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THESIS

LEVERAGING THE NPS FEMTO SATELLITE FOR ALTERNATIVE SATELLITE COMMUNICATION NETWORKS

by

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Femto satellites may provide solutions for the U.S. military in different areas. Specifically, these satellites may offer an effective and affordable alternative approach when the military faces a denial of access to primary space assets. Their low cost allows for the rapid simultaneous deployment of multiple Femto satellites, which contributes to rapid recovery from a denial situation. This thesis focuses on the communication application of Femto satellites by investigating the ability of the first and next generations of Naval Postgraduate School Femto Satellites (NPSFS) to provide a low data throughput. We modeled the first generation of NPSFS as a space-based network using System Tool Kit with QualNet (STK/QualNet) software. For the next generation of NPSFS, we conducted an experiment using Intel Arduino 101 to control the Iridium 9602 Modem, also known as the RockBlock MK2, to test the possibility of sending a text file from one terminal to another. The results confirmed the power limitation associated with Femto satellites, which reduces their suitability for implementation as a viable space network. Nevertheless, the results showed that providing a low data throughput is feasible. Finally, we suggest ways to improve the next-generation NPSFS.

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LIST OF ACRONYMS AND ABBREVIATIONS

AM	Amplitude Modulation
AODV	Ad Hoc On-Demand Distance-Vector
ASAT	Russian Anti Satellite
ASK	Amplitude Shift Keying
BER	Bit Error Rate
BPSK	Binary Phase Shit Keying
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CMSA/CA	Carrier Sense Multiple Access/Collision Avoidance
COE	Classical Orbital Elements
dB	Decibels
FDMA	Frequency Division Multiple Access
FM	Frequency Modulation
FSK	Frequency Shift Keying
FY-1C	Feng Yun
GEO	Geosynchronous Orbit
GND	Ground
GUI	Graphical User Interface
HEO	Highly Elliptical Orbit
Hz	Hertz
IP	Internet Protocol
ISL	Intersatellite Links
LEO	Low Earth Orbit
LLC	Logical Link Control
MAC	Medium Access Control
MANET	Mobile Ad-Hoc Network
MEMS	Microelectromechanical Systems
MEO	Medium Earth Orbit
NPS	Naval Postgraduate School
NPSFS	NPS Femto Satellite
OLSR	Optimized Link State Routing Protocol

PAM	Pulse Amplitude Modulation
PCM	Pulse Code Modulation
PH	Phase Modulation
PSK	Phase Shift Keying
RAAN	Right Ascension of the Ascending Node
RX	Receiver
S/N	Signal To Noise Ratio
STK	Satellites Tool Kit
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TX	Transmitter
UDP	User Datagram Protocol
UART	Universal Asynchronous Receiver/Transmitter
UV	Ultraviolet

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I. INTRODUCTION

A. BACKGROUND

As advances in technology have made satellite systems and their applications more reliable, militaries around the world increasingly rely on satellite systems in their operations. Among the most common applications are communications, remote sensing, and weather forecasting. Nevertheless, satellite systems have some drawbacks. For example, they are expensive and subject to failure. In addition, they are vulnerable to the dangers inherent to the space environment, such as collisions with comets. Most critical, satellites are vulnerable to adversaries who target them to prevent friendly military forces from using space-based systems (Commission to Assess United States National Security Space Management and Organization, 2004). These drawbacks raise the need for approaches that could support the military in cases where the current space systems shut down. One potential solution is the quick deployment of Femto satellites.

B. METHODOLOGY

This thesis provides a proof of concept for using Naval Postgraduate School Femto Satellites (NPSFS) as an alternative communication space-based network. The methodology is to investigate the ability of NPSFS to establish a space-based constellation in order to provide a reasonably low throughput data rate. We investigate two approaches: the KickSat approach and the Intel Arduino 101 and Iridium 9602 Modem (or RockBlock) approach. In the KickSat approach, a Mobile Ad Hoc Network (MANET) constellation of KickSats is modeled and tested. In the Arduino and RockBlock approach, the Arduino 101 board is programmed for eventual integration with the Iridium Network, which is then tested.

C. THESIS ORGANIZATION

The thesis addresses these questions: what is satellite communication, what are the problems related to satellite communication, and what is the potential solution? Chapter II describes the three major elements that comprise satellite communication.

Chapter III explains the threats to that communication. Chapter IV describes a new generation of satellite communication and a literature review of Femto satellite. Related papers and studies provide the rationale for the methodology used in this thesis. The remaining chapters answer the question: How can we implement the potential solution? Chapter VI describes the Cornell NASA 2011 KickSat Femto satellites modeling. Chapter VII describes the Intel Arduino 101 and Iridium 9602 Modem, or the RockBlock Femto satellites experiment. Finally, Chapter VIII explains the findings and presents the conclusion.

II. SATELLITE COMMUNICATIONS

The need to communicate with remote units or people who lack the means of communication and terrestrial infrastructure raises the demand for satellite communication. Three major elements comprise a satellite communication system: the payload, which is the communication system itself; the vehicle carrying that system, which is limited by orbital mechanics; and the network that extends the accessibility and utilities of the communication system.

A. COMMUNICATION SYSTEM

We need several physical and procedural elements to conduct communication through space and using the electromagnetic spectrum.

1. Power

Any communication system needs a power source that generates signals. The generated signal has a power represented by the square of its amplitude.

2. Frequency

The electromagnetic spectrum, as described by Dean (2012), contains electromagnetic waves, which are sinusoidal waves that vary from short to long wavelengths or similarly from low to high frequency. A wavelength is a complete cycle, and we measure it from a specific point with specific height to the next corresponding point that has same height. A frequency expresses the number of cycles in one second and is a measure of Hertz (Hz) (Dean, 2012). It is more common to use the frequency measure rather than the wavelength in communication systems.

3. Antenna

The antenna dimensions and radiation pattern, as explained by Carlson, Crilly, and Rutledge (1986), vary based on the service's specifications such as wavelength and power. The longer the wavelength, the larger the antenna needed. Dean (2012) adds that the antenna could be either omnidirectional or directional depending on the need as well as the energy resource available. He states that we use a directional antenna when sending or receiving signals as a point-to-point link, while an omnidirectional antenna sends and receives signals in all directions (Dean, 2012). Antenna gain measures the efficiency of the antenna to convert electrical current to radio waves in a specific direction. The gain, as described by Carlson et al. (1986), is measured with decibels (dB) that describe the ratio of the power produced by the antenna to the power produced by a theoretical isotropic antenna (Carlson et al., 1986).

Modulation, as described by Carlson et al. (1986), is a process that involves adding a modulating signal—the information—to a carrier wave to form a modulated wave, which we transmit over a medium. Conversely, demodulation reverses the process of modulation, which results in deriving the information from the modulated wave (Carlson et al., 1986). The modulation process modulates one or more of the sinusoidal wave characteristics, such as amplitude, frequency, and phase. The modulation types include analog, digital, or pulse modulation. The analog modulation refers to an analog signal suitable for transport by an analog wave (Carlson et al., 1986). This includes, for instance, amplitude modulation (AM), frequency modulation (FM), or phase modulation (PH). The digital modulation forms a digital signal suitable for transmission by an analog medium. This includes, for instance, amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK). The pulse modulation reforms an analog signal so that it is suitable for transmission by a digital medium. This includes pulse amplitude modulation (PAM) and pulse code modulation (PCM) (Carlson et al., 1986).

4. Coding

Coding, as stated by Carlson et al. (1986), is a process of converting a digital message to another symbolic form in order to provide more efficient communication. Such methods include source coding and channel coding. Channel coding, known as error correction, is a method used to detect and correct errors by adding extra data, such as Hamming Single-bit-Error-Correction Codes, on the message. The source coding method, also known as data compression, reduces redundancy in a message by optimizing the statistical knowledge of the source, as in Shannon-Fano coding (Carlson et al., 1986).

5. Multiplexing

Multiplexing is a process of combining different transferring signals to share one channel simultaneously, as explained by Carlson et al. (1986). This process is used to make the most of the available bandwidth. Multiplexing can be done by several techniques. Time Division Multiple Access (TDMA) assigns different signals to different non-overlapping time slots. Frequency Division Multiple Access (FDMA) assigns different signals to different frequencies, and Code Division Multiple Access (CDMA) assigns different digital pattern codes to different signals (Carlson et al., 1986).

6. Bandwidth and Data Throughput

Bandwidth is the theoretical rate of data being transmitted through a medium in a defined time as described by Dean (2012). It is measured as bits per second (bps). Data throughput is the rate of actual data, known as payload, transmitted in a defined time. Usually it is also measured as bits per second (Dean, 2012).

7. Noise

Noise, as explained by Sklar (2001), is any undesired signal that interferes with the actual communication system signal, which leads to a reduction in its efficiency. The noise can be generated from manmade sources that include switching transients, antenna, and radio signals. Sklar (2001) adds that other noise can come from natural sources such as the Sun and the atmosphere. One important type of natural noise that cannot be ignored is thermal noise (known as Johnson noise). The motion of electrons from an electrical component generates heat that provides thermal noise. To some extent, the noise, consequently, degrades the fidelity of an analog system and causes errors in a digital system (Sklar, 2001).

8. Losses

Losses occur when some part of the signals are scattered, absorbed, diverted, or reflected through their path in a communication channel, as described by Sklar (2001). Two types of losses exist: free space loss, caused by the atmosphere, and range (Sklar, 2001).

B. COMMUNICATION SYSTEM CONSTRAINTS AND TRADE-OFFS

Any communication system has some constraints and limitations that hinder designers from simultaneously optimizing data throughput and system utilization, as well as minimizing errors, required bandwidth and power, and processing load and cost. Therefore, accepting trade-offs is essential in designing a communication system to balance the system requirements. Sklar (2001) describes three important rules that can describe the limitations and help to evaluate the trade-offs.

1. Nyquist Rate Theorem

This theorem states that the sampling rate for analog waves should be at least twice the highest frequency. Otherwise, sampling pulses will interfere with the adjacent pulse, which results in Inter-Symbol Interference. The theorem suggests the minimum necessary bandwidth for a communication system (Sklar, 2001):

$$R_s = \frac{R}{k} = \frac{R}{\log_2 M}$$

where R_s is the symbol rate, R is the bit rate, k is the number of bits per symbol, and M is the size of the symbol set.

2. Shannon-Hartley Capacity Theorem

This theorem explains the maximum information rate that a channel with certain bandwidth and noise can transmit (Sklar, 2001):

$$C = W \log_2 (1 + \frac{S}{N})$$

where C is the capacity, W is the bandwidth, and S/N is the signal to noise ratio.

3. Link Budget Equation

The link budget equation is a tool to analyze the communication channel that comprises all elements starting from the signal’s source, including the coding and modulation, through sending and receiving by antennas up to the final terminal. The link budget equation shows the calculations of all gains and losses related to a communication path. This helps to evaluate the performance of a system with certain requirements in the presence of its associated errors. Thus, it helps communication system designers and engineers to make the appropriate trade-offs (Sklar, 2001). The equation is shown here:

$$\frac{E_b}{N_0} = \frac{P_s t_b}{kT} = P_t G_t \left(\frac{1}{\alpha}\right)\left[\frac{\lambda^2}{(4\pi d)^2}\right]\left(\frac{1}{L_I}\right)\frac{1}{kR_b} \times \frac{G_r}{T}$$

where P_s is receiver power, P_t is transmitter power, k is Boltzman's constant, T is temperature, G_t is transmitter antenna gain, G_r is receiver antenna gain, d is the distance, R_b is the data rate, L_I is the receiver loss, and α is the atmospheric attenuation.

Carlson et al. (1986) add that in this equation, all elements present and associate with the signal-to-noise ratio (S/N). The signal-to-noise ratio is a measure of a noise relative to an information signal. A large S/N is always desirable while a low S/N means errors exist in the system (Carlson et al., 1986). In this equation, $\frac{E_b}{N_0}$, which is a normalized form of S/N, represents the S/N ratio. A rule of thumb identified by Sklar (2001) is to obtain about 10 dB or higher of $\frac{E_b}{N_0}$ in order to have an acceptable signal transmitted through a communication system (Sklar, 2001).

C. ORBITAL MECHANICS

Orbits and trajectories are two essential elements for the deployment of a satellite at a desired altitude and speed to meet the mission requirements. To carry the satellite out to space, a rocket is needed. Therefore, Sellers, Astore, Giffen, and Larson (2005) emphasize that it is important to understand the rules and physics associated with a space mission. They describe the orbit types, elements, motion, and physics (Sellers et al., 2005).

1. Types of Orbits

Sellers et al. (2005) note that there are four main types of orbits, which are categorized by altitude. Low Earth Orbit (LEO) has an altitude that ranges from 160 to 2000 km with an orbital period of about 90 minutes. Medium Earth Orbit (MEO) has an altitude about 20,350 km with an orbital period of approximately 12 hours. Geosynchronous Orbit (GEO) has an altitude about 35,786 km with an orbital period of approximately 24 hours. Another type, also is considered GEO, is a Geostationary Orbit. A Geostationary Orbit has a zero-degree inclination (i) with respect to the equator plane and a velocity equal to the Earth's rotation velocity, which makes a satellite appear to hover above same point on the Earth's Equator. The fourth orbital type, the highly elliptical orbit (HEO), has unique features. The elliptical orbit with low altitude in perigee and high altitude in apogee allows the satellite to dwell over the Poles (Sellers et al., 2005).

