A Technical Evaluation of Integrating Optical Inter-Satellite Links into Proliferated Polar LEO Constellations

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SSC20-P4-02

Abstract

This study evaluates the technical requirements, benefits, and limitations of integrating optical inter-satellite links into a proliferated polar LEO constellation. When compared to traditional radio frequency (RF) links, optical links can transmit orders of magnitude more data at much lower powers in a far more secure method. However, these benefits come with stiff coarse and fine pointing requirements, complex thermal and vibrational satellite bus interfaces, as well as sensitivities to atmospheric conditions for LEO-ground connections. This study breaks optical inter-satellite links (OISL's) into three distinct categories; in-plane, out-of-plane (crosslink), and LEO-ground. General commercial off the shelf (COTS) state of the art OISL terminal parameters are established. Based on these parameters, varying constellation level implementation strategies are assessed based on latency, bandwidth and technical feasibility using Model Based Systems Engineering principles. These assessments were then re-run at different OISL parameters to evaluate whether the optimal integration technique will change in the future as OISL terminal capability increases. The study finds that the methodology outlined gives crucial insight into future OISL integration and implementation strategies for both current and future mega-constellation architects. This study finds that an RF-reliant in-plane architecture is the optimal integration architecture given the constellation configuration constraints. This assessment can help drive the trade space for both OISL vendors producing COTS terminals as well as commercial and military customers looking to integrate OISL terminals into their future constellations.

Introduction

Over the past five years, two independent spaceflight technologies have been maturing in parallel; free-space optical communications and LEO mega-constellation architectures. Past low Earth orbit (LEO) – ground and LEO – LEO missions such as OPALS[1] and NFIRE/TerraSAR-X[2] have demonstrated the ability to transmit huge volumes of data over vast distances with relatively small time and power requirements. While these links have much more stringent pointing requirements, their numerous benefits include improvements to the security and performance of the signal due to optical light's shorter wavelength and robustness to jamming or interference. As the transceiver technology has matured, the number of terminal manufacturers has proliferated with numerous commercial businesses being started solely to produce free-space optical communications hardware. From 'old-space' contractors like Ball Aerospace and L3Harris to modern tech giants like Facebook and infant companies like Skyloom, a plethora of commercial organizations have recognized the benefits that optical links provide and are actively working towards the production of cheap, light, stable, robust, high capacity optical terminals. However, for these companies to close their business case through the benefits of economies of scale they need a buyer in the market for 100's or even 1000's of terminals.

This study seeks to inform both mega-constellation architects as well as OISL terminal vendors as to what is the current optimal architecture for integration and how that optimal architecture may change as the cost of each terminal falls and the data capability increases. Four different integration strategies will be introduced with each of their technical feasibilities assessed. Each of these architectures will then be applied to two different case studies. The first case study will mimic OneWeb's current GEN1 constellation while the second will mimic a smaller constellation whose sole purpose is to transmit real-time, secure data between critical points on Earth. The latency, bandwidth and technical cost of each architecture will be assessed to determine which is optimal for each case study. Model-based systems engineering techniques will be introduced to determine this optimum and determine how sensitive the optimal architecture decision is to constellation design.

Methodology

The constellations were constructed using the parameters seen in Table 1. A maximum distance and angular velocity visibility filter was applied to the vectors between each node according to Equations (1) – (4). Table 2 describes the attributes of all four implementation strategies. An example of each implantation strategy can been seen in Figure 1. Equations (5) – (10) describe the link establishment algorithm for the 2OOP implementation strategy. Tables 3 displays the MBSE weightings and target values.

Table 1: Constellation Design Space

Parameter	Inclination (deg)	Altitude (km)	Number of Planes	Satellites per Plane	Offset Between Planes (deg)
Range	87.6	1200	6 – 20	20 – 50	360 / (2*SatsPerPlane)

