

Effects of Staged Deployment on the Economics of Global Broadband Internet Satellite Constellations

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Abstract – Historically constellations of communication satellites were designed to function optimally for a specific expected global demand. This estimation is based on assumptions of the number of users and the average activity per user, both of which are highly uncertain. This uncertainty can cause deployed constellations having a capacity far lower than demand, lowering performance and creating opportunity cost, or far higher than demand, potentially bankrupting the company that owns the system as income cannot recoup the initial investment. An approach has previously been proposed wherein a satellite constellation is deployed in stages with each stage increasing the capacity of the constellation through reconfiguration of on-orbit satellites and launch of new satellites. This method has been previously demonstrated to significantly reduce the lifecycle cost of low-earth orbit communication satellite constellations. Recent proposals for satellite constellations to support global broadband internet providers have introduced new technologies as well as new methods of constellation design resulting in far larger constellations than previously envisioned (mega-constellations). Renewed interest and investment in the development global broadband networks demand a return to this topic to investigate its impact in this space.

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1. Introduction

1.1 Motivation

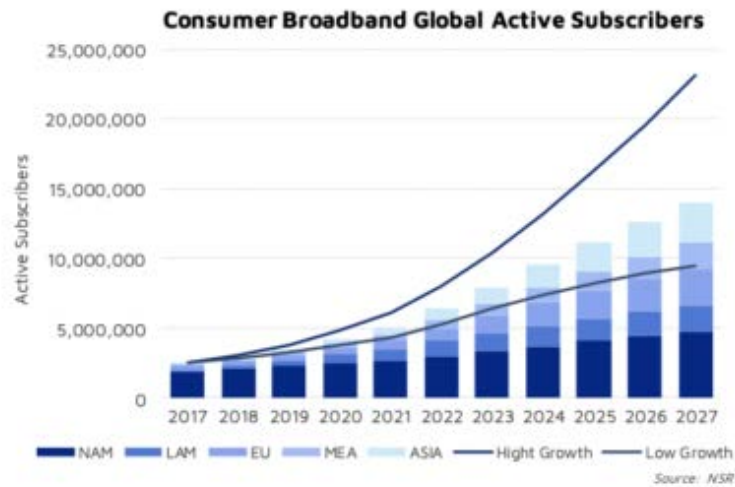
The concept of providing internet from space has regained popularity over the past few years, and with this resurgence in popularity has come a significant technological and monetary investment from both the government and private sector. Since 2014 over a dozen companies have applied to the Federal Communications Commission (FCC) to construct vast constellations of low or very low earth orbit (LEO, VLEO) satellites as part of a network to provide broadband satellite internet access. Many of these proposed constellations contain thousands of satellites with the largest, SpaceX's Starlink system, containing 11,943 individual satellites. Due to the greatly increased scale of these proposals compared to earlier satellite communication constellations (Iridium, GlobalStar) the term "mega-constellations" was coined to refer to these new systems.

In addition to this vastly increased scale, many new technologies are being incorporated into these new constellations that were not present in the communication satellite constellations of the 1990s. These new technologies, such as the use of digital communication payloads, multi-beam antennas, and advanced modulation and frequency use schemes help to increase the performance of individual satellites. Cost reductions from advanced manufacturing processes and reduced launch costs also help to reduce the cost of performance in these systems.

In 2015, potential satellite broadband provider OneWeb secured a significant investment of \$500 million to begin production of their satellite network. Since then, investment into their company has skyrocketed to over \$3.4 billion [13]. The satellite-based broadband industry is expected to account for only \$4 billion in revenue this year, but by 2024 revenue is expected to rise to \$22 billion, and to \$41 billion by 2029 [14]. Along with dedicated providers such as OneWeb and space industry players such as SpaceX, major corporations such as Facebook and Amazon have given commitments to enter this industry [15]. Investment into this industry in 2018 was the highest it has ever been, with over \$3.2 billion in total capital investment from a variety of sources, including almost \$2 billion in venture capital investment, an increase of 22% over last year.

Traditionally, satellite constellation systems are sized and constructed to meet a capacity estimated by market studies and extrapolations based on current demand. This estimate is subject to great uncertainty, as was shown in the case of the satellite telephone networks of the 1990s. Due to the unexpectedly rapid development of terrestrial cellular networks as well as uncompetitive pricing of satellite phone handsets and service charges, demand for satellite telephone services was far lower than anticipated. This caused the bankruptcy of Iridium and Globalstar companies, whose satellite constellations were vastly oversized for their market.

