Hybrid Wireless Mesh Network, Worldwide Satellite Communication, and PKI Technology for Small Satellite Network System

A project present to
The Faculty of the Department of Aerospace Engineering
San Jose State University

in partial fulfillment of the requirements for the degree
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By

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An Abstract of

Hybrid Wireless Mesh Network, Worldwide Satellite Communication, and PKI Technology for Small Satellite Network System

by

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May 2015

Small satellites are getting the spotlight in the aerospace industry because this earth-orbiting technology is well-suited for use in military service, space mission research, weather prediction, wireless communication, scientific observation, and education demonstration. Small satellites have advantages of low cost of manufacturing, ease of mass production, low cost of launch system, ability to be launched in groups, and minimal financial failure. Until now, a number of the small satellites have been built and launched for various purposes. As network simplification, operation efficiency, communication accessibility, and high-end data security are the fundamental communication factors for small satellite operations, a standardized space network communication with strong data protection has become a significant technology. This is also highly beneficial for mass manufacture, compatible for cross-platform, and common error detection. And the ground-based network technologies which fulfill Internet-of-Things (IOT) concept, which consist of Wireless Mesh Network (WMN) and data security, are presented in this paper.

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I would like to express my special gratitude to my committee members, Professor Mourtos, Professor Papadopoulos, and Professor Murbach. You all have been tremendous mentors for me. I really appreciate for encouraging my project and providing me aerospace knowledge. I would also like to thank my old collegue, Greenfield Trinh and MRMSS team. Greenfield introduced me to MPACE and Modular Rapidly Manufactured Small Satellite (MRMSS), and has worked together for many projects. And Kenneth Cheung, the project manager for MRMSS and Daniel Cellucci, have been there to support me with great advices and necessary equipment.

Special thanks to my family and friends. Words cannot express how grateful I am to my father, mother, sister, brother-in law, nephew, niece, my wife's brother, father-in-law, mother-in-law for all the prayer whom you've made on my behalf. I would also like to thank all of my best friends who supported me with prayers. There is one more person. I would like express appreciation to my beloved wife, Elizabeth Shin, who is always my support in every moment and every event.

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List of Abbreviations

BER	=	Bit Error Rate
COMM	=	Communication
ECC	=	Elliptic Curve cryptography
EIRP	=	Equivalent Isotropic Radiated Power
FSL	=	Free Space Loss
IOT	=	Internet Of things
LEO	=	Low Earth Orbit
MPACE	=	Multi-Purpose Avionics Core Element
MRMSS	=	Modular Rapidly Manufactured Small Satellite
NASA	=	National Aeronautics and Space Administration
NIST	=	US National Institute for Standards and Technology
NOAA	=	National Oceanic and Atmospheric Administration
PKI	=	Public Key Infrastructure
P-POD	=	Pico-Satellite Orbital Deployer
RFI	=	Radio Frequency Interference
SDU	=	Satellite Data Units
SHA	=	Shivest Hash Algorithm
WAP	=	Wireless Access Points
WEP	=	Wired Equivalent Privacy
WMN	=	Wireless Mesh Network

List of Symbols

m	=mass (kg)
	= half power beam width
	= wavelength
	= frequency
c	=speed of light
	= antenna diameter
	= antenna taper factor
*, ´,	= antenna efficiency factors
	= antenna beam solid angle
d	=slant range
S	=footprint area
A	=antenna area
C	=carrier power
$_0$	= noise density
	= information bit rate
	= energy per information bit
EIRP	= equivalent isotropic radiated power
	= transmit antenna gain
	= receive antenna gain
	= input power
	= free space loss
	= net attenuative loss

T =system noise temperature

= Boltzmann’s constant

I. Introduction

Since the first satellite, the Sputnik 1, was launched in 1957, about 6,600 satellites have been launched for diverse purposes through different organizations: military service, space mission research, weather, communications, navigation, education, etc (Davis, 2011). The demand of small satellite usage will be accelerated each year as related technology is developed. Simplification, efficiency, accessibility, and security are the main fundamental factors for manufacturing small satellites. And a standardized network system, which satisfies the factors, is highly beneficial for mass production, cross-platform compatibility, and low risk error system failure.

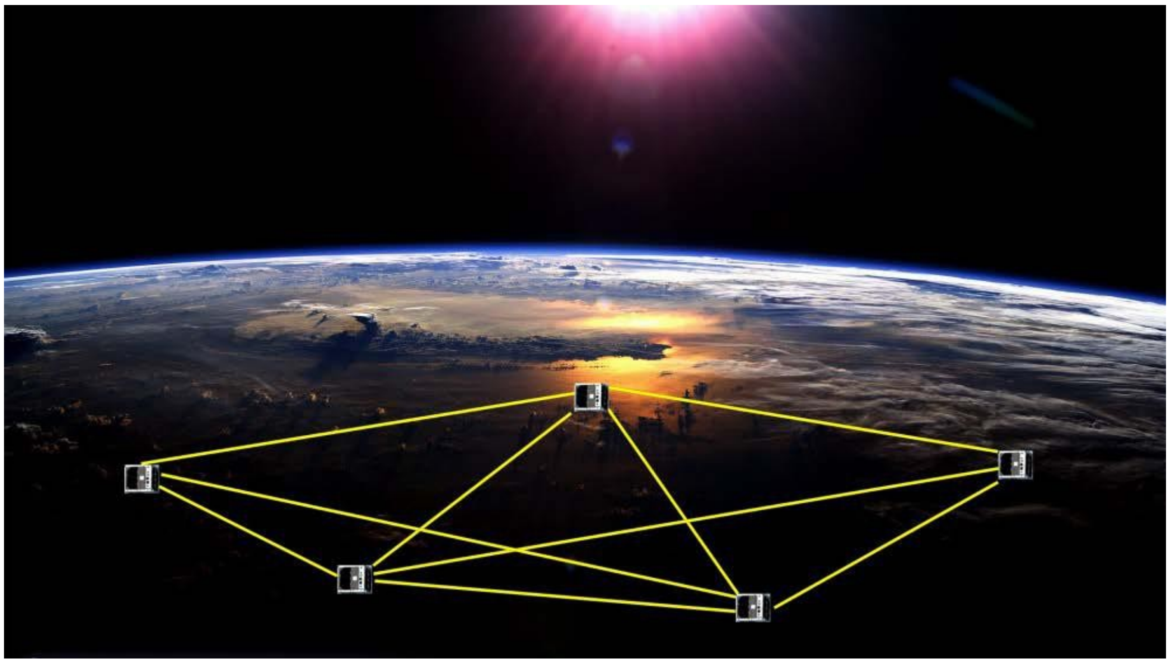


Figure 1. Artist rendition of the Wireless Mesh Network

A. Motivation

During my NASA volunteer projects, Multi-Purpose Avionics Core Element (M-PACE) and Modular Rapidly Manufactured Small Satellite (MRMSS), I was able to see many successful small satellite projects. However, we still have technical deficiencies for an advanced network communication, for instance, data transmission speed, avionic space usage, cross-over operations among components, data security, etc. Today, there are a number of ground-based technologies in network and security fields that can provide a great solution for the deficiencies. And such technology will contribute to the development of space mission projects in near future.

B. Objectives

The objectives of this project are as follows:

1. To research for ground-based wireless network architecture

2. To implement hybrid WMN with XBee series devices on cube satellite prototypes

   - Cooperated with the Modular Rapidly Manufactured Small Satellite (MRMSS) team, which implemented wireless communication with XBee Series 1

3. To deploy Public-key Infrastructure (PKI) for securing the satellite date

II. Literature Review

A. Brief summary of small satellites

Miniaturized satellite industry has been growing rapidly in recent years. Research by Cockrell (2012) states that miniaturized satellites are usually deployed in low earth orbits (LEO) and are grouped on launch and placed in elliptical orbits. This is called “swarms.” And small satellites can be classified according to mass. Microsatellite (or Microsat) masses are between 10 kg and 500 kg, a weight range of 22 pounds (lb) to 1100 lb. Nanosatellite (or Nanosat) masses are between 1 kg and 10 kg (2.2 lb and 22 lb). Picosatellite (or Picosat) masses are less than 1 kg (2.2 lb).

Advantages of Miniaturized satellites:

- Lower cost of manufacture
- Ease of mass production
- Lower cost of launch
- Ability to be launched in groups or "piggyback" along with larger satellites
- Minimal financial loss in case of failure

Disadvantages of Miniaturized satellites compared to larger size satellites:

- Generally shorter working life
- Reduced hardware-carrying capacity
- Lower transmitter output power capability

B. Communication architecture

Communication architecture is a network of satellites and ground points on earth that are interconnected by communication links. Communication links enable to carry tracking, telemetry, and command or mission data among satellites. Larson (2005) explains that the world's first artificial communication satellite, which is capable of relaying signals to points on earth, was

‘Echo-1’. It was a metallic balloon and inflatable satellite. In 1958, project SCORE used the first tape recorder to store and forward voice message to ground station (Larson, 2005).

Table 1 shows the advantages and disadvantages for each communication architecture type to provide relevant information for satellite mission projects.

Table 1

Comparison of Five Example Communications Architecture

Architecture	**Advantage**	**Dis-advantage**
A. Low altitude Store and Forward	-Low cost launch -Low cost satellite -Polar coverage with inclined orbit	-Long message access time and transmission delay
B. Geostationary Orbit	-No switching between satellites -Ground station antenna tracking not -required	-High cost launch -High cost satellite -Propagation delay -No coverage of polar region
C. Molniya Orbit	-Provides coverage of polar region -Low cost launch	-Requires several satellites for continuous coverage -Require ground station antenna -Complex network control
D. Geostationary Orbit w/ Crosslink	-Communication over greater distance w/o intermediate	-Higher satellite complexity and cost

	ground station relay -Reduced propagation delay -No ground stations in foreign territory	-No coverage of polar region -High launch cost
E. Low altitude Multiple Sat w/ crosslink	-Highly survivable – multiple paths -Reduce jamming susceptibility due to limited Earth view area -Low cost launch -Polar coverage with inclined orbit	-Complex link acquisition -Complex dynamic network -Multiple satellites required to cover full region

Note. Adapted from *Space Mission Analysis and Design*, p. 537, by Larson W., 2005, El Segundo: Microcosm Press.

C. Wireless Mesh Network

1. Wireless network topologies

Wireless network has much less cabling which lead to a neater internal network environment. It has flexibility on space usage inside of devices than wired and plug-in connectivity. Therefore, it has an advantage on unit expansion and multi-processing. XBee series 2 uses the IEEE 802.15.4 networking protocol for fast point-to-multipoint or peer-to-peer networking and performs to transmit data from one to another processing unit (Ahmed, 2012). Furthermore, XBee series 2 supports MESH topology, which has redundancy factor and avoids high traffic (Ahmed, 2012). In the network, all participating computers potentially communicate with each other directly. Akyildiz and Wang's (2004) research paper states that Wireless has only two topologies: infrastructure and ad hoc. This is a direct and natural result of the non-physical nature of interaction of computers in a wireless network.

1.1 Infrastructure Network Topology

Infrastructure wireless network topology is a hub and spoke topology, also known as a point to multipoint or one to many topologies. In the infrastructure topology, there is a single central wireless access point (WAP). It acts as the hub in the network, with all the other computers (or spokes) connecting to it (Akyildiz & Wang, 2004).

1.2 Ad Hoc Network Topology

Ad hoc wireless network topology is multipoint to multipoint topology. There is no central access point in an ad-hoc network structure; every computer on the network communicates directly with every other on the network. So, ad hoc wireless network topologies are essentially mesh networks (Akyildiz & Wang, 2004).