Sellers et al. (2005) add that orbits also can be categorized based on their inclinations. Thus, the Equatorial orbit has a zero-degree or 180-degree inclination. The Polar orbit has a 90-degree inclination. The Prograde orbit has an inclination represented as $0° \leq i < 90°$, and it mirrors the Earth's rotation direction. By contrast, the Retrograde orbit has an inclination represented as $90° < i \leq 180°$, and its rotation is the opposite of Earth's rotation direction (Sellers et al., 2005).

2. Classical Orbital Elements

The Classical Orbital Elements (COE) are six elements that can describe an orbit's size, shape, and orientation. Furthermore, the COE helps to identify the position of an object that moves in an orbit (Sellers et al., 2005).

a. Semi-major axis

The semi-major axis (a) defines the size of the orbit by detailing the distance from the Earth's center to perigee, the closest point from the orbit, plus the distance from the same center to the apogee, the farthest point from the orbit (Sellers et al., 2005).

b. Eccentricity

The eccentricity (e) defines the shape of the orbit by the result of the ratio between the two foci and the length of the major axis. When the eccentricity is 0, that means the orbit is circular. When e is less than 1, the orbit is elliptical. When e equals 1, it is a parabolic orbit. When e is greater than 1, the orbit is hyperbolic (Sellers et al., 2005).

c. Inclination

The inclination (i) defines the slope of the orbit with respect to the Earth's Equatorial plane. Orbits also can be categorized based on their inclinations. The Equatorial orbit has either a 0-degree or 180-degree inclination. The Polar orbit has a 90-degree inclination. The Prograde orbit has an inclination represented as $0° \leq i < 90°$, as well as a rotation that mirrors Earth's rotation direction. The Retrograde orbit, on the other hand, has an inclination represented as $90° < i \leq 180°$ and a rotation that is the opposite of Earth's rotation direction (Sellers et al., 2005).

d. Argument of Perigee

The argument of perigee (ω) defines the position of the perigee with respect to the Earth's Equatorial plane by knowing the angle between them (Sellers et al., 2005).

e. Right Ascension of the Ascending Node

The Right Ascension of the Ascending Node (RAAN), (Ω), defines the position of the ascending and descending nodes. These nodes are on the points at which the orbit crosses the equatorial plane. The ascending node is where it crosses from south to north, and the descending node is from north to south (Sellers et al., 2005).

f. True Anomaly

The true anomaly (ν) defines the position of the satellite vector within the orbit with respect to the perigee and it is measured in the direction of satellite motion (Sellers et al., 2005).

Figure 1 and Figure 2 illustrate the COE.

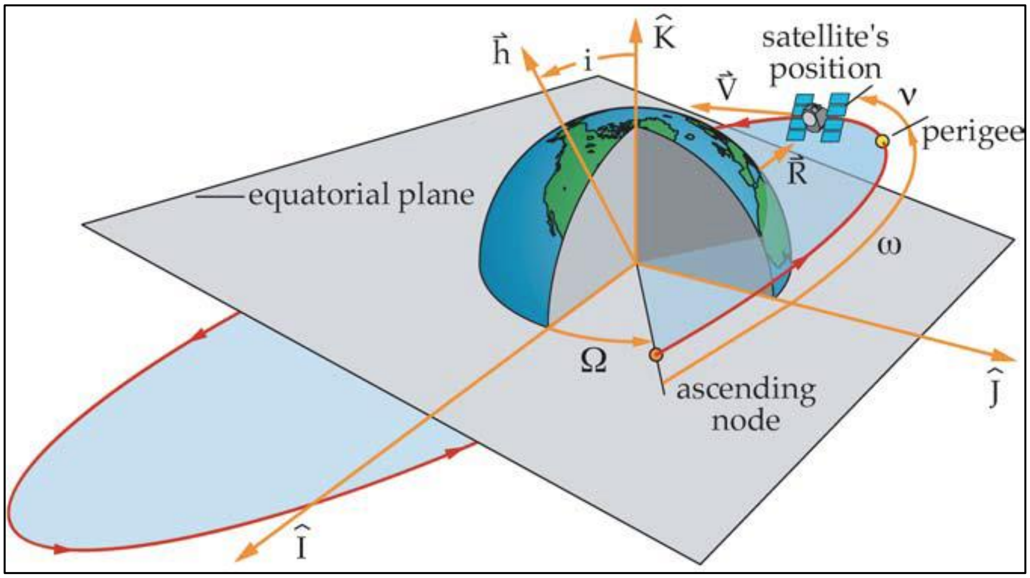

Figure 1. Classical Orbital Elements. Source: Sellers et al. (2005).

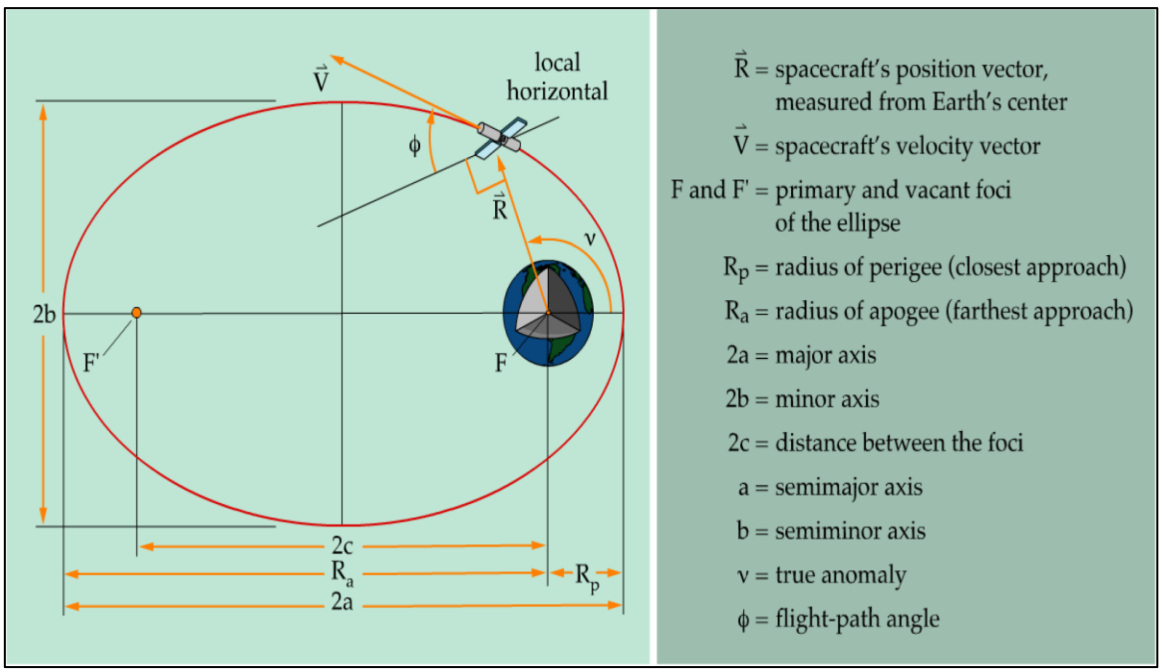

Figure 2. Different View of COE. Source: Siegenthaler and Saylor (n.d.).

3. Orbital Motion and Physics

Sellers et al. (2005) state that when a cannon fires a cannonball from the top of a mountain, the cannonball will fly and eventually fall to the Earth's surface due to the

Earth's gravity reaching a certain distance. At a given angle of elevation, the faster the cannonball, the farther the distance it travels. When the cannonball accelerates to a certain speed, it will not fall on the Earth's surface; instead, it will fall in space and because of the Earth's gravity, the cannonball will move around the Earth, forming an orbit based on the cannonball's velocity. This analogy provides the concept of freefall that applies to all objects in space (Sellers et al., 2005).

a. Kepler's Laws

Johannes Kepler, as stated by Sellers et al. (2005), founded three scientific laws of planetary motion. According to the first law, the planets move in elliptical orbits with the Sun at one focus. The second law states that the line joining the Sun to a planet sweeps equal areas in equal times, which means that a planet's speed depends on its distance from the Sun. According to the third law, the square of the orbital period of a planet is proportional to the cube of the mean distance from the Sun. This law helps to determine the period of the orbit based on altitude, and vice versa (Sellers et al., 2005).

b. Newton's Laws

Kepler laws, as described by Sellers et al. (2005), do not explain the forces behind the orbital motion. Instead, these forces can be defined by Newton's laws. Newton's first law states that a body continues in its state of rest, or of uniform motion in a straight line, unless compelled to change that state by forces impressed upon it. Momentum is the amount of resistance an object in motion has to change in speed or direction of motion. The object's velocity and mass compose its momentum. The two types of momentum are linear and angular. They are mainly formed from the type of velocity, which could be also linear or angular. Therefore, both kinds of momentum remain unchanged until they experience external force. Newton's second law states that the time rate of change of an object's momentum equals the applied force. In other words, the force must be comparatively high in order to quickly change an object's momentum, or the force must be comparatively low in order to slowly change an object's momentum. Newton's third law states that when body A exerts a force on body B, body B will exert an equal, but opposite, force on body A. Newton's fourth law is the Law of Universal Gravitation, which states that the force of gravity between two bodies is directly proportional to the product of their two masses and inversely proportional to the square of the distance between them (Sellers et al., 2005).

c. Constant of Orbital Motion

Sellers et al. (2005) assert that for a specific orbit with the absence of any force except gravity, the specific mechanical energy and the specific angular momentum always stay constant. Thus, only gravity affects satellite orbits without considering the drag or thrust. The specific mechanical energy, ε , is the total mechanical energy divided by the mass of the object. This helps to calculate the orbit velocity and period. The specific angular momentum, h, is a product of the two vectors that form an orbit: the velocity and position vectors. It is always perpendicular to them, which causes the orbital plane to be always constant (Sellers et al., 2005).

Without going deep into physics and mathematics, let us consider the following equations, which are derived from the previous laws. They are very useful tools for determining the position, the velocity, and the period of any object (Sellers et al., 2005):

$$E = KE + PE = \frac{1}{2}mV^2 - \frac{m\mu}{R}$$

$$\varepsilon \equiv \frac{E}{m} = \frac{V^2}{2} - \frac{\mu}{R} = -\frac{\mu}{2a}$$

$$V = \sqrt{2\left(\frac{\mu}{R} + \varepsilon\right)}$$

$$P = 2\pi\sqrt{\frac{a^3}{\mu}}$$

D. SATELLITE-BASED NETWORK

A satellite-based network is a means of passing data from one point to another via satellites and ground stations. Such a network could be built from a satellite constellation.

Wood (2001) categorizes satellite-based networks according to two approaches from a networking perspective: the ground-based approach and the space-based approach.

1. The Ground-Based Approach

In the ground-based network, Wood (2001) describes the satellites functioning as a relay network in which only layer one and layer two are involved in the space part of the network, as shown in Figure 3. This network is implemented using bent-pipe frequency shifting and amplification or by regenerating the signal with baseband digital signal processing. Wood (2001) adds that the signals are passed to reach the ground station, which is considered the last hop in the terrestrial network that will provide a seven-layer network to service users in different areas. In the space part of this network, however, some challenges arise regarding the Media Access Control (MAC), Logical Link Control (LLC), and handover. Another challenge is the limitation on extending the terrestrial network due to geographic, economic, and political considerations that limit the determination of the gateway location (Wood, 2001).

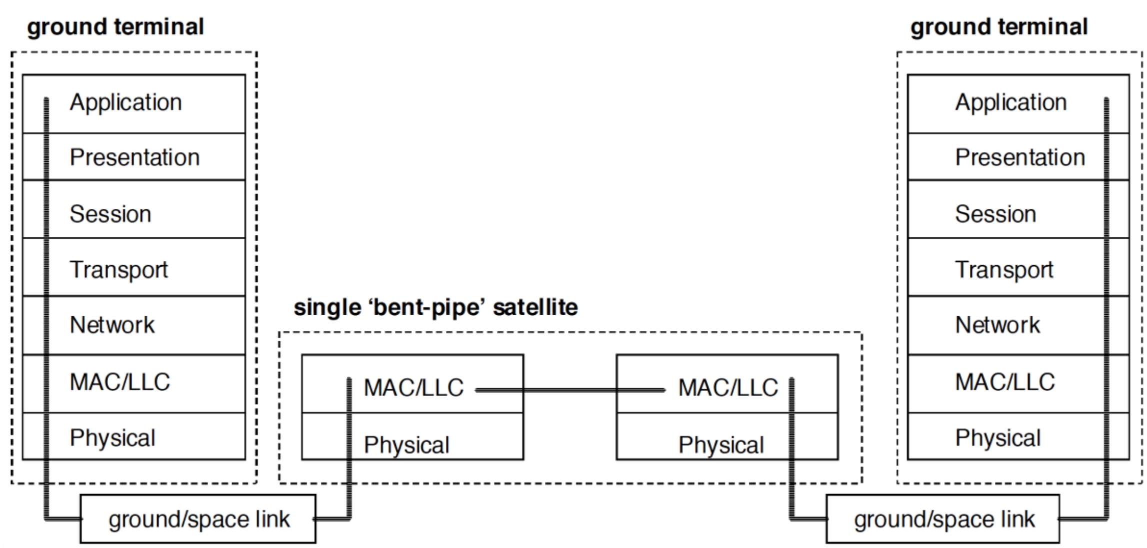

Figure 3. Ground-Based Network. Source: Wood (2001).

2. The Space-Based Approach

Wood (2001) explains that satellites in the space-based network perform onboard processing, which allows them to include layer three in the space segment of the network, which can work as a router or switch, as shown in Figure 4. Thus, each satellite is able to communicate with adjacent satellites via Inter-Satellite Links (ISL). Wood (2001) states that this allows a terminal operator in a ground station within satellite access range to communicate with the final terminal either directly through the satellite network alone or through both the terrestrial and satellite networks, without needing to pass a local gateway or having a complicated ground network infrastructure (Wood, 2001). By using this approach, satellites with ISLs are able to form a mesh network and each satellite is capable having a switch and a router onboard. This means each satellite constellation is a true network.