There is still significant uncertainty in the size of the satellite broadband internet market in ten years' time. Broadband satellite internet has the capability to reach millions of customers currently unserved by terrestrial networks. Conservative estimates place the number of global broadband subscribers before the end of the decade at ten million, while other estimates approach twenty five million.



Projections of Broadband Internet Demand, From [3]

As there is still significant uncertainty regarding the future size of the broadband internet market, there is significant risk in the process of designing a broadband satellite constellation for a specific forecasted capacity. Chaize [5] proposed an alternative, flexible approach to satellite constellation design in which a constellation is deployed progressively, starting with a smaller, more affordable constellation with a lower capacity that can be increased in stages through the launch of additional satellites. This ‘staged deployment’ methodology was shown to decrease the lifecycle cost of a satellite constellation compared to a traditional architecture that is optimized for a fixed capacity. This approach provides the system architects with real options that allow them to tailor the evolution of the system to an unfolding demand scenario by embedding flexibility into the design of the system.

This staged deployment method is well suited for use within the design space of currently proposed broadband satellite constellations. The vastly increased size and cost of proposed satellite broadband constellations as well as the new technologies included therein demand a return to this topic.

1.2 Background

Chaize has previously demonstrated the effects of staged deployment on the economics of satellite constellations within the design space of constellations of the 1990s and early 2000s. This analysis used a trade space previously developed by de Weck and Chang [8]. Chang [9] developed methods for calculating capacity of communication satellite constellations consistent with this architecture trade space design method. Del Portillo [4] performed a detailed analysis of the capacity of Telesat, SpaceX, and OneWeb’s proposed systems. Numerous accepted methods of evaluating spacecraft lifecycle costs exist, as detailed in [10]. For this analysis, the Unmanned Spacecraft Cost Model (USCM) was chosen to model lifecycle cost. Building upon the methods developed by Chaize, this paper analyzes the benefits of the flexibility enabled by staged deployment on lifecycle cost in the presence of uncertain demand.

1.3 Paper Objectives

The objectives of this paper are as follows: To develop a trade space representative of the proposed satellite constellations to provide global broadband internet access, to determine the possible architecture evolutions for broadband satellite systems, and to demonstrate the cost savings provided by staged deployment within this design space for a selected subset of potential demand scenarios.

2.0 Staged Deployment Strategy

2.1 Traditional Approach

The traditional approach to constellation design first establishes a required capacity for the system based on market studies and extrapolations of current demands. The two quantities that must be estimated are the expected global number of subscribers N_{Users} and the average activity level per user, A_{User} . The number of duplex channels that the system has to provide to satisfy this demand, N_{Ch} , represents the instantaneous capacity requirement.

$$N_{Ch} = \frac{N_{User} * A_{User}}{U_S * \frac{365}{12} * 24 * 60} \quad (1)$$

Where U_S is the percent global system utilization, a fractional value between 0 and 1 representing the amount of satellites currently available (i.e. over populated areas).

After the required number of channels is determined, a constellation is designed that minimizes lifecycle cost (LCC) while meeting this capacity requirement. LCC includes RDT&E, satellite manufacturing, satellite launch, deployment of ground stations, operations and satellite replenishment.

2.2 Flexible Approach

The flexible staged deployment approach developed by Chaize forsakes this process of sizing constellations in favor of a process that embeds flexibility by choosing an initial architecture that will give system architects the ability to adapt to market conditions. This poses new challenges to designers. The first challenge is that, instead of choosing a single architecture, architects must choose a 'path' of architectures that will allow them to progressively scale up their system. These paths are informed by legacy components from the initial stage which reduce the number of future developments available. The second challenge is that the chosen path must be demonstrated to be viable across all possible demand evolution scenarios, and as such uncertainty must be modeled into the design process.

2.4 Economic Advantages Afforded by Flexibility

The inclusion of flexibility in the design of a system allows the existence of decision points throughout the lifecycle of the system. At a decision point, the parameters that are subject to future uncertainty are analyzed, and a decision is made to adapt to them in the best possible manner. As these decision points are distributed throughout the lifecycle of the project, rather than in the initial design phase (as is the case with the traditional, single capacity design approach), uncertainty is reduced, thus reducing risk.