1.3 Advantages and Disadvantages of Wireless Network Topologies

This ad-hoc topology has an advantage of not requiring a central access point or WAP. However, this also means only a few security modes and much lower network speeds are available on such topology. And Akyildiz and Wang (2004) states wired equivalent privacy (WEP) and a maximum speed of 11 megabits per second are implemented on ad-hoc networks. On the other hand, Infrastructure topology has an advantage of higher speeds and stronger security to such network, but it requires the extra equipment of a central WAP.

Wireless networks fall into only two types of network topologies: infrastructure and ad hoc. Each of these typologies has its own advantages and disadvantages and is suitable for different usage situations. The infrastructure topology is typically used for permanent networks, while the ad-hoc topology is used for temporary networks (Akyildiz & Wang, 2004).

2. Wireless Mesh Network (WMN)

Wireless mesh network (WMN) is a network created through the connection of wireless access points installed at each network user's locale. Each network user is also a provider, forwarding data to the next node. This networking infrastructure is decentralized and simplified because each node only needs to transmit as far as the next node (Akyildiz & Wang, 2004).

2.1 Infrastructure Mesh Architecture

In infrastructure mesh architecture, mesh routers collectively provide a wireless backbone infrastructure. Client nodes are passive in mesh infrastructure. Via Ethernet links, conventional clients with Ethernet interfaces can be connected to mesh routers (Akyildiz & Wang, 2004).

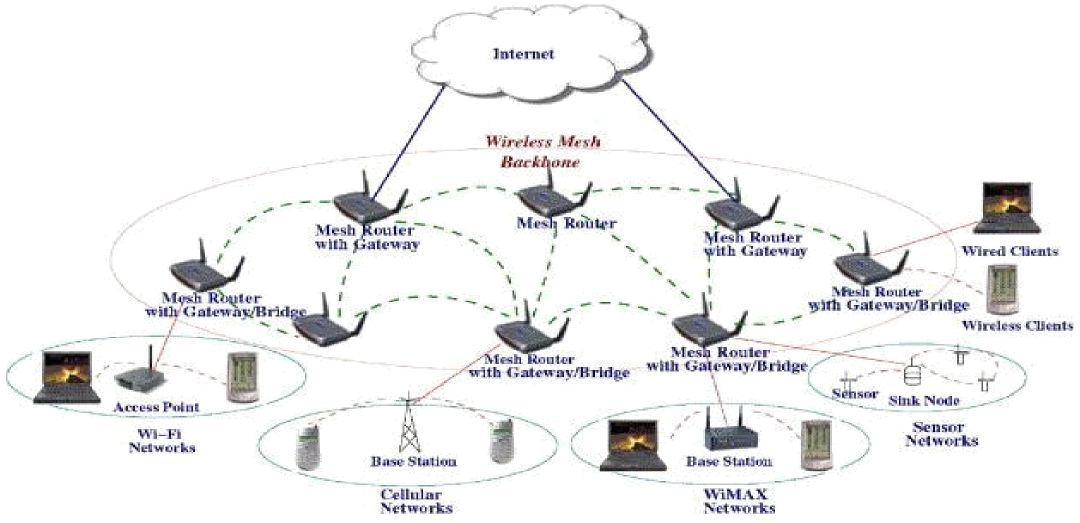


Figure 2. An example of Infrastructure Mesh Architecture. Adapted from *Wireless mesh networks: a survey* (p. 448), by I. Akyildiz, X. Wang, 2004, Bridgewater, NJ: Elsevier B.V. Copyright 2004 by Elsevier B.V.

2.2 Client Mesh Architecture

The client mesh architecture provides peer-to-peer networks among client devices. Here, no such mesh router is required. Clients will act like mesh routers by relaying the packets (Akyildiz & Wang, 2004).

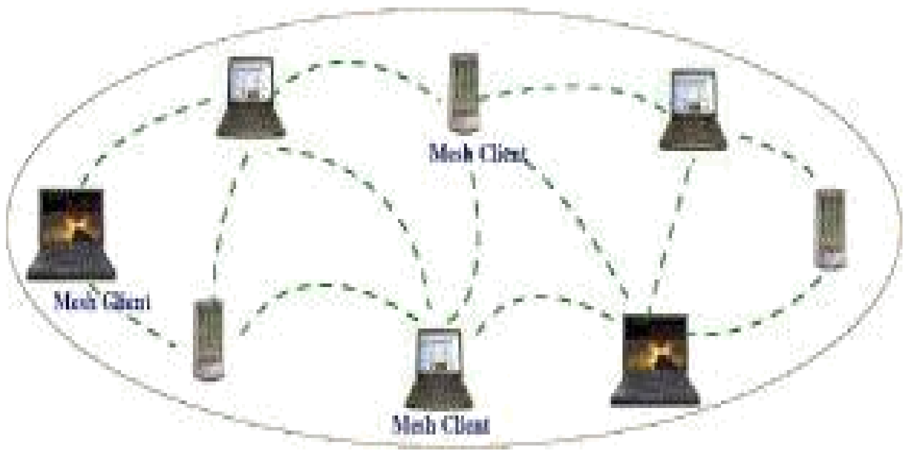


Figure 3. An example of Client Mesh Architecture. Adapted from *Wireless mesh networks: a survey* (p. 448), by I. Akyildiz, X. Wang, 2004, Bridgewater, NJ: Elsevier B.V. Copyright 2004 by Elsevier B.V.

2.3 Hybrid Mesh Architecture

In the hybrid mesh architecture, mesh routers provide the backbone of this network type. With the help of network municipalities such as routing and forwarding of data packets, clients can actively participate in the creation of the mesh (Akyildiz & Wang, 2004).

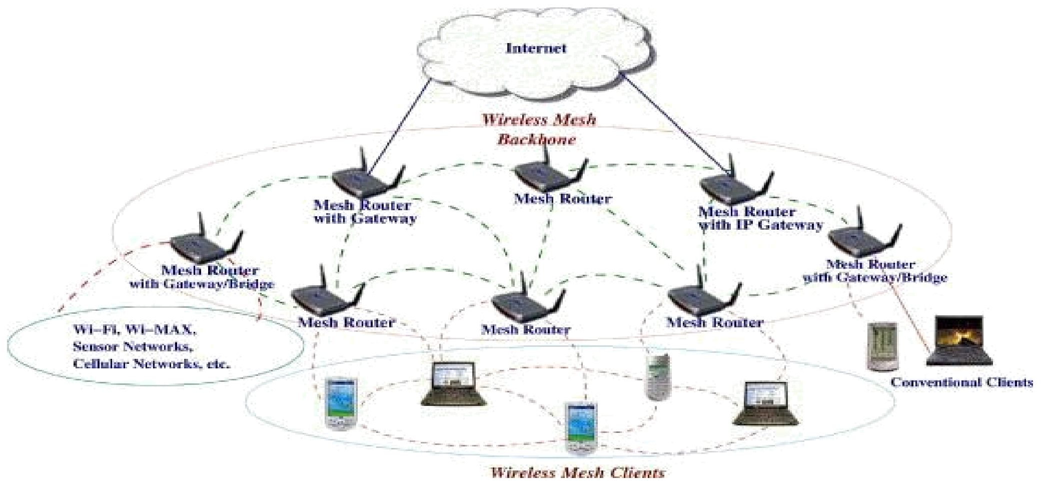

Internet
Wireless Mesh Backbone
Mesh Router with Gateway
Mesh Router
Mesh Router with IP Gateway
Mesh Router with Gateway/Bridge
Mesh Router with Gateway/Bridge
Mesh Router
Mesh Router
Mesh Router
Wi-Fi, Wi-MAX, Sensor Networks, Cellular Networks, etc.
Conventional Clients
Wireless Mesh Clients

Figure 4. An example of Hybrid Mesh Architecture. Adapted from *Wireless mesh networks: a survey* (p. 449), by I. Akyildiz, X. Wang, 2004, Bridgewater, NJ: Elsevier B.V. Copyright 2004 by Elsevier B.V.

D. XBee Radio Module

XBee is low-cost, low-power, and WMN capable radio module brand. Inexpensive cost for the units allows the technology to be widely deployed in wireless control and monitoring applications; low power-usage allows longer life with smaller batteries, and the mesh networking provides high reliability and larger range. The XBee radios can all be used with the minimum number of connections – power (3.3 V), ground, data in and data out, with other recommended lines being Reset and Sleep (Ahmed, 2012). Additionally, most XBee families have some other flow control, I/O, A/D and indicator line built in (Ahmed, 2012).

The XBee radio family consists of 16 different types according as range, power consumption, topologies, frequencies, etc. The two most common RF radios that are available from Digi are XBee Series 1 and Series 2. These two modules are a quite similar, but selection of a module should be based upon application-specific needs. (See Table 2 for detail information)

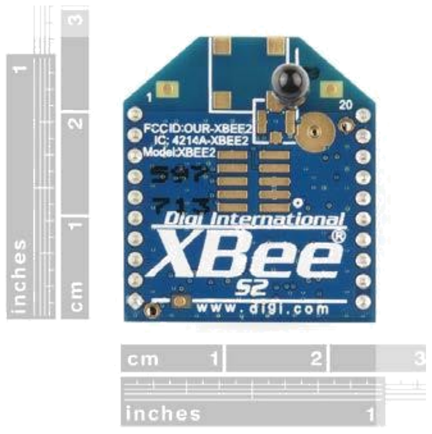


Figure 5. An example of XBee Series 2 image. Adapted from XBee 2mW wire antenna, In *Sparkfun*, n.d., Retrieved April 15, 2015, from https://www.sparkfun.com/products/10414.

1. Series 1 vs Series 2

Digi manufactured two most common RF radios, Series 1 and Series 2. The Series 1 and Series 2 modules are similar, but they are used based upon application-specific needs. They are not interoperable and have different application profile, which are unique to each radio group. Ahmed (2012) explains XBee Series 1 comes with 802.15.4 firmware while XBee Series 2 offers the ZigBee mesh firmware. And ZigBee XBee provides low-power scenarios with mesh network communication.

Table 2

XBee Series 1 & 2 Comparison

	XBee Series 1	XBee Series 2
Indoor range	up to 100 ft. (30m)	up to 133 ft. (40m)
Outdoor range	up to 300 ft. (100m)	up to 400 ft. (120m)
Transmit Power Output	1 mW (0dbm)	2 mW (+3dbm)
RF Data Rate	250 Kbps	250 Kbps

Receiver Sensitivity	-92dbm (1% PER)	-98dbm (1% PER)
Supply Voltage	2.8 - 3.4 V	2.8 - 3.6 V
Transmit Current (typical)	45 mA (@ 3.3 V)	40 mA (@ 3.3 V)
Idle/Receive Current (typical)	50 mA (@ 3.3 V)	40 mA (@ 3.3 V)
Power-down Current	10 uA	1 uA
Frequency	ISM 2.4 GHz	ISM 2.4 GHz
Dimensions	0.0960" x 1.087"	0.0960" x 1.087"
Operating Temperature	-40 to 85 C	-40 to 85 C
Antenna Options	PCB, Integrated Whip, U.FL, RPSMA	PCB, Integrated Whip, U.FL, RPSMA
Network Topologies	Point to point, Star, Mesh (with DigiMesh firmware)	Point to point, Star, Mesh
Number of Channels	16 Direct Sequence	16 Direct Sequence
Filtration Options	PAN ID, Channel & Source/Destination	PAN ID, Channel & Source/Destination

Note. Adapted from *Wireless Network System Based Multi-Non-Invasive Sensors for Smart Home*, p. 53, by Ahmed, R., 2012.