$$Maximum\ Visibility = 6400 * 0.9398^{Plane} \tag{1}$$

$$v = \sqrt{\frac{\mu}{R_E + altitude}} \tag{2}$$

$$Maximum\ Slew\ Rate = \frac{180}{MinimumSlewTime} \tag{3}$$

$$\omega = \frac{r \times (v_2 - v_1)}{\boldsymbol{r^2}} \tag{4}$$

Table 2: OISL Architecture Characteristics

Name	In-Plane OISL's	Number of IP OISL's per Satellite	Out-of-Plane OISL's	Number of OOP OISL's per Satellite	Hub	Hub Type	Strength	Weakness
Two-Out-of-Plane (2OOP)	YES	2	YES	2	NO	N/A	Lowest Latency Option	Expensive
One-Out-of-Plane (1OOP)	YES	2	YES	1	NO	N/A	Less expensive than 2OOP	Longer Optimal Path
Radio Frequency Hub (RFHub)	YES	2	NO	0	YES	Ka Band	No OOP terminals.	Large latency and RF bandwidth ceiling.
Optical Hub (OPTHub)	YES	2	NO	0	YES	Optical	Huge Bandwidth	Weather dependency

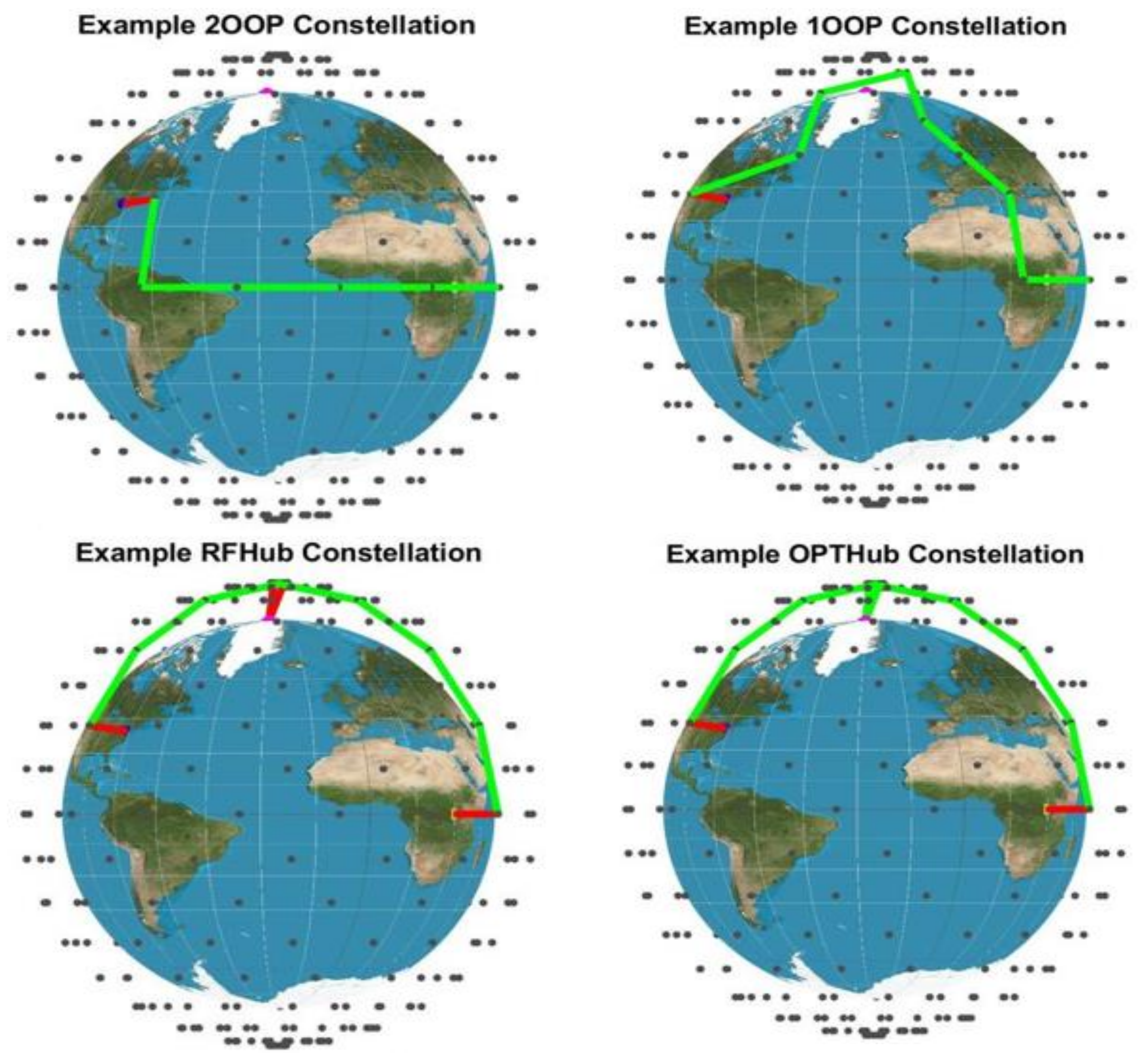

Figure 1: OISL Architecture Example Links

$$First\ Step = \min(\theta) = \min((\cos^{-1}\frac{(\boldsymbol{r_{RW}} \cdot \boldsymbol{r_{sat1}}}{||\boldsymbol{r_{RW}}||*||\boldsymbol{r_{sat1}}||})) \tag{5}$$

$$\boldsymbol{r_{Goal_n}} = \boldsymbol{r_{DC}} - \boldsymbol{r_{sat_n}} \tag{6}$$

$$(N-1)th\ Step = \min(\theta) = \min((\cos^{-1}\frac{(\boldsymbol{r_{sat_n}} \cdot \boldsymbol{r_{Goal_n}}}{||\boldsymbol{r_{sat_n}}||*||\boldsymbol{r_{Goal_n}}||})) \tag{7}$$