In the analysis of staged deployment of satellite constellations, demand is the uncertain parameter. The decision that this parameter informs is whether or not to expand the architecture of a satellite constellation beyond its current state in order to increase the capacity of the system. This approach represents an economic opportunity compared to the traditional way of designing systems because it allows designers to make decisions based on current and not future conditions. Two mechanisms explain this advantage. Staged deployment attempts to minimize the initial development costs of the system by deploying an affordable system. While this process does reduce initial costs, costs to transition between stages can be large, potentially offsetting the initial savings. However, since those expenditures are pushed towards future times, they are discounted. With discount rate r and cost Q , and t years between the current time and the time the cost will be incurred, the Present Value (PV) of the cost considered is given in Equation 2.

$$PV(Q) = \frac{Q}{(1+r)^t} \quad (2)$$

The present value, or cost, for deploying a new stage decreases with increasing t . Thus the first economic advantage afforded by staged deployment is that it spreads some expenditures (satellite production, launches) over time. A value of $r = 0.05$ was used for this analysis, identified as representative of these types of projects in [5].

The second advantage afforded by staged deployment is that future stages are deployed with greater knowledge of market conditions. If conditions are unfavorable, no additional capacity is deployed and expenditures are kept low. Likewise, if demand is large enough and revenues are sufficient, capacity can be increased with reduced risk. Note that the presence of sufficient revenue is not considered in this analysis.

3.0 Development of Trade Space

3.1 Choice of Design Variables

The architectural decisions under study in this paper are captured in the design vector, $x = [h, e, i, f, P_t, A, ISL]$. The constellation design vector is defined by its circular orbital altitude, h , minimum elevation angle of ground station antennas, e , satellite transmitter power, P_t , antenna type, A , type of inter-satellite link, ISL , and inclination of overlapping orbits, i . These variables contained within the vector were chosen for their compatibility with methods of trade space valuation developed by Chaize [5] and detailed in section 3.4. The trade space examined in this paper is a full factorial exploration of this vector between reasonable upper and lower bounds of every entry in the vector. The bounds of these variables were determined via analysis of several proposed designs for LEO constellations to provide broadband internet. In the traditional method of developing a constellation architecture, the value of these variables are constant throughout the life of the system.

With staged deployment, the values of some of these variables are allowed to change at each decision point. For technical or physical reasons only certain elements of the design vector can be changed after initial deployment of the system. The elements that comprise the design of an individual satellite, f , P_t , A , and ISL , are assumed to be constant over the lifetime of the system as satellites on

orbit cannot be modified and the addition of multiple satellite models introduces unnecessary and unrealistic complexity to the model as the cost of developing additional satellite models would deter this approach from ever being implemented. The elements of constellation design, h , e , and i , are allowed to evolve at each decision point. This allows the decomposition of the design vector into two parts, x_{flex} , comprised of constellation design elements which will change along the architecture path, and x_{base} , comprised of satellite design elements that will not change along the architecture path.

3.2 Parameters of Proposed Systems.

In order to develop a trade space representative of the design space for modern LEO broadband internet constellations, the designs of several proposed constellations were examined. FCC applications by five companies: LeoSat, OneWeb, Telesat, Kepler, and SpaceX, were used to benchmark the architectural design space. As shown in Table 1 below, designs vary greatly even when certain parameters (e.g. altitude and plane inclination in the case of LeoSat and OneWeb) are similar.

Provider	Inclination	Altitude	No. Sats	Min. Elevation Angle
LeoSat	90°	1400 km	78	10°
Kepler	98.6°	600 km	140	10.4°
OneWeb	87.9°	1200 km	720	55°
Telesat	99.5°	1000 km	117	20°
	37.4°	1248 km		
	53°	1150 km		
	53.8°	1110 km		
	74°	1130 km		
SpaceX	81°	1275 km	11943	40°
	70°	1325 km		
	53°	345.6 km		
	48°	340.8 km		
	42°	335.9 km		

Table 1: Orbital Parameters of Proposed LEO and VLEO Constellations

The above table informs the bounds of the trade space for elements of x_{flex} . The systems proposed by OnWeb, Telesat, and SpaceX are in the more advanced stages of development than those proposed by LeoSat and Kepler, and thorough analysis of these systems has been conducted by del Portillo [4]. These systems were used to benchmark the trade space boundaries for elements of x_{trad} . Values for these systems are shown in Table 2.

