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

Joshua Ingersoll
Georgia Institute of Technology
3862 Mohr Oak Ct, Fairfax, VA 22033; 585-451-0129
jingersoll3@gatech.edu

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 bandwidths, latencies and costs 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. Using both current OISL performance parameters as well as future improvements, 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.

Fortunately, there are currently four major players developing what have been come to be known as satellite 'mega-constellations' that could vastly benefit from the implementation of both optical intersatellite links (OISL's) and optical ground links. Amazon, OneWeb, SpaceX, and Telesat are all in different stages of their constellation development with SpaceX and OneWeb having launched 120 and 6 satellites respectively at the time of writing[3,4]. These mega-constellations all have the similar goal of providing global broadband internet and connecting the approximate remaining 3 billion people on Earth who do not have access as of 2019[5]. While none of the mega-constellation satellites currently flying have successfully implemented OISL terminals, OneWeb and SpaceX have both publicly stated that they will be introducing this technology in their second-generation constellations to increase both the back-haul bandwidth of the constellations as well as the ability to transmit jam-resistant data anywhere on the globe.

While the possible benefits of merging the two technologies of OISL's and mega-constellations are bountiful, the number of integration challenges are just as apparent currently. The largest technical hurdle currently is link acquisition and maintenance for 'Out-of-Plane' (OOP) terminals. While 'In-Plane' (IP) terminals only must adjust a few degrees depending on the distance between satellites in a single plane, OOP units must gimbal up to an entire hemisphere to maintain the link between terminals. While this process has been demonstrated on the ground, it has not occurred in space with representative angular ranges and slew rates. Once the link has been acquired, the next issue is minimizing the micro vibrations or 'jitter' that the terminal experiences. Because of the miniscule beam divergence, even microradians of vibrations can break the link. Because of this strict requirement put on the rest of the satellite bus by the OISL terminal, it is imperative that the OISL terminal is introduced early in the design of the platform. Finally, the cost of these units is prohibitively high currently due to poor industrialization techniques and low demand for low-cost units. OISL vendors cannot benefit from economies of scale currently and their units can cost hundreds of thousands of dollars each. When the business case of the mega-constellation architects depends on building hundreds of satellites at a hundredth of the cost of traditional communication satellites, implementing a new subsystem that is the same cost as the rest of the satellite is not feasible no matter the technical benefit. While the major costs outside of the production of the terminals themselves include network maintenance hardware and personnel, these costs are quite like the nominal RF mega-constellation operations that OneWeb, SpaceX, Amazon are already planning for and as such are not considered in this study.

This paper 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. Finally, the maximum bandwidth of each terminal will be increased to mimic the future improvements of the OISL terminals. The optimal architecture analysis will then be redone to determine if the optimum integration strategy will change in the future as the OISL terminal capability inevitably increases.

METHODOLOGY

Constellation Construction

The first challenge that was tackled as part of this study was to create a way to populate and propagate any number of polar LEO constellations. This was done by setting a few parameters to vary during the constellation building process. These parameters and the ranges used in this study can be seen in Table 1 and an example of the smallest and largest constellations can be seen in Table 1.

Table 1: Constellation Design Space

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

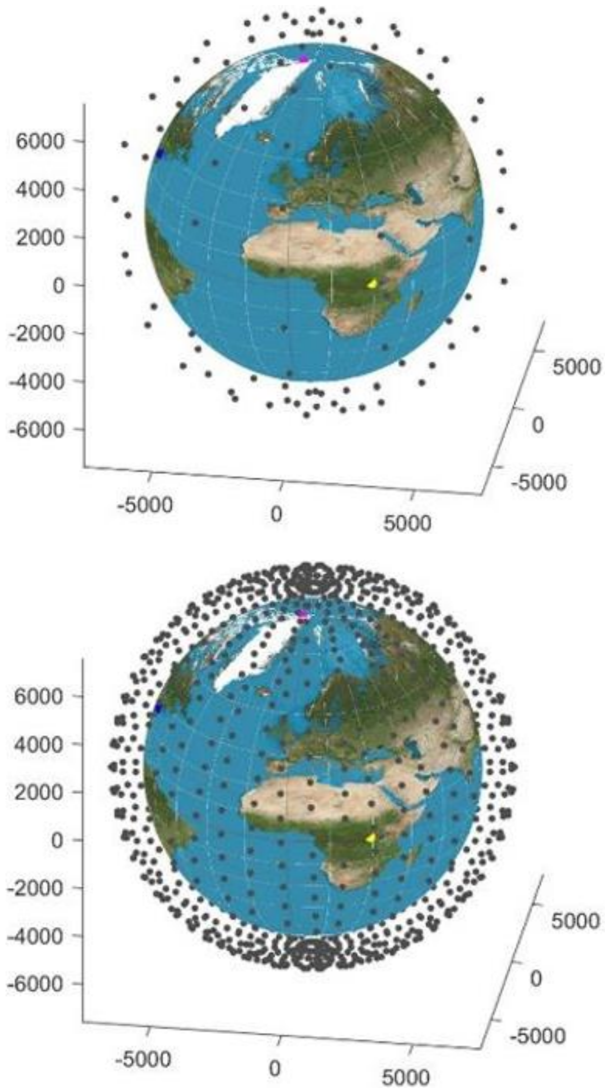

Figure 1: Smallest and Largest Constellations Considered

This population was done by using the rotation matrices seen in Equations (1)-(3) with every other orbital plane being offset by half the distance between each satellite in a plane.

$$\begin{bmatrix} r_{xi} \\ r_{yi} \\ r_{zi} \end{bmatrix} = \begin{bmatrix} cos\theta_i & -sin\theta_i & 0 \\ sin\theta_i & cos\theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} alt + R_E \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} r_{xi} \\ r_{yi} \\ r_{zi} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cosi_i & -sini_i \\ 0 & sini_i & cosi_i \end{bmatrix} * \begin{bmatrix} r_{xi} \\ r_{yi} \\ r_{zi} \end{bmatrix} \quad (2)$$

$$Plane_i = \begin{bmatrix} cosv_i & -sinv_i & 0 \\ sinv_i & cosv_i & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} r_{xi} \\ r_{yi} \\ r_{zi} \end{bmatrix} \quad (3)$$

Where $\boldsymbol{r}$ = position vector in km, θ = angle between each satellite in a plane in degrees, R_E = radius of Earth in km, alt = satellite altitude in km, i = inclination in degrees, and v = angle between each plane in degrees.

