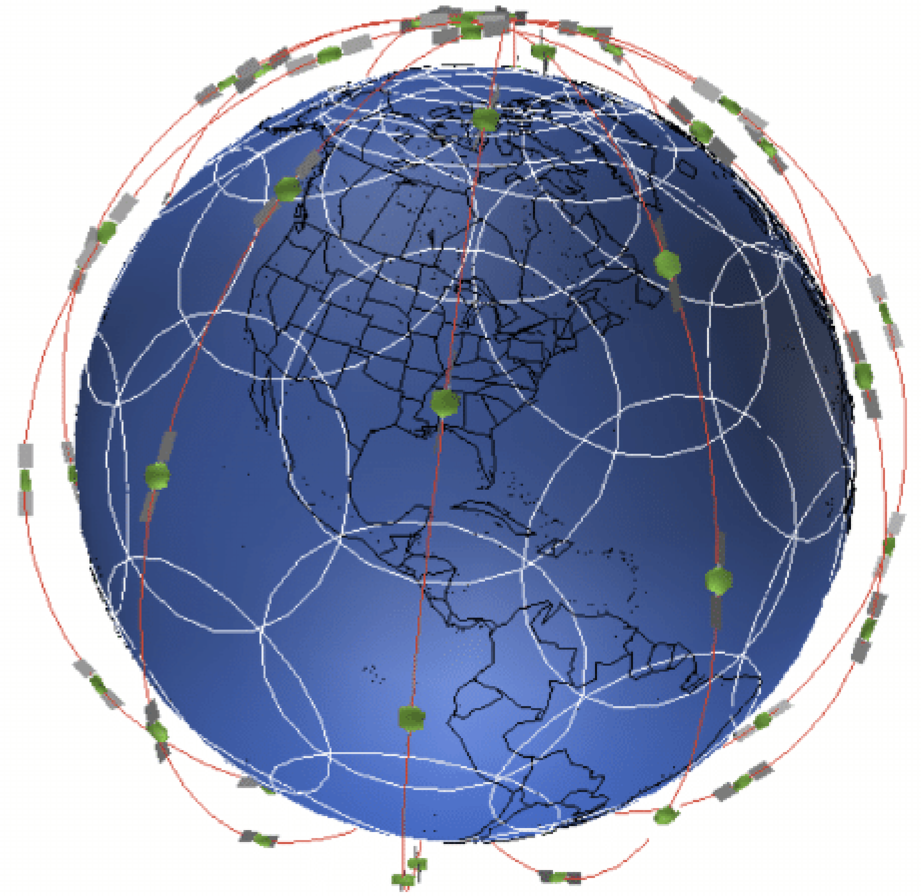
Global Satellite Networks, a solution to worldwide communication

A feasibility analysis of effective satellite network communication worldwide



Miles Osborne

Embry–Riddle Aeronautical University

December 2019

Letter of Transmittal

Miles Osborne
600 S Clyde Morris Blvd
Daytona Beach, FL, 32114

December 1, 2019

Brent Wells
OneWeb Headquarters
1430 Key Blvd
Arlington, VA 22201

Re: Research – Global Satellite Network Feasibility Analysis

Dear Mr. Wells,

Enclosed is a document analyzing the feasibility of establishing a global satellite network.

Sections within this document consist of:

1. Letter of Transmittal
2. Abstract
3. List of Figures
4. Introduction
5. Analysis of Factors
6. Recommendations
7. Conclusion

This report was limited due to no official or unofficial documentation being released at the time of writing regarding the implantation of a global satellite network. Despite any limitations, I am confident in the analysis of the report which will add to the development of global satellite networks.

If there are any questions or concerns, feel free to contact me at osborm10@my.erau.edu or (404) 547 – 7984.

Thank you for your time.