In a circular orbit, the velocity is constant at each point as explained by Wood (2001). Therefore, in any plane, each satellite can have fixed ISLs only with satellites immediately ahead of and behind it, because the satellites remain stationary relative to one another (Wood, 2001). However, in an elliptical orbit, it is difficult to maintain fixed ISLs between satellites due to the changing velocity at the apogee and the perigee. The drawback of the space-based network is that it requires deep considerations of orbit geometry (Wood, 2001).

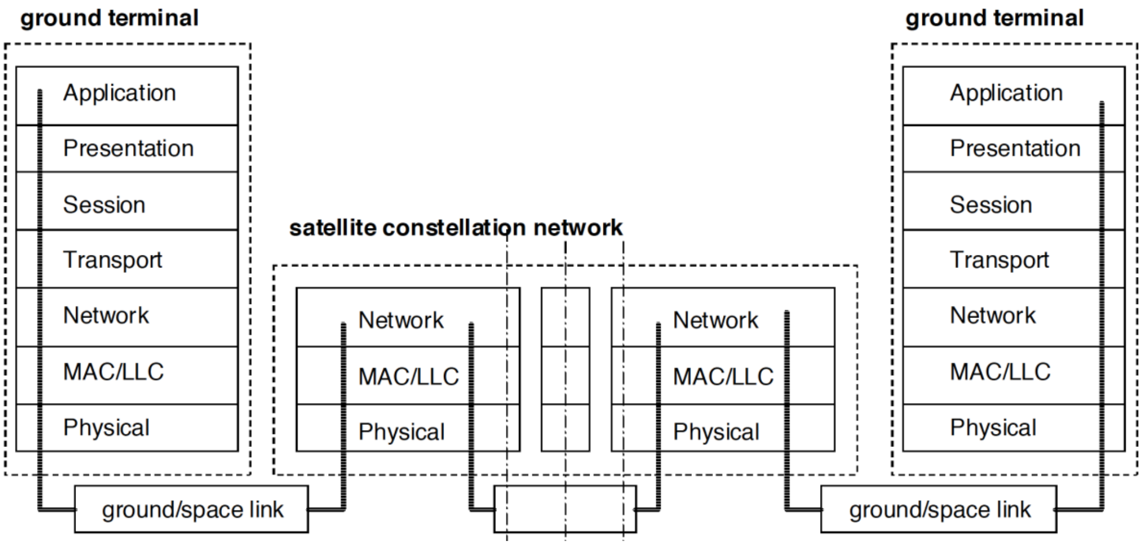

Figure 4. Space-based Network. Source: Wood (2001).

3. Space Segment Layers

In both ground-based and space-based networks, Wood (2001) states that the space segment is the most important part of the network, and this segment is considered the variable factor. The physical layer (layer one), the data link layer (layer two), and the network layer (layer three), are the only layers from the Open Systems Interconnection model that can be onboard satellites (Wood, 2001).

a. Physical Layer

The physical layer is responsible for bit-level transmission over a medium, as described by Horvath, Tackett, and Yaste (2012). Here, the link equation is applied to establish the needed communication channel, including the bit rate, error rate, and signal to noise ratio. Also in this layer, modulation, coding, and multiplexing are performed (Horvath et al., 2012).

b. Data Link Layer

This layer is responsible for transmitting data frames between hardware devices in the same network, as explained by Horvath et al. (2012). The frame contains the payload data plus the header and trailer. The header has the MAC address for the source and destination. The trailer has the control information and error checker. Horvath et al. (2012) add that one important protocol that works with MAC is the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). This protocol senses the next node and sees whether to send the frame or wait for a certain period, then send the frame. This technique helps to avoid potential collisions, if each device in the network sends frames randomly (Horvath et al., 2012).

c. Network Layer

The network layer is responsible for sending the packet from a specific node to reach its destination node, as described by Horvath et al. (2012). The Internet Protocol (IP) works in this layer and it is a logical address for a device in the network. To help accomplish its task, the IP relies on some routing protocols, including the Internet Control Message Protocol (ICMP) and Address Resolution Protocol (ARP) (Dean, 2012). Routers determine the next destination node to which to route the packet based on the routing protocol (Horvath et al., 2012). The routing protocol actually gathers data about the network to determine the best path. When using a mobile ad-hoc network (MANET) topology in a space-based network, the nodes—satellites—are dynamic. Therefore, MANET needs specific routing protocols that deal with many hosts with low bandwidth and energy. Furthermore, MANET routing protocols should require less overhead to discover and maintain nodes. Proactive, reactive, and hybrid are the three types of MANET routing protocols proposed (Horvath et al., 2012).

(1) Proactive Routing Protocols

In a proactive routing protocol, each node has a routing table that contains a topology of the entire network (Horvath et al., 2012). This requires more message exchanges and high overhead to maintain the process of updating the routing able. The updated table will accelerate the transmission process, but it also consumes more bandwidth and power. The update process uses one of two approaches: event-driven and regular updates. In the event-driven protocol, the update will be sent when a change in the network nodes happens. In the regular update protocol, nodes send their link state data periodically. An example of the proactive protocol is the Optimized Link State Routing protocol (OLSR) (Horvath et al., 2012).

(2) Reactive Routing Protocols

According Horvath et al. (2012), when a node needs to send in reactive routing protocols, it establishes a routing discovery process starting from the neighbor nodes until reaching the destination node. This protocol is more responsive to changes. It also reduces the overhead, which minimizes the needed bandwidth. However, it introduces latency. An example of the reactive protocol is the Ad Hoc On-Demand Distance-Vector routing protocol (or AODV) (Horvath et al., 2012).

(3) Hybrid Routing Protocols

The hybrid protocol combines the proactive and reactive protocols to overcome their limitations and optimize their advantages as explained by Horvath et al. (2012). A hybrid protocol can be implemented differently. The most popular approach is to divide the network into different zones then implement one protocol within a zone, for example, a proactive protocol, and the other protocol between zones, for example, a reactive protocol. An example of a hybrid protocol is the Enhanced Interior Gateway Protocol (EIGRP) (Horvath et al., 2012).

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III. SATELLITE THREAT

Satellites have become increasingly essential since more corporations, governments, and the military rely heavily on them for important services and applications. Additionally, advances in technology encourage industries to improve satellite systems and applications and to produce new and better innovations in this technology. Indeed, improvements to this technology are needed because satellites operate in space, where they are vulnerable to the space environment. Moreover, satellites are vulnerable to adversaries who seek to gain superiority in the space domain by disrupting the space communication system or shutting it down entirely. In general, we consider two fundamental threats: the space environment and space warfare.

A. SPACE ENVIRONMENT

The space environment consists of the surroundings that interact with a satellite. Olsen (2005) describes some elements from these surroundings that may cause harm to satellites.

1. Spacecraft Charging

Spacecraft charging, as explained by Olsen (2005), is an outcome of a contact operation between a satellite that has charged particles and high-energy photons. He adds that this contact will eventually result in either one or two undesired situations: surface charging or internal charging. The charging can occur through one of the following mechanisms:

- Charge flow resulting from the surrounding plasma
- Photoelectron emission from a satellite
- Secondary emission caused by plasma barrage

When one of these mechanisms forms a current flow to a satellite, the satellite frame (body) becomes a non-zero charge, which leads to non-zero potentials. Therefore, as Olsen (2005) states, this situation results in different charging currents. In fact, charging is harmful for satellites because it may lead to the following anomalies:

- Weakening of surface and sensors

- Arcing, which causes an interference in electrical circuits
- Accumulating results from an internal charge that occurs in electronic parts

All these anomalies can cause serious damage to the satellites, which results in the loss of satellite functionality or failure in the mission (Olsen, 2005).

2. Orbital Debris

Orbital debris, as described by Olsen (2005), consists of small objects in space and mostly exists in LEO. This debris contains the leftovers of artificial objects in space, such as nonfunctional satellites, remaining rocket bodies, and fragmented objects resulting from intentional or unintentional collision or explosion. Currently, there are approximately 10,000 tracked objects and many more of very tiny untracked particles in LEO. They range from about 1 millimeter to greater than 10 centimeters in diameter. A major concern of orbital debris is damage caused by a loss or breakup of a satellite. Table 1 shows the debris sizes, with estimated parameters and corresponding possible damage (Olsen, 2005).

Table 1. Debris Sizes and Their Potential Corresponding Damage. Source: Olsen (2005).

Size	**Diameter**	**Mass**	**Number**	**Detectability**	**Damage**
Small	Less than 1 mm	Less than 1 mg	10^{12}	By situ sampling	-Degradation of surface. -Damage to unprotected components
Medium	1 mm – 10 cm	1 mg – 10 kg	10^{7} - 10^{8}	Too small to catalog, too few for most in situ sampling	-Degradation of surface. -Damage to component. -Loss of spacecraft capabilities
Large	Larger than 10 cm	Larger than 10 kg	8000	Catalogable in LEO	-Loss of spacecraft capabilities -Harmful breakup

3. Meteoroid and Micrometeoroids

These are natural small parts of icy or rocky meteoroids that fly in space at a speed of 20 km/s, as described by Alexander, Belk, Cooke, Pavelitz, and Robinson (1997). There are more meteoroids and micrometeoroids in GEO than in other orbits. The threat coming from meteoroids is similar to the debris threat. The damage on the Hubble Space Telescope antenna is an example of damaging impact (Alexander et al., 1997)

4. Surface Effects

Surface effects, as described by Olsen (2005), include the following:

a. Atomic Oxygen Effect

The atmospheric density at a high altitude is much less than at lower altitude, 10 orders of magnitude below the one at sea level. Yet, about 10^{15} oxygen atoms/m^3 still exist there. A satellite with 1 m^2 area that moves at 8 km/sec will experience approximately 10^{19} interactions with surrounding atoms/sec, which result in about 5 eV of an efficient collision energy (Olsen, 2005). This collision will lead to a harmful process of oxidation and erosion of the satellite shell materials. Another negative impact is that because the solar cells are connected with wires made of silver, the wires could be eroded, causing a failure in the energy system (Olsen, 2005).

b. UV Degradation

The exposure to solar radiation, specifically ultraviolet (UV) and X-ray radiation, causes degradation in some surface materials of a satellite, as explained by Olsen (2005). The shorter the wavelength, the more energy the radiation has. Thus, a 4 eV of photon energy is associated with a wavelength of 0.3 μm. This process will result in degrading some of the chemical chains and therefore change the physical properties of the satellites' shells (Olsen, 2005).

c. Sputtering

Sputtering is a process of ejecting atoms from the satellites' shells when the surface interacts with high-energy atoms or ions. The sputtering could lead to an erosion or change in satellite shell properties (Olsen, 2009).

d. Molecular Contamination

This process is mainly caused by outgassing or offgassing as explained by Olsen (2005). He adds that usually objects in a vacuum will perform this process, which means that many atoms and molecules will be ejected from the surface and eventually will be accumulated as a contaminant.

On sensitive satellites, the offgassing parts, such as sensors and solar cells, will cause a change in the surface properties. A worst case is when UV radiation interacts with a contaminated surface. In this case, contaminant molecule films form on a surface like solar arrays (Olsen, 2005).

B. SPACE WARFARE

As advances in technology increase, the military's dependency on satellite services also increases. The military utilizes the majority of those services and gradually relies on them to be used in different applications in order to effectively and efficiently achieve military goals. Additionally, there is an increasing awareness of military competition in the space domain. For instance, the Pentagon has realized that spaced-based communication is a vital asset for the U.S. military such that a failure in this system can diminish or obstruct completing any combat mission (Krepon & Thompson, 2013). Krepon and Thompson found from a comprehensive view experienced in a wargaming simulation that "space assets were like a crystal goblet: exquisite but easily shattered" (p. 9). In reality, most satellites are orbiting around the earth, typically in a constant path and at a constant speed. Thus, they can be an easy target for an adversary, which could disable the satellite, causing the paralysis of all space-based services so recovery would not be possible in one day (Krepon & Thompson, 2013). Therefore, space becomes an important domain that requires improved, updated, and secure solutions for Information Assurance, especially in wartime. Their advanced capabilities and the rich experience make the United States, China, and Russia the key players in space domain.

1. Overview of Russian Counterspace Weapons

The competition between the United States and the former Soviet Union in space capabilities in the Cold War encouraged the Soviets to come up with the Anti Satellite (ASAT) system to deter the United States. The first evidence of the Soviet ASAT appeared in 1963, when the Soviets launched the Istrebitel Sputnik system that had the ability to attack U.S. space assets in LEO (Gallton, 2012). After that, the ASAT system experienced inconsistent phases of development because of political and economic situations (Gallton, 2012). The concept of the operation for ASAT was "the hot metal kill." The idea was to have an explosion in the surrounding area of a target satellite that creates debris hitting the satellite (Gallton, 2012). A test held in 1963 showed the advanced capabilities of a vehicle that carried ASAT missiles and could maneuver, including changing its orbit altitude and inclination (Gallton, 2012). After the Cold War, Russia completed the Soviet ASAT system development. In the beginning of the 1990s, Russia had already tested several ASAT capabilities. Some were space-based, such as missiles carried by MiG-31 aircraft, and others were air-based that used directed-energy weapons (Gallton, 2012). The major development, however, has been the Naryad ASAT system that has advanced maneuverability and can reach targets in GEO (Gallton, 2012).