Visibility Filters

Following the construction of the constellation, the next step was to determine the visibility between each satellite so that the optimal path between two points on Earth could be calculated. There were two main filters applied to the visibility condition between each node. The first filter was a hard-maximum range that the OISL link could possibly span. The maximum was set according to Equation (4). Equation (4) was empirically created using a logarithmic fit based on the maximum link distance of the example OISL terminal and the maximum IP link distance before atmospheric effects needed to be considered (6400km).

$$Maximum\ Visibility = 6400 * 0.9398^{Plane} \quad (4)$$

The second filter applied to the visibility condition can be seen in Equation (7) and is related to the relative angular velocity of the two nodes. In order to maintain an OOP link, the relative angular velocity between the two satellites must be less than the maximum slew rate of the OISL terminal. Assuming circular orbits, the velocity of each satellite was calculated using Equation (5). The maximum slew rate was calculated using Equation (6) based on the minimum time it would take for the OOP terminal to hemispherically slew across 180 degrees. For this study the minimum slew time was set to 30 seconds based on the time-step used for the orbit propagation.

$$v = \sqrt{\frac{\mu}{R_E + altitude}} \quad (5)$$

$$Maximum\ Slew\ Rate = \frac{180}{MinimumSlewTime} \quad (6)$$

$$\omega = \frac{r \times (v_2 - v_1)}{\boldsymbol{r^2}} \quad (7)$$

Where $\boldsymbol{v}$ = velocity vector in meters per second, μ = gravitational parameter of Earth in km^3/s, r = position vector magnitude in km, and ω = relative angular velocity between nodes in radians per second. If both the visibility range and relative angular velocity conditions were met, a logical value was assigned to the distance vector between the two nodes. The result of one of these visibility calculations can be seen in Figure 2.

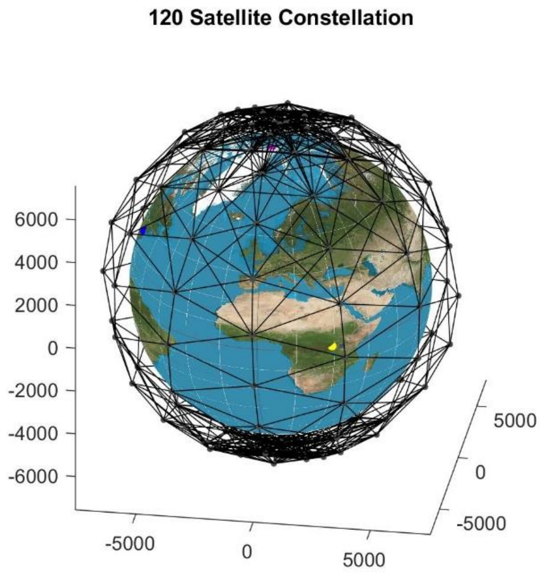

Figure 2: Visibility Filter Example

Implementation Architectures

After the constellation was built and the visibility between each node was calculated, the four different integration strategies of the OISL's were introduced and the search algorithms for each strategy were developed. The attributes of the four integration strategies can be seen in Table 2. Each architecture has different strengths and weaknesses that will be evaluated. The visual difference between the four different architectures can be seen in Figure 3. The connection shown here displays the lowest latency connection between Rwanda and Washington D.C. with the optional hub location being Alert, Nunavut, Canada. These three locations were chosen as many remote areas of Rwanda are without the 'last mile' section of internet infrastructure and would need a space link to serve many of its citizens[18], there is a profound interest to use secure optical links to better command US military assets in the field through programs like DARPA Blackjack[19], and Alert, Canada provides the furthest north developed location for the inter-plane handoff. The constellation in Figure 3 is representative of OneWeb's current constellation configuration with 12 planes with each plane containing 49 satellites. The connections in Figure 3 are red for Ka-band radio-frequency connections and green for 1550nm optical connections.

Table 2: OISL Architecture Characteristics

Name	Two-Out-of-Plane (2OOP)	One-Out-of-Plane (1OOP)	Radio-Freq. Hub (RFHub)	Optical Hub (OPTHub)
In-Plane OISL's	YES	YES	YES	YES
Number of IP OISL's per Satellite	2	2	2	2
Out-of-Plane OISL's	YES	YES	NO	NO
Number of OOP OISL's per Satellite	2	1	0	0
Hub	NO	NO	YES	YES
Hub Type	N/A	N/A	Ka Band	Optical
Strength	Lowest latency connection .	Less expensive than 2OOP.	No OOP terminals. Large bandwidth.	Huge bandwidth and only 1 OOP terminal.
Weakness	Expensive due to 4 terminals per satellite	Longer optimal path due to mandatory IP links	Large latency and RF bandwidth ceiling.	Large latency and weather dependent.