Respectfully,

Miles Osborne

Abstract

This feasibility analysis explored the concept of implementing a global satellite network to provide global internet coverage. Using a constellation or cluster of satellites to form a mesh network has been a developing solution to solving communication issues particularly in countries with poor coverage. The intended audience includes but not limited to satellite manufacturers, aerospace engineers, and potential investors. The main areas of focus for implementing a global satellite network were redundancy in the case of unexpected events, network and satellite security, and satellite mechanics such as orbit and operational time. However, there are rising concerns regarding cost, orbital debris, and effectiveness. Despite this, research showed that orienting satellites into Low Earth Orbit (LEO) would provide much greater coverage to multiple areas across the world. Failures due to unexpected events would be avoided with spare nodes in orbit to manage current tasks. Effective recommendations that address the major concerns of satellite networks is to add a collision-avoidance system and to plan for a post-mission disposal method.

Keywords: Constellation, Satellite Network, Low Earth Orbit (LEO), Collision-Avoidance, Post-Mission Disposal, Redundancy, Mesh Network, Orbital Debris

List of Figures

Table of Contents

Introduction

Background

For multiple areas around the world, internet access is not absolute nor is it a simple problem to solve. This is especially true for countries outside of the Americas and European regions. Multiple companies and engineers have begun developing satellite systems to provide internet access to these areas. As of 2019, progress has been rapidly increasing but there is no official document released by the respective company, organization or third party which verifies if these concepts will be successful.

Purpose

Global communication remains an issue without a reliable solution. Particularly with internet access, multiple areas around the world, go without any means of connecting to a network.

Subject

The possibility of implementing global satellite networks to alleviate this problem

Audience

The audience will consist of satellite engineers, software developers, and potential investors

Context

This document is important to the commercial aerospace industry, satellite industry, and internet industry. Furthermore, this is of interest to citizens and users in areas such as the Arctic where full coverage is not a guarantee. This report demonstrates the potential of creating a global satellite network as well as the numerous benefits that can be obtained. This report is intended to support the cause of developing global satellite networks and ending dead communication zones worldwide.

Method of Inquiry

Multiple companies are planning and beginning to develop their own satellite networks. The base concept is nearly identical amongst all iterations, but it is not an absolute that their projects are going to be a success. The goal is to analyze the current uses and limitations of Low Earth Orbit satellites and determine if global satellite networks can become an implemented system.

Literature Review

- Becker , C., & Garrick , M. (2017, August 5). Mesh Network Architecture for Enabling Inter Spacecraft Communication. Retrieved October 20, 2019
- DeCristofaro, M. A., Lansdowne, C. A., & Schlesinger, A. M. (2014, May 5). Heterogeneous Wireless Mesh Network Technology Evaluation for Space Proximity and Surface Applications. In NASA Technical Reports Server .
- Ellis, A., Mercury , M., & Brown , S. (2012, August 13). Global Coverage from Ad-Hoc Constellations in Rideshare Orbits
- Hudaib, A. A. Z. (2016). Satellite Network Hacking & Security Analysis. *International Journal of Computer Science and Security*, 10(1)
- Matney , M., Vavrin , A., & Manis , A. (2017, April 18). Effects of CubeSat Deployments in Low-Earth Orbit. Retrieved November 7, 2019
- Pattan, B. (1993). Satellite systems: Principles and Technologies. New York: Van Nostrand Reinhold.
- Pelton, J. N., Madry, S., & Camacho-Lara, S. (2017a). Handbook of Satellite Applications (2nd ed., Vol. 1). Cham, Switzerland: Springer International Publishing AG
- Pelton, J. N., Madry, S., & Camacho-Lara, S. (2017b). Handbook of Satellite Applications (2nd ed., Vol. 2). Cham, Switzerland: Springer International Publishing AG.
- Pisacane, V. L. (2005). Fundamentals of Space Systems. New York: Oxford University Press.
- Startup, J., Lee, D. K., & Heuvel, D. V. (2015, April 13). Smallsat/Cubesat Ground Communication Methods and Limitations Jim Startup

Most sources come from the NASA Technical Report Server and the Embry-Riddle Aeronautical University Hunt Library. The NASA Technical Report Server is a database containing technical reports, conference papers, and experimental documents for the purpose of documenting and promoting research. While *Satellite systems: Principles and Technologies* is an older source much of its information is still valid. It’s content over satellite operations and mechanics is still relevant today and beneficial to this report. The contents of this technical report were not paid for or funded in any matter by external parties.