$$\varphi = \cos^{-1}((R_E/(R_E + alt)) * \cos(\varepsilon)) - \varepsilon \tag{8}$$

$$r_{term} = \sqrt{R_E^2 + (R_E + alt)^2 - 2 * R_E * (R_E + alt) * \cos(\varphi)} \tag{9}$$

$$Nth\ Step = \mathbf{r_{Goal}}\ when\ ||\boldsymbol{r_{Goal}}|| < r_{term} \tag{10}$$

Table 3: MBSE Weights and Target Values

Parameter	Bandwidth Weight	Latency Weight	Cost Weight	Target Bandwidth	Target Latency	Target Cost
Variable	α	β	γ	$Bandwidth_T$	$Latency_T$	$Cost_T$
Value	0.2	0.3	0.5	$0.0085 * \#Sats * Bandwidth_{Minimum}$	$17 * \#Sats * \Sigma \boldsymbol{r_{sat}}/c$	$Cost_{Minimum}$

Case Studies

By implementing the methodology laid out in the previous section, two case studies were conducted. Table 4 describes the constellation parameters for the OneWeb and 120Sat cases. The latencies and bandwidths over time can be seen in Figure 2. Overall, RFHub provided the greatest amount of architecture capability for both case studies.

Table 4: Case Study Orbital Parameters

Parameter	Inclination (deg)	Altitude (km)	Orbital Planes	Satellites Per Plane	Total Satellites
OneWeb	87.6	1200	12	49	588
120Sat	87.6	1200	6	20	120