2. Radio Frequency Interference

Radio frequency interference (RFI) is radiation or conduction of radio frequency energy. It is emitted from sources of RFI, and it directly affects to performance of other devices into local network environment. Most electrical devices can produce RFI. And the common sources of RFI include several components, such as, power supplies, motors, work processors, computing devices, etc. XBee also produces RFI and influences to other internal components into satellites, so understanding of XBee RFI rate is critical factor for wireless communication inside of satellites. ComSitePro, which is the only tool on the market to help identify, analyze, locate and resolve RFI, will be used in this project to measure RFI rate of XBee modules. It is capable to calculate accurate values of RFI rate by analyzing transmitter noise, receiver desensitization, transmitter and receiver produced intermodulation products, harmonics, and spurious output ("ComSite Pro Wireless", 2014).

E. Internet of Things (IoT)

The Internet of Things (IoT) is a network of physical objects connected over the internet. When objects can detect or measure current conditions through sensors and communicate to each other, then they are able to identify themselves to other devices.

In IoT, a thing can be a person with a heart monitor implant, a farm animal with a biochip transponder, an automobile that has built-in sensors to alert the driver when tire pressure is low (Kevin, 2009). Any other natural or human-made object that has an assigned IP address and an ability to transfer data over a network is a thing. So far, the Internet of Things has been most closely associated with machine-to-machine (M2M) communication in manufactures and powers by oil and gas utilities. Products with M2M communication capabilities are often referred to as being smart (Kevin, 2009).

G. Satellite Constellation

1. LEO Satellite Constellation Services

LEO satellite constellation is a group of satellites in Low-Earth Orbit, cooperating together to provide multiple communication services to the ground. There are three major satellite communications in the low-earth low (LEO): Globalstar, Iridium and the IsatPhone. All three have different communication network environments, and each has advantages and disadvantages.

1.1 Iridium

Alan G. (2012) described that iridium satellite service is the only satellite phone provider which provides worldwide coverage, including all the oceans and Polar Regions. The Iridium satellite constellation is made of 66 Low Earth Orbiting (LEO) satellites that include the polar orbit. This has polar orbits at an altitude of 485 miles and orbits from pole-to-pole gathering close together as they approach the Polar Regions.

1.2 IsatPhone

Alan G. (2012) described that IsatPhone satellite provides worldwide coverage excluding only the Polar Regions. The IsatPhone uses Inmarsat's three I4 satellites covering a majority of the earth. Some areas, including Northern Alaska, Greenland, and Northern Russian, may have limited access or no coverage. It would be these areas where the Iridium phone would give the only coverage available with a satellite phone. They are in a geostationary orbit 37,786 km (22,240 miles) above the Earth and beam their signals down to earth like numerous super flashlights.

1.3 Globalstar

Alan G. (2012) described that Globalstar satellite service provides global regional coverage in over 100 countries throughout the world. The Globalstar satellite constellation is made of 32 Low Earth Orbiting (LEO) satellites which are 876 miles from the earth. Globalstar uses "bent-pipe" technology that transmits telecommunications from one location on Earth to a satellite location, and then again down to another location on Earth. A call comes from a Globalstar phone is routed via CDMA technology to a satellite dish or ground station, and then the call is routed locally through the terrestrial telecommunications system.

G. Data Security and Encryption Algorithms

In these years, network security has become a significant topic. According to “The case of Elliptic” (2009), network security can provide many business benefits: Data's protection from business disruption, qualifying regulatory compliance, reducing the risk of legal action from theft, and business reputation. There are several techniques to protect the shared data which focus on cryptography to secure the data while transmitting on the network protocols.

1. Data vulnerability issue

As satellite technology has improved in worldwide states, the issue of communication security is a top priority. In conventional satellite communication up and downlinks, a satellite implements an antenna to receive and transmit commands and data. A concern involved throughout this transaction process is a misuse of the communication and intercepting information.

In October 2014, Ruben Santamarta who is a principal security consultant at IOActive Security Services, spoke about satellite communication systems vulnerability issue during the Black Hat USA conference. Santamarta published a paper that states security vulnerabilities issues on the systems made by Cobham and Iridium, and he even shows how they can get an access satellite data units (Matt, 2014).

And satellite network vulnerability issue actually occurred last year in the U.S.A. The

National Oceanic and Atmospheric Administration (NOAA)'s Satellite Data and Information service network was hacked in September, 2014. It caused a disruption in satellite feeds and several pivotal websites. To block the attacker, government was forced to shut down some of its services, and it explains why satellite data was cut off in October 2014 (Thurber, 2014; Werner, 2012).

2. Available Key Encryption Algorithms

For over 20 years, the first generation of public key cryptographic algorithms, AES, DES, and RSA, has secured internet communication. Here, these algorithms are presented and compared based on the diverse factors ("The Case for Elliptic," n.d.).

Table 3

AES, DES and RSA comparison

Factors	AES	DES	RSA
Developed	**2000**	**1977**	**1978**
Key Size	**128,192,or 256 bits**	**56 bits**	**1024 or 2048 bits**
Block Size	**128 bits**	**64 bits**	**Min. 512 bits**
Ciphering & deciphering key	**Same**	**Same**	**Different**
Algorithm	**Symmetric**	**Symmetric**	**Asymmetric**
Encryption	**Faster**	**Moderate**	**Slower**
Decryption	**Faster**	**Moderate**	**Slower**
Power Consumption	**Low**	**Moderate**	**High**
Key Used	**Same key for**	**Same key for**	**Different key for**

	Encrypt and Decrypt	Encrypt and Decrypt	Encrypt and Decrypt

Note. Adapted from *The Case for Elliptic Curve Cryptography, byace Mission Analysis and Design*, 2009, Retrieved from https://www.nsa.gov/business/programs/elliptic_curve.shtml

The majority of public key systems in use today apply 1024-bit parameters for RSA, but the US National Institute for Standards and Technology (NIST) has recommended that 1024-bit systems are only sufficient until 2010. The first option to follow the recommendation is simply to increase the public key size, and the other option is to move away from the first generation key algorithm to the elliptical curve cryptography ("The Case for Elliptic," n.d.).

ECC is a public key encryption technique based on elliptic curve theory. The main advantage of ECC in comparison with non-ECC cryptography is that the same level of security provided by keys of smaller size. Table 5 is the list of NIST recommended key sizes for symmetric, RSA, ECC cryptographies. ECC provides greater security, more efficient performance, and better US government support than the first generation public key algorithms now in use ("The Case for Elliptic," n.d.).

Table 4

ECC and RSA comparison

Advantage of ECC:	**Advantage of RSA:**
Smaller keys, ciphertexts and signatures	Very fast, very simple encryption and verification
Very fast key generation	Easier to implement than ECC
Fast signatures	Easier to understand

Moderately fast encryption and descryption	Widely deployed, better industry support
Better US government support	
Binary curve are really fast in hardware	

Note. Adapted from *The Case for Elliptic Curve Cryptography, byace Mission Analysis and Design*, 2009, Retrieved from https://www.nsa.gov/business/programs/elliptic_curve.shtml

Table 5

NIST Recommended Key Sizes

Symmetric (DES, AES) Key Size (bits)	RSA Key Size (bits)	Elliptic Curve Key Size (bits)
80	1024	160
112	2048	224
128	3072	256
192	7680	384
256	15360	521

Note. Adapted from *The Case for Elliptic Curve Cryptography, byace Mission Analysis and Design*, 2009, Retrieved from https://www.nsa.gov/business/programs/elliptic_curve.shtml

IV. Technology Development

A. Communication Architecture

Data from small satellite are transmitted through two levels of WMNs and a satellite communication service to the ground station. XBee Series 2 is used for internal (level-1 WMN) small satellite communication. And for external (level-2 WMN) communication, XTend 900 is used among satellites. An iridium module should be implemented on a coordinate satellite and transmit data to ground based users through Iridium communication service. This communication concept of operation is drawn in Figure 6.

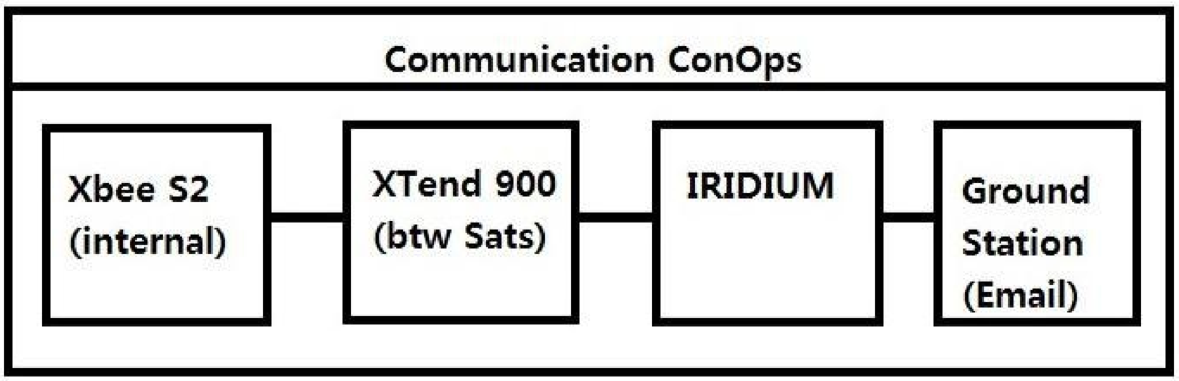


Figure 6. Communicaiton ConOps

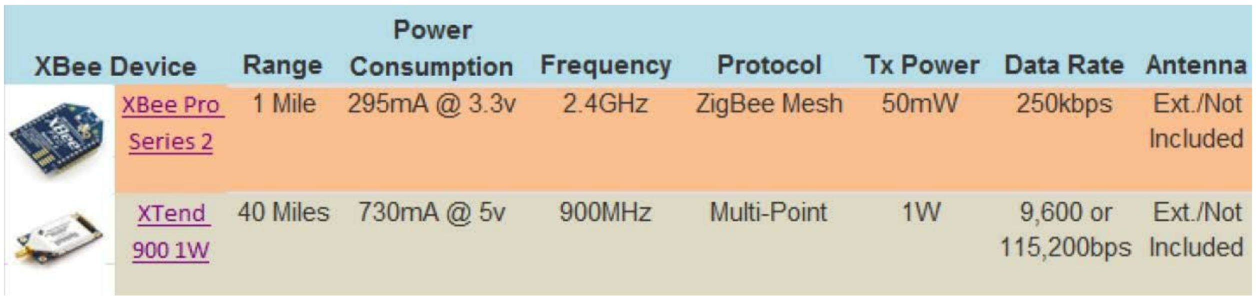
B. Hybrid WMN with XBee devices

1. Overview

For setting up hybrid WMN environment, I decided to use two different type of XBee devices, respect to communication range, power consumption, and supported protocol type: XBee Pro Series 2 and Xtend 900 1w. XBee Pro Series 2 has 1 mile maximum range with 295 mA at 3.3 volts power consumption, and this is used for level-1 network communication in this project. XTend 900 1W has maximum 40 miles range with 730 mA at 5 volts power consumption. This device has the longest range on XBee series and is adequate for communicating among small satellites in LEO (Ahmed, 2012).