Orbit Selection

For implementing a global satellite network, a geosynchronous orbit is not a practical choice. While there are advantages such as longer proposed lifetimes, fewer satellites in place, and easier to maintain, these come at the cost of expense and performance. Geosynchronous orbits take place at approximately 36,000 kilometers above the equator which requires larger launch vehicles or spacecraft to reach that orbit. Even with fewer satellites in geosynchronous orbit, intercommunication between satellites becomes much more difficult due to the distance requiring more power when compared to a low earth orbit alternative. In addition, “solar and lunar gravity, solar pressure and varying gravitational forces” (Pattan, 1990, p.47) are still present and will cause deviations to the intended orbit. To counter the forces, satellites will require more fuel, velocity, and energy to maintain their stationary orbit. In particular, it would take “approximately ten times more energy” (Pelton, Madry, Camacho-Lara, 2013, p.104) to maintain an exact geosynchronous orbit and requires some method of active stabilization or correction. This raises a problem since the majority of communication satellites including current variations are not equipped or intended to counter forces in geosynchronous orbit. A satellite lost at that point may not be recoverable and can cause some functionality lost to the global satellite network. Based on this, geosynchronous orbits would not satisfy the conditions of a global satellite network.

In regard to elliptical orbits, these would benefit specific areas but are not entirely suited to building a global satellite network. Elliptical orbits maintain a noticeably higher altitude limit with the lower bound starting at 1,000km and the upper bound at approximately 40,000 km and upwards. While it is an attractive alternative to a geosynchronous orbit, drawbacks make it unsuitable for a global satellite network. Elliptical orbits are very beneficial to polar and high latitude regions such as Russia but would struggle for simultaneous global coverage. The operational time is limited to “its highest apogee phase for a period of 6-8 hours” (Pelton, Madry, Camacho-Lara, 2013, p.110). Furthermore, due to limited operational times, multiple satellites need to be in a position to provide continuous service. This would increase the price of a global satellite network and produce diminishing returns. The complexity now increases when trying to incorporate multiple geosynchronous orbits to cover larger areas.

Low Earth Orbits are the most commercially viable and popular option thus far. It takes fewer resources to be placed in low earth orbit and typically experiences much greater performance due to the decreased distance to the surface. However, for continuous coverage, a larger number of satellites are needed which the satellite constellation satisfies the need of. Due to the proximity of satellites in this orbit, gravitational forces are much stronger and the concern of orbital debris becomes present. As a result, low earth orbits are considered the most difficult to maintain. However, low earth orbits offer the greatest coverage able to target the majority of North American and European countries as well as high latitude countries with an inclined orbit. While the increase in satellite nodes does increase the complexity, it does improve redundancy systems for unexpected failures. A Low Earth Orbit would be the most practical and effective orbit for satellite global communications.

Figure 1 Comparison of Potential Orbits for Satellite Operation		
Orbit	Altitude	Typical lifetime
1. Low Earth Orbit	1,600 km	7 – 10 years
2. Medium Earth Orbit	2,000 km	8 – 12 years
3. Geosynchronous Orbit	35,786 km	15 – 20 years
4. Elliptical Orbit	1000km to 35,786km	7 – 10 years*
Note: **There are different elliptical orbit types so the lifetime will vary due to orientation and satellites used in the operation		

Figure 1: A comparison between different types of orbits used for satellite operations as a function of altitude and typical lifetime. Compiled from *Handbook of Satellite Applications (2nd ed., Vol. 1)*.

Satellite Sizing and Variations

The introduction of CubeSat and other microsatellite systems are an effective solution to full-size satellites. Until recently, satellites were much larger in mass and only a few could be launched into orbits at a time. With the introduction of cubesats and other small form factor satellites, the number of active objects in orbit can be increased. The benefits of CubeSat satellites include but are not limited to, lighter masses, scalability and greater quantity with similar functionality to full size. Likewise, there is the benefit of "reducing satellite complexity and development cost" (Startup, Lee, Heuvel 2015, p.10). In addition, the decrease in mass creates more options for deployment and "for a rapid deployment of constellations and replacements" (Hudaiib, 2016, p.14), in the event a node was compromised. By comparison, both MUOS and Iridium made by Lockheed Martin and Iridium Communications Inc. respectively are communication satellites built on a larger scale. Both satellites have a lesser number of active nodes in orbit but cost upwards of five billion dollars and have a significant increase in satellite mass. In addition, both satellite systems are much harder to control and replace in the event of an unexpected failure. It should be noted that both satellite systems mentioned are older and this is not a price to price comparison. However, the same trend remains true where development and launch cost is significant for larger-scale satellites.