Provider	Frequency	Transmit Power	Antenna Diameter	Inter Satellite Links
OneWeb	Ka, Ku	22.5 dBW	2.4 m	None
Telesat	Ka, Ku	26.9 dBW	3.5 m	Optical Mesh
SpaceX	Ka, Ku, V	33.2 dBW	3.5 m	Optical Mesh

Table 2: Satellite Design Parameters of Proposed LEO and VLEO Constellations

3.3 Chosen Trade Space

The trade space chosen for this paper is shown below, informed by the design parameters of proposed systems. Upper and lower bounds of variables that expressed in units, rather than choices, have been extended beyond the values of proposed systems in order to ensure that the trade space represents the vast majority of feasible architectures. This trade space simplifies several key aspects of constellation design process, including ground station architecture and user terminal architecture. Design parameters dealing with these aspects of the system are held constant for all designs within the trade space. As the goal of this study is to examine the relative, rather than absolute, benefits of staged architecture, this assumption does not have significant impact on the analysis performed. Another simplification of the trade space is the inclusion of only three choices for inclination of overlapping orbits. In reality proposed systems such as SpaceX's Starlink use a variety of inclinations for their overlapping orbits. Due to the extreme enumeration of the tradespace that would result from simulating this type of constellation as well as the lack of available literature from SpaceX justifying this choice, this particular design option was omitted. Inclinations of 30° and 50° were chosen to serve 75% and 95% of the world's population respectively, per [7].

Variable	Units	Range	Step
Altitude	km	400-1600	200
Min. Elevation	°	15-60	15
Inclination of Overlapping Orbits	-	None, 30°, 50°	
Frequency Band	-	Ka/Ku, V	
Transmitter Power	W	200-2200	400
Antenna Diameter	m	2-4	1
ISL Geometry	-	None, Ring, Mesh	

Total Architectures Considered: 9072

Table 3: Chosen Architectural Trade Space

3.4 Choice and Determination of Evaluation Metrics

Evaluation of the trade space requires metrics by which individual systems can be compared. Chosen metrics were Lifecycle Cost and Capacity, (number of supportable users). These variables have previously been used by Chaize to demonstrate the value of flexibility in a trade space of systems representative of previous generation satellite telephony systems.

3.4.1 Modeling of Capacity

Calculations for capacity (adapted from [6]) integrate the link budget equation for space-based radiofrequency communications with bandwidth, frequency, and time division concerns. It is assumed that the bottleneck for capacity in all cases is the downlink to users. The link budget is governed by the following equation typically evaluated in decibels:

$$E_b/N_o = EIRP + G/T - L_{fs} - L_{other} - k - R_d \quad (3)$$

Where R_d is the data rate that can be provided in bits per second. All proposed systems use frequency division multiple access (FDMA) and time division multiple access (TDMA) schemes to establish channels for downlink to users. The combination of these two channel division methods is referred to as MF-TDMA. The number of channels that can be delivered for an MF-TDMA system for a given data rate is governed by the equation below.

$$N_{Ch,Sat} = \frac{Z}{2K} \frac{B_{Sat}}{B_T+B_G} \frac{R_d T_f - F}{n + R_d T_G} \quad (4)$$

Where all variables other than data rate R_d are variables concerning bandwidth allocation that are held constant for all simulated systems due to assumptions detailed in section 3.5. The total capacity of the system can then be calculated by multiplying the capacity of an individual satellite by the number of satellites in the constellation. From the number of channels, the user capacity of the satellite can be calculated using equation (1).

The variable U_s in equation (1) is global percent utilization of the system, a number between 0 and 1. This variable represents the percentage of satellites serving customers at any given time, i.e. satellites that are over inhabited areas and not over large ‘dead’ zones such as oceans, deserts, or the Arctic and Antarctic circles. For purely polar systems with no inter-satellite links this quantity is typically ~ 0.1 per [12]. This value increases to 0.7 for systems utilizing Ring ISL architecture, in which data can be transmitted between satellites in the same orbit, and 0.9 for systems utilizing Mesh ISL architecture, in which data can also be transmitted to satellites in adjacent orbits.