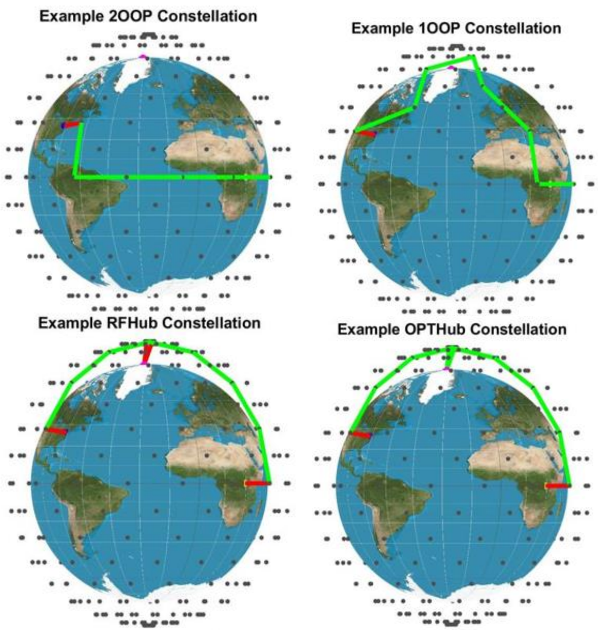

Figure 3: OISL Architecture Example Links

2OOP

The Two-Out-of-Plane (2OOP) architecture is the most technically costly architecture. Using 2OOP, each satellite would have four OISL terminals. Two IP terminals that can gimble up to a few degrees to connect each polar ‘ring’ together and two OOP terminals with hemispherical gimbal capabilities to link between the rings. Here the relative angular velocity limit visibility requirement is quite important as satellites in consecutive planes that are close together are moving too fast relative to each other to establish a link. This condition negatively effects the overall bandwidth of the connection and positively effects the latency as will be discussed later. The search algorithm to establish the optimal 2OOP link utilized Equations (8)-(13) and was essentially a 3-Dimensional line search to get from Rwanda to Washington DC. The first RF link was chosen based on the satellite node with the highest elevation in the Rwandan sky. To accomplish this, the angle between the position vector of Rwanda and each possible satellite link was minimized. Equation (8) was used to accomplish this. Once in the network, each subsequent step was chosen by creating a goal vector (Equation (9)) and moving to the node with the smallest angle between each possible link vector and the goal vector. The goal vector was then updated, and the process run in perpetuity until the termination condition was met. This termination distance was created by setting a minimum elevation above the horizon in D.C. ($\varepsilon = 15^{\circ}$) and solving for the angle between the DC location vector and the proposed elevation vector (φ) in Equation (11). Finally, the termination distance was solved using law of cosines in Equation (12). Equation (13) states that when the goal vector magnitude became less than the termination distance, an RF connection was established between the current satellite node and Washington DC.

$$First\ Step = \min(\theta) = \min\left(\cos^{-1}\frac{(\boldsymbol{r_{RW}}\cdot\boldsymbol{r_{sat1}})}{||\boldsymbol{r_{RW}}||*||\boldsymbol{r_{sat1}}||}\right) \quad (8)$$

$$\boldsymbol{r_{Goal_n}} = \boldsymbol{r_{DC}} - \boldsymbol{r_{sat_n}} \quad (9)$$

$$(N-1)th\ Step = \min(\theta) = \min\left(\cos^{-1}\frac{(r_{sat_n}\cdot r_{Goal_n})}{||r_{sat_n}||*||r_{Goal_n}||}\right) \quad (10)$$

$$\varphi = \cos^{-1}((R_E/(R_E+alt)) * \cos(\varepsilon)) - \varepsilon \quad (11)$$

$$r_{term} = \sqrt{R_E^2 + (R_E+alt)^2 - 2 * R_E * (R_E+alt) * \cos(\varphi)} \quad (12)$$

$$Nth\ Step = \mathbf{r_{Goal}}\ when\ ||\boldsymbol{r_{Goal}}|| < r_{term} \quad (13)$$

The 2OOP architecture provides the lowest bandwidth, lowest latency for a very high technical cost. Figure 3 displays this as the 2OOP example has the fewest nodes and shortest path between Rwanda and Washington DC. Because of the relatively long links between nodes in this architecture, 2OOP provides the lowest bandwidths of the 4 architectures as will be seen later.

1OOP

The search algorithm seen in Equations (8)-(13) for 2OOP is mostly replicated for the 1OOP architecture. The main difference between 2OOP and 1OOP is the number of OOP OISL terminals per node. Under 1OOP, each satellite has two IP terminals and only one OOP terminal. This is done in the interest of cost savings and decreasing the technical complexity of the system. Because each satellite has only one hemispherical gimbaling terminal, after each OOP link there must be an IP link. This is because the one OOP terminal will be in use for the previous link and cannot be used for the next link at that instant. Figure 3 displays this phenomenon. The only change to the search algorithm is a logical condition applied after each step. This condition can be seen in Equation (14).

$$if\ Step_{n-1} = 'OOP',\ then\ Step_n = 'IP' \quad (14)$$

After each IP link, the condition is removed, and the algorithm once again considers all possible links. The 1OOP architecture provides a higher bandwidth, higher latency connection relative to 2OOP and at a 25% terminal savings. The cost benefit would most likely be greater than 25% since the OOP terminals tend to be more expensive that the IP ones because of their increased capability.

RFHub

The RFHub architecture includes no OOP terminals and instead replaces the interplane transfer capability with a polar hub located in the town of Alert, Nunavut Canada for the purposes of this study. This hub operates in the Ka-band and acts as the hand off point between the different polar rings. The search algorithm for this architecture is much simpler than the one used for 2OOP and 1OOP. Equation (8) is used to pick the first link between Rwanda and the network as well as the links to and from the hub. Equations (11)-(13) are used again to determine the termination conditions and the final link from the network to DC. The RFHub architecture provides a much higher latency, higher bandwidth connection than either 2OOP or 1OOP due to high number of nodes and relative short distance between nodes. This architecture is also much more cost effective as the RFHub technology already exists and is being demonstrated by OneWeb in Norway[6]. One disadvantage of the RFHub architecture is the bandwidth bottleneck that comes with relying on an RF connection in the link. While free space optical connections have demonstrated gigabits of bandwidth[7], SpaceX's Starlink satellites have capped their Ku-band link at 610 mbps at the time of writing[8]. Another issue with the RFHub architecture is the network single point of failure that the hub creates. If an issue occurs at the hub, the whole network will fail.