	Cost	Satellite Mass	Satellites in Constellation	Total Throw
MUOS	$7B	6800 lbs.	4	27,200 lbs. (to GEO)
Iridium	$5B	1513 lbs.	66	99,858 lbs.
SmallSat	Lower	45.3 lbs.	660	29,883 lbs.

Figure 2: Comparison between satellite systems as a function of mass, number of satellites in constellation, and total throw. Adapted from *Satellite systems: principles and technologies* by Bruno Pattan.

While cubesats and other microsatellite variations remain efficient, unlike their larger counterparts, they have an increased rate of creating orbital debris. Most satellites and space objects follow the 25-year rule where objects can be properly disposed of or placed into a reentry orbit. Cubesats, currently do not have many regulations regarding end of life, post-mission recovery, and or post-mission disposal (PMD). The figure by the NASA Orbital Debris Program Office, predicts the number of catastrophic collisions over a 200-year time span with two post-mission disposal rates. The higher the post PMD rate is, the greater the probability of post-mission disposal. In each case, the dashed line denoted as J2 has a post disposal mission rate of 0%. For both scenarios, an operation with no plans or means of post-mission disposal produces an exponential increase in collisions and orbital debris as a result. The data represented considers the increasing number of satellites being placed into low earth orbit which does concern satellite global networks

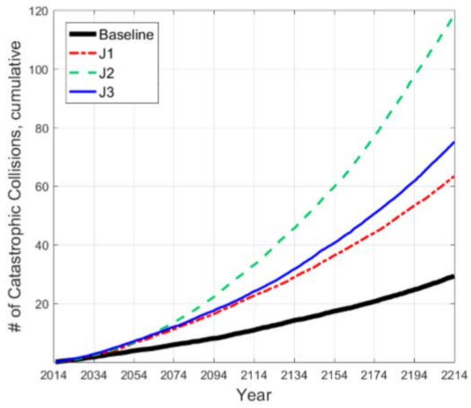


Figure 3: Cumulative number of catastrophic collisions in LEO over 200-year projection with a PMD success rate of 60%. Adapted from “Effects of CubeSat Deployments in Low-Earth Orbit” by Mark Matney, Andrew Vavrin, and Alyssa Manis

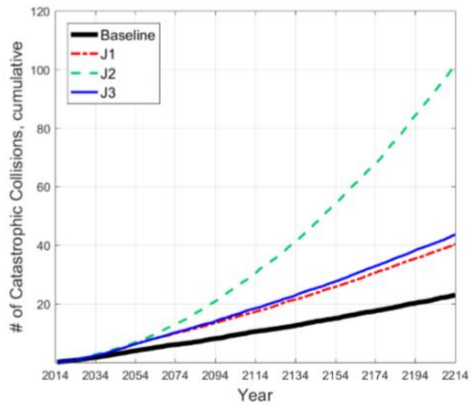


Figure 4: Cumulative number of catastrophic collisions in LEO over 200-year projection with a PMD success rate of 90%. Adapted from “Effects of CubeSat Deployments in Low-Earth Orbit” by Mark Matney, Andrew Vavrin, and Alyssa Manis

During the development of this report, OneWeb has successfully deployed 648 satellites into low earth orbit with SpaceX following suite recently launching the first set of 60 Starlink satellites. The number is expected to increase into the thousands by 2020 for both companies. “Placing hundreds or thousands of small satellites on similar 25-year decay orbits could create unprecedented collision-avoidance problems for the International Space Station (ISS) and other human activities in LEO” (Matney, Varin, Manis 2017, p.1). This aspect does not currently affect the feasibility of achieving a global satellite network, but it may affect actually implementing it. Missions can be altered and in a worst-case scenario, rejected if the risk of orbital debris becomes too great.