Nonetheless, Russia keeps modernizing its counterspace weapons, which raises concerns in the United States. In their article published by the National Defense University, Gompert and Kofman (2012) explain the concern regarding Russian ASAT weapons. They emphasize that a failure to recognize the ramifications of such a Russian counterspace action can worsen the problem (Gompert & Kofman, 2012). They recommend the U.S. government convince the Russian government to stop developing its ASAT systems (Gompert & Kofman, 2012).

2. Overview of Chinese Counterspace Weapons

In the mid-1980s, the Chinese military started to foster an ASAT system project and research. Recently, however, they have concentrated on an ASAT system as their overall space capabilities grow (Gallton, 2012). After multiple ASAT missions tested in 2005, China eventually had a successful ASAT mission in 2007. Using a mobile ground-based missile system, they intended to intercept their nonfunctional satellite Feng Yun (FY-1C), which was in a polar LEO.

According to a U.S. Department of Defense report to Congress on Chinese military capabilities, China has made consistent progress in developing its space-based assets as well as its anti-space capabilities (Department of Defense [DOD], 2016). China seeks to have space dominance and deter its adversaries. From the People's Liberation Army documents, there is an emphasis on the need for effective counterspace systems to destroy any space assets when needed (DOD, 2016). China is working on improving its counterpace capabilities, such as directed energy weapons and space-based asset electronic warfare. More importantly, China has made progress in developing and testing an ASAT missile system, which can be a serious threat to U.S. space assets (DOD, 2016).

IV. EVOLUTION OF SMALL SATELLITES

A. INTRODUCTION

Small satellites first emerged in the Cold War era with the launching Sputnik I, Explorer I, and Vanguard 1 into the LEO. Technological and industrial limitations at that time, however, obstructed progress in developing small satellites. Nowadays, advances in technologies have enabled the production of more compact hardware and faster software. Recent technologies such as the integrated circuit and Microelectromechanical Systems (MEMS) and the Complementary Metal–Oxide–Semiconductor (CMOS) as well as some economic factors drive companies, governments, and researchers to invest more in small satellites (Bell, Gilchrist, Bilen & McTernan, 2012).

In 2016, the White House published "Harnessing the Small Satellite Revolution to Promote Innovation and Entrepreneurship in Space," stating that small satellites have become a more important factor to create affordability and adaptability in the U.S. space domain (White House, 2016).

Satellites are categorized based on their weight, as shown Table 2. The Femto satellite is the smallest satellite among them.

Table 2. The Satellite Size Categories. Source: Gallton (2012).

Satellite Category	Weight (Kg)
Large	> 1000
Medium	500 – 1000
Mini	100 – 500
Micro	10 – 100
Nano	1 – 10
Pico	0.1 - 1
Femto	< 0.1

B. SMALL SATELLITE BENEFITS

"Large Benefits of Small Satellite Missions," is a paper written by researchers from NASA, Stanford University, and Colorado University, and addresses some advantages of small satellites. The most important benefit is the cost and convenience of the inexpensive commercial-off-the shelf satellite. For example, the KickSat costs about $35. Another cost-related advantage is its inexpensive launch. These two benefits lead to even more benefits. By having small satellites, scientists and researchers can gain frequent access to space, which accelerates space development programs (Baker & Worden, 2008).

From a military perspective, small satellites provide a rapid launch capability that can provide a quick space-based service. Besides that, small satellites are difficult to track, so the adversary is less likely to detect them and shut them down.

C. SMALL SATELLITE LIMITATIONS

There are some restrictions associated with small satellites, though, as described by Sandau, Brieb, and D'Errico (2010). One of these is a short life cycle. For example, the KickSat, which is a Femto satellite, can live in LEO for about two to three weeks. Limited capacity is another disadvantage because it provides low power and a low data throughput rate. Furthermore, they are difficult to control and monitor due to their small size. This limited size hinders communications engineers and designers in optimizing the platform for a better communication system (Sandau et al., 2010).

D. KICKSAT AS AN EXAMPLE OF FEMTO SATELLITE

Zachary Manchester, a Ph.D. student at Cornell University, was inspired by the concept of cheap, low-power, and very small commercially available electronics that emerged with the advances in smart phones. This inspiration ignited the idea of inventing a chip-sized spacecraft that eventually became known as KickSat. The KickSat, also called Sprite, is a chip-sized satellite that weighs about five grams and is 3.5 x 3.5 cm. Moreover, it has integrated circuits made from low-cost and low-power components that make it a chip-sized spacecraft bus for general purposes. Sprite uses a Texas Instruments CC430 microcontroller and radio system-on-chip, which provides 4 kB of RAM and 32 kB of flash memory. It is equipped with a CC1101 UHF transceiver with output power of about 10 mW and data rates of about 500 kbps. Also it has Spectrolab TASC solar cells, an InvenSense ITG-3200 3-axis MEMS gyro, and Honeywell HMC5883L 3-axis magnetometer. The antenna is an isotropic half-wave V-dipole antenna (Manchester, 2013).

E. THE NEED FOR FEMTO SATELLITES: A LITERATURE REVIEW

The report of the Commission to Assess United States National Security Space Management and Organization discusses the need for improving U.S. space capabilities to overcome vulnerabilities such as disruption activities or potential adversary attacks, which deny access to space systems. The report states that the United States must enhance a large number of space capabilities. Some of the important capabilities are the assured and timely access to space and the development of an end-to-end set of information capabilities to provide decision makers and warfighters necessary information when they need it (Commission report, 2004).

As noted previously, the U.S. Department of Defense reported to Congress on advances in China's space capabilities. According to that report, China successfully launched in LEO a new small space launch vehicle, the LM-11, which is considered a rapid solution for use in emergencies in September 2015 (DOD, 2016). In addition to this, China had an inaugural launch using a light capacity and rapid launch rocket, the LM-6, carrying 20 small satellites—four of which weighed only 100 g (like Femto satellites) (DOD, 2016). Admiral Cecil D. Haney, commander of U.S. Strategic Command, spoke in 2015 about concerns regarding improvements in Russian and Chinese counterspace weapons and their programs in developing small satellites: "As I'm sure you're aware," he told the audience, "they're also developing multidimensional space capabilities supporting their access-denial campaign." (Pellerin, 2015)

In his thesis "Developing and Applying Synthesis Models of Emerging Space System," Michael M. Ordonez documents research he conducted at the Naval Postgraduate School (NPS) in 2016. He discusses the threat of space systems being destroyed or denied access by adversary anti-satellite weapons, which drives the United States to look for new and innovative methods to assure continuous access to the space domain. His thesis suggests a small satellite system as one potential solution to overcome the constraints associated with large satellites (Ordonez, 2016).

Eberhard Gill, the chair of Space Systems Engineering at Delft University of Technology in the Netherlands, echoes the view in his research paper "Enhancing Ground Communication of Distributed Space Systems" that Femto satellites are advantageous in terms of cost and development time. The redundancy and robustness of Femto satellites, and the ability to expand them, would provide a good distributed network system. The distributed system will add benefits to space functionalities such as communication, by enabling the deployment of hundreds of Femto satellites (Sundaramoorthy, Gill, & Verhoeven 2012).

In "Investigating a New Approach to Space-Based Information Network," a thesis written by NPS students Horvath, Tackett, and Yaste (2012), the authors recount building and testing several space-based constellations modules and simulations using Satellites Tool Kit (STK) and QualNet. In the LEO constellations model, they emulated Iridium constellations and tried different routing protocols to investigate the bit rate. In terms of network bandwidth efficiency, they found that the OSPFv2 protocol is slightly better suited to space-based networks that have a mixed constellation of static and dynamic links.

Currently, NPS Femto Satellites projects are under development. Professor Peter Ateshian leads the NPS Femto Satellites group interns, who in the summer of 2016 programmed an Intel Quark D2000 microcontroller to communicate with the RockBlock, providing random data from its built-in sensors (Bigham, Ramirez, Ramirez, & Zamora, 2016).

In other research related to NPS Femto satellites, Lieutenant David Justamante wrote a master's thesis for NPS, "Randomness from Space," documenting the next-generation NPS Femto satellite capabilities that provide a true random number generation. He utilized the onboard BMC 150 6-axis eCompass in the Intel Quark D2000. He concluded that the next-generation NPSFS is a good source for entropy (Justamante, 2017).

Although such valuable literature pertaining to the NPSFS exists, to the author's best knowledge, there is no paper or study pertaining to the NPS Femto Satellites communication network.

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V. KICKSAT COMMUNICATIONS NETWORK MODELING

A. INTRODUCTION

This chapter explains the modulation of a KickSat network that was used for communication between different ground stations, and subsequently a ship and an aircraft in three different scenarios. The first scenario is designed to investigate the capability of a simple network and to try three different routing protocols in that network. Only two KickSats were used to build the network that allowed a ground station to communicate with another ground station. The design of the second scenario extends the simple network with more satellites, ground stations, a ship, and an aircraft, implementing the routing protocol that had the best network performance in the first scenario. The third scenario proposes a different KickSat constellation design and investigates its performance using the same parameters as the second scenario. STK with a QualNet interface as a plug-in was used to build and model all scenarios. STK allows a user to design the physical environment of the network nodes, including orbit geometry, antennas, transmitters, and receivers (System Tool Kit, 2017). Additionally, STK can calculate the access time, range, and link budget between any two nodes (System Tool Kit, 2017). The QualNet interface imports each antenna's position and parameters from STK to model a seven-layer network as shown in Figure 5 (System Tool Kit, 2017).

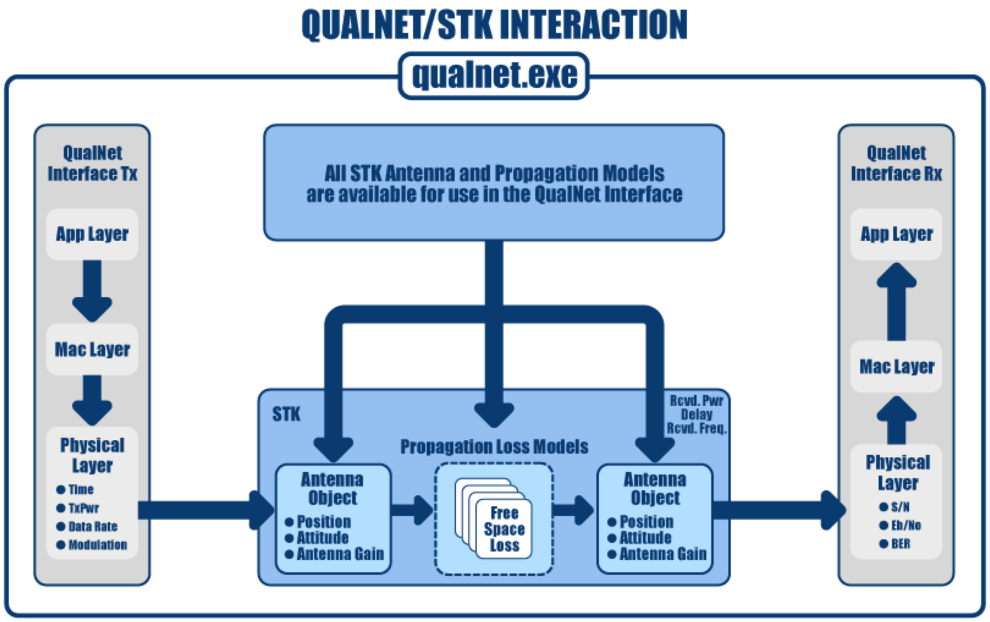

Figure 5. STK/QualNet Interaction. Source: System Tool Kit (2017).

B. SCENARIO 1: SIMPLE KICKSAT NETWORK

In this scenario, a simple network was built to include only two KickSats and two ground stations—a MOC simulating a Maritime Operation Center and an AFOC simulating Air Force Operation Center. Three routing protocols were chosen: AVOD, OSPFv2, and OLSRv2. These are based on the recommendations from an NPS thesis, "Investigating a New Approach to Space-Based Information Network," which suggests a couple of protocols that can perform better in a space-based network (Horvath, Tackett & Yaste, 2012). These three routing protocols were tested to find the best routing protocol performance in terms of data throughput to be implemented for the next scenarios. Therefore, this scenario ran three times, and each time the scenario was implemented with a different routing protocol, there were three different results. The scenario was set up first by designing the needed orbital geometry and devices based on the actual parameters and capabilities of KickSat.

1. Orbital Geometry Setting

The orbits were designed to be polar circular orbits. This means each orbit would have an inclination of 90 degrees and the same altitude for both apogee and perigee. The main consideration was the maximum range of the KickSat radio, which was 500 km. Therefore, orbits were determined to be LEO with an altitude of 300 km. Both satellites had a 0 degree of true anomaly, which put them in parallel positions. Additionally, the difference of RAAN degrees between the two satellites was determined to be 4 degrees. Thus, depending on satellites' orbital positions, the distance between the two parallel satellites ranged from 350 km to 450 km. Figure 6 shows the orbital geometries of satellite 1; Figure 7 shows the orbital geometries of satellite 2.