Table 6

XBee Series Candidates



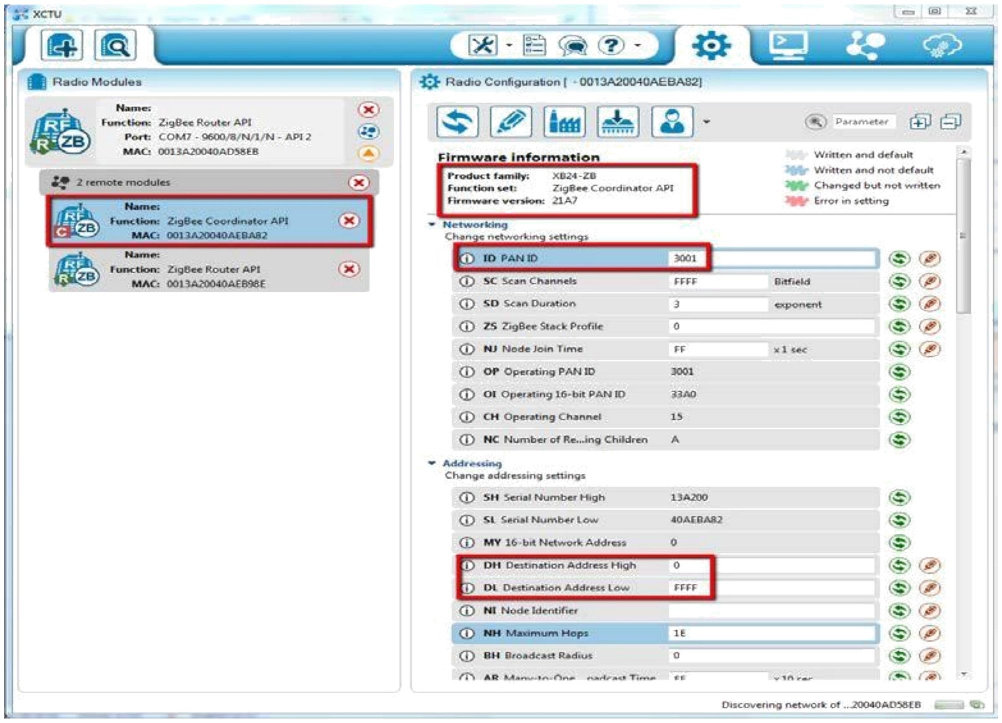
XBee Device		Range	Power Consumption	Frequency	Protocol	Tx Power	Data Rate	Antenna
	XBee Pro Series 2	1 Mile	295mA @ 3.3v	2.4GHz	ZigBee Mesh	50mW	250kbps	Ext./Not Included
	XTend 900 1W	40 Miles	730mA @ 5v	900MHz	Multi-Point	1W	9,600 or 115,200bps	Ext./Not Included

Note. Adapted from *Wireless Network System Based Multi-Non-Invasive Sensors for Smart Home*, p. 53, by Ahmed, R., 2012.

2. XBee Series 2 for level-1 communication

2.1 XBee coordinator and router settings

ZigBee Mesh protocol for XBee modules requires at least one coordinator to manage routers or end-devices communication. X-CTU is an application to interact among Digi RF modules on a user interface, and it is used to program each XBee module with its firmware. See Appendix D and E for procedures of setting up XBee coordinator and router on X-CTU.


XCTU

Radio Modules

Name:
Function: ZigBee Router API
Port: COM7 - 9600/8/N/1/N - API 2
MAC: 0013A20040AD58EB

2 remote modules

Name:
Function: ZigBee Coordinator API
MAC: 0013A20040AEBA82

Name:
Function: ZigBee Router API
MAC: 0013A20040AEB98E

Radio Configuration [- 0013A20040AEBA82]

Firmware information

Product family: XB24-ZB
Function set: ZigBee Coordinator API
Firmware version: 21A7

Written and default
Written and not default
Changed but not written
Error in setting

Networking
Change networking settings

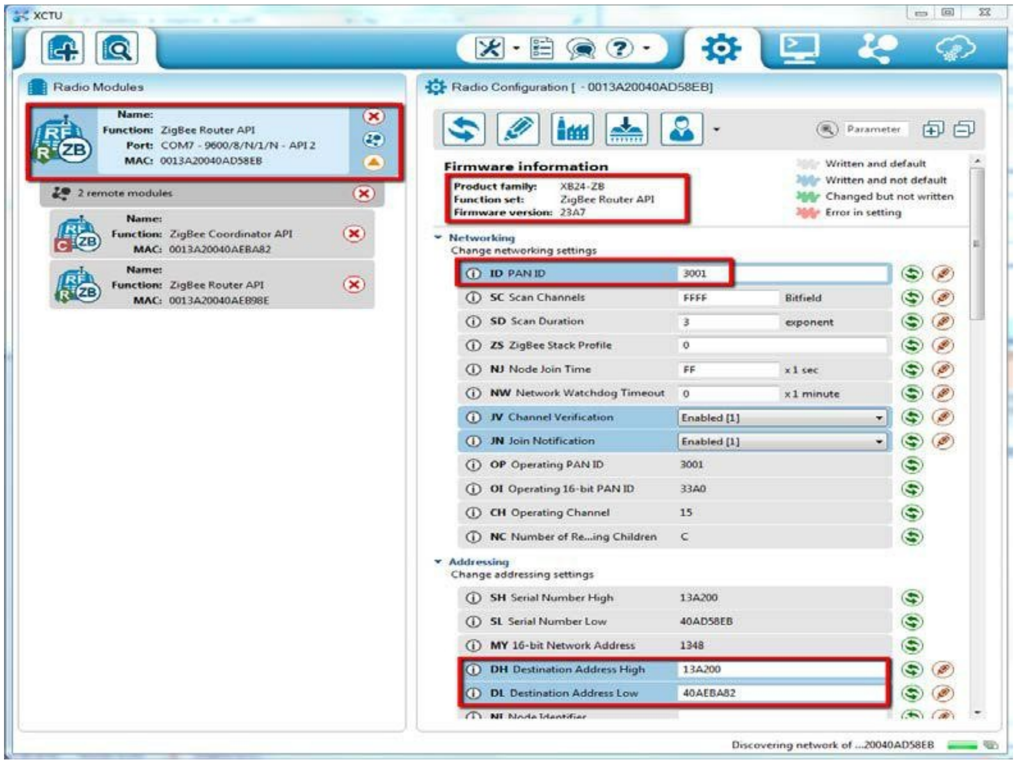
```
ID PAN ID                          3001
SC Scan Channels                   FFFF    Bitfield
SD Scan Duration                   3       exponent
ZS ZigBee Stack Profile            0
NJ Node Join Time                  FF      x 1 sec
OP Operating PAN ID                3001
OI Operating 16-bit PAN ID         33A0
CH Operating Channel               15
NC Number of Re...ing Children     A
```

Addressing
Change addressing settings

```
SH Serial Number High              13A200
SL Serial Number Low               40AEBA82
MY 16-bit Network Address          0
DH Destination Address High        0
DL Destination Address Low         FFFF
NI Node Identifier
NH Maximum Hops                    1E
BH Broadcast Radius                0
```

Discovering network of ...20040AD58EB

Figure 7. XBee Series 2 coordinator set up


XCTU

Radio Modules

Name:
Function: ZigBee Router API
Port: COM7 - 9600/8/N/1/N - API 2
MAC: 0013A20040AD58EB

2 remote modules

Name:
Function: ZigBee Coordinator API
MAC: 0013A20040AEBA82

Name:
Function: ZigBee Router API
MAC: 0013A20040AEB98E

Radio Configuration [- 0013A20040AD58EB]

Firmware information

Product family: XB24-ZB
Function set: ZigBee Router API
Firmware version: 23A7

Written and default
Written and not default
Changed but not written
Error in setting

Networking
Change networking settings

```
ID PAN ID                          3001
SC Scan Channels                   FFFF         Bitfield
SD Scan Duration                   3            exponent
ZS ZigBee Stack Profile            0
NJ Node Join Time                  FF           x 1 sec
NW Network Watchdog Timeout        0            x 1 minute
JV Channel Verification            Enabled [1]
JN Join Notification               Enabled [1]
OP Operating PAN ID                3001
OI Operating 16-bit PAN ID         33A0
CH Operating Channel               15
NC Number of Re...ing Children     C
```

Addressing
Change addressing settings

```
SH Serial Number High              13A200
SL Serial Number Low               40AD58EB
MY 16-bit Network Address          1348
DH Destination Address High        13A200
DL Destination Address Low         40AEBA82
```

Discovering network of ...20040AD58EB

Figure 8. XBee Series 2 routers set up

A coordinator is connected to two routers to accomplished mesh network through XCTU software. Fig. 9 and 10 represent a successful connection with three XBee devices, and data packages are transmitted from router devices to the coordinator device in API mode.

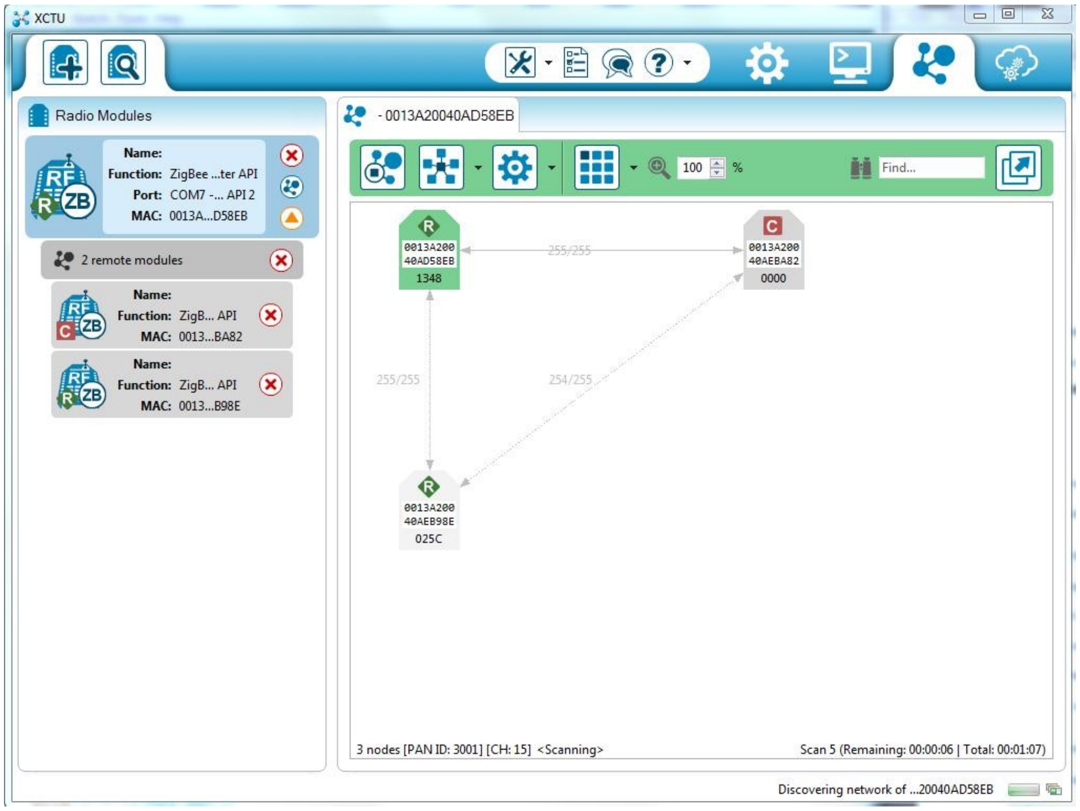
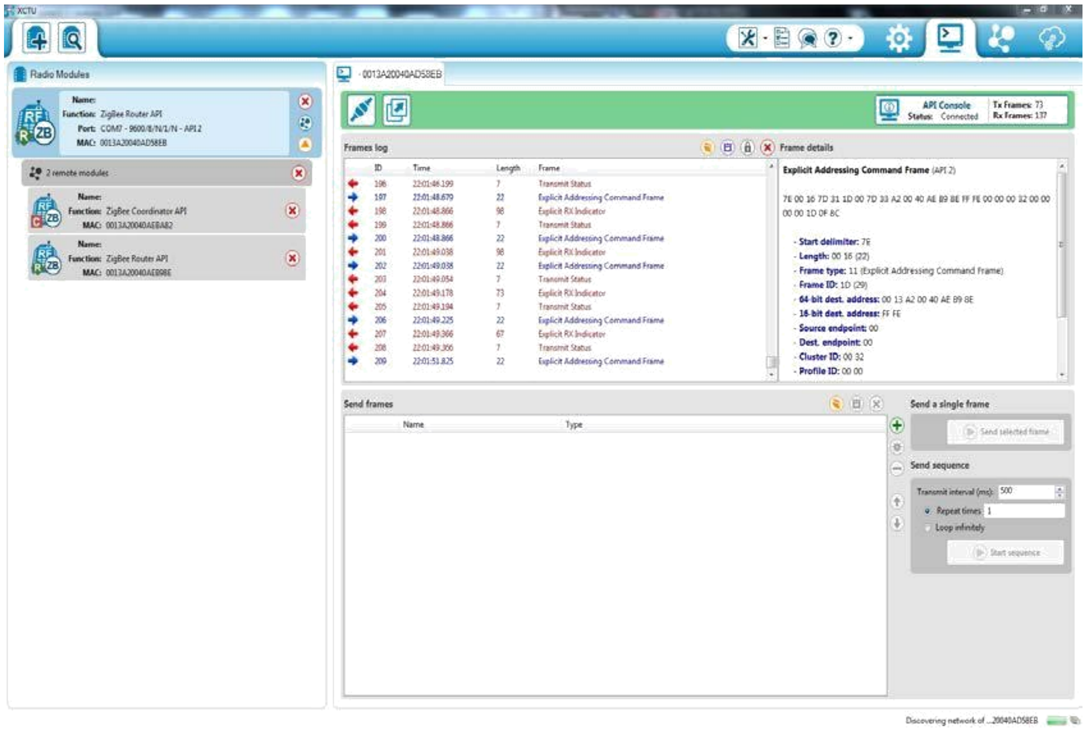