Satellite Redundancy & Failure

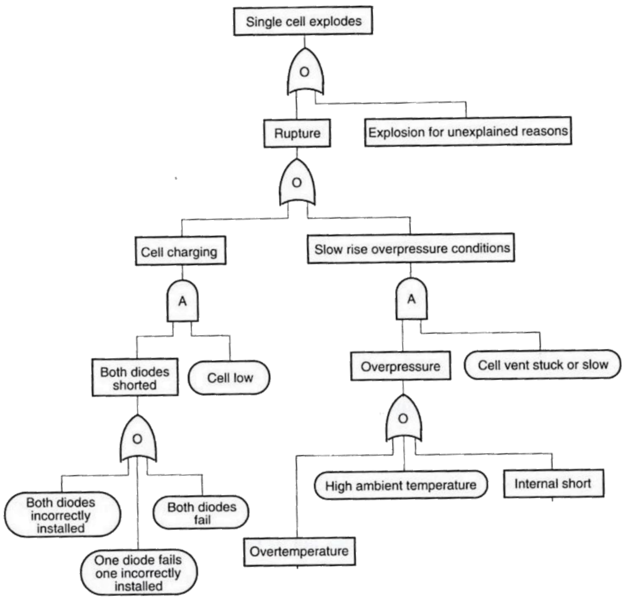


Figure 5: Lithium thionyl chloride singe cell safety tree. Adapted from *Fundamentals of Space Systems* by Vincent Pisacane

A major aspect of implementing a satellite global network is autonomy or the ability to handle unexpected situations without any human input. Since many satellite network concepts utilize cubesats constellations and clusters with a large number of operating satellites in low earth orbit, failure prevention becomes a much higher priority. There is a potentially infinite list of factors that can cause a spacecraft anomaly. For the purposes of implementing a global satellite network, the biggest risks are gravity and electronics failure.

Since gravity is much stronger at a low earth orbit, the occurrence of collisions and premature reentry of space objects before its total lifetime has been served is present. With the sheer number of satellites in orbit, the chances of collisions increases. Ground systems such as SPACETRACK AND Lockheed Martin’s S-band space fence which are tasked with providing “cataloging and identification, satellite attack, warning, timely notification to US forces of satellite flyover, space treaty monitoring and scientific and technical intelligence gathering” (Pelton, Madry, Camacho-Lara, 2013, p.1451). These systems are a large network of fail-safes that are intended to be used for a larger number of satellites, unique orbits, and track smaller objects. Furthermore, some satellites are equipped with additional thrusters and fuel to make orbit corrections and avoid collisions. These features are not commonly found in cubesats and other small form satellites as of November 2019 but research into these areas is being implemented by companies such as NASA.

In regard to electronics failure, there is very little chance of being able to fix the problem manually. Having satellite autonomy to trigger when a fault is found is a very interesting solution. Autonomous solutions are based on rules for each potential scenario that may occur. Each rule is given a priority level that will determine when to fire and how many times to occur. For instance, some failures are caused by space radiation which could cause a hard failure or permanent damage to a satellite’s onboard components. The “autonomous corrective action may be to switch over to a backup (redundant) hardware unit” (Pisacane, 2005, p.623), which the satellite would be able to achieve independent of any interaction. In a constellation of satellites, an autonomous system will need to be implemented on a much larger scale but in turn, is much more secure. At a given moment, “each spacecraft in the constellation must be capable of detecting anomalous behavior not just within itself but also within other members of the constellation” (Pisacane,2005, p.624). When that rule is broken or a defect of some kind is detected, all nodes need to be informed and take appropriate action to resolve the issue and or keep any active functions operational.

Mesh & Ad-Hoc Networks

For a global satellite network, mesh networks are the most effective and popular choice for establishing communication between satellites and the surface. The purpose of implementing them is two-fold. The first is intercommunication between satellites is to and the second is to allow signals to be transmitted to the surface.