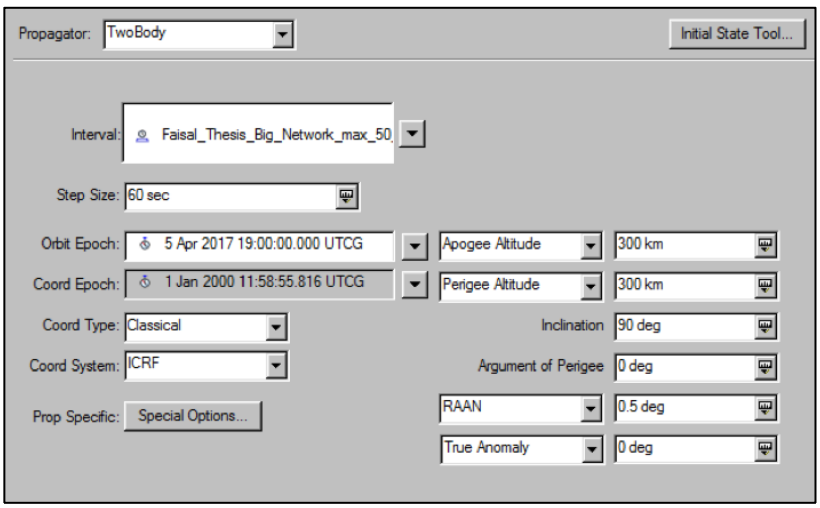

Figure 6. Orbital Geometries for Satellite 1

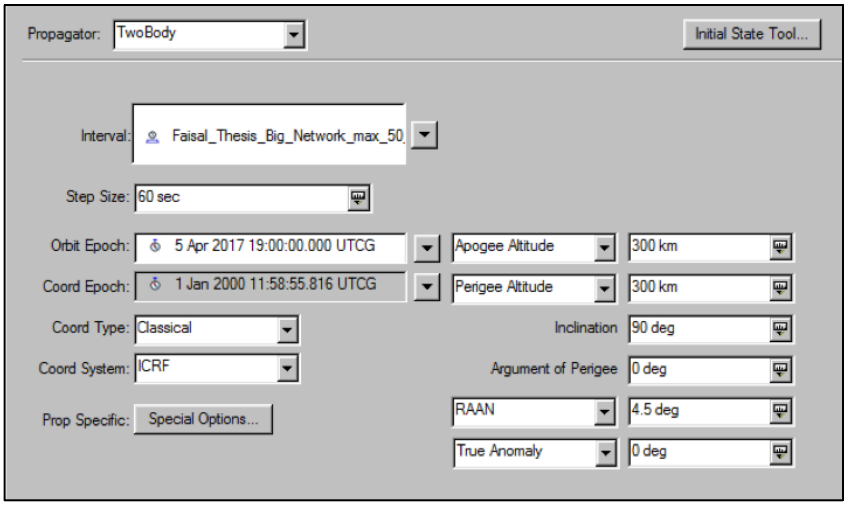

Figure 7. Orbital Geometries for Satellite 2

2. Communication Devices and Parameters Setting

Antennas, transmitters, and receivers were configured for satellites and ground stations. For satellites, the KickSat radio characteristics, which were described in Chapter IV, were used to configure satellites antennas, transmitters, and receivers. For ground stations, a parabolic antenna 7.3 meters in diameter and with 55 dB of power was used as shown in Figure 8. The purpose in using a large antenna was to increase the antenna gain, which was needed in this situation where the power of a KickSat transmitter was very limited. All links—the uplink, crosslink, and downlink—were set to have a data rate of 500 kb/s, a bandwidth of 640 MHz, and a BPSK and CDMA modulation as shown in Figure 9.

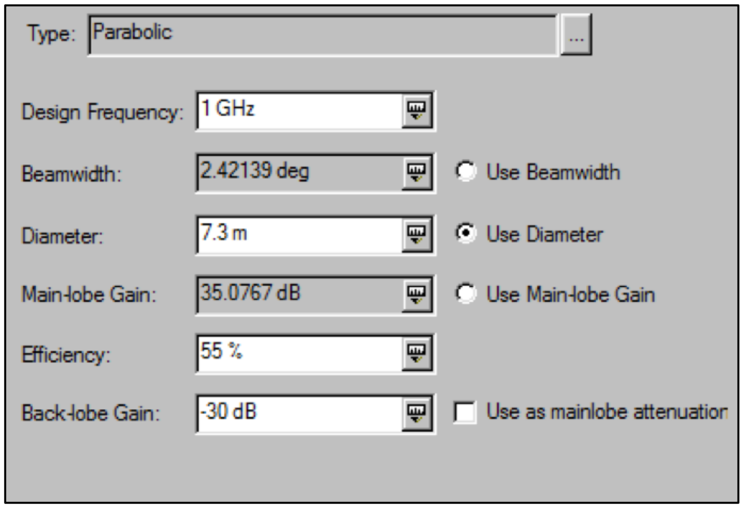

Figure 8. Ground Station Antenna Parameters

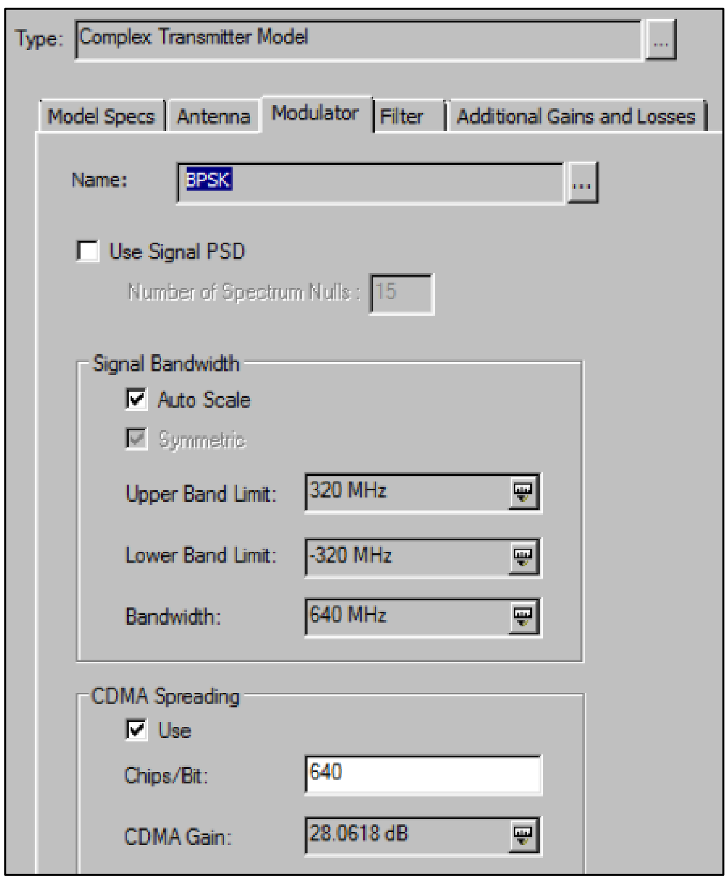

Figure 9. Ground Station Antenna Parameters

3. Link Budget Calculation

Based on the previous settings, STK could calculate the link budget between any two objects. The link budget of uplink, crosslink, and downlink was calculated for transmitting and receiving. The result showed that every link had acceptable values of S/N and BER. The link from a ground station to a satellite—uplink—had an S/N ratio of about 88 dB with a BER of about $1*10^{-30}$. The link from a satellite to another satellite—crosslink—had an S/N ratio of about 11 dB with a BER of $3.7*10^{-8}$. The link from a satellite to a ground station—downlink—had a S/N ratio of about 48 dB with a BER of about $1*10^{-30}$. Figure 10 shows the simple network set. The figure also shows in the top left a summary of the link budget for the uplink (yellow), crosslink (blue), and downlink (green), where the left portion is the transmitting side and the right portion is receiving one for each link.

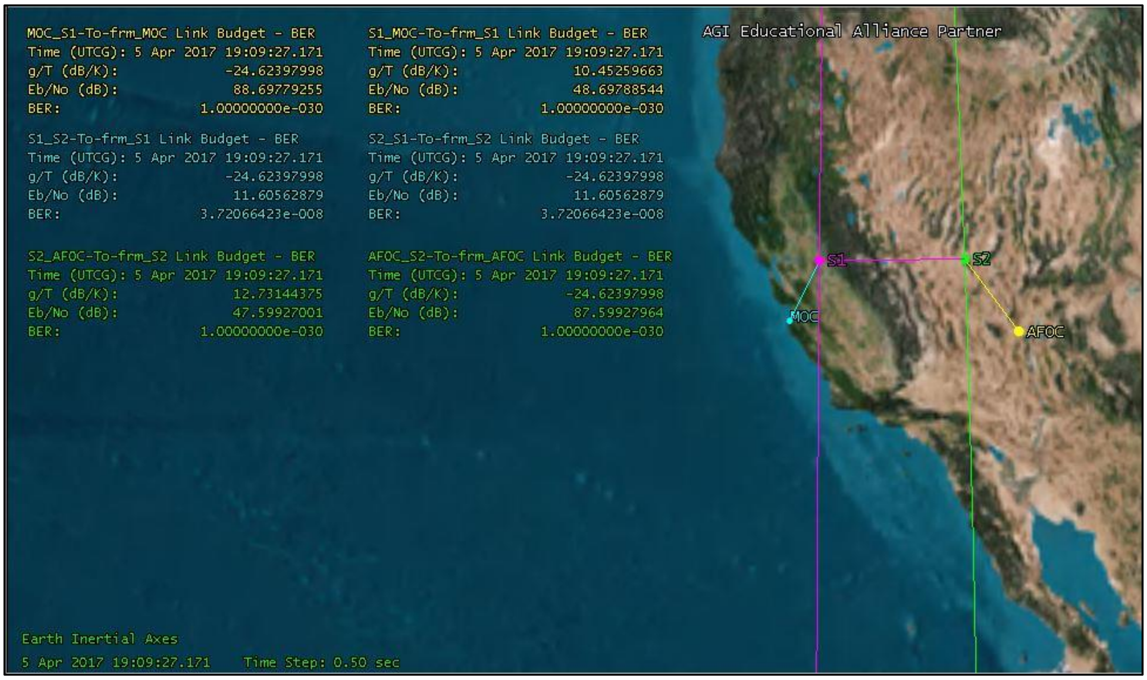

Figure 10. The Simple Network with Link Budgets

4. Access Time Calculation

STK calculates the access time to be when a satellite has a line of sight with a ground station (System Tool Kit, 2017). In these scenarios, however, the access time corresponded to the maximum satellite radio range, which is 500 km. Thus, the ground stations' antennas constraint was configured to have a maximum range of 500 km so the actual access time for a satellite could be calculated. The access time for uplink in a 24-hour period was 101.15 seconds and for downlink was 94.71 seconds.

5. QualNet Settings

When QualNet imports the node's data from STK, it imports only the antenna's position and parameters (System Tool Kit, 2017). Thus, the physical layer needed to be reconfigured. Additionally, the rest of the network layers for each node needed to be configured as well. Doing this required first creating an interface for each node to be able to communicate through a link with another node. Then one interface was created for each ground station to communicate with the satellite above, and two interfaces were created for each satellite. One of these interfaces communicated with a ground station below and the other communicated with the satellite next to it. The data link layer was configured to have a generic MAC, and the net layer was configured to have an IPv4 protocol. The routing protocol changed between the chosen protocols to test the best network performance in terms of data throughput.

For the application layer, two applications were configured. The first one was constant bit rate (CBR). This application sent defined items as traffic from a client to a server at a constant bit rate using User Datagram Protocol (UDP) (Scalable Network Technologies, 2014). Figure 11 presents the settings for CBR application. The configuration was set to send "0" item—which is 40 bytes—from the MOC to the AFOC in a 1-second interval, and starts from second 5 and ends at second 0. This configuration allowed the application layer to send one item every second for as long as the scenario ran. The second application used the File Transfer Protocol (FTP/GENERIC), which sent data from the client to the server using Transmission Control Protocol (TCP) (Scalable Network Technologies, 2014). Figure 12 presents the configuration settings. The number of items was set to 0 and the item size set to 3 kb; it started from second 1 and ended at second 0. This configuration allowed the applications to send a random number of items from the MOC to the AFOC while the simulation was running (Hicks & Seeba, 2017). After configuring the interfaces, we created three subnets: one for uplink, another for crosslink, and the last for downlink. Each subnet included the needed interfaces to create a link. Other input configurations were left to the default, following the STK/QualNet scenario tutorial.

Property	Value
Items to Send	0
Item Size (bytes)	40
Interval	1S
Start Time	1S
End Time	0S
+ Priority	Precedence
Enable RSVP-TE	No
Enable MDP	No
Session Name	[Optional]

Figure 11. CBR Configuration Settings

Property	Value
Items to Send	0
Item Size (bytes)	3000
Start Time	1S
End Time	0S
+ Priority	Precedence
Session Name	[Optional]

Figure 12. FTP Configuration Settings

6. Scenario 1 Results

After we set the actual parameters of the current KickSat characteristics, the network modeled by QualNet failed to perform at the application layer even though the link budget modeled in STK appeared to be sufficient for communication. In other words, no message was received from the first ground station (MOC) by the second one (AFOC). One reason for this failure, however, could be the limitation in the satellite power, which makes sense since the satellites acted as routers in this network and needed enough power to perform well in this dynamic environment. Therefore, to make the network viable, the power of the ground stations and satellites was changed to 100 dB and 70 dB, respectively, where the latter power was the minimum power required for the satellites. This was realized after extensive modeling.

Two data sets were chosen from the QualNet simulation's resulting data. These were the number of messages received and the data throughput at the receiver at the application layer. The simulation ran three times. Each of the three times the simulation ran, it had a different routing protocol. The AVOD demonstrated the best result in both applications—CBR and FTP—when compared to OSPFv2 and OLSRv2. Table 3 shows CBR results, and Table 4 shows FTP results.