Figure 9. XCTU Mesh Network successful connection with three XBee Series 2



Radio Modules

Name:
Function: ZigBee Router API
Port: COM7 - 9600/8/N/1/N - API2
MAC: 0013A20040AD58EB

2 remote modules

Name:
Function: ZigBee Coordinator API
MAC: 0013A20040AEBA82

Name:
Function: ZigBee Router API
MAC: 0013A20040AEB98E

0013A20040AD58EB

API Console
Status: Connected
Tx Frames: 73
Rx Frames: 137

Frames log

	ID	Time	Length	Frame
⬅	196	22:01:46.199	7	Transmit Status
➡	197	22:01:48.679	22	Explicit Addressing Command Frame
⬅	198	22:01:48.866	98	Explicit RX Indicator
⬅	199	22:01:48.866	7	Transmit Status
➡	200	22:01:48.866	22	Explicit Addressing Command Frame
⬅	201	22:01:49.038	98	Explicit RX Indicator
➡	202	22:01:49.038	22	Explicit Addressing Command Frame
⬅	203	22:01:49.054	7	Transmit Status
⬅	204	22:01:49.178	73	Explicit RX Indicator
⬅	205	22:01:49.194	7	Transmit Status
➡	206	22:01:49.225	22	Explicit Addressing Command Frame
⬅	207	22:01:49.366	67	Explicit RX Indicator
⬅	208	22:01:49.366	7	Transmit Status
➡	209	22:01:51.825	22	Explicit Addressing Command Frame

Frame details

Explicit Addressing Command Frame (API 2)

```
7E 00 16 7D 31 1D 00 7D 33 A2 00 40 AE B9 8E FF FE 00 00 00 32 00 00
00 00 1D 0F 8C
```

- **Start delimiter:** 7E
- **Length:** 00 16 (22)
- **Frame type:** 11 (Explicit Addressing Command Frame)
- **Frame ID:** 1D (29)
- **64-bit dest. address:** 00 13 A2 00 40 AE B9 8E
- **16-bit dest. address:** FF FE
- **Source endpoint:** 00
- **Dest. endpoint:** 00
- **Cluster ID:** 00 32
- **Profile ID:** 00 00

Send frames

Name	Type

Send a single frame

Send sequence

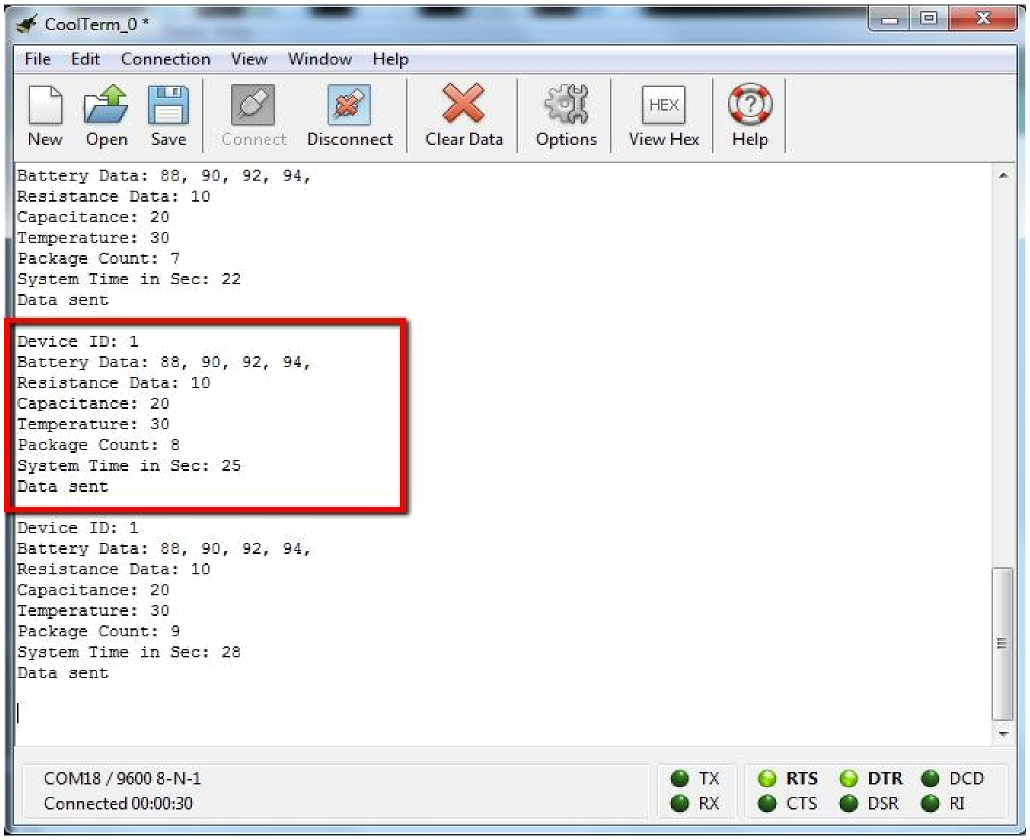
Transmit interval (ms): 500
Repeat times: 1
Loop infinitely

Discovering network of ...20040AD58EB

Figure 10. Three XBee Series 2 connected to each other, and data transmitted in API mode

2.2 Arduino programming codes for coordinator and routers

There are two Arduino programming codes for coordinator and routers. Routers perform mission operations with implemented modules and collect measured values, and then they transmit the values in API mode with “uint_8” data type. A coordinator receives the transmitted data and converts to an Iridium packet data type (see Appendix A for example Arduino programming codes). Figure 11 and 12 are outputs of routers and coordinator transmissions.


CoolTerm_0 *
File Edit Connection View Window Help
New Open Save Connect Disconnect Clear Data Options View Hex Help

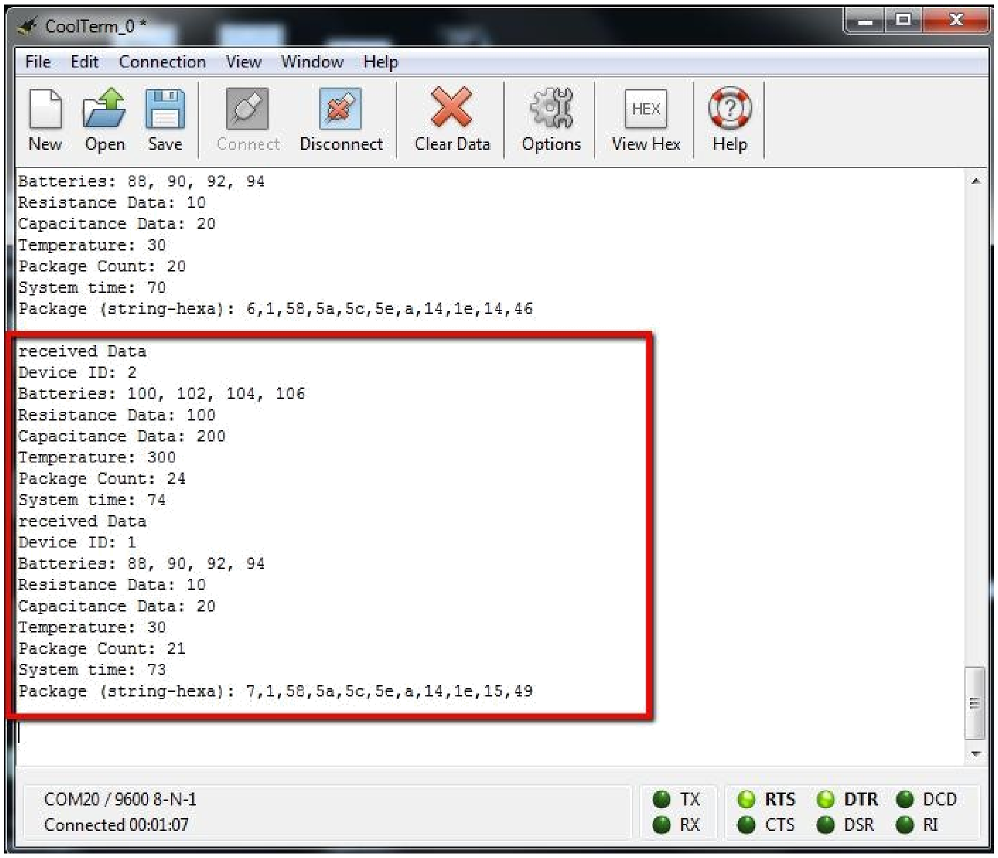
```
Battery Data: 88, 90, 92, 94,
Resistance Data: 10
Capacitance: 20
Temperature: 30
Package Count: 7
System Time in Sec: 22
Data sent

Device ID: 1
Battery Data: 88, 90, 92, 94,
Resistance Data: 10
Capacitance: 20
Temperature: 30
Package Count: 8
System Time in Sec: 25
Data sent

Device ID: 1
Battery Data: 88, 90, 92, 94,
Resistance Data: 10
Capacitance: 20
Temperature: 30
Package Count: 9
System Time in Sec: 28
Data sent
```

COM18 / 9600 8-N-1
Connected 00:00:30

Figure 11. Router XBee transmitted data to other devices on same network


CoolTerm_0 *
File Edit Connection View Window Help
New Open Save Connect Disconnect Clear Data Options View Hex Help

```
Batteries: 88, 90, 92, 94
Resistance Data: 10
Capacitance Data: 20
Temperature: 30
Package Count: 20
System time: 70
Package (string-hexa): 6,1,58,5a,5c,5e,a,14,1e,14,46

received Data
Device ID: 2
Batteries: 100, 102, 104, 106
Resistance Data: 100
Capacitance Data: 200
Temperature: 300
Package Count: 24
System time: 74
received Data
Device ID: 1
Batteries: 88, 90, 92, 94
Resistance Data: 10
Capacitance Data: 20
Temperature: 30
Package Count: 21
System time: 73
Package (string-hexa): 7,1,58,5a,5c,5e,a,14,1e,15,49
```

Figure 3. Coordinator XBee received data package from two other routers at the same time frame

2.3 Mesh network routing test

The most attractive advantages of WMN are load balance and fail-over on a data transmission system. In other words, WMN can provide alternative routing paths when one of them failed to transmit data packages to the coordinator. This section describes a configuration setting of WMN fail-over simulation.