Regarding transmitting signals to the surface, mesh networks have an advantage in coverage and reliability. Mesh networks operate on nodes that form bridges with each other. Each node "can automatically discover its neighbors and act as a relay" (DeCristofaro, Lansdowne, Schlesinger, 2014, p.2). Data is routed to take the shortest path and the system can be dynamically altered in the event a node fails. This ensures data integrity and network speed. The figure by NASA Johnson Space Center analyzes two network protocols and the probability of a route switching outage with a moving WIFI receiver. Each line represents the type of network protocol. Adding a "hop" indicates that the signal transmitted has been passed to another node on the network. The protocols that added a "hop" observed a predicted total outage time that was significantly less than when removing or not utilizing a "hop."

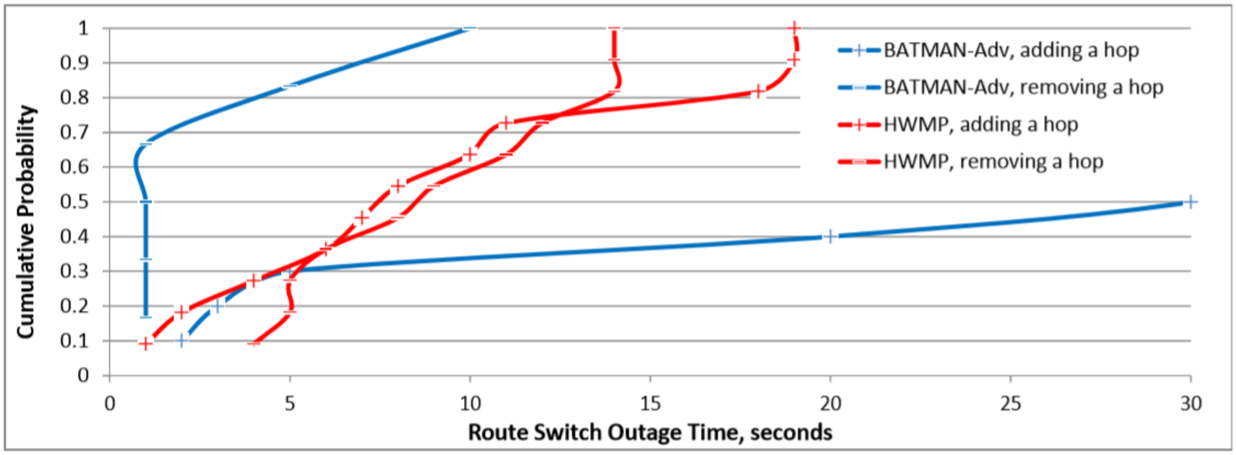


Figure 6: Probability of network outage and outage time using a mobile wi-fi node over 750m. Adapted from "Heterogeneous Wireless Mesh Network Technology Evaluation for Space Proximity and Surface Applications" by Michael DeCristofaro, Chatwin Lansdowne, and Adam Schelesinger.

Global satellite network follows the same principles as a traditional satellite concerning communication. Signals need to be transferred from the surface to the satellite and vice versa. Additionally, Information may need to be transferred to additional satellites and nodes in orbit if the condition applies. When looking at traditional wireless networks, the typical setup is on a point to point link between the receiver and transmitter at a fixed or variable distance. While this works for smaller applications such as households and buildings, for space applications it becomes much more difficult to implement. Despite the difficulty though, mesh networks have been used in spacecraft and other space applications before as well. Satellite constellations such as Iridium, SPACETRACK and particularly satellites in elliptical orbit take some form of mesh networking to relay signals and information. Furthermore, the NASA Marshall Space Flight Center has demonstrated that mesh networks can be used in space. Their simulation considers environmental forces such as solar radiation and gravity causing nodes to deviate from the planned course. “As the spacecraft positions deviated from their planned formation positions due to environmental disturbance forces, by exchanging information across the mesh network, the individual nodes were made aware of the deviation and could correct for it” (Becker, Merrill, 2017, p.6). This alleviates the burden that small satellites and cubesats have on telemetry systems as they are predicted to “stress ground communication capabilities” (Becker, Merrill, 2017, p.1). Incorporating a mesh network in this regard would also satisfy requirements for satellite autonomy which would be a useful feature to implement in a constellation.