Table 3. CBR Application Results

Protocol	**CBR**					
	Messages Sent	**Messages Received**	**Messages Delivery Efficiency**	**Bit/s Sent**	**Bit/s Received**	**Bit/s Efficiency**
AODV	899	502	56%	320	263.84	82%
OSPFv2	899	485	54%	320	256.95	80%
OSLRv2	899	472	53%	320	252.85	79%

Table 4. FTP Application Results

Protocol	FTP					
	Messages Sent	**Messages Received**	**Messages Delivery Efficiency**	**Bit/s Sent**	**Bit/s Received**	**Bit/s Efficiency**
AODV	1260	1254	99.52%	50.8 K	50.5 K	99.41%
OSPFv2	1055	1049	99.43%	42.5 K	42.3 K	99.53%
OSLRv2	660	653	98.94%	26.6 K	26.3 K	98.87%

C. SCENARIO 2: EXTENDING THE KICKSAT NETWORK

In this scenario, the goal was to extend the previous network to cover large areas and increase the access time. The scenario included a ship, an aircraft, and an extra ground station—a NOC simulating the Network Operation Center. The distance between the MOC and the AFOC was 615 km and the distance between the AFOC to the NOC was 575 km. The distance between the aircraft and the ship was about 6600 km. The network constellation consisted of 63 KickSats spread along the four polar orbits so that it covered most of ground nodes without leaving gaps. The orbital geometry setting for this scenario was the same for Scenario 1 except for the extra satellites that needed to have a different degree of true anomaly to put them in the same orbit. The true anomaly degree should have a four-degree difference between any two adjacent satellites that were in the same orbit. This kept the distance between them at a range of 500 km. Additionally, to put the extra satellites in the new orbits, they should have a four-degree difference of RAAN from the adjacent satellites on the next orbit. Figure 13 shows the constellation.

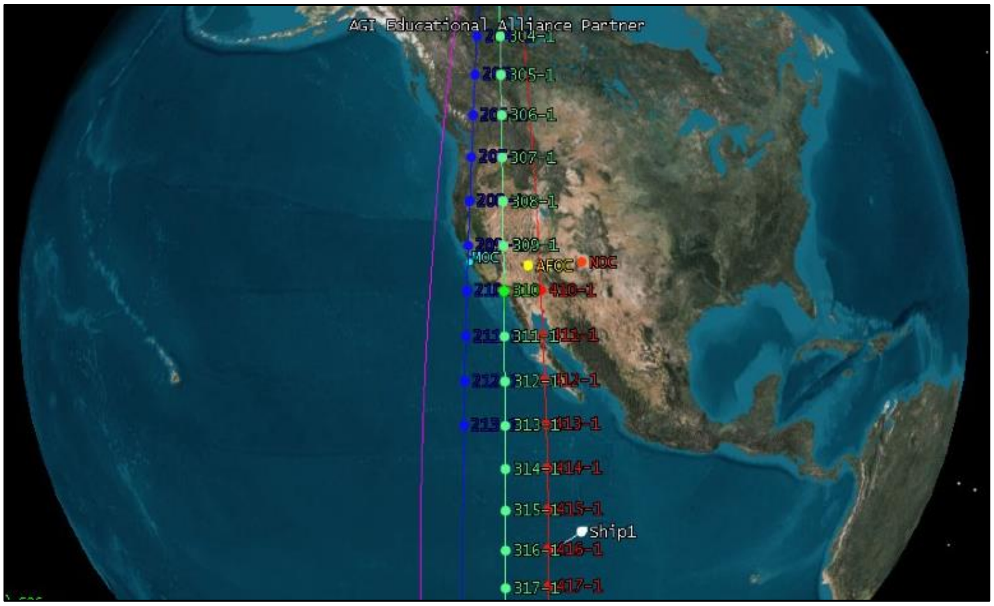

Figure 13. The Satellite Constellation

1. Access Time Calculation

The access time was calculated for 24 hours in the focused area, starting from 1900 the first day to the same time on the second day. The calculation showed that the network extension increased the access times for ground stations. For the MOC, it showed that it had access to the space network in two periods each day, as shown in Figure 14, where each (+) sign presents a satellite access time. The first period started at 1908 and lasted for 30 minutes as shown in Figure 15, where each line represents the duration of one satellite's access time. The second period started at 0739 and lasted for 30 minutes, but it had a two-minute gap from 0744 to 0746. The AFOC period started from 1908 and lasted for 30 minutes as shown in Figure 16. The NOC period started from 0609 and lasted for 30 minutes as shown in Figure 17.

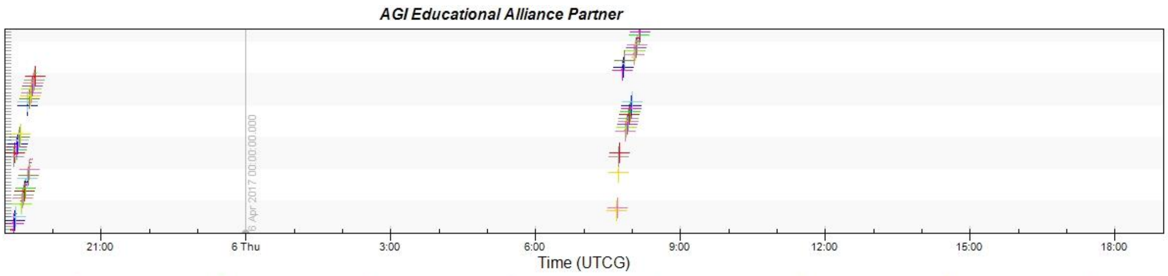

Figure 14. MOC Access Time for One Day

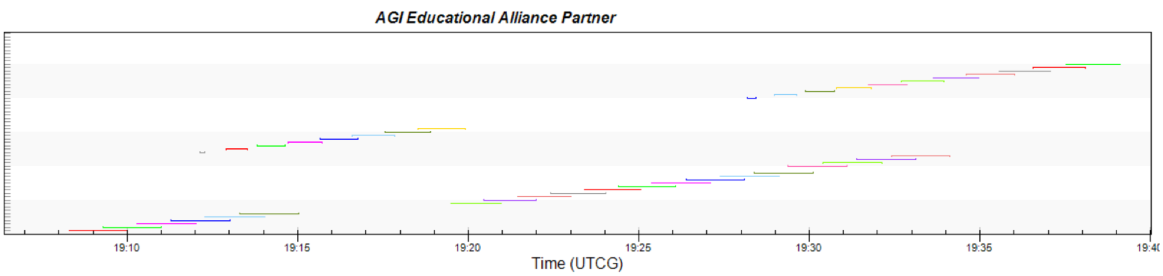

Figure 15. MOC Access Time for the First Period

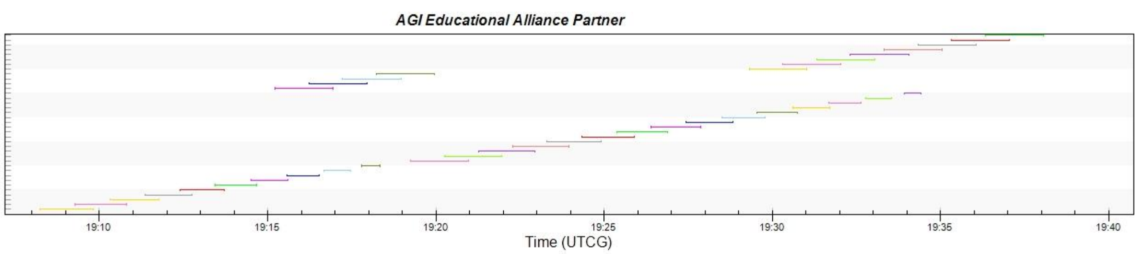

Figure 16. AFOC Access Time.

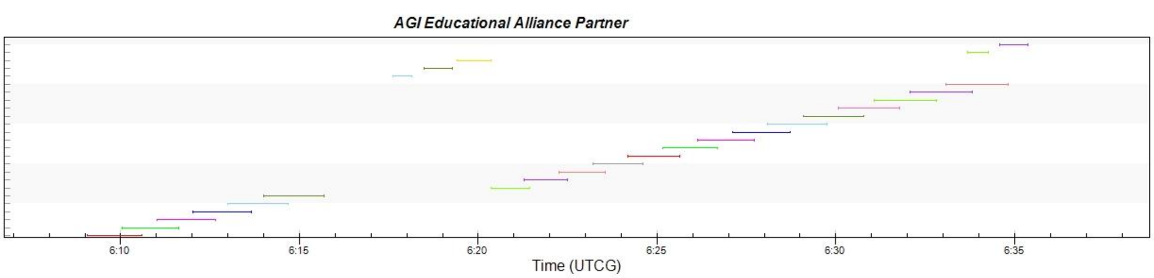

Figure 17. NOC Access Time

2. QualNet Settings

After the QualNet configuration was complete, the first problem that arose while running the simulation was that the simulation crashed every time. Hicks and Seeba also experienced this problem when they ran their simulations for their thesis. There were limitations: the STK/QualNet license was an educational one, which only allowed simulation at a maximum of 50 nodes (Hicks & Seeba, 2017), and there were too many interfaces. The simulation ran successfully once both obstacles were overcome by modifying the scenario. The number of satellites was reduced to 38 KickSats, each with only one interface. Moreover, Dr. Alexander Bordetsky, an NPS professor in the Information Science department, recommended having one interface for every node, which was more realistic when running the simulation (personal communication, April 12, 2017). Additionally, he recommended using only one subnet to run as a local network since one 255.255.255.0 subnet can provide 255 IPs, which satisfied this scenario.

Another limitation recognized from this setting was that the 70 dB power for a satellite was not enough to connect the nodes in the network; thus, it was changed to 90 dB as a minimum value to make the network available. One reason behind this anomaly might be the more dynamic environment that required more energy to keep a satellite updated in terms of MAC and routing protocols.

The MAC protocol was chosen to be CSMA/CA because of the realistic nature of the KickSat dynamic environment, which may have some nodes come in and others go out. The AODV protocol was used for routing as the best choice from Scenario 1. Four applications were run at the same time. Two were CBR applications and the others were FTP_GENERIC. Both had the same configuration as Scenario 1 except the item sizes: the CBR was changed to 50 bytes and FTP was changed to 1 kb. The first CBR was configured to test the traffic from the MOC to the NOC, and the second CBR was configured from the aircraft to the ship. For the FTP, the first CBR was configured to test the traffic from the MOC to the AFOC, and the second was from the NOC to the ship. This simulation ran for 2580 seconds, which was the duration of the first satellite constellation's flight over the nodes. Figure 18 shows the positions for ground stations, the ship, the aircraft, and the satellite constellation after the modifications.

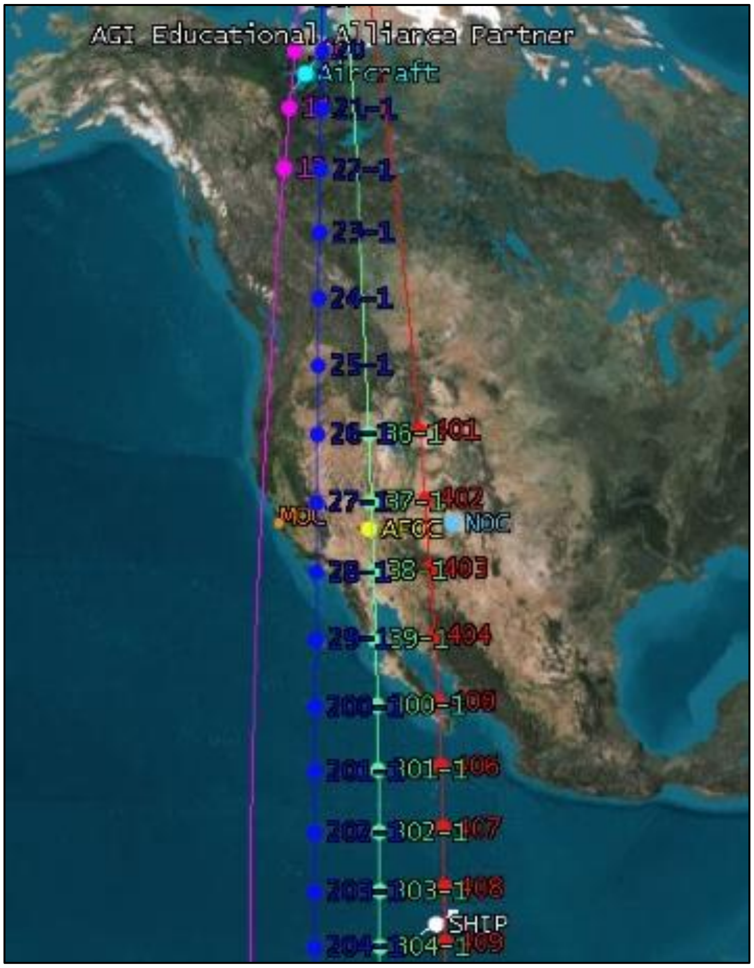

Figure 18. The Network after the Modifications

3. Scenario 2 Results

The scenario showed that the network worked and delivered messages to the defined nodes. However, the delivery efficiency percentage tended to be low in terms of the number of messages sent compared with the messages received. One reason might be that the use of minimum power was needed to make the network function. Another reason was the different access time for every ground station. For example, in the CBR application, the client node kept sending packets every second during the simulation—regardless of whether there was a route to the network or not. The same reasons apply for FTP application results. This led to dropping about 2594 packets due to no route, as shown in Figure 19, where the number is distributed over the nodes. Tables 5 and 6 show the results of the CBR and the FTP applications.