OPTHub

Like the RFHub architecture, OPTHub requires each satellite to only establish IP LEO-LEO links. The search algorithm for OPTHub is the same as RFHub. The main difference between the two hub implementations is under OPTHub the facility in Alert, Canada will be equipped with multiple LEO-Ground optical connections. This change increases the bandwidth of the overall connection but incurs the additional cost of adding one LEO-Ground OISL terminal to each satellite. Another main issue with the OPTHub architecture is the weather dependency of the hub links. The 1550nm optical connection is sensitive to atmospheric aberration and can lose up to 90% of its signal strength as it passes through the atmosphere, decreasing the available bandwidth logarithmically[9]. This is of great concern for the current hub location as Alert, Nunavut, Canada is mostly cloudy or overcast more than half the year according to WeatherSpark[10]. This data can be seen in Figure 4. Because of these competing advantages and disadvantages, the ranking of OPTHub relative to the other architectures is hard to discern. By taking the average of the curve found in Figure 4, the speed of the LEO-Ground connection for OPTHub was decreased by 67% to account for time that only 10% of the signal would be able to get through.

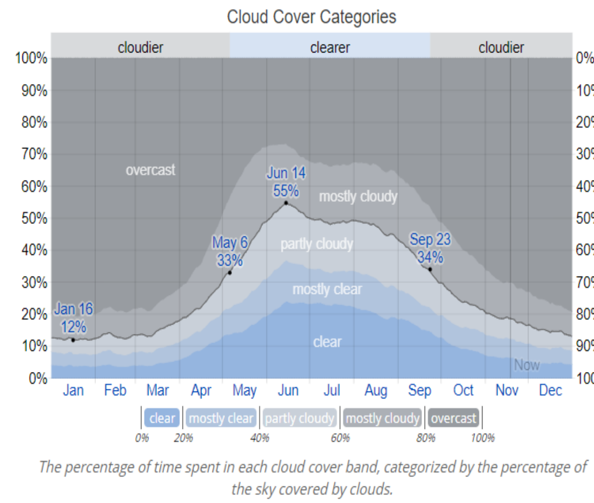

Figure 4: Cloud Cover over Alert, Canada

OISL Baseline

After the four different implementation architectures and their accompanying search methods were established. The baseline performance of the IP and OOP ISL terminals was established. The parameters given in Table 3 are not based on the state of the art OISL units but instead are highly scaled down to represent what an industrialized commercial unit would look like. The issue here is the cost to performance ratio of OISL terminal currently is quite steep. If mega-constellation architects were to go after the multi-gigabit state of the art, the cost of equipping each satellite with >2 terminals would completely negate any network benefits. For this reason, Table 3 displays a much more conservative terminal with a lower bound data rate of 100mbps at a maximum link distance of 5000km. The latency per terminal value of 15ms is driven by the processing time on board the spacecraft as it moves the data between the receiving and transmitting OISL terminals. This standard is much more akin to the type of unit currently being developed by Skyloom, Mynaric, or Xenesis[11,12,13]. For the OOP ISL, a relatively low maximum slew rate of 6 degrees per second was chosen as an input for the angular velocity filter. Because industrialized and state of the art OISL units are fundamentally different, once a few primary high-volume vendors are established they will be able to iterate and develop their design to increase the bandwidth and decrease the cost of their units while still operating at a low enough cost to close the mega-constellation architects business case.

Table 3: OISL Performance Parameters

Max Power Draw (W)	Mass (kg)	Minimum Data Rate (mbps)	Maximum Link Range (km)	Latency per Terminal (ms)
10	5	100	5000	15

Architecture Evaluation Metrics and Methods

The three metrics that each implementation method was evaluated on were latency, bandwidth, and technical cost/feasibility. The method for calculating latency included the 15ms per terminal that the signal passed through and the speed of light latency between each terminal and the ground. This relationship can be seen in Equation (15).

$$Total\ Latency\ (ms) = 0.15 * N_{Nodes} + \Sigma \boldsymbol{r}_{\boldsymbol{sat}_n}/c \tag{15}$$

Where c = speed of light in meters per second. The instantaneous average bandwidth of the connection was approximated by averaging all the individual links in the connection. While this approach is a bit more abstract than finding the slowest link at each timestep, it allows for a better overall view of the architecture performance as the optimal path can change every time step. The bandwidth of each link was approximated using the difference in space-loss as function of the link distance. The known bandwidth used to anchor this approximation is 100mbps at a link distance of 5000km. Each shorter optical link's bandwidth was calculated using Equation (16) with the instantaneous connection bandwidth calculated with Equation (17). The RF connections were conservatively approximated using OneWeb's established 450mbps bandwidth[14].

$$Link_n\ Bandwidth\ (mbps) = \left(\frac{5000^2}{r_{sat_n}^2}\right) * Bandwidth_{Minimum} \tag{16}$$

$$Connection\ Average\ Bandwidth = \frac{\Sigma Link_n Bandwidth}{N_{links}} \tag{17}$$

The technical feasibility of each architecture was established by assigning a cost to each OISL terminal and the hub type and multiplying by the number of units per constellation. The cost values assigned to each piece of hardware can be seen in Table 4.