A coordinator is configured with unique PAN ID, and this ID must be provided to all routers. Both routers can be connected to each other and may even join to the coordinator directly as configured on previous section. In this routing test, one of two routers will only be connected to the other one and will not be directly connected to the coordinator for certain period.

There are certain steps to set up the routing test environment. First of all, a coordinator is powered up with unique PAN ID; this should be provided to both of routers. As soon as one of the routers is powered up, there will be a two-way connectivity between the coordinator and first router. Then the coordinator should be powered down. And then when second router is powered up, there will be a two-way connectivity between two routers, but no connectivity between routers and coordinator. Lastly, the coordinator needs to be powered up again. As figure 13 shows, second router is not connected to the coordinator and will search for the coordinator destination address.

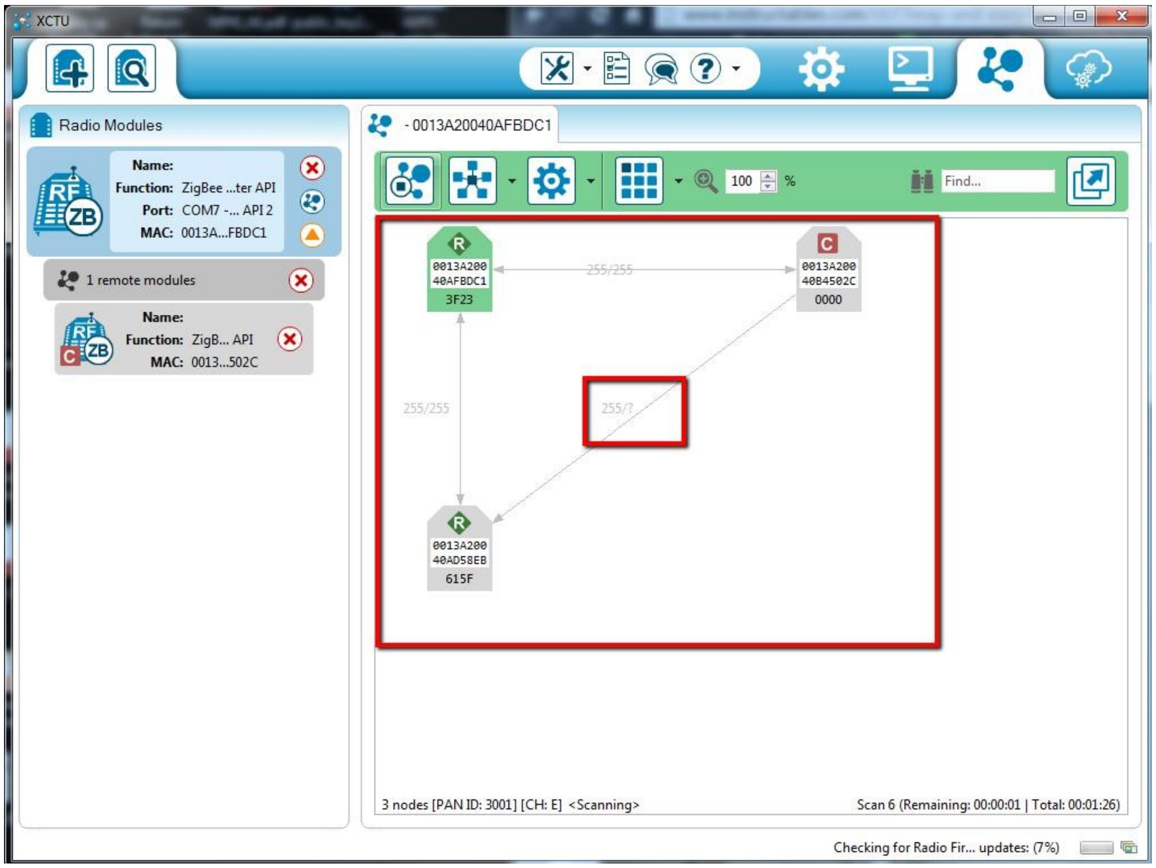


Figure 43. Mesh network routing test

3. XTend 900 for level-2 communication

Ahmed (2012) describes XTend-900 device has an incredible wide range up to 40 miles with the low-power consumption rates; indoors it can go up to 3000ft. And this has an attached RP-SMA antenna connector and uses Frequency Hopping Spread Spectrum to avoid interference by moving to new frequency on every packet transmission. This transmits data among small satellites until the maximum capable range.

C. Iridium Link Budget

A link budget is actually accounting of simple calculation of gains and losses within an RF link. The result is an estimate at the end of system performance. A number of factors must be considered for an accurate value, such as the uplink power amplifier gain, noise factors, transmit antenna gain, slant angles, atmospheric loss over distance, satellite transponder noise levels, etc (Larson, 2005).

Link budget needs the following information (Dey, 2014):

• Latitude and longitude of the uplink and downlink earth stations

• Planned data or information rate

• Modulation type (BPSK or QPSK)

• Forward error correction rate (1/2 or 3/4)

• Spread Factor - if any (use only for spread spectrum systems)

• Uplink and Downlink frequencies

• Uplink and Downlink antenna sizes

• Uplink and Downlink antenna efficiency

• Uplink and Downlink transmit and receive gains at frequency

• Minimum digital signal strength (EB/No) for desired Bit Error Rate (BER) performance

Link budget calculation involves (Dey, 2014):

• To minimize the cost of spacing one satellite in the proper channel in space for better Communication

• To respond to the real-world problem by proposing effective power calculation

• To control the satellite orbiting in the range of our requirements

• Losses control

• Equivalent isotropic radiated power (EIRP) Calculation

• FSL calculation

• Carrier to noise ratio calculation

• BER (Bit Error Ratio) performance

  • The losses experienced by the signal fall within these categories:
  • Free Space Loss (FSL)
  • Rain
  • Oxygen
  • Antenna Misalignment

In link budget calculation, the carrier-to-noise ratio (C/N) is a measurement of the received carrier power relative to the strength of the received noise. Here is the equation how to calculate for C/N.

a) The Received carrier power is

= _ * _ = (1)

b) Transmit gain is

(1)

c) Footprint area can be derived from Transmit gain equation.

= *

(2)

d) Receive gain is

=

e) Receiver equivalent area is

=

(3)

f) The equation of EIRP is

(5)

g) Free space loss is

= � �

(4)

h) Received carrier power is

� �

= = =

� �

(5)

i) Thermal noise power in bandwidth B

(6)

== (7)

Where the spectral noise density is

= (8)

j) The system temperature *T* and Boltzmann's constant is

= .⁻ / (9)

$[\ \ ] = -228.6$ dBW K Hz

k) Carrier to noise ratio

$\_ = \quad \_\_\_\_\_\_$ **(10)**

l) Carrier to noise density ratio

$\_\_ = \_ = \quad \_\_\_\_\_$ **(11)**

Then the link budget equation is expressed in logarithmic (dB) form as follows (dB values indicated by brackets):

Uplink budget:

$\_\_� = [] + � \quad \_� - [\ \ ] - [\ \ ] - [\ \ ] - [\ \ ]$ **(12)**

Downlink budget:

$\_\_� = [] + � \quad \_� - [\ \ ] - [\ \ ] - [\ \ ] - [\ \ ]$ **(13)**

Total link budget:

$\_ = \_ + \_$

� � � � � � **(14)**

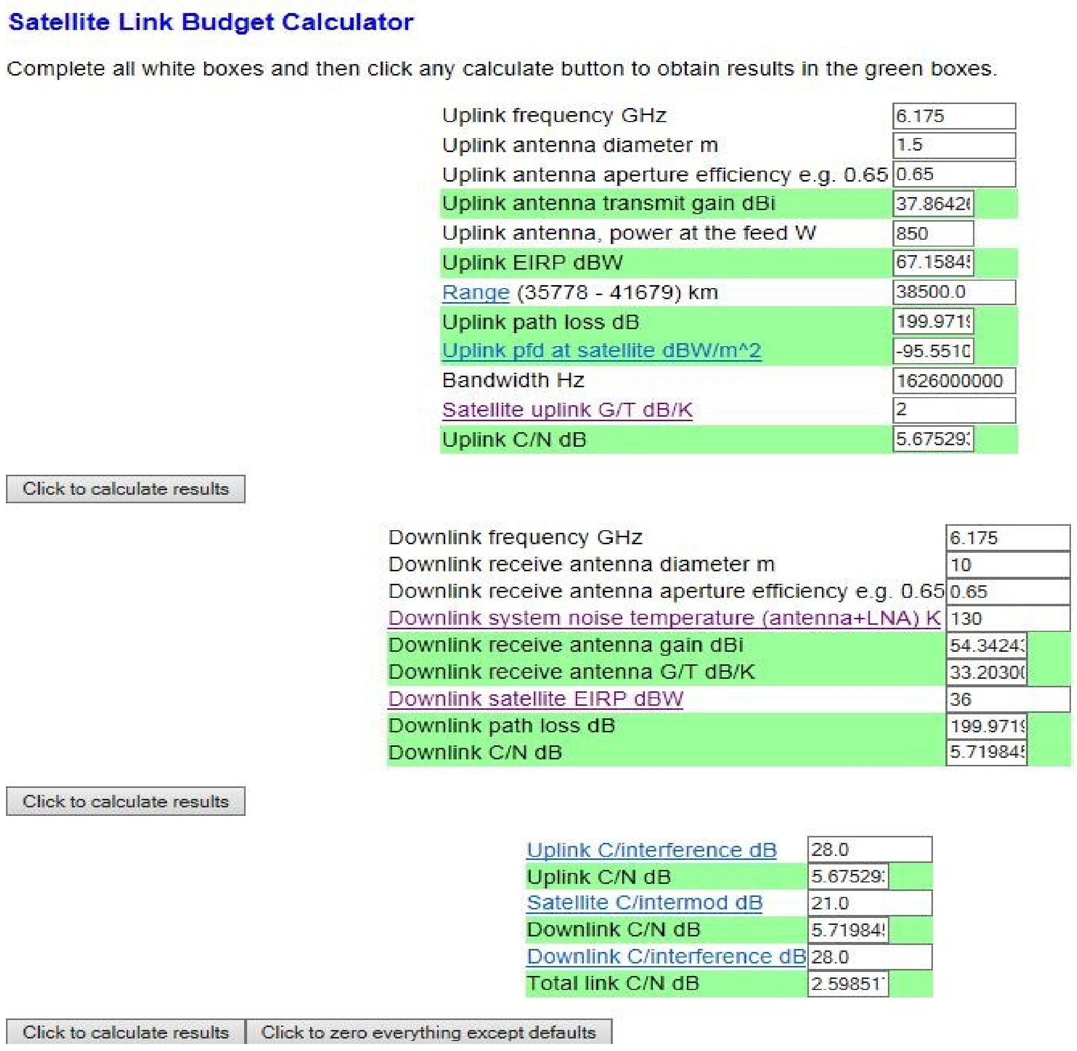
In this paper, a standardized Satellite Link Budget software tool is used for performing all of the relevant calculations based on given parameter specification in Table 7.

Table 7

Iridium Link Budget parameter specification

Parameter	**Specification**
Bandwidth	1626 MHz
Uplink frequency	6.175 GHz, C-band
Uplink antenna diameter	1.5 m
Uplink antenna aperture efficiency	0.65
Uplink antenna power	850 W
Range	38500 km
Uplink G/T	2
Downlink antenna diameter	10 m
Downlink noise temp.	130 K
Downlink EIRP	36 dBW

Note. These are arbitrary values based on the options of antennas, bandwidth, ranges etc.