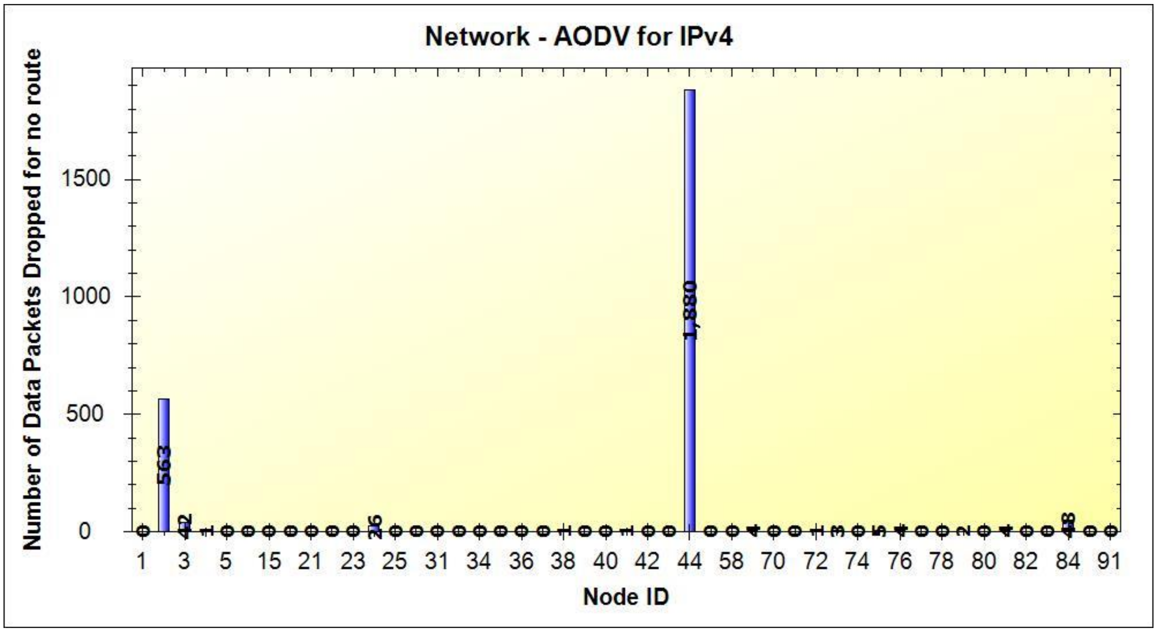

Figure 19. Number of Dropped Packets for Every Node in Scenario 2

Table 5. CBR Application Results

Route	CBR					
	Messages Sent	**Messages Received**	**Messages Delivery Efficiency**	**Bit/s Sent**	**Bit/s Received**	**Bit/s Efficiency**
MOC to NOC	2579	29	1.12%	400	7.67	1.92%
Aircraft to Ship	2579	106	4.11%	400	25.42	6.36%

Table 6. FTP Application Results

Route	FTP					
	Messages Sent	**Messages Received**	**Messages Delivery Efficiency**	**Bit/s Sent**	**Bit/s Received**	**Bit/s Efficiency**
MOC to AFOC	38	22	57.89%	584.60	85.32	14.59%
NOC to Ship	95	77	81.05%	1303.48	430.22	33.01%

D. SCENARIO 3: SATELLITES' CONSTELLATION MODIFICATION

In this scenario, the goal was to try a different constellation to improve the network efficiency. All the settings except for one were the same those as in Scenario 2. The only change done in this third scenario was to modify the RAAN for adjacent satellites by 2 degrees and keep the next adjacent satellites with no change on RAAN. In other words, instead of having parallel satellites on different orbits, the satellites on the adjacent orbit moved by 2 degrees of RAAN. Figure 20 shows the new satellite constellation.

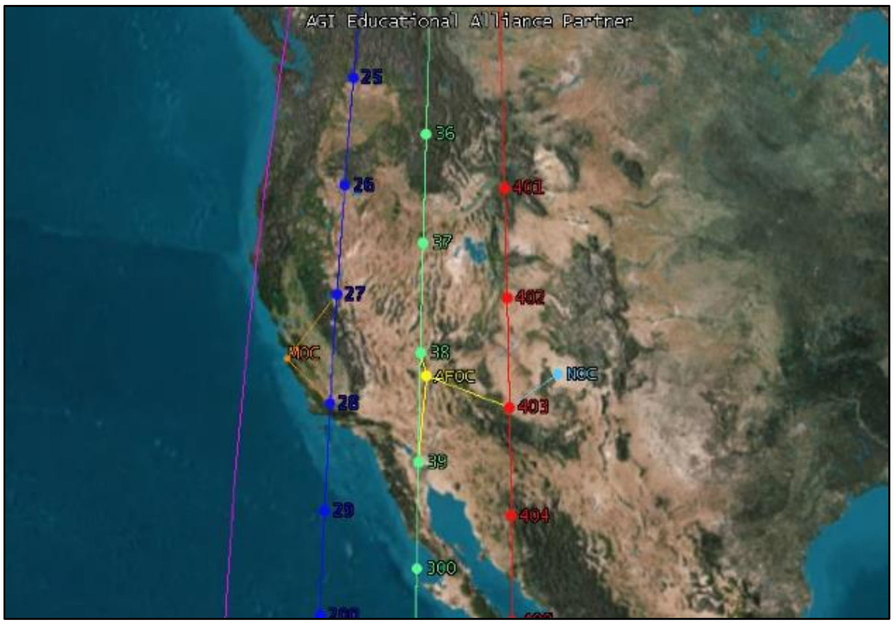

Figure 20. The Constellation after the Modifications

1. Scenario 3 Results

In this scenario, improvements in the CBR applications contributed to the number of messages delivered increasing tenfold for the first application, and that number doubled for the second application. Further, the FTP application showed improvement for the first application but a decline in the second application. These improvements came because the positions of the new satellites covered larger areas and filled gaps between satellites, which led to a reduction in the number of dropped packets to 1973, as shown in Figure 21. This number decreased by 76 percent from Scenario 2. Tables 7 and 8 show the results of the CBR and the FTP applications.

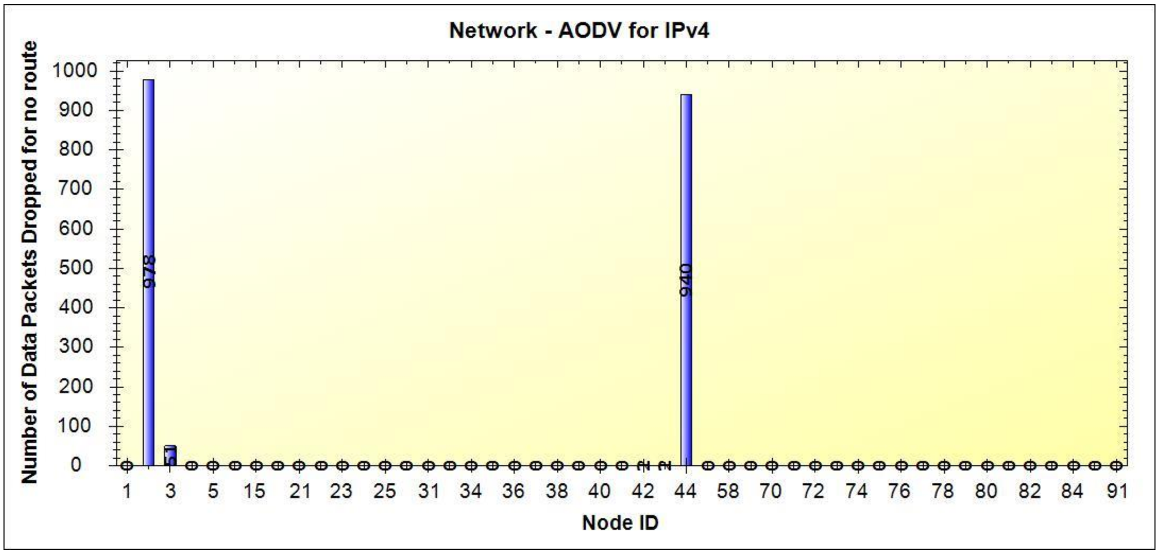

Figure 21. Number of Dropped Packets for Every Node in Scenario 3

Table 7. CBR Application Results

Route	CBR					
	Messages Sent	**Messages Received**	**Messages Delivery Efficiency**	**Bit/s Sent**	**Bit/s Received**	**Bit/s Efficiency**
MOC to NOC	2579	280	10.86%	400	68.75	17.19%
Aircraft to Ship	2579	202	7.83%	400	49.34	12.34%

Table 8. FTP Application Results

Route	FTP					
	Messages Sent	**Messages Received**	**Messages Delivery Efficiency**	**Bit/s Sent**	**Bit/s Received**	**Bit/s Efficiency**
MOC to AFOC	209	191	91.39%	2.8 K	844.18	30.15%
NOC to Ship	30	13	43.33%	404.4	69.16	17.10%

E. SUMMARY

The first scenario was set with only four nodes to test the availability to perform a space-based network and to investigate the best routing protocol. The results from investigating two applications—CBR and FTP—at the same time showed the space-based network was viable if the KickSats power was increased to 70 dB. The investigation also revealed that AODV performed the best routing protocol. The second scenario was set to extend the Scenario 1 network to include 38 KickSats implementing the best routing protocol found. The satellite constellation imitated the Iridium constellation; however, because the number of nodes was limited by the education licenses, the constellation was designed considering the number of satellites allowed, the Earth's rotation, and the ground nodes' locations. The results from investigating four applications—two CBRs and two FTPs—at the same time showed the network could operate if the satellites' power increased to 90 dB; however, the results also showed the delivery efficiency percentage tended to be lower in terms of the number of messages sent in comparison to the messages received. The third scenario was set to redesign the constellation to improve the network's efficiency. The result showed that the efficiency improved dramatically for three applications and decreased in one.

All scenarios operated at the minimum power. All results showed a percentage of failure to deliver all messages. This can be explained by three reasons. First, the use of minimum power was needed to make the network function. The second reason is the use of CSMA/CA, which consumed more power. The third reason is the different access time for every ground station, which led to many dropped packets due to no route being found.

Redesigning the satellite constellation in Scenario 3 helped to optimize the satellites' positions, covering more area and creating some routes, which led to a reduction in the number of dropped packets.

VI. ARDUINO AND ROCKBLOCK EXPERIMENT

A. INTRODUCTION

This chapter describes an experiment to investigate the feasibility to use the next-generation NPS Femto Satellites for low data throughput communication. The next-generation NPS Femto Satellites include a RockBlock and a microcontroller that controls the RockBlock. An Intel Arduino 101 was chosen as the microcontroller for this experiment. The experiment codes are available in the appendix.

B. ROCKBLOCK MK2

The RockBlock is a small device that allows a user to send and receive small sized messages anywhere in the world by using the Iridium Network. The 9602 Iridium Modem embedded in the RockBlock enables the RockBlock to access the network. The RockBlock is also equipped with a 25-mm square ceramic patch antenna. The RockBlock can send up to 370 bytes and receive up to 270 bytes in a good sky view. The messages can be sent to a user account in the RockBlock server, a defined email, or another RockBlock device, as shown in Figure 22. In order to integrate with the RockBlock, the RockBlock has 10 pins. The device appears as a serial interface and can be controlled using AT commands. The RockBlock can be connected to FTDI TTL-232R-3V3 cable, which provides a virtual com port on a USB host (Rock Seven Mobile Services Ltd, 2016).

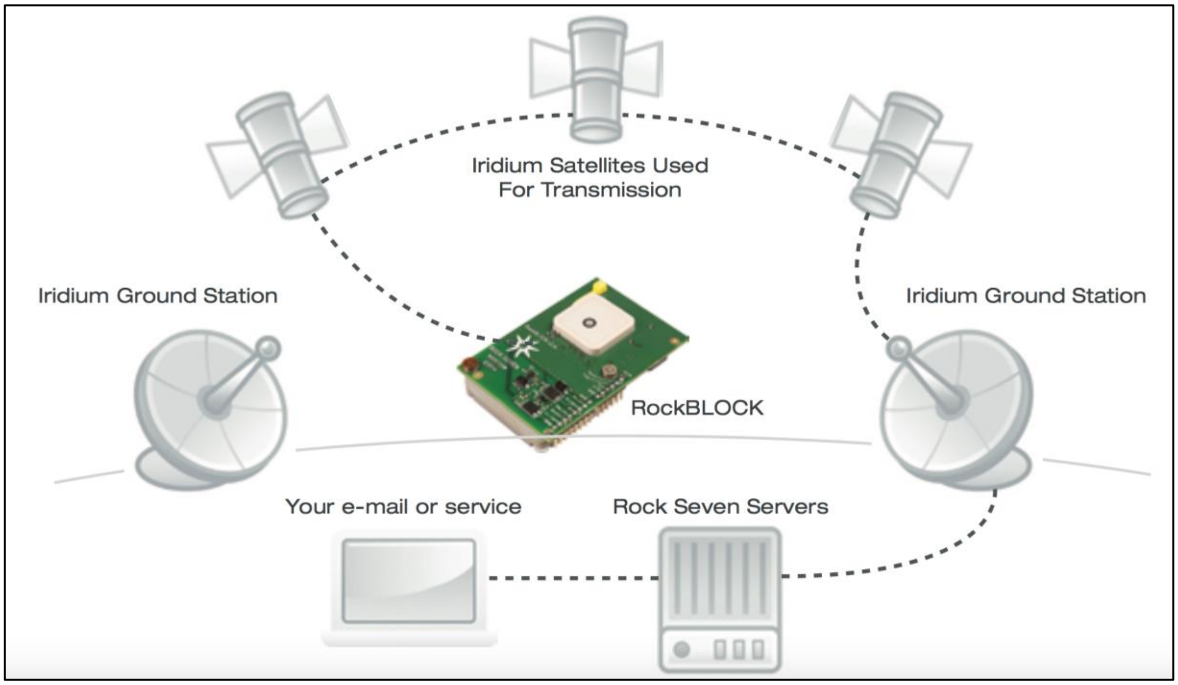

Figure 22. RockBlock Communications. Source: Rock Seven Mobile Services Ltd. (2016).