3.4.2 Modeling of Lifecycle Cost

Lifecycle costs (LCC) were evaluated from the USCM and the model proposed in [11]. LCC consists of numerous cost elements, some recurring (C_R) and some nonrecurring (C_{NR}). Recurring costs consist satellite production costs (C_P), of launch costs (C_L), and operation and maintenance costs (C_O). Nonrecurring costs consist of RDT&E costs (C_{RD}). Where T is the lifetime of the system, $N_{Sat,i}$ is the number of satellites deployed in year i (including replacements over the lifetime of the constellation), and L_{Cap} is the number of satellites that can be accommodated in a single launch and r is the discount rate., LCC for a single architecture can be computed from these terms as follows. LCC calculations for flexible systems are given in section 4.2.

$$LCC = C_{RD} + \sum_{i=0}^T \frac{N_{Sat,i} \left(\frac{C_L + C_P}{L_{Cap}} \right) + C_O}{(1+r)^i} \quad (5)$$

3.5 Assumptions and Limitations of Model

Several major assumptions are inherent to the model of the trade space. The most important of these are those involved in the determination of the capacities of the system. As shown in this figure from [4], the beam footprints for several proposed systems (Telesat, SpaceX, and OneWeb) vary in both size and shape. In reality, constellation design and optimization of the parameters in the trade space chosen for this analysis would be done in conjunction with optimization of FDMA, TDMA, and beam pattern parameters. For the performance of this analysis, these variables were held constant, as adding

them to the trade space would not have added additional flexibility to the system while greatly complicating capacity analysis. Parameters for FDMA, TDMA and beam pattern schemes for both Ka/Ku and V band systems were taken from SpaceX's FCC filings for their Ka/Ku and V band systems respectively. SpaceX's FDMA, TDMA, and beam pattern schemes were chosen due to their and the fact that their design is representative of a unified engineering effort and thought process for both Ka/Ku and V band systems, and their system is conventional in its use of fixed size, circular beams.

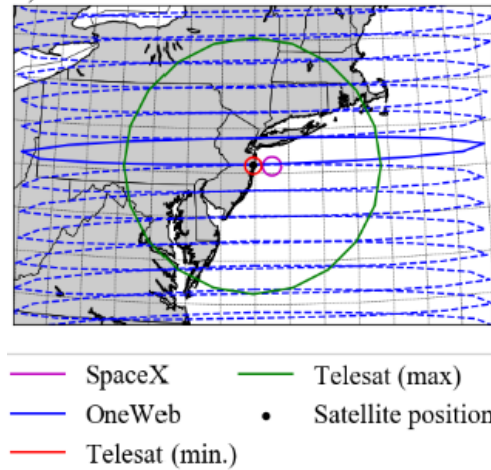


Figure 2: Beam footprints of several proposed systems, from [4]

3.6 Presentation of Trade Space

Of the over 9000 members of the trade space, the vast majority have very similar, relatively low lifecycle costs. The pareto frontier is comprised of the non-dominated systems along the lower edge of the group having the highest capacity of all systems at a similar lifecycle cost.