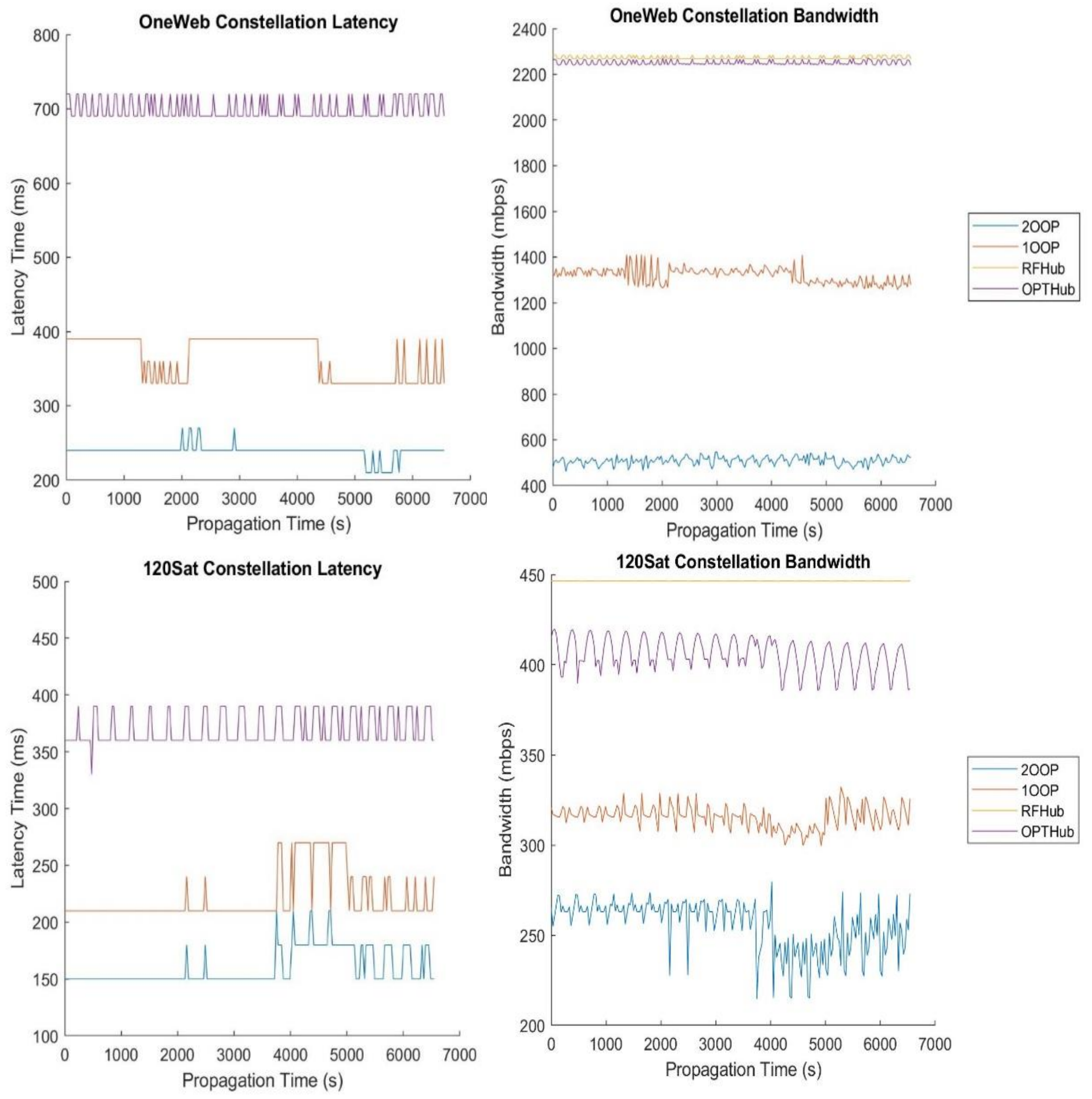

Figure 2: Case Study Results

After the case studies were analyzed with the current state of the art OISL parameters, a future development study was conducted to assess if the optimal architecture would change as OISL's improve. The bandwidth was increased while the latency and the cost were decreased. The results of these improvements can be seen in Figure 3 as a function of OISL bandwidth.