Table 4: Hardware Cost Values

Hardware Type	Cost (USD)
IP OISL Terminal	$50,000.00
OOP OISL Terminal	$90,000.00
RF Hub Facility	$7,000,000.00
Optical Hub Facility	$18,000,000.00

The difference in cost between IP and OOP terminals is due to the additional hemispherical gimbal needed for each unit. The relatively large difference in cost between the RF and Optical Hubs is based on the technology readiness level disparity. While OneWeb is already pursuing an RFHub facility in Norway[15], a multi-laser ground-based passthrough facility does not currently exist.

Propagation and MBSE Evaluation

Due to the dynamic nature of the mega-constellation configurations as the satellite nodes orbit the Earth, it was necessary to propagate the constellations over one orbital period. The instantaneous bandwidth and latencies of the optimal connections at each time step were averaged to better assess each architecture. The propagation technique used in this study was a simplified 2-body problem in the Earth-centered Earth-fixed (ECEF) reference frame. The higher order oblateness terms such as J2 were ignored because they are a function of the satellite inclination and because the entire constellation inclination was held constant these effects cancel out. The velocity vector and magnitude were calculated using Equation (18) and Equation (19) with the Earth rotation rotations matrix applied using Equation (20) where Ω is the angular rotation rate of Earth. Equation (19) holds because the propagation assumes that all the satellites are in circular orbits, so the velocity vector is always perpendicular to the position vector. For the purposes of this study, the timestep used in the propagation was set equal to the minimum slew time of the OOP terminals. This was to ensure that the OOP could translate 180 degrees to establish the next connection if needed. At each timestep the search algorithm was applied, and performance parameters calculated before propagating the constellation forward one timestep. An example of how the optimal path can change over time can be seen in Figure 5. Figure 5 used the OneWeb constellation and the 1OOP architecture at $t = 0$ and $t = 360\ (s)$.

$$\boldsymbol{v_c} = \sqrt{\mu/(R_E + alt)} \tag{18}$$

$$v_c \cdot r_{sat} = 0 \quad (19)$$

$$r_{sat} = \begin{bmatrix} \cos(\Omega * t) & -sin(\Omega * t) & 0 \\ sin(\Omega * t) & cos(\Omega * t) & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} r_{xi} \\ r_{yi} \\ r_{zi} \end{bmatrix} \quad (20)$$

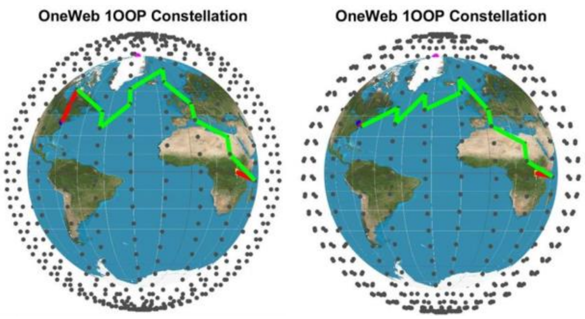

Figure 5: Example of Constellation Propagation at t = 0s & t = 360s

With the period averaged latency and bandwidth calculated, Model-Based Systems Engineering (MBSE) techniques were then applied to evaluate the overall architecture. To do this, the benefits of each architecture (bandwidth) were normalized by the drawbacks of each architecture (latency, cost). The full MBSE evaluation function can be seen in Equations (21)-(24) with the attribute target values and weights in Table 5.

$$NRB = \alpha * \left(\frac{Bandwidth}{Bandwidth_{Target}}\right) \quad (21)$$

$$NRL = \beta * \left(\frac{Latency}{Latency_{Target}}\right) \quad (22)$$

$$ARC = \gamma * \left(\frac{Cost}{Cost_{Target}}\right) \quad (23)$$

$$ArchCap = \frac{NRB}{NRL+ARC} \quad (24)$$

Where NRB is Network Relative Bandwidth, α = Bandwidth weight, NRL is Network Relative Latency, β = Latency weight, ARC is Architecture Relative Cost, γ = Cost weight, and ArchCap is Architecture Capacity.

Table 5: MBSE Weights and Target Values

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

CASE STUDIES

The methodology laid out above was applied to each case study to recommend the optimal OISL implementation architecture. The mega-constellation orbital parameters of the two case studies below can be seen in Table 6 and a visual representation of both constellations in Figure 6.

Table 6: Case Study Orbital Parameters

Parameter	OneWeb	120Sat
Inclination (deg)	87.6	87.6
Altitude (km)	1200	1200
Eccentricity	0	0
Orbital Planes	12	6
Satellites per Plane	49	20
Total Satellites	588	120

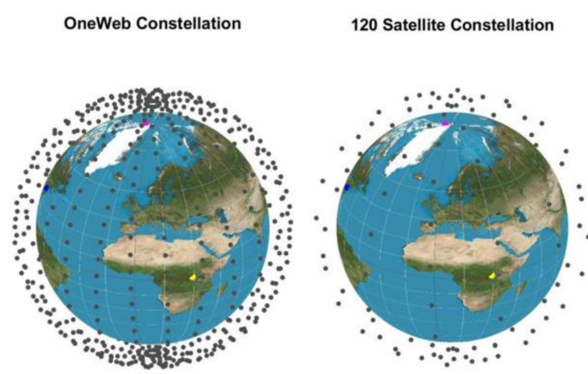

Figure 6: Case Study Constellations

OneWeb

As stated before, the first case study that this study's methodology will be applied to mimics OneWeb's current constellation configuration. While OneWeb has already stated that it will not be including OISL terminals on their GEN1 constellation[13] instead opting for more than 40 ground-based RF gateways, development has already begun for both spin-off designs of their GEN1 platform dubbed 'Arrow'[16] as well as their GEN2 system. These new designs could benefit greatly from the inclusion of any form of OISL's, as found by Inigo del Portillo Barrios of MIT in his recent mega-constellation report. The first optimal connection for all four OISL implementation architectures can be seen in Figure 7 below.