Satellite Link Budget Calculator

Complete all white boxes and then click any calculate button to obtain results in the green boxes.

Uplink frequency GHz	6.175
Uplink antenna diameter m	1.5
Uplink antenna aperture efficiency e.g. 0.65	0.65
Uplink antenna transmit gain dBi	37.8642
Uplink antenna, power at the feed W	850
Uplink EIRP dBW	67.1584
Range (35778 - 41679) km	38500.0
Uplink path loss dB	199.971
Uplink pfd at satellite dBW/m^2	-95.5510
Bandwidth Hz	1626000000
Satellite uplink G/T dB/K	2
Uplink C/N dB	5.67529

Downlink frequency GHz	6.175
Downlink receive antenna diameter m	10
Downlink receive antenna aperture efficiency e.g. 0.65	0.65
Downlink system noise temperature (antenna+LNA) K	130
Downlink receive antenna gain dBi	54.3424
Downlink receive antenna G/T dB/K	33.2030
Downlink satellite EIRP dBW	36
Downlink path loss dB	199.971
Downlink C/N dB	5.71984

Uplink C/interference dB	28.0
Uplink C/N dB	5.67529
Satellite C/intermod dB	21.0
Downlink C/N dB	5.71984
Downlink C/interference dB	28.0
Total link C/N dB	2.59851

Click to calculate results
Click to zero everything except defaults

Figure 54. Satellite link budget calculator (Johnston, E. 2015)

D. PKI technology

1. PKI Methodology

At present there isn't a standardized data transaction security protocol between small satellites and ground based control center. A failure of data protection can cause enormous damages to gov't, organization, commercial company, and even individual. I am suggesting PKI technology for securing communication between satellites and control center. Liu (2013) stated, "PKI is a well-known asymmetric key encryption methodology to protect data and provide authentication. A public key infrastructure (PKI) is the combination of software, encryption technologies, processes, and services that enable an organization to secure its communications and business transactions." The ability of PKI to secure communication and business transactions is based on the exchange of digital certificates between authenticated users and trusted resources.

You can design a PKI solution to meet the following security and technical requirements of your organization (Liu & Tuey, 2013):

- **Confidentiality**. You use PKI to encrypt data that is stored or transmitted.
- **Integrity**. You use PKI to digitally sign data. A digital signature helps you identify whether another user or process modified the data.
- **Authenticity**. PKI provides several authenticity mechanisms. Authentication data passes through hash algorithms, such as Shivest Hash Algorithm 1 (SHA1), to produce a message digest. Then the message digest is digitally signed by using the sender's private key to prove that the message digest was produced by the sender.
- **Nonrepudiation**. When data is digitally signed, the digital signature provides proof of the integrity of the signed data and proof of the origin of the data. A third party can verify

the integrity and origin of the data at any time. This verification cannot be refuted by the owner of the certificate that digitally signed the data.

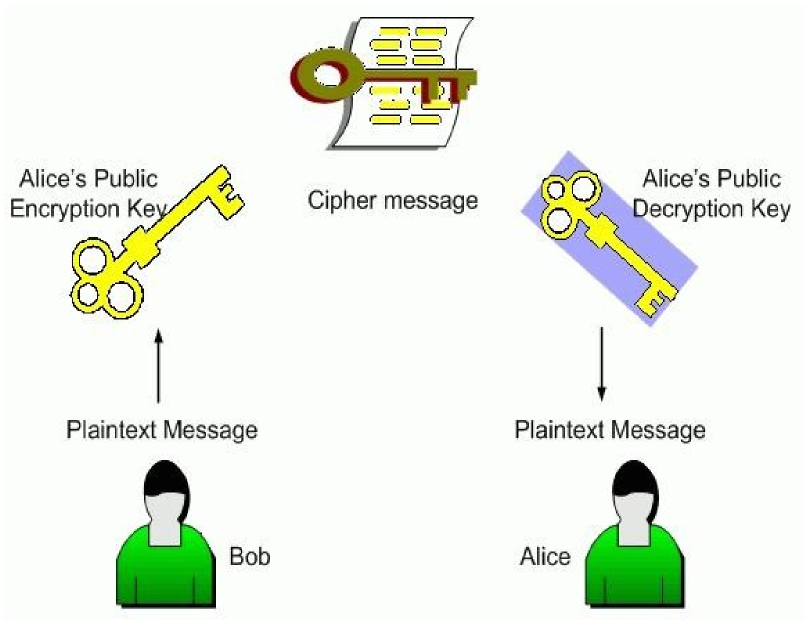


Figure 15. PKI Data confidentiality procedure. Adapted from *Zyxeltech PKI FAQ,* n.d., Retrieved April 15, 2015, from http://www.zyxeltech.de/snotezw5_362/faq/pki_faq.htm.

2. Encryption / Decryption data – RSA cryptography

In this paper, RSA cryptography keys are used since RSA is widely deployed in the current market and has better industry support. According to Symantec National PKI (2009), "By employing the right mix of authentication, encryption, and digital signatures, governments can significantly reduce the risk of forgery, theft, or abuse of identification credentials." A sample codes for encryption and decryption of RSA cryptography keys is provided in Appendix C.

First, public keys are distributed to clients (satellites) on the same network from Certificate Authority. And each coordinator operating system of satellites should have both private and public keys in a file directory. Before encrypting a file with a public key, data file and public key should be in same directory; “ls -all” command can verify the information on terminal. To encrypt a data file, “Openssl” package is required. This is an open source toolkit for SSL/TLS, and this can be downloaded and installed from openssl.org site (Czeskis, n.d.). Using commands in the toolkit requires specific command usage format. An example of “Openssl” command usage format for encryption is in Appendix C.

Decryption of encrypted files has same procedure as encryption, but it requires a private key to unlock the encrypted files. Since a private key is unique one, only encrypted files can be decrypted by the corresponded private key. “Openssl” has different command usage format for decryption with specific parameters (Czeskis, n.d.). An example of using “Openssl” command usage format for decryption is in Appendix C.

IV. Discussion and Future Work

As illustrated on the preceding sections, through a number of advanced network and data security technologies, a standardized communication has been demonstrated that can be adapted to small satellite mission projects. However, there are further tasks left for future work.

Future work for the WMN and PKI system will be applied to the Modular Rapidly Manufactured Small Satellite (MRMSS) project. XBee series 2 Mesh Network discussed previously may provide a solution for data failover and load balance. PKI certificate cryptography ensures strong data protection from security threats against space mission projects. In regard to other applications, the technical feasibility for large scale of space structures is very high, and might be proved as a robust spacecraft communication system. Also, level-2 mesh network by using Xtend 900 will be tested for inter-satellites communication.

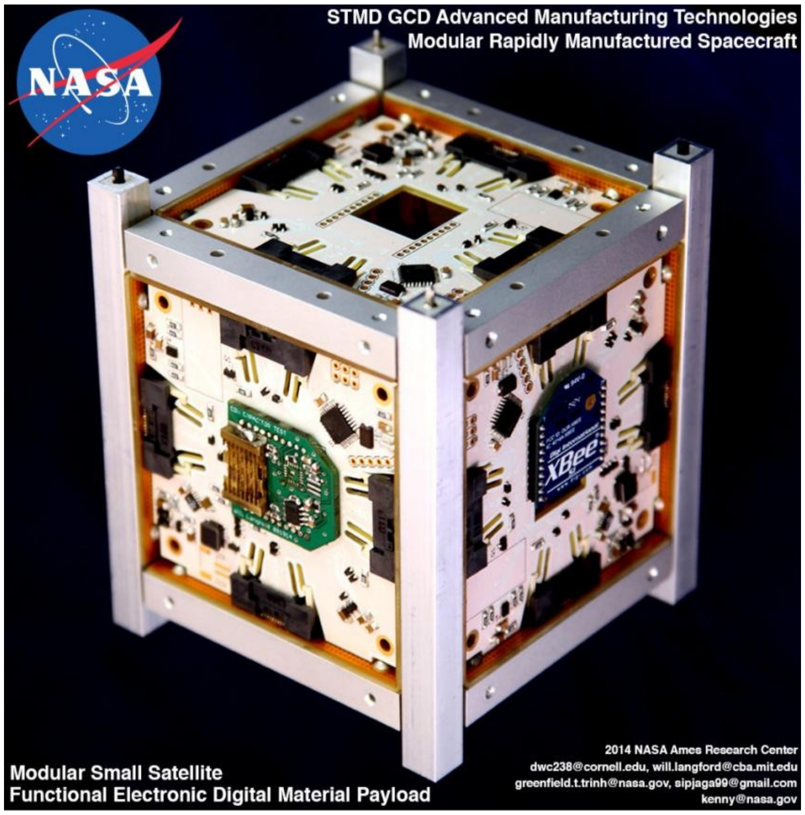

STMD GCD Advanced Manufacturing Technologies
Modular Rapidly Manufactured Spacecraft
NASA
XBee
Modular Small Satellite
Functional Electronic Digital Material Payload
2014 NASA Ames Research Center
dwc238@cornell.edu, will.langford@cba.mit.edu
greenfield.t.trinh@nasa.gov, sipjaga99@gmail.com
kenny@nasa.gov

Figure 16. The Modular Rapidly Manufactured Small Satellite (MRMSS) prototype image

V. Conclusion

A standardized network communication for small satellites that include WMN, world-wide satellite communication, and PKI technology has been proposed in this paper. 2-level of WMN has been developed with XBee Series 2 and Xtend 900. World-wide satellite communication service, Iridium, provides continuous internet accessibility for transmitting data from small satellites to ground stations. Open-source version of PKI technology for data transaction has an ability to securely protect data from satellites to ground-based users safely by using a paired key usage algorithm. In addition, RFI prevention has been included with its intended software, ComSitePro, by analyzing and measuring RFI rates into satellites.

This network communication is very efficient for low budget and mass production space mission projects with advanced features. I hope that this paper can contribute relevant information for engineers and students who are interested to develop their own satellite projects.