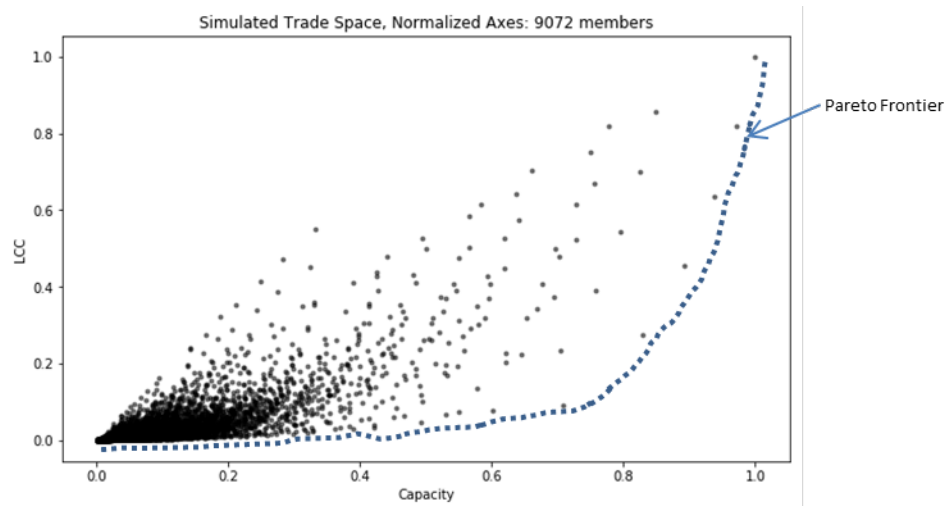


Figure 3: Simulated Trade Space with Normalized Bounds

4.0 Valuation of Flexibility

4.1 Identification of Viable Paths and Evolution Rules

In order to determine realistic architecture paths, formalized options for evolution need to be established. These rules characterize the possible changes in the elements of x_{flex} during evolutions, after the parameters of x_{base} have been established. These rules are governed by what reasonable changes to the system can be made. As there is a cost associated with the evolution of the system, ΔC , it is assumed that each evolution of the system involves the addition of new satellites. Stationary ground stations can be configured to interact only with satellites at elevations greater than their minimum elevation, but cannot interact with satellites below their initial elevation as this would require repositioning of the ground station antenna. Finally, an additional sub-constellation can be added to purely polar systems, but only one inclined subsystem can be present in a satellite system, and the inclination of a subsystem cannot be changed once deployed. With these limitations in mind the following evolution rules are proposed:

1. The number of satellites increases with each evolution
2. Elevation (e) can increase or decrease, but cannot be reduced below its original value
3. Inclined orbits can be added to purely polar systems, but cannot be changed or removed

4.2 Decision Model for Architecture Evolution

The decision to expand a satellite constellation in real life is contingent upon a number of factors including current demand, expectations of future growth, technical ability, and presence of sufficient revenue to fund the expansion. The decision model used in this analysis is greatly simplified and is equivalent to the model used by Chaize [5]: if the demand in year t exceeds the capacity of the system in that year, the evolution of the system to a new architecture that can support the demand is undertaken. This removes uncertainty relating to future demand and funding considerations from the analysis.

4.2 Computation of Lifecycle Cost for Flexible Architecture

Evaluations of lifecycle cost for flexible systems over simulated demand cases are given in [5]. Lifecycle cost for a single flexible architecture path is given in equation (6).

$$LCC_{Path} = C_{RD} + \sum_{j=1}^{N_S} \left(\sum_{i=t_j}^{T_j} \left(\frac{N_{Sat,i} \left(\frac{C_{L,j}}{LCap} + C_{P,j} \right) + C_{O,j}}{(1+r)^i} \right) + \Delta C_{j,j+1} \right) \quad (6)$$

Where N_S is the number of stages deployed, t_j and T_j are the year of deployment of and year of retirement (due to deployment of the next stage or reaching the end of the system lifetime) of stage j , and $C_{L,j}$, $C_{P,j}$, and $C_{O,j}$ are the yearly launch, production, and O&M costs of stage j , and $\Delta C_{j,j+1}$ is the cost of transitioning from stage j to stage $j+1$.

4.3 Method for Valuing Flexibility

The value of embedding flexibility is equal to the difference between the lifecycle cost of the traditional architecture that can meet the forecasted demand and the lifecycle cost of the architecture path that can meet this demand. The percent cost reduction afforded by flexibility is given in equation (7). After the value of embedding flexibility into the system is determined, the price to embed this flexibility can be determined. If the cost of embedding flexibility is less than the value that it provides, the flexibility should be embedded into the system in question.

$$\% \text{ Reduction} = \frac{LCC_{Trad} - LCC_{Path}}{LCC_{Trad}} \quad (7)$$

5.0 Case Study

Trends for the value of flexibility in satellite communication system constellations are characterized in [5]. For this analysis, two specific scenarios were chosen to demonstrate the value of flexibility in systems designed to deliver broadband internet. These cases are the ‘High Growth’ (Scenario A) and ‘Low Growth’ (Scenario B) cases forecasted by the Northern Sky Research group in [3].

5.1 Definition of Scenarios

The lifetime T_{sys} chosen for study is 10 years, with options for expansion every two years. Demand at each decision point for Scenarios A and B are listed below. The per-user activity rate, A_{User} , is set to 6hr/week, representative of the average amount of time spent on the internet in an average week in U.S. households per [2].