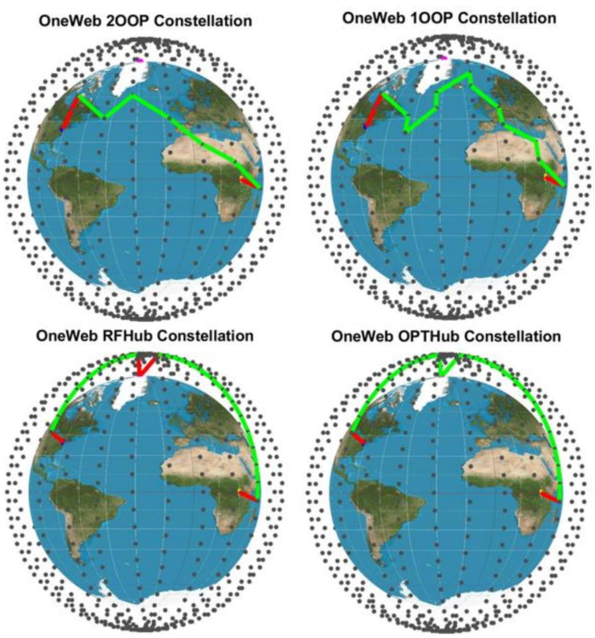

Figure 7: OneWeb Case Study Optimal OISL Connections

The orbital period averaged latency and bandwidth values, technical costs as well as the result of Equation (21) can be seen in Table 7. Figure 8 and Figure 9 display the instantaneous connection bandwidth and latency over one orbital period. It is quite apparent that the RFHub architecture is the optimal implementation strategy for OneWeb's current constellation plans.

Table 7: OneWeb Case Study Results

Implementation Architecture	*2OOP*	*1OOP*	*RFHub*	*OPTHub*
Average Latency (ms)	238.8	365.7	**699.3**	699.3
Target Latency (ms)	50	70	**80**	80
Average Bandwidth (mbps)	508	1319	**2273**	2251
Target Bandwidth (mbps)	500	500	**500**	500
Cost (Million USD)	164.6	111.7	**65.8**	128.7
Target Cost (Million USD)	65.8	65.8	**65.8**	65.8
Architecture Capability	0.0757	0.2184	**0.2912**	0.2501

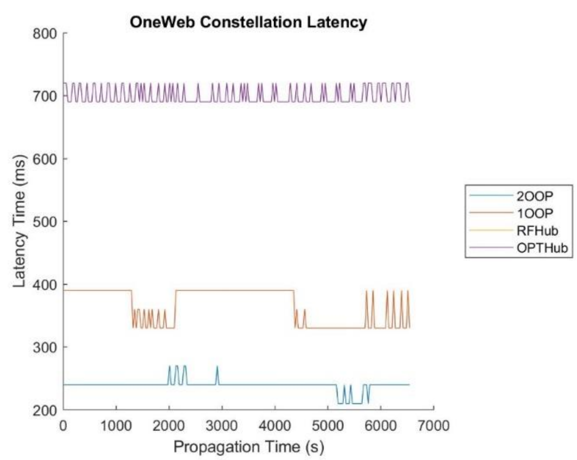

Figure 8: OneWeb Constellation Latency

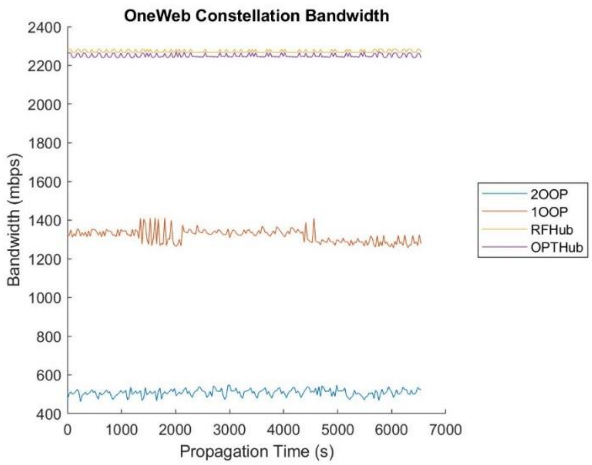

Figure 9: OneWeb Constellation Bandwidth

120Sat

The second case study this study's methodology was applied to is a much smaller 120 satellite constellation that could be purchased by a third party or government customer from a mega-constellation producer to serve a specific purpose or meet a specific need. The benefits of this smaller constellation include a smaller production cost and overall much lower latencies for all architectures while the lower level of proliferation hinders the bandwidth available across the network. Thus, this type of constellation is best suited for real-time decision-making during event such as military combat scenarios or natural disasters. The first optimal connection for all four OISL implementation architectures can be seen below in Figure 10.

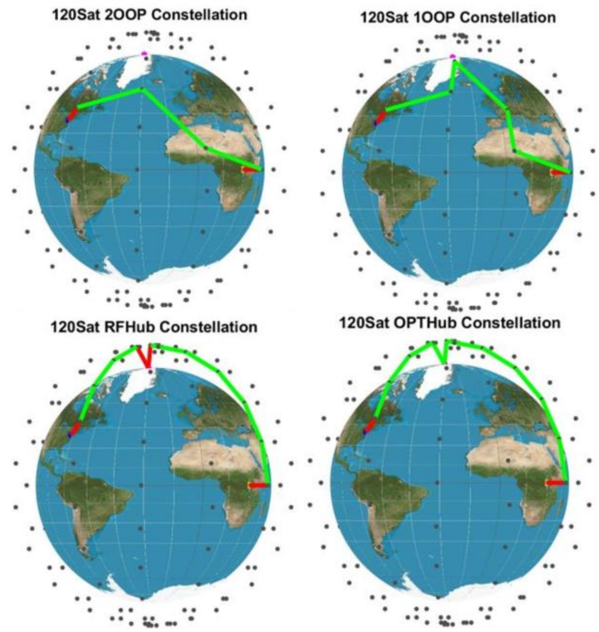

Figure 10: 120Sat Case Study Optimal OISL Connections

The orbital period averaged latency and bandwidth values, technical costs as well as result of Equation (21) can be seen in Table 8. Figure 11 and Figure 12 display the instantaneous connection bandwidth and latency over one orbital period. It is quite apparent that the RFHub architecture is the optimal implementation strategy for this type of constellation.