C. INTEL ARDUINO 101

The Arduino 101 board is a microcontroller that has an Intel Curie processor, a low-power consumption model. It includes two cores, uses a 32-bit ARC architecture, and is core clocked at 32 MHz. The board operates at 3.3 volts. The board can be powered with a 7-12 V DC jack, a 5V USB connector, or a 7-12 V VIN pin. Additionally, it can provide a regulated 5V power output. The Arduino 101 is equipped with a Bluetooth LE module, a 6-axis accelerometer, and a gyroscope. In addition, the Arduino 101 has 20 input/output pins, of which 14 are digital pins and six are input analog pins only. The board can be connected by USB for serial communication (Arduino, 2017). The most important advantage to using an Arduino is that it has a pre-existing library for RockBlocks programmed by Mikal Hart, making the implementation easier (Hart, 2013). To control the RockBlock using the Arduino, four or five pins (the Sleep pin is optional) need to be connected as shown in Table 9.

Table 9. Wire Connections from Arduino to RockBlock. Source: Hart (2013).

RockBlock Connection	Arduino Connection
+5V (Power)	+5V (Power)
GND	GND
TX	TX Serial Pin
RX	RX Serial Pin
SLEEP	+5V or GPIO pin

The TX and RX lines use TTL-level serial protocol with 19200 baud. Thus, it is possible to connect to a built-in universal asynchronous receiver/transmitter (UART) or to establish a soft serial by using any two defined pins. The Arduino 101 provides two UARTs. One was used to talk to the RockBlock and the other for communicating with the connected computer. Utilizing the SLEEP pin allows the Arduino to place the RockBlock in power-save mode when not in use (Hart, 2013). One important functionality provided by the library is the non-blocking retry strategy. Due to the nature of satellite communication, which requires a clear sky view, establishing a link to LEO satellites may be hampered by atmospheric conditions. Thus, the non-blocking retry functionality makes the RockBlock keep trying to connect to the satellites until the link is established and the desired data is sent or received (Hart, 2013) Additionally, the library provides functions to send messages in binary or text message format in the specified mode: send only, receive only, or send and receive mode (Hart, 2013).

Initially, this library contained several errors that prevented its proper functioning, compilation, and use. With these errors corrected, the library provided a powerful interface for controlling the RockBlock. Figure 23 shows the RockBlock connected to the Arduino 101. Figure 24 shows the RockBlock Arduino set connected to the computer.

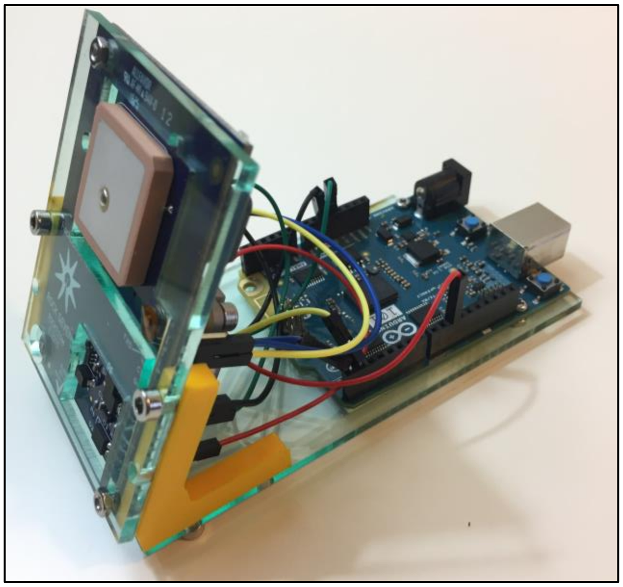

Figure 23. The RockBlock Connected to the Arduino 101

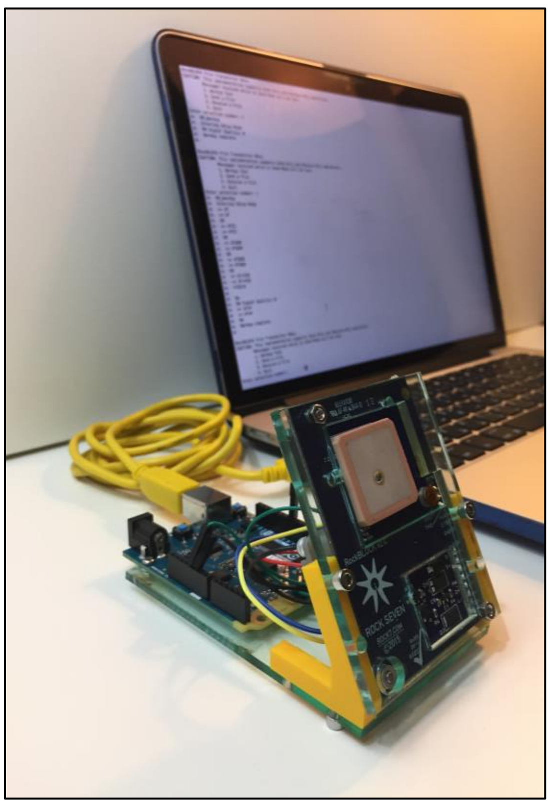

Figure 24. The RockBlock Arduino Set Connected to the Computer

D. THE EXPERIMENT SETTING

The main objective in this experiment is to send a text file from a computer to another computer using two sets, each consisting of an Arduino 101 and a RockBlock. One set is for sending and the other is for receiving. For this experiment, the computer represents any piece of equipment on the Femto satellite that can interface with the microcontroller and the Arduino 101, the RockBlock-controlling microcontroller. The transmission process begins with the user initializing the system from the computer and then sending/receiving a file with that computer. We use a Python program to provide a user interface and to transfer the sent/received file between the computer and the Arduino 101. Figure 25 shows a high-level diagram of the experiment settings.

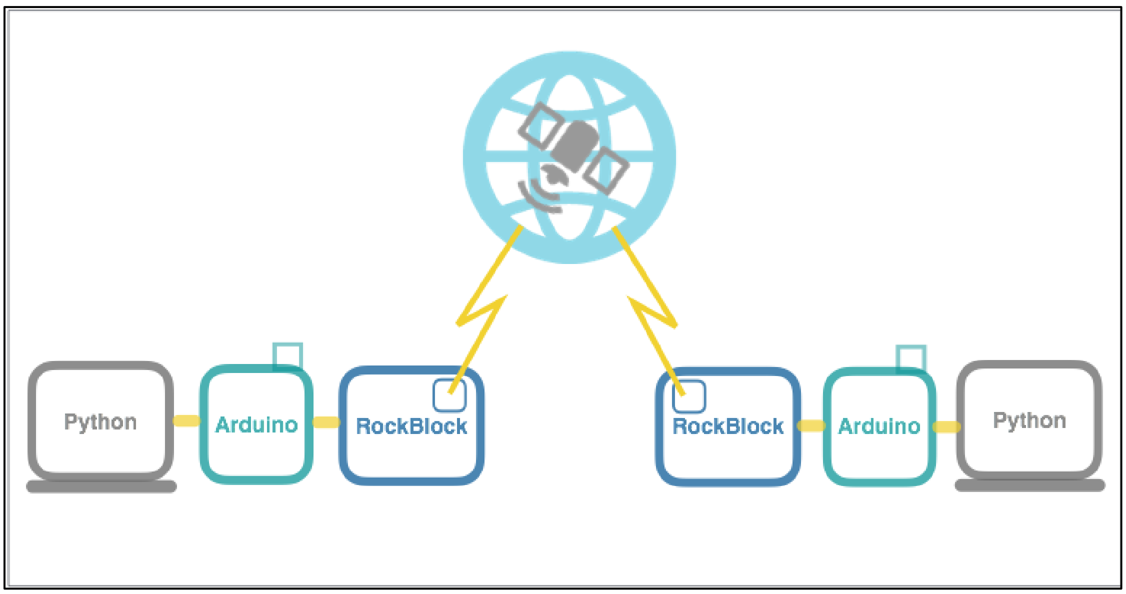

Figure 25. High-Level Diagram of the Experiment

The Python program setup requires two command line arguments. For the first, the user must specify the serial port that connects to the Arduino (usually “COM#” on Windows or “/dev/usbtty#” on Mac and Linux). For the second, the user provides the serial number of the connected RockBlock. Figure 26 shows the usage message displaying the required arguments and an example.

```
Faisals-MacBook-Pro:Desktop f15mac$ python RBFileTransfer.py
Error: provide USB/Serial communication port
Usage: RBFileTransfer.py [USB/Serial port] [RB Name]
Example: RBFileTransfer.py COM5 RB0010757
```

Figure 26. A Snapshot of the First Step to Run the Python Program

Running the program begins by entering a loop and providing a menu with four functions: warmup test, send a file, receive a file, and quit. When the user selects a function, Python completes the actions required on the computer while also sending commands to the Arduino in order to process the selected task. The Arduino then directs the RockBlock as necessary using functions from the RockBlock library. Figure 27 presents a snapshot of the menu.

```
RockBLOCK File Transmitter Menu
CAUTION: This implementation supports Send Only and Receive Only operations.
        Messages received while in Send Mode will be lost.
        1. Warmup Test
        2. Send a File
        3. Receive a File
        4. Quit
Enter selection number:
```

Figure 27. A Snapshot of the Python Program Menu

Due to the data transmission limits of both serial connections and Iridium, the files are separated into segments prior to transmission. In sending a file, for example, the Python program first divides the input file into segments for serial transmission. The Arduino is sent the number of segments to expect, and then all of the segments of the file are sent to the Arduino. The Arduino then recompiles the segments before dividing them into small segments for transmission via Iridium (a process that allows the fewest number of Iridium messages to be used, regardless of the serial segment size used). This process occurs in reverse when a file is received. If the destination for the file is another RockBlock, the user is asked for the target RockBlock's ID number. This is prepended to each Iridium message so it can be directed to the target. As the Arduino commands the

RockBlock to transmit messages and the RockBlock replies, the Arduino sends these communications back to the Python program for display to the user. This communication includes important information, such as signal quality, satellite network access status, number of segments sent, and any errors or failures, so the user can monitor the process.

In summary, the Arduino's role is to receive a tasking from Python program, the user interface, to control the RockBlock, and receive feedback from RockBlock and forward it back to the Python program.

E. THE EXPERIMENT FINDINGS AND RESULTS

We were successful in sending a 150-byte text file from one computer and receiving it at another computer. A significant finding from this experiment was the identification of an undocumented limitation in the RockBlock regarding maximum message size. The RockBlock documentation states that the RockBlock can send up to 370 bytes and receive up to 270 bytes. However, the AT serial command protocol has a limit of 120 data bytes being sent with the transmission command to the RockBlock. Sending messages greater than 120 bytes via the serial command to the RockBlock would have required implementing new functionality in the IridiumSBD library. A further restriction was found during practical experimentation: 120-byte messages were failing to send despite being successfully sent from Arduino to the RockBlock. The maximum size the RockBlock succeeded in sending and receiving was 60 bytes. One cause may be due to our low-power focused setup. Further investigation may yield a solution.

For our experiments, the 150-byte file separated into three Iridium messages. Once a high signal quality connection was established, sending and receiving the 150-byte file took approximately two minutes. During the experiment, however, the average time from send to receive fluctuated depending on the sky views and the weather conditions. Therefore, the average time ranged from four to nine minutes.

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VII. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

This thesis has examined the need to develop an alternative space-based network solution for the denial of space access situation, which may result from the space environment or adversary threats. In particular, the research focused on the communication aspect of a space-based network, suggesting that Femto satellites could offer a potential solution to provide a low data throughput. Using STK/QualNet software, the thesis investigated the feasibility of having a space-based network built as MANET using the first-generation NPSFSs. The modeling required an increase of power to the first-generation NPSFS's actual power by nine factors for the network to function. Such a significant increase in power was required because the STK/QualNet cannot model the method that is used in KickSat to overcome the power limitation. This confirmed the power dilemma that is associated with Femto satellites. Thus, all scenarios ran at the minimum power needed. The average receiving data throughput was 250 bit/s.

Additionally, this thesis investigated the capability of the next-generation NPSFS to send a text file from one terminal to another. An experiment was conducted using Python and the Arduino 101, which were programmed to control a RockBlock MK2 to accomplish this task. The result showed that a 150-byte text file could be sent as three 50-byte-size segments. These segments were eventually consolidated at the final terminal in a period of four to nine minutes, depending heavily on the sky view and weather conditions.

B. RECOMMENDATIONS

For modeling the first-generation NPSFS, a further study may investigate different network topologies that may consume lower power. Another suggestion is to select a programming mode in STK/QualNet if the model includes many nodes and interfaces. Selecting a programming mode versus a graphic user interface (GUI) mode would dramatically reduce the time consumed when the user wants to redesign the constellation or change parameters for many nodes. For example, rather than changing the power for each node, which takes about an hour to go through every interface in the GUI mode, changing one command in programming mode would reduce this work to about a minute.

For the next-generation NPSFS, a further study can improve the RockBlock library to include more AT commands for allowing more than a 50-byte Iridium message. Additionally, a further study can improve the connection link between a computer and the Arduino by employing a wireless connection. This could be accomplished through the use of a small embedded radio with an Arduino library, such as an Xbee radio.

APPENDIX. THE EXPERIMENT CODES

All codes are freely available from the following link:

https://github.com/FaisalAlshaya/NPSFS.git

They also can be found by contacting:

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(415) 470-1008, Android Google

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