Network & Satellite Security

Satellite global networks will have security vulnerabilities that need to be accounted for with the proper countermeasures. The biggest threat to satellite networks is hacking which can be expanded to four types: jam, eavesdrop, hijack, and control. There is overlap between the variations but with each type, an undesired external party gains control over the satellite, obtains the ability to exploit systems, and or block communication in some manner. In the event that a satellite hacking were to occur, depending on the severity and number of nodes compromised, the remaining nodes can take up tasks and maintain functionality. The Global Positioning System (GPS) is an example of this system. The Global Positioning System (GPS) is a constellation of 31 satellites in a medium earth orbit at 20,200 kilometers. To maintain functionality, GPS only needs “4 satellites to operate at full capacity, and 3 for reduced accuracy.” (Hudaib, 2016, p.13). This frees other satellites in orbit to perform other tasks and allows nodes to become substitutes in the case of any failure or a hacking attempt.

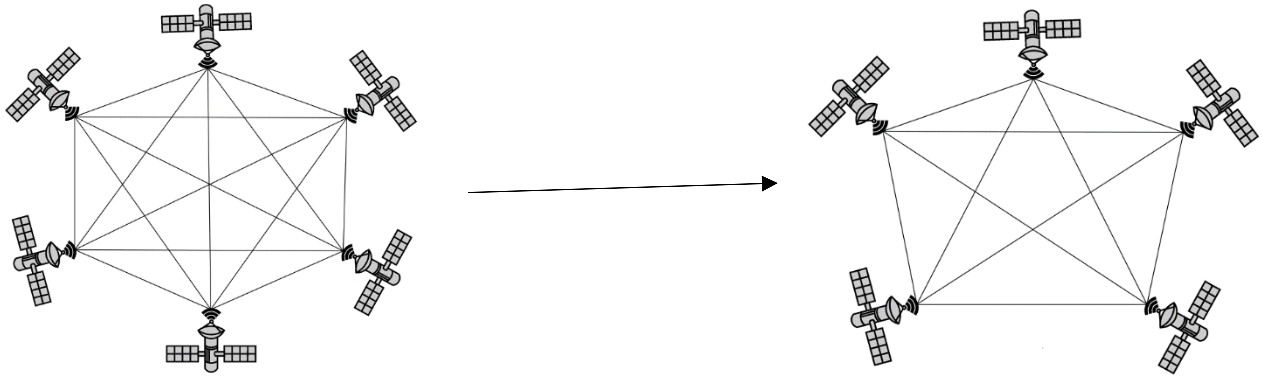


Figure 7: Visual representation of node failure. When a node fails, the system scales and adjust itself to function using remaining nodes.

In any case, satellite hacking can lead to complete system failures, data loss, and a significant increase in orbital debris due to collisions. There is no method to completely eliminate the risk associated with wireless and satellite communication of any type even with countermeasures in place. During the test conducted by NASA Johnson Space Center evaluating mesh networks, it was noted that “clients or nodes could connect to the mesh without sharing the secret key, although they were configured to use encryption.” (DeCristofaro, Lansdowne, Schlesinger, 2014, p.8). Potentially, any user could connect to the same network that the satellites operate on and control their behavior. Even with autonomous functions and redundancy checks, there is no guarantee that these would be sufficient enough countermeasures. Fortunately, some variants of satellite hacking “require sophisticated and expensive hardware, such as multiple antennas or a high-grade inertial measurement unit (IMU)” (Hudaiib, 2016, p.47). Most of this equipment is not off the shelf or available to most consumers under normal circumstances which does improve security. While this test was conducted in 2014 and on a smaller scale than an actual global satellite network, the same security protocols for wireless networks are used today.

Recommendations

The following recommendations are determined based on the greatest concerns or points of failure within a global satellite network. Implementing potential solutions and variations of them will ultimately serve to improve the design of satellite networks.