Table 8: 120Sat Case Study Results

Implementation Architecture	*2OOP*	*1OOP*	*RFHub*	*OPTHub*
Average Latency (ms)	*159.8*	*221.4*	***369.8***	*369.8*
Target Latency (ms)	*124*	154.3	**176.1**	176.1
Average Bandwidth (mbps)	*255.5*	315.6	**446.4**	405.7
Target Bandwidth (mbps)	*102*	102	**102**	102
Cost (Million USD)	*33.6*	22.8	**19**	40.8
Target Cost (Million USD)	*19*	19	**19**	19
Architecture Capability	*0.3242*	0.6005	**0.7746**	0.4669

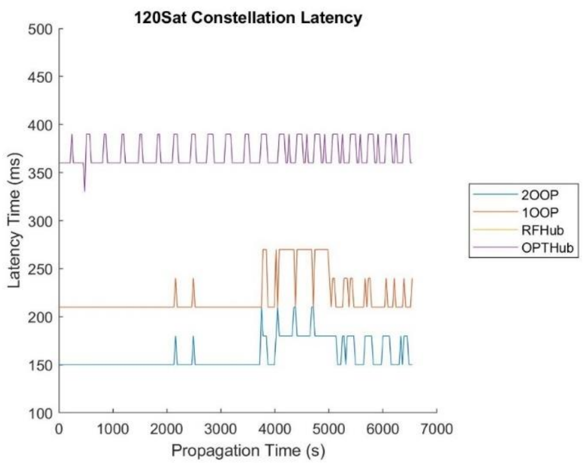

Figure 11: 120Sat Constellation Latency

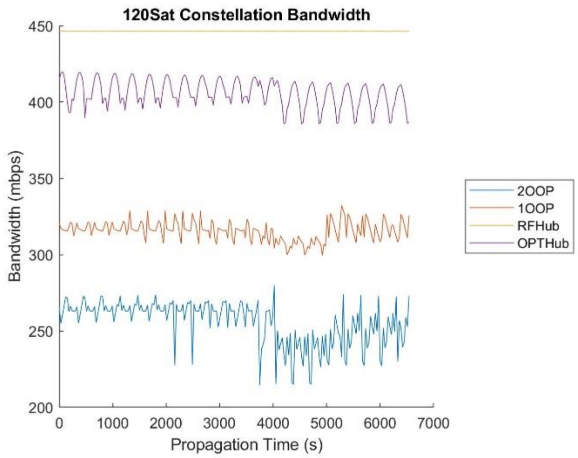

Figure 12: 120Sat Constellation Bandwidth

DISCUSSION

As Table 7 and Table 8 show, the RFHub architecture provides the highest architecture capability based on the weighting of cost being weighted heavier than latency which is weighted slightly heavier than bandwidth. This result did not change for either case study. One reason for this consistency may be due to the connection beginning and end points being held constant across all the simulations. The difference in longitude between Rwanda and Washington D.C. may cause the polar handoff an undue advantage under this study's success criteria. Because of the heavy weighting on cost, it is quite unlikely that the optimal architecture will change as the constellation configuration proliferates. Given the current performance levels of COTS OISL terminals, it is not yet effective to include OOP links in mega-constellation designs. Instead, architects should pursue an efficient system of IP links paired with RF gateways on the ground to handoff the signal between different orbital planes.

While the optimal implementation architecture is RFHub under the current weights, there may still be a need for an in-space end-to-end connection for security purposes. Given the single point of failure weakness that both the RFHub and OPTHub architectures pose, certain architects may require no ground handoffs in their constellation. Given this additional requirement, Table 7 and Table 8 show that 1OOP consistently overperformed the 2OOP architecture. The cost benefit of requiring one less terminal per satellite with minimal latency increases and a small bandwidth benefit contribute to this effect. At this point in time, the only reason to pursue a 2OOP architecture would be to allow for complex inter-planar handoffs between different inclination or altitude orbital planes (much like SpaceX's Starlink constellation[17]).

While RFHub is the clear path forward currently, as COTS OISL's are further developed they will be able to achieve higher bandwidths for the same system weight and power. As this technology progresses and the minimum bandwidth increases, will there be an inflection point under the current assessment criteria at which the optimal integration architecture changes? In order to test this theory, the above methodology was rerun for all four architectures using the OneWeb constellation multiple times. Each time the minimum bandwidth at 5000km of the OISL terminals was increased according to Table 9 and the cost of the OOP and IP terminals decreased according to Equation (25). Table 10 displays how the Equation (21) parameters changed as the bandwidth increased with the overall changes to the architecture capability shown in Table 11. The changing architecture capabilities are visualized in Figure 13.