Time (yrs)	Demand (Scenario A)	Demand (Scenario B)
0	2,500,000	2,500,000
2	3,750,000	3,150,000
4	6,000,000	4,250,000
6	10,325,000	6,350,000
8	16,250,000	8,150,000
10	23,000,000	9,500,000

Table 4: User Demand in Scenarios A and B

Note that there is an implicit assumption that one system will be serving the entire customer base. With scenarios established, traditional architectures can be established.

5.2 Determination of Traditional Architecture

Traditional architectures for each scenario, $x_{trad,A}$ and $x_{trad,B}$, are the pareto-optimal (minimum lifecycle cost) architectures with capacities greater than Cap_{Max} . Parameters of these systems for Scenario A and B are given below.

Parameter	$x_{trad,A}$	$x_{trad,B}$	Units
h	1,600	1,400	km
e	30	15	°
i	None	30°	-
f	Ka/Ku	Ka/Ku	-
Pt	1,600	1,400	W
A	2	3	m
ISL	Ring	Mesh	-
Cap	23,054,294	10,040,895	Users
LCC	123.81	50.52	­B

Table 5: Parameters of Traditional Architectures for Scenarios A and B

5.3 Choice of Flexible Architectures

Choice of a flexible architecture path begins with the choice of the initial stage and values of x_{base} . Note that the ideal starting point for a path may not be a pareto-optimal architecture, as a path may become more optimal as it evolves. For this analysis the pareto-optimal initial architecture was chosen for both cases. Parameters of the the initial architecture are shown below. The variables of x_{flex} are the parts of the initial architecture that can be altered in order to increase the capacity of the system.

	Parameter	$x_{initial}$	Units
x_{flex}	h	1,600	km
	e	30	°
	i	None	-
x_{base}	f	Ka/Ku	-
	Pt	200	W
	A	2	m
	ISL	Ring	-
	Cap	2,561,588	Users
	LCC	10.44	­B

Table 6: Parameters of Initial Architecture

For the first several stages in each scenario several possible evolutions exist. In both cases the optimal evolution path does not immediately deploy an overlapping sub-constellation, but rather waits until the third evolution to deploy a new constellation. This particular evolution incurs significant cost due to the high number of satellites that must be launched, and waiting several years to do so allows the present cost of the evolution to decrease significantly. Evolution paths for scenarios A and B are shown in tables 7a and 7b below.

Time (yrs)	N_{User} (Scenario A)	Capacity	Evolution
0	2,500,000	2,561,588	None
2	3,750,000	4,996,524	Decrease altitude to 1400 km, increase elevation to 30°
4	6,000,000	7,747,109	Decrease altitude to 1200 km
6	10,325,000	11,620,663	Add an overlapping constellation at 30°
8	16,250,000	27,945,155	Increase altitude to 1400 km, increase elevation to 45°
10	23,000,000	27,945,155	None

Table 7a: Optimal Architecture Path in Scenario A

Time (yrs)	N_{User} (Scenario B)	Capacity	Evolution
0	2,500,000	2,561,588	None
2	3,150,000	3,293,471	Increase Elevation to 30°
4	4,250,000	4,996,524	Decrease Altitude to 1400 km
6	6,350,000	7,686,960	Add an overlapping constellation at 30°
8	8,150,000	11,620,663	Decrease altitude to 1200 km
10	9,500,000	11,620,663	None

Table 7b: Optimal Architecture Path in Scenario B.

5.4 The Value of Flexibility in These Cases

In both scenarios the introduction of flexibility into the system was effective in reducing the lifecycle cost of the system. Additionally, there is room for continued expansion in both cases, as neither the altitude nor minimum elevation of each system have reached their final capacity-maximizing values.

Variable	Scenario A	Scenario B	Units
LCC, xtrad	123.81	50.52	\$B
LCC, path	103.89	38.90	\$B
Value of Flexibility	19.92	11.62	\$B
% Cost Reduction	16	23	%

Table 8: Value of Flexibility in Scenarios A and B

6.0 Conclusions and Future Work

The addition of flexibility to satellite broadband systems via staged deployment does indeed create value in cases where market growth is present. In order to determine whether or not this value in fact yields an economic opportunity additional research must be done into pricing the flexibility. An additional productive avenue of future research would be to further refine this analysis to yield only paths that generate sufficient revenue to fund the evolution of the system.

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