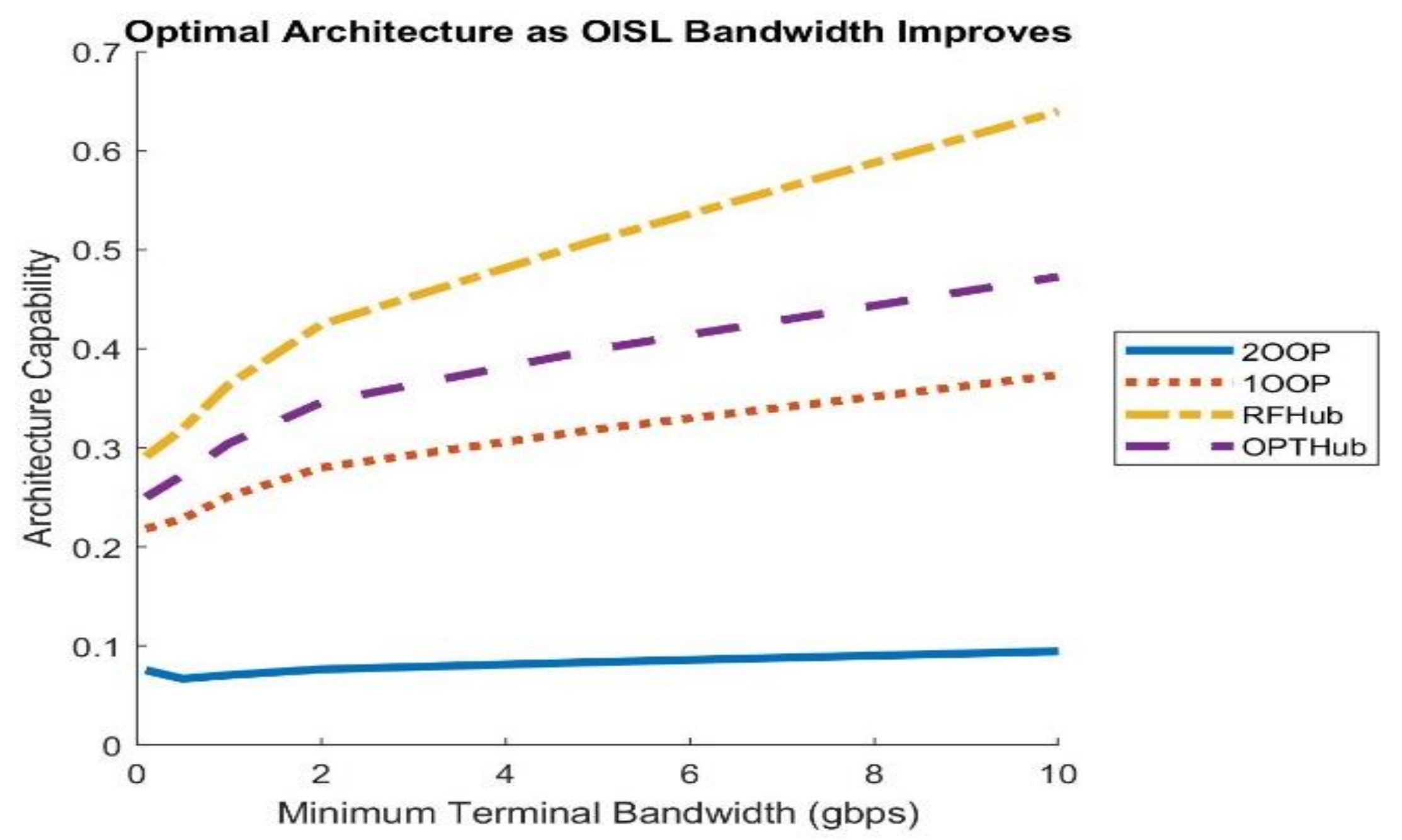

Figure 3: Architecture Capability as OISL Terminals Mature

Even as the OISL terminals improved, the optimal integration strategy remained stagnant. Because of this, polar mega-constellation architects should pursue the constructions of RF hub installations near the poles to transfer data between constellation planes.

Conclusion

This effort studied different implementation architectures for optical inter-satellite links in proliferated polar LEO constellations and analyzed each architecture's cost, latency and bandwidth characteristics. Four different architectures were put forth as potential solutions to create fast, secure links with minimal ground network use between two point on the Earth. Constellation configurations were varied, and the optimum was found for the current state of the art as well as future terminal capabilities. In particular, this study focused on maintaining a cost-balanced approach as the entirety of the target market is comprised of commercial, not government entities.

The results of this study show that the RFHub architecture is the current optimum overall for the foreseeable future with the 1OOP being the optimal in-space only architecture. RFHub provided the lowest cost, second highest bandwidth with the latency penalty not being great enough to tip the model-based systems engineering evaluation equation out of its favor. While OPTHub also poses the ability to increase the bandwidth ceiling imposed by the RF LEO-Ground connection, the atmospheric attenuation sensitivity of the chosen 1550nm laser poses too much of a connection penalty. Looking forward, utilizing the orbital plane intersection point near the poles will be integral to creating an inter-satellite connection between different points on the globe. While OOP OISL terminals may be useful for different constellation configurations, they are not worth the non-recurring engineering cost needed to develop them for use in a polar use case. Focusing on industrializing the IP efforts will provide significantly more utility at a much lower cost.

Acknowledgements

Dr. Glenn Lightsey – Georgia Tech
Dr. Brian Gunter – Georgia Tech
George Nagy – OneWeb Satellites
Patricia Feingold – OneWeb Satellites
Brian Heider – OneWeb Satellites
Christina Staples – OneWeb Satellites
Steve Isakowitz – The Aerospace Corporation
Sirisha Bandla – Virgin Galactic