D. and de Weck, O. L., "Basic capacity calculation methods and benchmarking for MF-TDMA and MF-CDMA communication satellites," *To appear in : International Journal of Satellite Communications*.

[4] E. Lutz, M. Werner, A. J., *Satellite Systems for Personal and Broadband Communications*, Springer-Verlag, 2000.

[5] de Weck, O. L., *Multivariable Isoperformance Methodology for Precision Opto-Mechanical Systems*, Doctoral thesis, MIT, Department of Aeronautics and Astronautics, 2001.

[6]Adams, W. and Rider, L., "Circular Polar Constellations Providing Single or Multiple Coverage Above a Specified Latitude," *The Journal of the Astronautical Sciences*, Vol. 35, April 1987.

[7]Rider, L., "Optimized Polar Orbit Constellations for Redundant Earth Coverage," *The Journal of the Astronautical Sciences*, Vol. 33, No. 2, April-June 1985.

[8]Richharia, M., *Satellite Communications Systems: Design Principles*, McGraw-Hill, NewYork, 3rd ed., 1999.

[9]Springmann, P. N. and de Weck, O. L., "Parametric Scaling Model for Nongeosynchronous Communication Satellites," *Journal of Spacecraft and Rockets*, Vol. 41, No. 3, 2004, pp. 472–477.

[10]Isakowitz, S. J., *International Reference Guide to Space Launch Systems*, 4th ed., 2004.

[11]"www.jsc.nasa.gov/bu2/SVLCM.html," .

[12]Wertz, J. R. and Larson, W. J., *Space Mission Analysis and Design*, Microcosm Press, 3rd ed., 1999.

Appendix

Table 4. Link parameters of Iridium and Globalstar used in calculating capacity for MF-TDMA and MF-CDMA systems

Parameter	MF-TDMA	MF-CDMA
downlink frequency [GHz]	1.6239	2.5
BER	0.001	0.01
Convolutional code rate	0.75	0.5
T_f [ms]	90	-
R_b [bps]	4800	2400
T_g [ms]	0.36	-
B_{sat} [MHz]	5.15	11.35
B_T [kHz]	41.67	1230
B_g [kHz]	1.236	-
K	12	-
Channels per cell	10	9
Modulation Scheme	QPSK	QPSK
l_m [dB]	16	6

Table 5. Mapping between Indices of initial iso-capacity set of 70 designs and later final set of feasible 51 designs used for evaluating LCC

Final	Initial	Final	Initial	Final	Initial	Final	Initial
1	1	14	25	27	41	40	57
2	2	15	26	28	42	41	58
3	3	16	28	29	43	42	59
4	4	17	30	30	45	43	60
5	5	18	32	31	46	44	61
6	9	19	33	32	47	45	62
7	11	20	34	33	48	46	63
8	15	21	35	34	49	47	64
9	16	22	36	35	50	48	65
10	17	23	37	36	52	49	66
11	20	24	38	37	54	50	68
12	21	25	39	38	55	51	69
13	24	26	40	39	56		