- Add onboard collision-avoidance software or autonomy to minimize orbital debris
- Plan for post-mission disposal or retrieval of satellites when the operational period has ended
- Have redundancy & automation rules in place for any possible failures

The most recurring concern when introducing a satellite global network is orbital debris. Since satellite global networks have a much higher chance of producing orbital debris, missions could be rejected or run the risk of damaging the environment. By adding onboard collision and plans for post-mission disposal, the amount of orbital debris can be considerably reduced which also ensures current satellites in orbit remain functional.

Since a satellite global network could become an integral piece of society, having a system failure would be catastrophic. While spare nodes in orbit can mitigate this problem, the fastest solution would be for the satellites to automatically correct for any errors. This includes any network errors or unexpected dead zones over certain areas.

Conclusion

Based on the information presented, the feasibility of a global satellite network is within the realm of possibility. The best implementation with the highest potential of success thus far is using a constellation of microsatellites or cubesats in a low Earth orbit or slightly higher than low earth orbit. There are more benefits that outweigh the disadvantage of this configuration. The smaller satellites have the advantage of being easier and less expensive to produce to and be placed in orbit. Furthermore, the network established will be more reliable due to an increase in nodes which improves redundancy and lower altitude which improves performance and coverage. Identically, this is the approach that many companies favor and are proceeding with. If the recommendations mentioned previously are resolved and an emphasis on security and performance are placed, a global satellite network can be implemented in the very near future.

References

Becker , C., & Garrick , M. (2017, August 5). Mesh Network Architecture for Enabling Inter-Spacecraft Communication. Retrieved October 20, 2019, from https://ntrs.nasa.gov/search.jsp?R=20170009051&hterms=mesh+networking&qs=N=0&Ntk=All&Ntt=mesh%20networking&Ntx=mode%20matchallpartial&Nm=123|Collection|NASA%20STI||17|Collection|NACA

DeCristofaro, M. A., Lansdowne, C. A., & Schlesinger, A. M. (2014, May 5). Heterogeneous Wireless Mesh Network Technology Evaluation for Space Proximity and Surface Applications. In NASA Technical Reports Server . Retrieved from https://ntrs.nasa.gov/search.jsp?R=20140011882&hterms=mesh networking&qs=N=0&Ntk=All&Ntt=mesh%20networking&Ntx=mode%20matchallpartial&Nm=123|Collection|NASA%20STI||17|Collection|NACA

Ellis, A., Mercury , M., & Brown , S. (2012, August 13). Global Coverage from Ad-Hoc Constellations in Rideshare Orbits. Retrieved November 7, 2019, from https://ntrs.nasa.gov/search.jsp?R=20130009126

Hudaib, A. A. Z. (2016). Satellite Network Hacking & Security Analysis. *International Journal of Computer Science and Security*, 10(1), Retrieved October 20, 2019, from http://www.cscjournals.org/library/manuscriptinfo.php?mc=IJCSS-1200

Matney , M., Vavrin , A., & Manis , A. (2017, April 18). Effects of CubeSat Deployments in Low-Earth Orbit. Retrieved November 7, 2019, from https://ntrs.nasa.gov/search.jsp?R=20160013676&hterms=Effects+cubeSat+Deployments+Low-+Earth+Orbit&qs=N=0&Ntk=All&Ntt=Effects%20of%20cubeSat%20Deployments%20in%20Low-%20Earth%20Orbit&Ntx=mode%20matchallpartial

Pattan, B. (1993). Satellite systems: Principles and Technologies. New York: Van Nostrand Reinhold

Pelton, J. N., Madry, S., & Camacho-Lara, S. (2017a). Handbook of Satellite Applications (2nd ed., Vol. 1). Cham, Switzerland: Springer International Publishing AG

Pelton, J. N., Madry, S., & Camacho-Lara, S. (2017b). Handbook of Satellite Applications (2nd ed., Vol. 2). Cham, Switzerland: Springer International Publishing AG.

Pisacane, V. L. (2005). Fundamentals of Space Systems. New York: Oxford University Press.

Startup, J., Lee, D. K., & Heuvel, D. V. (2015, April 13). Smallsat/Cubesat Ground Communication Methods and Limitations Jim Startup . Retrieved April 7, 2019, from http://2015.spacesymposium.org/sites/default/files/downloads/J.Startup_31st_Space_Symposium_Tech_Track_paper.pdf.