Table 9: Future OISL Terminal Parameters

Version	Bandwidth (gbps)	Terminal Latency (ms)	IP Terminal Cost (USD)	OOP Terminal Cost (USD)
1	0.1	15	$50,000.00	$90,000.00
2	0.5	13	$49,285.00	$88,713.00
3	1	11	$48,405.00	$87,129.00
4	2	9	$46,690.00	$84,042.00
5	5	7	$41,905.00	$75,429.00
6	10	5	$35,000.00	$63,000.00

$$Cost_{Bandwidth_n} = Cost_{Bandwidth_0} * e^{-0.036(Bandwidth_n)} \quad (25)$$

Table 10: Future OISL Terminal MBSE Results

Bandwidth (gbps)	Implementation Architecture	Target Cost (Million USD)	Cost (Million USD)	Target Bandwidth (gbps)	Average Bandwidth (gbps)	Target Latency (ms)	Average Latency (ms)
0.1	2OOP	65.8	164.6	0.5	0.508	50	238.8
	1OOP	65.8	111.7	0.5	1.319	70	365.7
	RFHub	65.8	65.8	0.5	2.273	80	699.3
	OPTHub	65.8	128.7	0.5	2.251	80	699.3
0.5	2OOP	65	162.3	2.5	2.089	50	207
	1OOP	65	110.1	2.5	6.297	70	316.9
	RFHub	65	65	2.5	11.06	80	606
	OPTHub	65	128.1	2.5	11.099	80	606
1	2OOP	63.9	159.3	5	4.064	50	175.1
	1OOP	63.9	108.1	5	12.52	70	268.2
	RFHub	63.9	63.9	5	22.04	80	512.8
	OPTHub	63.9	126.2	5	22.16	80	512.8
2	2OOP	61.9	153.7	10	8.016	50	143.3
	1OOP	61.9	104.3	10	24.97	70	219.4
	RFHub	61.9	61.9	10	44	80	419.6
	OPTHub	61.9	122.3	10	44.281	80	419.6
5	2OOP	56.3	138	25	19.87	50	111.5
	1OOP	56.3	93.6	25	62.3	70	170.7
	RFHub	56.3	56.3	25	109.9	80	326.3
	OPTHub	56.3	111.6	25	110.64	80	326.3

10			
2OOP	1OOP	RFHub	OPTHub
48.2	48.2	48.2	48.2
115.2	78.2	48.2	96.2
50	50	50	50
39.63	124.5	219.7	221.25
50	70	80	80
79.6	121.9	233.1	233.1

Table 11: Future OISL Terminal Architecture Capabilities

Bandwidth (gbps)	*2OOP*	*1OOP*	*RFHub*	*OPTHub*
0.1	0.0757	0.2184	**0.2912**	0.2501
0.5	0.0671	0.2285	**0.3191**	0.2725
1	0.0708	0.251	**0.3638**	0.3046
2	0.0766	0.2801	**0.4244**	0.3458
5	0.0839	0.3189	**0.51**	0.3996
10	0.0948	0.3735	**0.6395**	0.4727

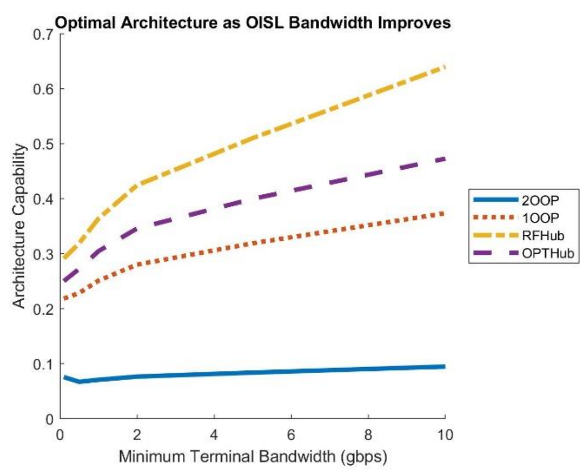

Figure 13: Architecture Capability as OISL Terminals Mature

Given the results of improving the capability of both the IP and OOP OISL terminals, it is apparent that RFHub is the optimal architecture to pursue independent of constellation or minimum bandwidth when assessing the connection between Rwanda and Washington DC. This is driven by the low cost of not including any OOP or LEO-Ground OISL's on each satellite in this configuration. At this point in time, for polar constellations such as OneWeb's, the development of OOP terminals should not be prioritized over industrializing the IP OISL production.

CONCLUSIONS

This paper 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.

OUTLOOK

Case Studies for Multiple Connection Endpoints / Hub Locations

For the purposes of this study, the beginning and end points of the OISL connection were held constant in Rwanda and Washington DC. This created a constant difference in latitude and longitude between the start and end points, possible skewing which architecture is most effective. Future studies should hold the constellation and architecture constant will varying the endpoints in order to assess the flexibility of each architecture. Additionally, the hub location in Alert, Nunavut, Canada was held constant. Future studies should move this location to other probable sites (Norway) and reassess the optimal architecture.

Low Inclination Orbital Planes

This study kept the inclination of the orbital planes constant at 87.6 degrees. While this was necessary to eliminate another variable. Telesat and SpaceX are proposing constellations with multiple inclinations, some of which are much lower inclination than the planes used in this study. Future works should include multiple plane inclinations, some of which are lower inclination.

LEO-MEO Connections / Hybrid OISL Architectures

The altitude of each satellite in the constellation was held constant in this study. There is interest in using 'handoff' satellites in MEO to move data between orbital planes instead of direct LEO-LEO OOP links. This approach minimizes the relative angular velocity between nodes, decreasing the pointing requirements. Future research should analyze the effects of these satellites for GEN2 constellations. Additionally, hybrids of the four architectures proposed in this study should be investigated. For instance, a mixture of OPTHub and RFHub that uses the RF link when the hub is under cloud cover could provide huge benefits. Future research should investigate this additional facet to the optimization problem.

OISL Imperfect Connection Considerations

This study assumed a perfect OISL connection with acquisition time occurring before the propagator started recording connection statistics. This neglection of connection failure overinflated the ability of OOP terminals in particular as the higher slew rates will cause I higher chance of signal loss. Because of this relationship, RFHub would still prove optimal so the conclusions of this study will not be affected. However, future works should implement a probabilistic approach for connection success when assessing non-polar constellations to provide a more accurate assessment of each architecture.

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