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VII. Appendices

Appendix A: Arduino codes for XBee Series 2 – Coordinator

```
/**********************************************************************
 *                                                                    *
 * Xbee Series 2 Wireless Mesh Network coordinator coding             *
 *                                                                    *
 * This coordinator receive arbitrary data as below from router       *
 * and build up package                                               *
 *                                                                    *
 * 1.  Device ID                                                      *
 *   2. Battery Data                                                  *
 *   3. Resistance Data                                               *
 *   4. Capacitance Data                                              *
 * 5.  Temperature Data                                               *
 * 6.  Number of Package Data                                         *
 * 7.  System Time Data                                               *
 **********************************************************************/ /*

Include library */

#include <XBee.h>

/  Declar packet String array & temp_count
String Packet;
unsigned int tlm_Packet_Count = 0;
unsigned int pack_cnt = 0;

/  Device ID variable
uint8_t device_id;

/  Multiple int
packets union packet{
uint8_t bytes[2];
  int value;
};
packet batterydata1;
packet batterydata2;
packet batterydata3;
packet batterydata4;
packet packagecount;
packet systemtime;

/  temperature, capacity, resistance
union rct_packet{
  uint8_t bytes[2];
  int value;
};
rct_packet rctData1;
rct_packet rctData2;
rct_packet rctData3;

/  XBee objects XBee
xbee = XBee();
XBeeResponse response = XBeeResponse();
ZBRxResponse rx = ZBRxResponse();
Rx64Response rx64 = Rx64Response();
Rx16Response rx16 = Rx16Response();


/  Reading data
void readingData(){

 device_id = rx.getData(0);
 Serial.print("Device ID: ");
 Serial.println(device_id);

 /  switch router 1,2
 batterydata1.bytes[0] = rx.getData(1);
 batterydata1.bytes[1] = rx.getData(2);
 batterydata2.bytes[0] = rx.getData(3);
 batterydata2.bytes[1] = rx.getData(4);
 batterydata3.bytes[0] = rx.getData(5);
 batterydata3.bytes[1] = rx.getData(6);
 batterydata4.bytes[0] = rx.getData(7);
 batterydata4.bytes[1] = rx.getData(8);
 Serial.print("Batteries: ");
 Serial.print(batterydata1.value);
 Serial.print(", ");
 Serial.print(batterydata2.value);
 Serial.print(", ");
 Serial.print(batterydata3.value);
 Serial.print(", ");
 Serial.println(batterydata4.value);

 rctData1.bytes[0] = rx.getData(9);
 rctData1.bytes[1] = rx.getData(10);
 rctData2.bytes[0] = rx.getData(11);
 rctData2.bytes[1] = rx.getData(12);
 rctData3.bytes[0] = rx.getData(13);
 rctData3.bytes[1] = rx.getData(14);
 Serial.print("Resistance Data: ");
 Serial.println(rctData1.value);
 Serial.print("Capacitance Data: ");
 Serial.println(rctData2.value);
 Serial.print("Temperature: ");
 Serial.println(rctData3.value);

 packagecount.bytes[0] = rx.getData(15);
 packagecount.bytes[1] = rx.getData(16);
 systemtime.bytes[0] = rx.getData(17);
 systemtime.bytes[1] = rx.getData(18);
 Serial.print("Package Count: ");
 Serial.println(packagecount.value);
 Serial.print("System time: ");
 Serial.println(systemtime.value);

 pack_cnt = pack_cnt + 1;
}

///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
//Function: Build Packet
//Type: Void
//
//This function constructs the packet to be sent over Iridium
//
///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
void build_packet(){

  String temp_value;

    // Assign Packet Number
    tlm_Packet_Count = tlm_Packet_Count+1;
    temp_value = String(tlm_Packet_Count);
    Packet = temp_value;
    Packet = String(Packet + ",");

    // Transfer Device ID
    temp_value = String(device_id, HEX);
    Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    /  Transfer battery usage data into Packet[]
    temp_value = String(batterydata1.value,
    HEX); Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    temp_value = String(batterydata2.value, HEX);
    Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");
    temp_value = String(batterydata3.value, HEX);
    Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    temp_value = String(batterydata4.value, HEX);
    Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    // Transfer will data into Packet[]
    temp_value = String(rctData1.value, HEX);
    Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    temp_value = String(rctData2.value, HEX);
    Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    temp_value = String(rctData3.value, HEX);
    Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    // Transfer Packet Count into Packet[]
    temp_value = String(packagecount.value,
    HEX); Packet = String(Packet + temp_value);
    Packet = String(Packet + ",");

    // Transfer System Time into Packet[]
    temp_value = String(systemtime.value, HEX);
    Packet = String(Packet + temp_value);

}

void setup()
{
    Serial.begin(9600);
    Serial3.begin(9600);
    xbee.setSerial(Serial3);
    Serial.println("Begin reading data");
}

void loop()
{
    xbee.readPacket(1000);
    if (xbee.getResponse().isAvailable())
    {
      Serial.println("received Data");

        if (xbee.getResponse().getApiId() == ZB_RX_RESPONSE)
        {
         //Read the packet
         xbee.getResponse().getZBRxResponse(rx);
         readingData();

         if (pack_cnt == 2){
           /  Build packet - convert
           build_packet();
           pack_cnt = 0;

           Serial.print("Package (string-hexa): ");
           Serial.println(Packet);
           Serial.println();
         } //packet buildup
        } // xbee.getResponse
    } // xbee.isAvailable
} // loop
```

Appendix B: Arduino codes for Xbee Series 2 - routers

```
/*************************************************************************
 *                                                                      *
 * Xbee Series 2 Wireless Mesh Network Router coding                    *
 *                                                                      *
 * This router transmits arbitrary data as below to coordinator Xbee   *
 * 1.  Device ID                                                        *
 *   2. Battery Data                                                    *
 *   3. Resistance Data                                                 *
 *   4. Capacitance Data                                                *
 * 5.  Temperature Data                                                 *
 * 6.  Number of Package Data                                           *
 * 7.  System Time Data                                                 *
 ************************************************************************/

/* Include library */
#include "Arduino.h"
#include "Wire.h"
#include "MAX1704.h"
#include "XBee.h"
#include "math.h"

/* Data package */
uint8_t packet1[19];

int num_batt = 4;
int num_pack = 0;
int charge_int = 0;
int current_time = 0;
XBee xbee = XBee();
unsigned long start =0;

/* Union type Data - for conversion of byte to int
*/ union Data{
  uint8_t bytes[2];
  int value;
};

Data batterydata;
Data resdata;
Data capdata;
Data tempdata;
Data packcnt;
Data packtime;

/* Xbee Series 2 package transmitt */
```

```
XBeeAddress64 addr64 = XBeeAddress64(0x0013A200, 0x40B4502C);
ZBTxRequest tx = ZBTxRequest(addr64,packet1, sizeof(packet1));

//TxStatusResponse txStatus = TxStatusResponse();
ZBTxStatusResponse txStatus = ZBTxStatusResponse();

//Add battery voltageData to package1
void voltageData(int charval,int cnt)
{
 batterydata.value = charval;
 packet1[cnt] = batterydata.bytes[0];
 packet1[cnt+1] = batterydata.bytes[1];

 Serial.print(batterydata.value);
}

//Add temperature, capacity, resistance to package1
void tcrData(int res, int cap, int temp)
{
  resdata.value = res;
  capdata.value = cap;
  tempdata.value = temp;

  packet1[9] = resdata.bytes[0];
  packet1[10] = resdata.bytes[1];

  packet1[11] = capdata.bytes[0];
  packet1[12] = capdata.bytes[1];

  packet1[13] = tempdata.bytes[0];
  packet1[14] = tempdata.bytes[1];
  Serial.print("Resistance Data: ");
  Serial.println(resdata.value);
  Serial.print("Capacitance: ");
  Serial.println(capdata.value);
  Serial.print("Temperature: ");
  Serial.println(tempdata.value);
}

//Add package count to packet1
void packagecount(int charval)
{
 packcnt.value = charval;
 packet1[15] = packcnt.bytes[0];
 packet1[16] = packcnt.bytes[1];

 Serial.print("Package Count: ");
 Serial.println(packcnt.value);
```

```
}

//Add System time in seconds to packet1
void systemtime(int charval)
{
 packtime.value = charval;
 packet1[17] = packtime.bytes[0];
 packet1[18] = packtime.bytes[1];

 Serial.print("System Time in Sec: ");
 Serial.println(packtime.value);
}


/  Transmit package through Xbee
void transmit()
{
  xbee.send(tx);
  if (xbee.readPacket(5000)) {
    if (xbee.getResponse().getApiId() == TX_STATUS_RESPONSE) {
      xbee.getResponse().getZBTxStatusResponse(txStatus);
      if (txStatus.getDeliveryStatus() == SUCCESS) {
        /  success. time to
        celebrate delay(3000);
      }
      else {
        /  the remote XBee did not receive our packet. is it powered on?
        //Serial.println("Reomte XBee didn't receive our packet. Is it powered on?");
      }
    } //xbee.getResponse()
  }//xbee.readPacket();
  else if (xbee.getResponse().isError()) { //"Error
  reading packet. Error code:"
  //Serial.println(xbee.getResponse().getErrorCode());
  }//xbee.getresponse().iserror()
  else {
    // local XBee did not provide a timely TX Status Response. Radio is not configured properly
or connected
  }
}//end of transmit

MAX1704 fuelGauge;

void setup(){

 Wire.begin();
 Serial.begin(9600);
 Serial3.begin(9600);
 xbee.setSerial(Serial3);
 Serial.println("Starting up...");

 fuelGauge.reset();
 fuelGauge.quickStart();
 fuelGauge.showConfig();
 packet1[0] = (uint8_t) 1; // Device ID

}

void loop(){


 Serial.print("Device ID: ");
 Serial.println(packet1[0]);
  //float charge = fuelGauge.stateOfCharge();
  /  arbitrary battery data
  float charge = 88;
  int charge_int1 = (int) charge;
  int charge_int2 = (int) charge;
  int charge_int3 = (int) charge;
  int charge_int4 = (int) charge;

 Serial.print("Battery Data: ");

  /  first package - 4 batteries int
  j = 0; // data package count for
  (int i = 0; i < num_batt; i++){

    switch(i){
      case 0:
        charge_int = charge_int1;
        j = i;
        break;
      case 1:
        charge_int = charge_int2+2;
        j = i+1;
        break;
      case 2:
        charge_int = charge_int3+4;
        j = i+2;
        break;
      case 3:
        charge_int = charge_int4+6;
        j = i+3;
        break;
      default:
        Serial.println("wrong # of switch");
```

```
   }
   voltageData(charge_int,j+1);
   Serial.print(", ");
  }
  Serial.println(" ");

  /  arbitrary resistance, capicitance, temperature data
  int resistance = 10;
  int capacitance = 20;
  int temperature = 30;
  tcrData(resistance, capacitance, temperature);


  /  number of package count
  packagecount(num_pack);

  /  system time data start =
  millis(); start = start/1000;
  current_time = (int) start;
  systemtime(current_time);


  transmit();

  num_pack = num_pack++;
  Serial.println("Data sent");
  Serial.println();
  delay(3000);
}
```

Appendix C: Encryption / Decryption Sample code in Arduino

++++++++++++ Bash script for openssl commands (cert.sh) ++++++++++++

```
#!/bin/bash

# Encrypt data file using openssl command

openssl rsautl -encrypt -inkey public_key.pem -pubin -in data.txt -out data.dat

# Decrypt the encrypted file, a private key is required.

# openssl rsautl -decrypt -inkey private_key.pem -in data.dat -out data_out.txt

#purposely not cleaning up after the program.
```

++

++++++++++++++ Python file for bash script (cert.py) +++++++++++++++

```
import os
def main():
   os.system("sh cert.sh")
if __name__=="__main__":
main()
```

++

++++++++++++++ Execute python script on Arduino code ++++++++++++++

```
#include <Process.h>

void setup() {

 Serial.begin(9600);  // Initialize the Serial

}

void loop() {

…..

Process p;

p.runShellCommand("python /mnt/sda1/arduino/www/test/do_p.py 12.0 76.0");

…..

}
```

++

Appendix D: XBee Coordinator Setting on XCTU

XBee set to work as a Coordinator.

1) The Modem Configuration.

2) Select Modem XBee according to the models used.

3) Change Firmware to ZIGBEE Coordinator API

(with models XBee XB24-ZB) or ZNET 2.5 ROUTER / END DEVICE API (with models XBee XB24-B).

4) Set the PAN (Personal Area Network) can be set as the user is assigned.

However, here I will set up a 3001.

5) Destination (destination you want. Transfer data) by setting as below:

DH = 00.

DL = FFFF.

6) Select the check mark to Always Update Firmware and then click Write.

7) Set API mode 2

*XBee defined as the Coordinator will not work in standby mode. Save energy.

Appendix E: XBee Router Setting on XCTU

XBee set to run as a Router.

1) The Modem Configuration.

2) Select Modem XBee according to the models used.

3) Change Firmware to ZIGBEE ROUTER API (with models XBee XB24-ZB) or

   ZNET 2.5 ROUTER / END DEVICE API (with models XBee XB24-B).

4) Set the PAN (Personal Area Network) will be set up as Coordinator.

5) Destination (destination you want. Transmission) and Node names by setting the following:

   DH = Coordinator SH

   DL = Coordinator SL

   NI = Node name as desired.

6) Set API mode 2